Key Points:

- We conducted structural analysis on Thrace Macula, a chaotic terrain on Europa, based on imaging and newly processed topographic data
- We found that preexisting strike-slip faults border Thrace Macula and have constrained its emplacement and areal distribution
- We provide insights into the history of Thrace and identify it as a prime location for future missions to sample fresh subsurface material

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Evolution of Thrace Macula on Europa: Strike-Slip Tectonic Control and Identification of the Youngest Terrains

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Abstract Chaos terrains are geologically young and extensively disrupted surface features of Europa, thought to be an expression of the subsurface ocean interacting with the surface. The most prominent examples of this terrain on Europa are Conamara Chaos, and Thera and Thrace Maculae, all prime targets for the upcoming JUICE and Europa Clipper missions to assess the astrobiological potential of Europa. Of the three features, Thrace Macula is currently the least studied and understood. It intersects both Agenor Linea to the north and Libya Linea to the south, two important regional-scale bands whose interaction with Thrace is yet to be fully unraveled, especially in terms of their relative ages of emplacement and activity. Using Galileo Solid State Imager data and Digital Terrain Models, we conducted detailed structural mapping and terrain analysis to develop a novel hypothesis on the mechanisms involved in the study area. We find that Thrace Macula is bordered along most sides by preexisting strike-slip faults that have constrained its emplacement and areal distribution. We determine a sequence of events in the area involving the formation of Agenor Linea, followed by that of Libya Linea first and Thrace Macula later, and ultimately by strike-slip tectonic activity likely driven by Libya Linea, that displaced a portion of Thrace Macula. Therefore, Thrace's subsurface material, uprising along faults postdating its formation, represents the freshest possible that could be sampled by future spacecraft in this region, a major consideration for the upcoming Europa Clipper mission.

Plain Language Summary Europa, an icy moon of Jupiter with a large subterranean water reservoir, has unique surface features known as chaos terrains, believed to result from interactions between its subsurface ocean and surface. Of these terrains, Conamara Chaos and Thera and Thrace Maculae are prime targets for upcoming missions to investigate the astrobiological potential of Europa. However, Thrace Macula, which is situated between Agenor Linea to the north and Libya Linea to the south (two large-scale bands, linear geological features), remains poorly understood. In this study, we used detailed mapping of faults and lineaments, together with topographical analysis, to propose a new hypothesis for the formation and evolution of Thrace Macula. Our findings suggest that preexisting tectonic faults constrained its emplacement and distribution, while a sequence of events starting with the formation of Agenor Linea, followed by Libya Linea first and Thrace Macula later, culminated in strike-slip tectonic activity likely driven by Libya Linea that displaced a portion of Thrace Macula. These results imply that future spacecraft could sample Thrace's subsurface material uplifting along faults postdating its formation, the freshest available in this region. This research sheds light on Europa's regional history and its astrobiological potential.

1. Introduction

Chaos terrains on Europa are geologically very young (Doggett et al., 2009; Figueredo & Greeley, 2004) and extensively disrupted surface features, generally consisting of blocks of preexisting terrain within a hummocky matrix material (Collins & Nimmo, 2009). On Europa, chaos is one of the major terrain types, covering ~25%–40% of the surface (Collins & Nimmo, 2009; Figueredo & Greeley, 2004). While typically considered compositionally distinct from their surroundings due to their reddish-brown color, likely from hydrated sulfates (Dalton et al., 2005) or sulfuric acid hydrate (Carlson et al., 1999), recent studies have shown that endogenous sodium chloride sourced from a subsurface ocean is probably present at some leading-hemisphere chaos regions (Trumbo et al., 2019a, 2019b, 2022). Preexisting ridged and banded terrains are disrupted by chaos at varying degrees. In some chaos regions, ridged terrain is preserved on the top of relatively intact large blocks and can be used to infer the relative degree of translation, rotation, and tilting experienced by the blocks (Spaun et al., 1999). The formation of chaos terrains on Europa has been extensively debated, with main hypotheses including diapirism (e.g., Pappalardo et al., 1998; Schenk & Pappalardo, 2004), melt-through (e.g., Greenberg et al., 1999; O'Brien, 2002), and the collapse of a melt-lens within the ice shell (e.g., B. E. Schmidt et al., 2011; Soderlund et al., 2014).

Collins and Nimmo (2009) propose a comprehensive set of both rigorous and flexible constraints for each chaos formation hypothesis, based on meticulous observations of chaos terrains. They emphasize that any chaos formation hypothesis must adequately account for several observational constraints, including the characteristics of the matrix and blocks, topographic variations, block translation and rotation, exposure of hydrated salts and/or acids, a broad range in planform size (1–1,000 km in diameter), and extensive global distribution. Similarly, the relationship between chaos and Europa's pits and domes (or lenticulae), preservation and destruction of preexisting terrains, and chaos growth through coalescence should be considered by models. It has been suggested by Leonard et al. (2018) that each of the presently proposed mechanisms for chaos formation can address only a portion of these constraints, hinting at the potential combination of mechanisms in the formation of chaos terrains. The existing uncertainty on the formation of Europa's chaos terrains, and their relatively young surface age (Doggett et al., 2009; Figueredo & Greeley, 2004; Prockter & Schenk, 2005; B. E. Schmidt et al., 2011), makes characterizing these regions critical to constrain Europa's habitability. Previous studies propose that chaos terrains are an expression of subsurface ocean-surface interactions, whether the interchange occurs via the solid, frozen transport of icy materials (e.g., Howell & Pappalardo, 2018; Johnson et al., 2017; Kattenhorn & Prockter, 2014) or through the formation, migration, and eruption of liquid water and brines (e.g., Greenberg et al., 1999; B. E. Schmidt et al., 2011) or viscous lavas (Quick et al., 2017). The exchange of material between Europa's surface and subsurface is crucial for maintaining chemical imbalances that may facilitate the emergence or continuity of habitable environments and, possibly, life (Hand et al., 2007, 2009; Vance et al., 2016). Therefore, understanding the formation of chaos terrains is a key aspect in evaluating the habitability prospects of Europa's icy shell and subsurface ocean.

The largest and most well-studied example of chaos terrain on Europa is Conamara Chaos (e.g., Carr et al., 1998; Greenberg et al., 1999; Head & Pappalardo, 1999; Schenk & Pappalardo, 2004), characterized by a quasi-circular shape and seemingly floating ice blocks (up to several km in size), standing out topographically from its lower surroundings and seeming to contain raised lower-albedo matrix "domes" (B. E. Schmidt et al., 2011; Spaun et al., 1999). Another notable instance of chaos terrain on Europa is Thrace Macula (Figure 1), slightly smaller—both in terms of areal distribution and coverage in the literature—yet still one of the largest chaos regions on Europa, easily identifiable in global-scale images due to its extensive coverage and low relative albedo (Figure 1). Centered at 46°S; 172°W in the southern trailing hemisphere of Europa, Thrace Macula intersects two prominent linear bands, namely Agenor Linea to the northwest and Libya Linea to the south. It spans approximately 220 km in the NNE-SSW direction along its major axis, with a width ranging from 25 to 60 km. The distinctive lobate margins of Thrace Macula have led to early hypotheses suggesting its formation from cryomagmas that were effusively emplaced on the surface (Miyamoto et al., 2005; Wilson et al., 1997); however, subsequent higher-resolution images from the Galileo spacecraft revealed that Thrace Macula is instead a type of chaos, a terrain characterized by significant surface disruption. Preliminary mapping of Thrace Macula conducted by Kortz et al. (2000) indicated that it did not display the pronounced fragmentation, rotation, and translation of crustal plates observed in other chaos regions like Conamara Chaos (e.g., Spaun et al., 1999). Instead, these authors also observed that the boundary between Thrace and its surrounding areas exhibits a more gradual transition compared to Conamara Chaos and is characterized by evidence of embayment. Most significantly, they noted that multiple preexisting linear features can be traced into and across the macula, indicating in situ modification. Kortz et al. proposed brine mobilization as a potential process that could explain these observations. Thrace Macula has been additionally interpreted as the outcome of disruption and darkening of the pre-existing surface caused by a thermal source (diapir or freezing liquid body) impinging from below, which might have mobilized near-surface brines leading to the formation of the dark, low-lying deposits (Fagents, 2003). Only at the margins of Thrace, there is substantial evidence of low-viscosity fluids being confined by the preexisting topography of the surrounding ridged plains (Fagents, 2003). Based on the analysis of topographic data, it appears that the interior of Thrace is situated at or slightly above the elevation of the surrounding terrain (Prockter & Schenk, 2016; B. E. Schmidt et al., 2012). Another nearby large chaos region, Thera Macula, was shown to have a very different morphology and topography, displaying large blocks of preexisting terrain and being relatively low with respect to the surrounding terrain. This has been attributed to the subsidence and disaggregation of the existing terrain, which is believed to be caused by the presence of a liquid melt lens in its immediate subsurface (B. E. Schmidt et al., 2011). Thrace Macula has also been proposed to have a similar origin while considering it as being at a later stage in such an evolutionary model and therefore being older than Thera (B. E. Schmidt et al., 2012). Therefore, the origins of Thrace Macula remain debated and overall less investigated, compared to Thera (Fagents et al., 2022).
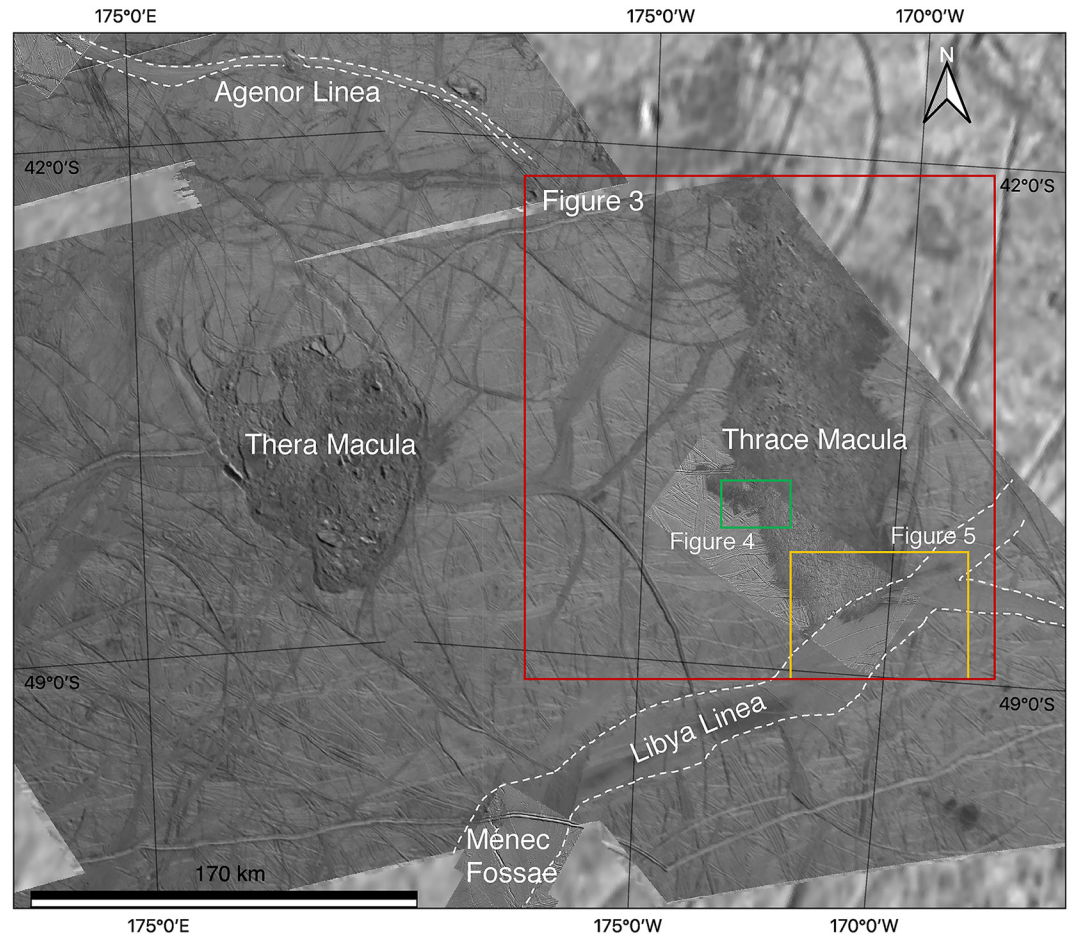
Figure 1. Regional map on photogrammetrically controlled *Galileo* Solid-State Imager (SSI) image mosaics, the red box depicts the study area, represented in Figure 3, locations of other figures are also shown. To the SW of the study area, Ménec Fossae is recognizable, while Thera Macula is located to the W. Agenor Linea is a large-scale bright band, located to the NW of Thrace Macula, while Libya Linea, a large-scale smooth band, intersects Thrace Macula at its southern tip along a SW-NE trend. The local *Galileo* SSI images 9765r, 9778r, and 9800r at the southernmost portion of Thrace Macula have ~44 m/px resolution, the surrounding regional SSI images 4413r and 4414r have ~220 m/px resolution, while the background global image mosaic has a resolution of ~500 m/px.

Given the relatively young age of these features and potential evidence of emplacement at the surface of material originating from within Europa's interior, both Thera and Thrace maculae are sites of high interest for the upcoming *Europa Clipper* mission with two spacecraft flybys over their locations planned (Lam et al., 2018). Of specific interest will be the compositional measurements by the Surface Dust Analyzer (SUDA, Kempf et al., 2014) instrument. During these low-altitude flybys, SUDA will acquire in situ mass spectra of ice grains knocked off the surface by the ambient micrometeoroid bombardment (e.g., Krivov et al., 2003) and subsequently encountered by the spacecraft. By back-tracing to their point of origin (Goode et al., 2021, 2023), compositional mapping of the chaos terrains will be possible (Postberg et al., 2011). Given its geological significance and the limited prior investigations, our study has specifically chosen to focus on Thrace Macula and its surrounding areas, in preparation for the *Europa Clipper* mission.

2. Data and Methods

Digital Terrain Models (DTMs) of the selected areas were generated using the photoclinometry (PC) technique (e.g., Schenk & Pappalardo, 2004) and the Shape-from-Shading (SfS) tool (Alexandrov & Beyer, 2018) of the Ames Stereo Pipeline (ASP, Beyer et al., 2018). The DTMs were created from *Galileo*'s Solid-State Imager (SSI) images (Belton et al., 1992), which were processed using the Integrated Software for Imagers and Spectrometers

(ISIS 4.4.0, https://isis.astrogeology.usgs.gov/7.0.0/index.html). The processing of Galileo SSI raw image data involved the utilization of SPICE smithed kernels. The processed data were then projected onto a spheroid with a radius of 1,560.800 km, corresponding to the IAU-defined mean radius for Europa. This reference height was also adopted for the DTMs generated from the processed data (Bland et al., 2021a). Background imagery in the form of photogrammetrically controlled image mosaics was employed (Bland et al., 2021b).

The PC/SfS technique is particularly valuable for Europa due to the limited availability of multiple images covering the same surface area, which is typically required for traditional stereophotogrammetry-based DTM production. In this technique, the smoothness parameter μ of the SfS tool plays a crucial role, it determines the smoothness of the resulting DTM and is influenced by surface properties. Finding optimal μ values that yield DTMs with a good signal-to-noise ratio requires a trial-and-error approach, as different values may need to be applied for each image. A detailed explanation of how μ affects the resulting DTMs can be found in Lesage et al. (2021). To ensure the quality of the DTMs, manual quality checks were performed by estimating the height (H) of features using shadow length (L) and incidence angle (α; the angle between the sun and the surface normal), where $H = L/\tan(\alpha)$ (manual quality check values shown in Table S1). The SfS tool used in this study assumes uniformity in albedo and photometric parameters across the entire image, based on the reflectance model used. Here we have chosen the Hapke reflectance model, the most commonly adopted for icy moons (Belgacem et al., 2020). Although these properties can vary at regional or local scales, the overall uncertainties in the vertical resolution of the SfS DTMs are estimated to be within the range of 10%–15%, as previously discussed in the literature (Bierhaus & Schenk, 2010; Bland et al., 2021b; Lesage et al., 2021; Schenk & Pappalardo, 2004; Schenk et al., 2020). As well as these estimated average errors, we observe another relative error, based on varying surface properties. As mentioned in Section 1, Thrace Macula exhibits a significantly lower albedo in contrast to the surrounding bright surface of Europa. Thus, the requirements (uniform surface properties) for accurate DTM reconstruction by SfS are unfulfilled. In practice, this leads the SfS algorithm to misinterpret the low albedo of Thrace Macula as shadows, putting it topographically below the surrounding bright surface. We are fully aware of this inadequacy, and thus limited the tracing of topographic profiles to either high albedo units (e.g., the ridged plains surrounding Thrace Macula) or low albedo ones (e.g., those forming Thrace Macula), without tracing "cross-albedo" profiles that could have been misinterpreted. Therefore, the DTM we produced through PC/SfS accurately represents (vertical resolution uncertainties not higher than 10%–15%, as discussed above) the topography of either the low or the high albedo parts of the study area. In addition, we performed structural mapping of the selected areas on SSI images 9765r, 9778r, and 9980r in stereographic projection (center coordinates are those at the center of Figure 1: 45.8°S; 176.4°W) using QGIS3 (QGIS.org, 2022. QGIS Geographic Information System. QGIS Association http://www.qgis.org). The resolution of these image frames was approximately 44 m/pixel, resulting in a nominal map scale of 1:88,000. Linear structural features, including faults, were identified by analyzing distinctive morphological characteristics such as scarps and lateral offsets. This analysis was complemented by examining the topography derived from the DTMs. The structural mapping was also conducted on the regional SSI images 4413r and 4414r (~220 m/px resolution) and the global image mosaic (~500 m/px resolution). The scientific color map *batlow* (Crameri, 2021) is used in the DTM presented in this study to prevent visual distortion of the data and exclusion of readers with color-vision deficiencies (Crameri et al., 2020).

3. Results

Within the study area, we produced high-resolution DTMs of the 9765r, 9778r, and 9980r SSI image frames (Figure 2) using the PC/SfS technique described in Section 2.

We identified and mapped several lineaments in the surroundings of Thrace Macula (Figure 3). As some structural and geomorphological mappings of this area had already been conducted (Kortz et al., 2000; Prockter & Schenk, 2016), we focused our study on mapping those lineaments that either (class 1) display clear lateral offsets of preexisting features, that is, strike-slip faults, or (class 2) those features that can be related to major strike-slip structures. We analyzed both high-resolution *Galileo* SSI images (9765r, 9778r, and 9800r; ~44 m/px) at the southernmost portion of Thrace Macula and the low-resolution 4413r and 4414r (~220 m/px) SSI images. The lower resolution of the latter images limited the accuracy of the analysis, but major lineaments' trends are still identifiable. Our geomorphological interpretation of different units within the high-resolution images' area is based on the detailed geomorphological map of Prockter and Schenk (2016).

The structural mapping we conducted is displayed in its entirety in Figure 3, subsequent figures (Figures 4 and 5) contain details of selected areas. We identified ~100 segments of lineaments that fit our classifying criteria of
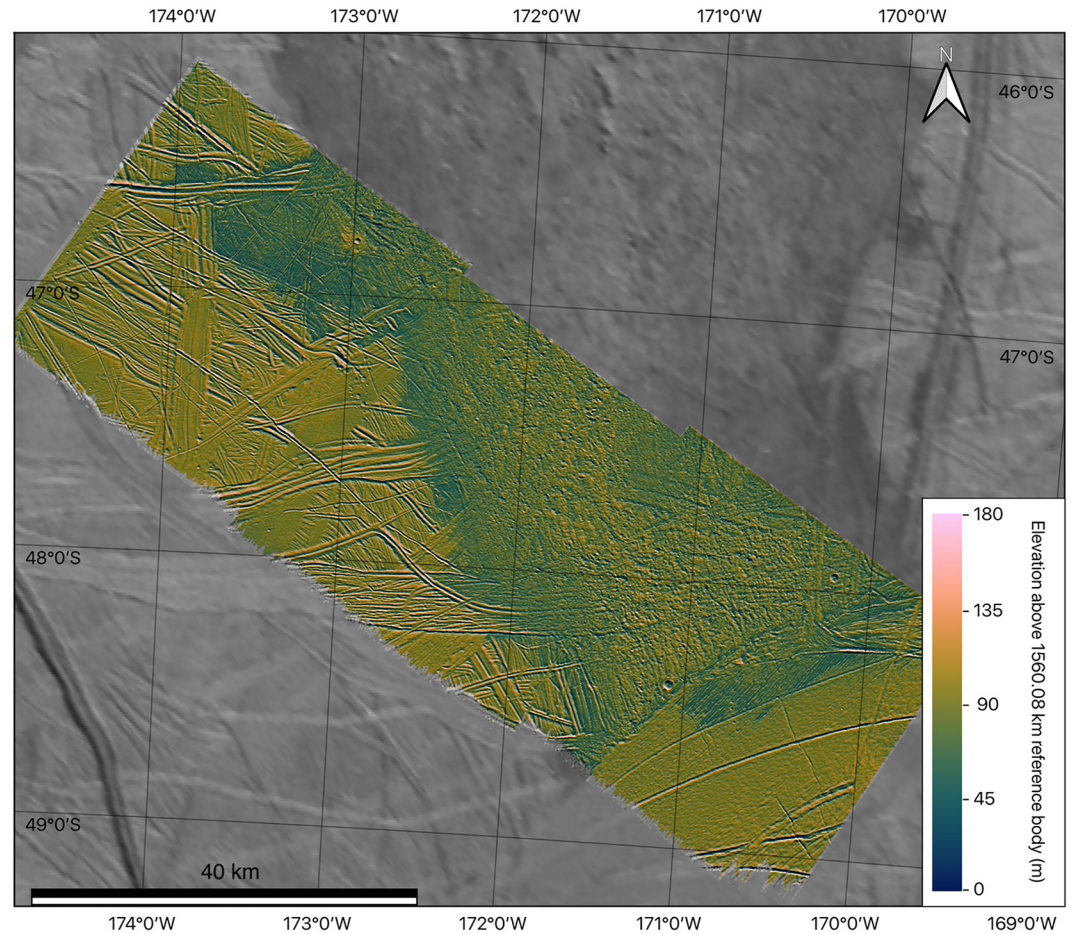
Figure 2. Regional Digital Terrain Model (DTM) of the southern portion of Thrace Macula, individual DTMs are of 9765r, 9778r, and 9800r *Galileo* Solid-State Imager image frames, later mosaicked together. The DTM has a smoothness parameter (μ) value of 0.001 for each image frame. Image centered at 47.5°S; 172°W.

either (class 1) displaying clear lateral offsets of preexisting features, that is, strike-slip faults, or (class 2) those features that can be related to major strike-slip structures.

Developing from the NW of the mapped area and originating from the eastern tip of the bright band Agenor Linea, four of these lineaments (numbered 1–4 in Figure 3) are easily interpreted as falling in the second class, as discussed in detail in Section 4. These extend across the mapped area for several hundred km, in a roughly NW-SE trend, becoming indistinct where they intersect Thrace Macula while being again clearly distinguishable where they are not overlapping with Thrace and seem to terminate at the SE of the mapped area.

In the northern part of the mapped area, several other lineaments intersect Thrace Macula at various locations, also becoming indistinct and altered. Among these, one displays lateral offsets up to 6,500 m (45.5°S; 175.5°W, Figure 3), while another lineament, which displays clear lateral offsets outside the mapped area to the north, borders Thrace Macula at its north-easternmost extent (very low-resolution imaging, but the contact is still distinguishable, Figure 3 from 43°S; 173°W to 45.8°S; 173.2°W), continues toward the south at the center of Thrace, and ultimately terminates bordering it to the west (45.8°S; 173.2°W). All these features, therefore, fall into the first class of our criteria.

Within the high-resolution images 9765r, 9778r, and 9800r, covering the southern tip of Thrace Macula, we could identify several features that fall into our first class (i.e., those lineaments classified as strike-slip faults). Some of these lineaments have indeed lateral offsets of 1,800 m (47.3°S; 173.2°W, Figures 3 and 4a), 10 km (45.2°S; 169°W, Figure 3), 600 m (48.4°S; 172°W, Figures 3 and 5a), and 8,500 m (47.3°S; 174.2°W, Figure 3). One ridged band displaying a 60–70 m deep trough (Figure 4b, topographic information from DTM; geomorphological units
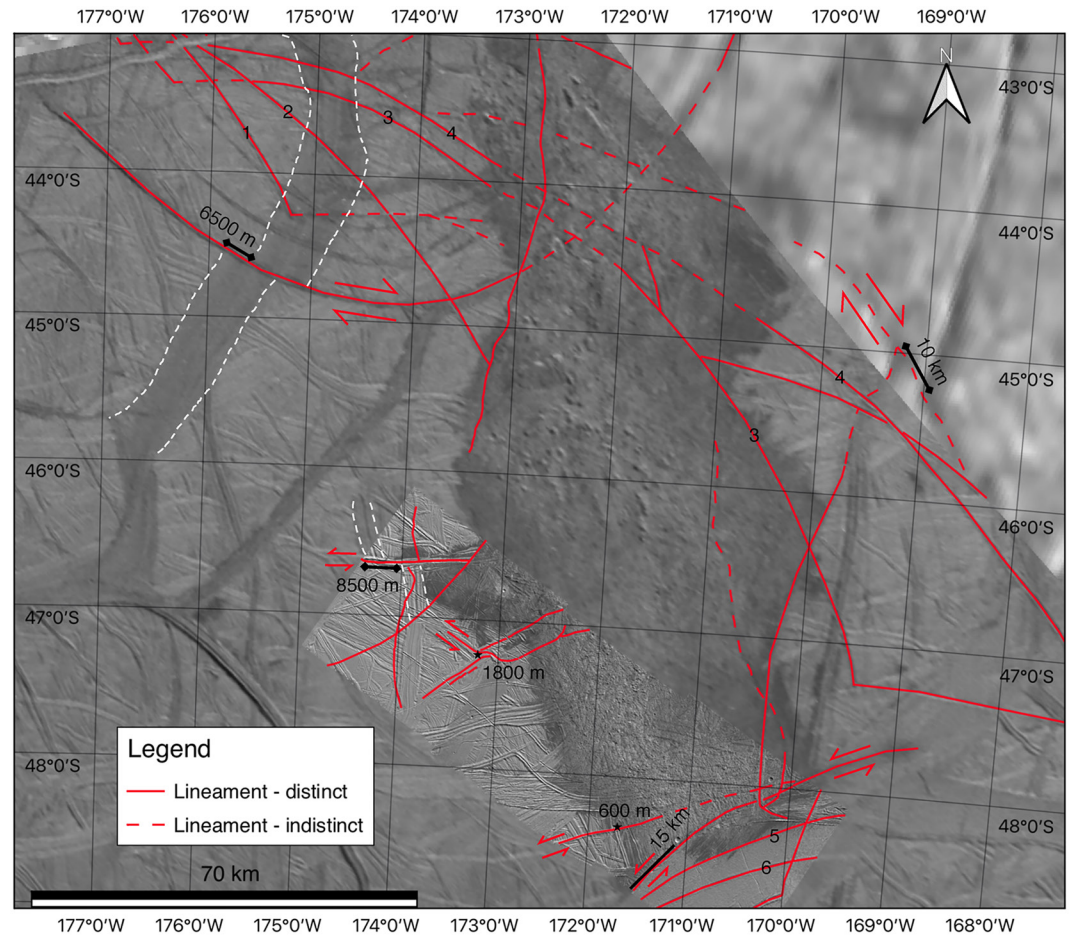
Figure 3. Selected mapping of lineaments, in the area of Thrace Macula, as shown by the red rectangular inset in Figure 1. The lineaments either display (class 1) clear lateral offsets of preexisting features, that is, they are strike-slip faults, or are (class 2) features that can be related to major strike-slip structures. Class 2 lineaments are numbered (1–6) in the figure. Among them, features 1–4 represent tailcracks, secondary tension fractures, formed at Agenor Linea's eastern tip, see Section 4. Thrace Macula is bordered along most sides by linear strike-slip features. Some measured offsets are shown, and arrows indicate the sense of motion where determinable. Various smaller-scale areas are shown in subsequent figures (Figures 4 and 5, locations shown in Figure 1).

from Prockter & Schenk, 2016) crosscuts at a left bend another ridged band, with measurable left-lateral displacement of 1,800 m (Figure 4a, 47.3°S; 173.2°W). Along the latter feature, some very small-scale transtensional features (probably pull-apart basins—i.e., basins generated in transtensional tectonic settings; e.g., Gürbüz, 2010) are present (around 47.5°S; 173.3°W, Figure 4b), suggesting its likely strike-slip nature, even though lateral offsets are not clearly identifiable along it. Around 48.4°S; 172°W, one ridge-like fault (Kattenhorn, 2004) crosscuts several other features with a constant left-lateral offset of 600 m and then continues toward the NNE into Thrace Macula (48.4°S; 172°W, Figure 5a), becoming extremely altered and almost unidentifiable. From relative offset directions, we can infer a left-lateral movement along it.

Toward the boundaries of Thrace Macula, smooth dark material embays low-lying areas and is commonly confined by topographic obstacles. This effect is most evident at the NW edge of the high-resolution images (between 46.5°S; 174°W and 47°S; 173°W, Figure 2), at 47.3°S; 172.8°W (Figure 4), and along the contact Thrace-Libya Linea (around 48.4°S; 170.5°W Figure 5a), whose other observed characteristics are hereafter described.

At the southernmost portion of Thrace, several structures depict its complex interaction with the smooth band Libya Linea, against which parts of Thrace truncate abruptly (Figure 5a). The contact between these two very different terrains is sharp and occurs along a curved line, with dark material only present close to the contact
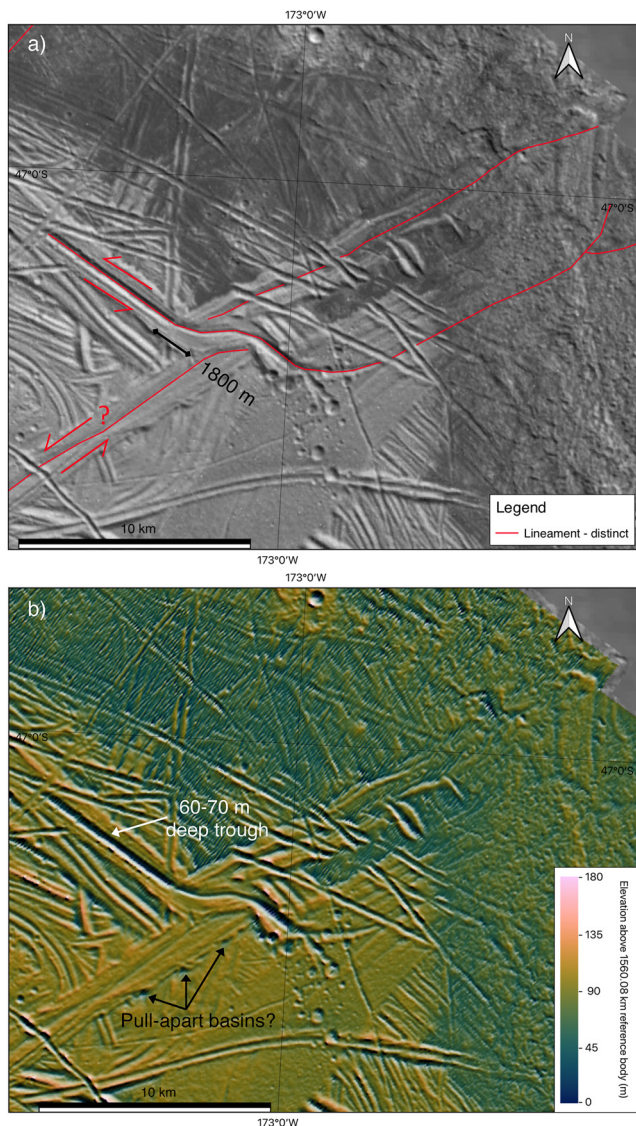
Figure 4. Inset contained within the green rectangle in Figure 1. (a) Interaction of different structural lineaments belonging to distinct tectonic regimes. A lateral offset of ~1,800 m is present, generated by a NW-SE oriented sinistral strike-slip ridged band, onto an older NE-SW oriented ridged band. The morphology of the smooth dark material at the center of the figure is an example of embayment and confinement by topographic obstacles, described in Section 3. (b) Topographic data derived from Digital Terrain Model (DTM). We infer the presence of at least three small pull-apart basins, related to the NE-SW oriented lineaments. The multiple parallel lines present, particularly in the northern part of the image, represent artifacts of the DTM, which have been reduced to the minimum possible extent but could not be completely removed.

in the central and northern parts of the high-resolution image 9800r, while being absent along the southern portion of the contact. The curved lineament marking the contact between Thrace Macula and Libya Linea continues to the NE for several additional km, around which dark material can be seen (white dashed line in Figure 5b).

We interpret this phenomenon as being related to a left-lateral strike-slip fault that represents the contact between Thrace Macula and Libya Linea (indicated as 1 in Figure 5a), with a ~15 km lateral offset (Figure 6). Some additional lineaments (indicated as 2 and 3 in Figure 5a), subparallel to fault 1, are present within Libya Linea. Yet, it is not possible to infer their nature, as no clear lateral displacement is visible, and no other tectonic indicators are present. However, the patch of dark material (centered at 48.4°S; 170.5°W, indicated as 4 in Figure 5a) stops abruptly at the contact with lineament 2, except for a very small patch present to the south of lineament 2 (Figure 5a). Within the low-resolution images, along the eastern part of the Thrace Macula-Libya Linea contact, a 26 km extensional displacement with a minor lateral component (i.e., likely a transtensional motion) is clearly identifiable between two portions of a low albedo double ridge (centered at 48.5°S; 169.5°W, yellow dashed line in Figure 5a).

Another lineament (indicated as 5 in Figure 5a) seems to crosscut all the above-mentioned features. Even if its northernmost extent corresponds with the edge of the high-resolution image 9800r, which complicates the interpretation, lineament 5 does not appear to continue further north in the corresponding low-resolution image. This lineament has the morphological characteristics of a ridge and the structures formed at its southern tip are identifiable as tailcracks, curved secondary tension fractures generated at the tip of slipping interfaces and faults. Tailcracks oriented clockwise from the tip indicate dextral shearing, while those oriented counterclockwise from the tip indicate sinistral shearing (Kattenhorn, 2004; Kattenhorn & Marshall, 2006). In the present case, tailcracks are formed at an angle of 70.5° in a clockwise orientation with respect to the strike of the fault and therefore indicate a right-lateral relative movement for their parent feature (Kattenhorn, 2004; Prockter et al., 2000).

4. Discussion

Strike-slip tectonic settings are commonly observed on Earth (e.g., Donzé et al., 2021). Similar tectonic features have also been documented on other terrestrial planets, including Mars (e.g., Mars, Andrews-Hanna et al., 2008; G. Schmidt et al., 2022), as well as on ocean worlds such as 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). Europa, too, exhibits several examples of strike-slip structures, such as along Agenor Linea in the southern trailing hemisphere and Astypalaea Linea in the south polar region (Hoyer et al., 2014; Kattenhorn, 2004; Prockter et al., 2000; Tufts et al., 1999, 2000). The identification of strike-slip faults on Europa has also revealed that certain fractures in the ice shell are not primarily caused by global tidal stresses but rather by lateral motions along strike-slip faults. These curved secondary tension fractures are termed tailcracks (see Section 3) yet sometimes also indicated as wing cracks, kinks, or horsetail fractures (Kattenhorn, 2004; Kattenhorn & Marshall, 2006; Prockter et al., 2000). Agenor Linea, a prominent bright band located in Europa's southern hemisphere (Figure 1), extends for approximately 1,500 km. This distinctive feature has experienced significant offset, with displacements reaching up to 20 km, and its current configuration may have been influenced by a complex history involving both strike-slip and dilational motion (Hoyer et al., 2014; Prockter et al., 2000). At
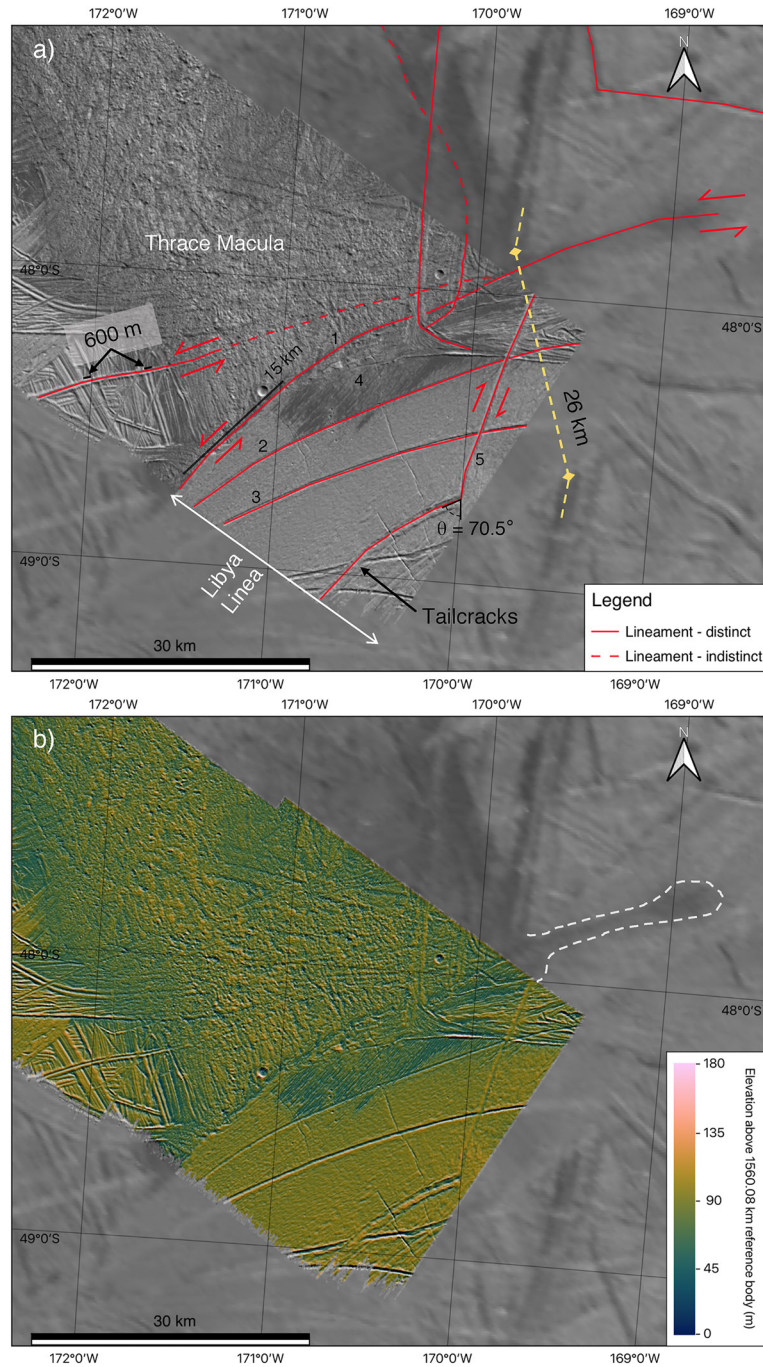
Figure 5. Inset contained within the yellow rectangle in Figure 1, depicting the transitional area between the chaos terrain Thrace Macula and the smooth band Libya Linea. (a) Annotated structural map. The presence of a left-lateral strike-slip fault along the contact between Thrace Macula and Libya Linea (indicated as 1) suggests that such tectonic activity has displaced a portion of Thrace, as dark material (centered at 48.4°S; 170.5°W, indicated as 4) most likely originating from Thrace (along with other features belonging to Thrace present along the contact) is displaced by ∼15 km from the SW toward the NE. Such tectonic event is likely driven by Libya Linea's dynamics (see Section 4). Some additional lineaments (indicated as 2 and 3) subparallel to fault 1 are present within Libya Linea, yet it is not possible to infer their nature as no clear lateral displacement is visible, nor other tectonic indicators are present. However, the patch of dark material indicated as 4 stops abruptly at the contact with lineament 2, except for a very small patch present to the south of it. The lineament indicated as 5 displays tailcracks formed at an angle of 70.5° in a clockwise orientation with respect to the strike of the fault, which indicate a right-lateral relative movement for their parent feature (see Section 3). A 26 km extensional displacement with a minor lateral component (i.e., likely a transtensional motion) is present between two portions of a low albedo double ridge (centered at 48.5°S; 169.5°W, yellow dashed line). (b) Topographic data derived from Digital Terrain Model. The white dashed line highlights the dark material patch located to the NE of Thrace Macula, along fault 1. The highlighted area likely represents fresh subsurface material originating from Thrace that has infiltrated along fault 1 and spread on the surface (see Section 4).
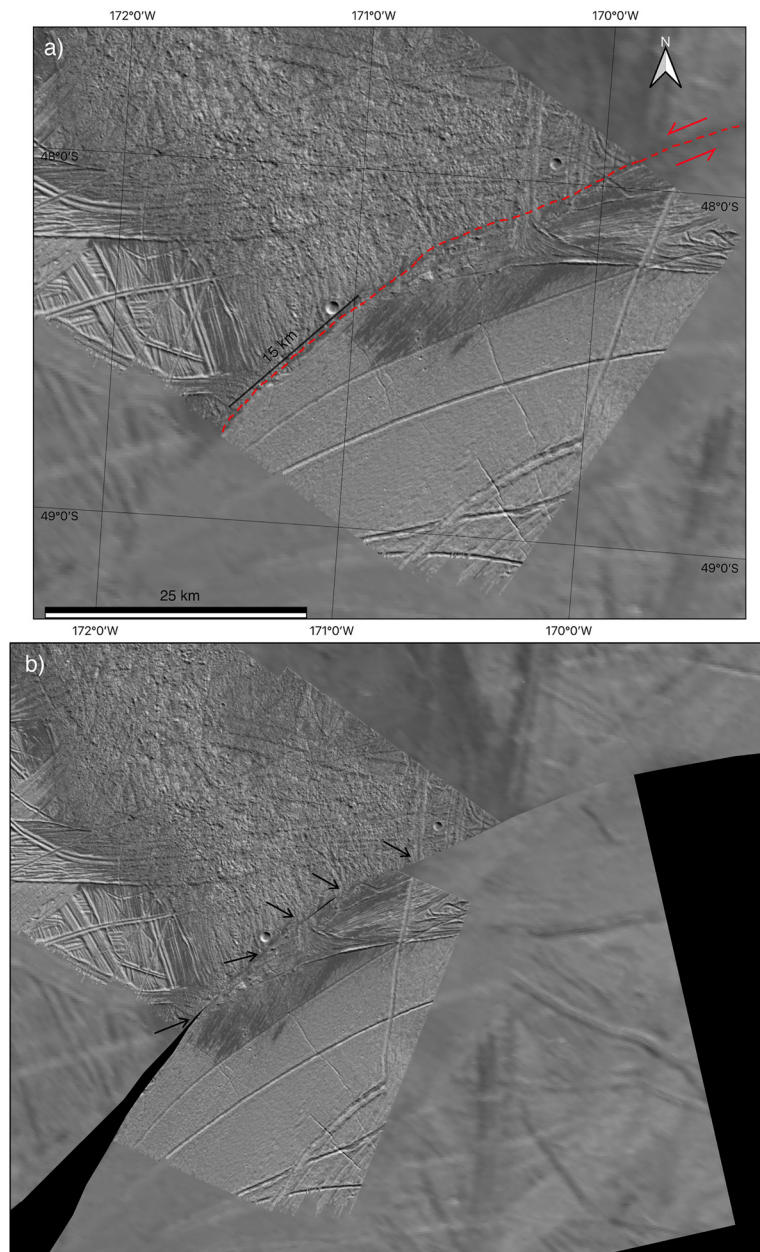
Figure 6. Location corresponding to Figure 5. (a) Geological setting at the time of data acquisition around the contact between Thrace Macula and Libya Linea. Left-lateral strike-slip fault trace (fault 1 in Figure 5a) shown as a dashed red line, with 15 km displacement (see Figure 5a for a detailed structural interpretation). (b) Reconstruction of geological setting before proposed fault 1 onset (corresponding to the third stage of the sequence of events described in Section 4). Black arrows mark some of the points where the two sides of the fault show the best match.

its eastern tip, Agenor Linea displays a distinctive feature of at least six pronounced, curved trough-like tailcracks extending toward the southern direction, indicating right-lateral strike-slip motion (Kattenhorn, 2004; Kattenhorn & Marshall, 2006; Prockter et al., 2000). In Figure 3, some of the numbered (1–4) linear features bordering and intersecting Thrace Macula are the southern continuation of these tailcracks, which demonstrates their strike-slip origin. At locations where these tailcracks intersect Thrace, the latter always crosscuts and disrupts them, proving Thrace's relatively younger age in comparison to the tailcracks and Agenor Linea, from which they originate.

The boundaries of chaos terrains are often accompanied by the presence of smooth, dark deposits. The edges of Thrace Macula indeed exhibit low-albedo material that has characteristics such as embayment, confinement

by topography, and lobate morphologies (Fagents, 2003). The origin of these dark deposits, whether they result from subsurface liquid or the sublimation of bright surface frosts, remains uncertain (Fagents, 2003; Fagents et al., 2000). Similar dark deposits can also be observed filling the spaces between ridges around Castalia Macula, a large dark area adjacent to a chaos terrain. Analysis of a stereo DTM of that region reveals that while the dark material is confined to topographic lows, it is not completely flat, suggesting that a simple explanation of liquid pooling does not fully account for the observations. It is possible that substantial surface motion has occurred subsequently, or that the material has drained back into the interior (Prockter & Schenk, 2005).

The structural mapping we conducted led to the identification of several strike-slip faults and lineaments, bordering Thrace Macula along most sides (Figure 3). In many cases, these linear structures continue into it, although their morphologies become distinctly altered, suggesting in situ modification of background terrain by the mechanisms that formed Thrace Macula and therefore proving its relatively young age, as previously noted (Collins & Nimmo, 2009; Kortz et al., 2000; Prockter & Schenk, 2016; B. E. Schmidt et al., 2012). Moreover, in most cases, where lineaments run parallel to Thrace Macula, sharp albedo changes are present (Figures 3–5). This suggests that preexisting linear structures might act as impermeable barriers for fluids, impeding the further migration of—low albedo—partially molten materials or brines (Aydin, 2006). Therefore, preexisting linear structures likely have constrained Thrace Macula's emplacement and areal distribution, although some may be coeval with the formation of Thrace and could be the result of loading on the surface, such as at Murias Chaos (Figueredo, 2002).

At Thrace Macula's southernmost tip, our interpretation (see Section 3) of a left-lateral strike-slip fault (indicated as 1 in Figure 5a) marking the contact between Thrace Macula and Libya Linea suggests that such tectonic event has displaced a portion of Thrace as dark material (indicated as 4 in Figure 5a) most likely originating from Thrace (along with other features belonging to the macula present along the contact) is displaced by ~15 km from the SW toward the NE. We propose that such tectonic activity is likely driven by the band Libya Linea, considering its intrinsic tectonic nature. Bands are in fact, on Europa, surface features where new crustal material has intruded, formed by dilation, contraction, and/or strike-slip motions (i.e., are tectonic features) (Kattenhorn & Hurford, 2009). Therefore, bands are thought to represent a phenomenon analogous to Earth's mid-ocean ridge spreading centers (Prockter et al., 2002). Most models for bands' evolution include different stages of various tectonic regimes in a varying stress field (e.g., Hoyer et al., 2014), thus implying possible reactivation of structures (Kattenhorn & Hurford, 2009; Wesley Patterson & Head, 2010), that could also represent cases of episodic block plate tectonism (Collins et al., 2022).

Altogether, even if a comprehensive work focusing specifically on Libya Linea is not present in the literature yet, through the observations presented here and the bands' models just exposed, we reckon that left-lateral shear motion driven by Libya Linea (a large-scale tectonic feature in itself), in one deformation style among the various that likely characterized it throughout its evolution, represents the most probable cause for the onset of the strike-slip fault (indicated as 1 in Figure 5a) marking the contact between Thrace Macula and Libya Linea.

A reconstruction of the geological setting at Thrace Macula's southernmost tip before the proposed onset of fault 1 is shown in Figure 6b. This deformation event probably occurred over a relatively long period, as the structures formed are complex and the offset is substantial. The presence of the dark material along fault 1, to the NE of Thrace Macula (white dashed sketch line in Figure 5b), suggests a different behavior for those lineaments whose most recent activity postdate Thrace, in comparison to those that predate it and act as fluid barriers. Indeed, in the early deformation stages, these faults might act as conduits for fluids (Aydin, 2006). Subsurface material originating from Thrace can infiltrate along them and spread on the surface as it is unconfined (what we likely observe in the area highlighted by the dashed white line in Figure 5b). This material then represents the freshest that could be encountered and sampled by future space missions, such as *Europa Clipper*. Over time, the fault might act as a barrier for the further spreading of fluids, as previously emplaced material freezes and blocks the exchange between the surface and the subsurface (Aydin, 2006).

The presence of the lineament indicated as 5 in Figure 5a, which we interpret as a right-lateral strike-slip fault due to the orientation of tailcracks at its southern tip (Kattenhorn, 2004; Kattenhorn & Marshall, 2006) needs to be explained, to support the interpretation given above in which Thrace Macula is crosscut by a left-lateral strike-slip fault with a ~15 km offset (indicated as fault 1 in Figure 5a), whose activity is likely driven by Libya Linea. Lineament 5 seems to be present within both Thrace and Libya and to be crosscut and displaced by fault 1 (Figure 6b). However, within Thrace, lineament 5 is highly disrupted and disaggregated, suggesting its older age

in comparison to it (Figure 5). Concurrently, within Libya, it is not disrupted, and it crosscuts every other structure and lineament present, indicating its younger age in comparison to Libya, regardless of our interpretation of lineament 5 as a strike-slip fault due to the presence of tailcracks (Figure 5). It could be then argued that the two portions of lineament 5 are instead two separate lineaments formed at different times. Nevertheless, even if its northernmost observable extent corresponds to the edge of the high-resolution image 9800r and north of this area only low-resolution images are present, we could not find a continuation for lineament 5 (its portion within Libya) northern of the hypothesized fault 1 (Figure 5).

Considering all the above-mentioned observations and given the match of the two portions of lineament 5 displayed in the reconstruction shown in Figure 6b, along with that of several other portions of the Thrace-Libya contact, we favor an interpretation of lineament 5 as being continuous at the time of fault 1 onset and formed after Libya Linea (and crosscutting the lineaments and structures contained within Libya) yet predating the emplacement of Thrace Macula (which then disrupts it). Left-lateral strike-slip tectonic activity along fault 1, likely related to Libya Linea's dynamics, seems to be the most recent event in the study area, at least relative to the interaction Thrace-Libya. This interpretation seems to be the one that best fits all the above-mentioned observations, even if it is partially limited by the quality of the available data.

To summarize, we propose the following sequence of events to explain the observed complex interaction between Thrace Macula and Libya Linea:

1. Formation of the smooth band Libya Linea.
2. Imposition of lineament 5 (likely a right-lateral strike-slip fault, based on the presence and orientation of tailcracks at its southern tip), on both Libya Linea and on the area north of it that will later be occupied by Thrace Macula.
3. Emplacement of the chaos terrain Thrace Macula in a vast area comprising also the northernmost local portions of Libya Linea (testified by the presence of a dark material patch onto Libya Linea, indicated as 4 in Figure 5a) and disruption of lineament 5 by Thrace Macula (this stage of the sequence corresponds to the setting shown in Figure 6b).
4. Activation (or possible reactivation) of fault 1 as a left-lateral strike-slip fault, likely driven by Libya Linea. Fault 1 has crosscut lineament 5 and parts of Thrace Macula (among other features, the dark material patch marked as 4 in Figure 5a), dislocating by ∼15 km all these features.

Our relative age argument for tectonic activity related to Libya Linea postdating the emplacement of Thrace Macula can be further extended, with Agenor Linea now determined to be older than both these two regional-scale structures, as tailcracks originating at its easternmost tip (Kattenhorn, 2004; Prockter et al., 2000)—its most recently formed features—are always being intensely altered in correspondence of Thrace Macula and therefore predate it (Figures 1 and 3). Nonetheless, Agenor is considered to be geologically young (Hoyer et al., 2014); thus, our findings suggest that all three structures—Agenor, Libya, and Thrace—are relatively young geological features on Europa's surface.

The 26 km dilational displacement with a minor lateral offset, among two portions of a dark double ridge, immediately to the east of the contact between Thrace Macula and Libya Linea (centered at 48.5°S, 169.5°W, yellow dashed line in Figure 5a), whose direction also matches in the tectonic reconstruction shown in Figure 6b, hints either at a multistage tectonic evolution of Libya Linea with different strike-slip and extensional phases in a varying stress field (as it has been proposed for Agenor Linea, Hoyer et al., 2014; Kattenhorn, 2004) or to the fact that transtension (i.e., strike-slip motion with an extensional component, Fossen et al., 1994) has been dominant within Libya Linea at a previous stage of its evolution. An in-depth analysis of the varying tectonic setting along the whole Libya Linea would be necessary to determine which of these two hypotheses should be favored, a goal that goes beyond the scope of the present work. It is, however, worth noting that local transtension has already been observed in other parts of Libya Linea (e.g., Matteoni et al., 2023).

5. Conclusions

In summary, through the present structural mapping study, we are able to determine that:

- Several preexisting strike-slip faults and linear structures border Thrace Macula along most sides, the majority of which likely have constrained Thrace's emplacement and areal distribution.

- The stratigraphy of the most important features in this portion of Europa's surface is represented by a sequence of events involving the formation of Agenor Linea, followed by that of Libya Linea first and Thrace Macula later. Ultimately, strike-slip tectonic activity likely driven by Libya Linea displaced a portion of Thrace Macula by ~15 km.
- Thrace Macula is a relatively young feature, as was previously determined, yet some of its parts have been displaced by strike-slip tectonics. Such tectonic activity is the most recent event within the studied area that has interested Thrace. The related faults might act as conduits for (uprising) Thrace's subsurface material, which then represents the freshest possible that could be sampled by future spacecraft in this region, a major consideration for the upcoming *Europa Clipper* mission and specifically the SUDA instrument.
- Our findings are more consistent with a formation model for the chaos terrain Thrace Macula that involves slow diapiric emplacement (e.g., Figueredo, 2002; Mével & Mercier, 2007; Pappalardo et al., 1998; Rathbun et al., 1998; Schenk & Pappalardo, 2004), or brine mobilization driven by diapirism (e.g., Collins et al., 2000; Head & Pappalardo, 1999), rather than with a model involving the quicker and more recent collapse of a melt-lens (e.g., B. E. Schmidt et al., 2011).

Data Availability Statement

Galileo's SSI data used in this manuscript can be accessed from the PDS Cartography and Imaging Science Node (Thaller, 2000), while the SSI photogrammetrically corrected base map mosaics can be accessed from the USGS Astrogeology website (Bland & Lynn, 2021). The Digital Terrain Model (Figure 2) and data of the structural map (Figure 3) produced are available on the Freie Universität Berlin Repository—Refubium (Matteoni & Neesemann, 2023).

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