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Understanding the Ice-shell Evolution of Europa and Enceladus from Geomorphological
Observations and Experimental-Analogue Modeling

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of
Philosophy in Geology

by

Erin Janelle Leonard

2019

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ABSTRACT OF THE DISSERTATION

Understanding the Ice-shell Evolution of Europa and Enceladus from Geomorphological Observations and Experimental-Analogue Modeling

by

Erin Janelle Leonard

Doctor of Philosophy in Geology

University of California, Los Angeles, 2019

Professor An Yin, Chair

Although sub-surface oceans have been detected on Europa and Enceladus, two of the best studied icy satellites in the outer solar system, the birth and evolution of these oceans and their impacts on the tectonic history of the overlying ice shells remain poorly understood. One of the fundamental questions regarding Europa and Enceladus is how the apparently young surfaces, evident from a lack of impact craters, are resurfaced and how this is related to the evolution of the underlying oceans. In this dissertation, I address this question by examining the cross-cutting relationships and spatial association of key morphological features on the two satellites. The results are expressed as sets of geomorphological maps that quantify the spatial and temporal relationships of the geologic features, which can then be related to the physical states of the ice shells.

For the Europa studies, I constructed a global geologic map at 1:15M scale and the first detailed structural-geology map using the highest-resolution (~14 m/pixel) Galileo SSI images with a corresponding regional geological map for context. The main mapping results of my work include: (1) establishment of a global three-stage evolutionary model of the features on Europa's surface, and (2) recognition of a transition from distributed to discrete deformation potentially resulting from ice-shell cooling and thickening. In order to further understand how the observed morphological relationships have developed, I used a gravity-scaled physical analogue model to analyze the formation of the ridged plains, the oldest surface features visible on Europa. I performed a series of two-layer physical analogue experiments, with a brittle layer above a ductile layer. The model permits a systematic test of two competing hypotheses for the formation of the ridged plains: horizontal ice-shell compression versus horizontal ice-shell extension. With these experiments, I showed that the similarity between the experimentally generated landscape and the observed ridged plains morphology strongly favors the compression mechanism.

For the Enceladus study, I conducted a systematic investigation of high-resolution Cassini ISS images focusing on establishing regional structural relationships and the kinematics of major shear zones across the southern part of the Leading Hemisphere Terrain (LHT). The study area displays a unique morphological feature informally known as the "cratered islands" and referred to in this study as the relic cratered blocks. The blocks are characterized by isolated heavily cratered domains surrounded by younger ridged terrain that is essentially free of craters. The main finding of this work is that the relic cratered blocks have experienced vertical-axis rotation during distributed ductile strike-slip shear deformation. In order to understand how the ductile shear deformation evolved, I developed an analytical thermo-mechanical model that relates the shear strain rate of ductile deformation constrained by surface observations to the heat flow

during the formation of the deformed features. The model results indicate that the ice shell of Enceladus likely experienced several periods of intense but local heating ($> 0.3 \text{ W/m}^2$), causing ice-shell thinning, ductile flow, and local resurfacing.

By evaluating the formation mechanisms of first-order surface morphological features on Europa and Enceladus, I show that the predicted past ice-shell thicknesses on Europa and Enceladus are considerably thinner than their current values. This in turn implies that the underlying oceans may have experienced episodic development caused by the evolution of the overlying ice shell. As a result, this may have an effect on the potential habitability of the underlying oceans if the thermal and chemical environment is not stable over geologic time.

The dissertation of Erin Janelle Leonard is approved.

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- Chapter 1 -

Introduction

1.1 Introduction

Since the Voyager 1 and 2 flybys of the outer planets occurred in the 1970s and 80s, scientists have been tantalized by the idea that some icy satellites in the outer solar system could be habitable worlds that possess the key ingredients for producing and sustaining life (Reynolds et al., 1983; Mood, 1983; Reynolds et al., 1987; Squyres, 1989; Gaidos et al., 1999; Chyba, 2000; Greenberg, 2010; Russell et al., 2017). The idea of habitable ice-covered oceans was bolstered by the apparently geologically young surfaces of the moons, especially Europa in the Jovian system (Fig. 1.1; Lucchitta and Soderblom, 1982; Squyres et al., 1983a; Greeley et al., 1998; Pappalardo et al., 1999; Greeley et al., 2004) and Enceladus in the Saturnian system (Fig. 1.1; Smith et al., 1982; Plescia and Boyce, 1983; Squyres et al., 1983b; Kargel and Pozio, 1996; Kirchoff and Schenk, 2009; Crow-Willard and Pappalardo, 2015).

In order to assess the potential habitability of an icy satellite, it is necessary to identify the presence of a liquid water ocean (Hendrix et al., 2019). Sub-surface oceans were detected at Europa (Khurana et al., 1998; Kivelson et al., 2000; Zimmer et al., 2000) and Enceladus (Thomas et al., 2016) when the Galileo and Cassini spacecraft returned to the Jovian and Saturnian systems, respectively. However, because the presence and physical properties of a sub-surface ocean are linked to the overlying ice-shell, it is also key to understand how the ice-shell has evolved through time (e.g., thickness and rheology). If oceans on these worlds are short-lived or change quickly over time, they may be less conducive to producing and sustaining life (Russell et al., 2014; Vance et al., 2016).

This dissertation revolves around the mapping and analysis of surface features on Europa and Enceladus in order to further understand how the ice shells and oceans of these bodies have evolved through time. Thus, I focus on the questions:

(1) What are the resurfacing mechanisms that cause the surface of Europa and Enceladus to appear young?

(2) How has the ice-shell evolved through the visible surface history?

In this dissertation, I provide insights to the formation of surface features at the global, regional, and local scales through geomorphologic mapping and by comparing these observations to a two-layer physical analogue model. Chapters 2 and 3 focus on the geomorphological mapping for Europa at the global and local scale. Chapter 4 introduces the use of a two-layer physical analogue model to further constrain ridged plains formation on Europa and explore the implications for the state of the ice-shell. Chapter 5 shifts to Enceladus, with a structural map and analysis of features on the leading hemisphere tectonized terrain and a simple thermos-mechanical model to get at how the ice-shell may have evolved through time. Chapter 6 summarizes and synthesizes the results of the previous chapters.

Europa is one of the four main moons, or Galilean satellites, of Jupiter (Galilei, 1610). Its surface is covered in crisscrossing lineaments, and mottled terrains consisting of disrupted surface known as chaos (Fig. 1.1). Europa's surface lacks an abundance of large (>10 km diameter) craters, implying that the surface is ~60 Ma (Schenk et al., 2003; Zahnle et al., 2003; Bierhaus, 2009). This young surface indicates that Europa must have resurfaced at some point in its geologically recent past. However, the exact processes and mechanisms responsible for the resurfacing remain poorly understood. Current hypotheses addressing this issue vary from cryovolcanism, to plate tectonic processes (e.g., Crawford and Stevenson, 1988; Greenberg et al., 1998; Pappalardo et al., 1999; Greeley, 2000; Greenberg and Geissler, 2002; Figueredo and Greeley, 2004; Doggett et al., 2009; Kattenhorn and Prockter, 2014). Deciphering the history of resurfacing on Europa will allow us to further understand the potential interaction between the

ice-shell and ocean, as well as how the system has evolved through time. The ridged plains are of particular interest because they are the oldest visible surface features and therefore represent the oldest period of deformation that we can observe on Europa. By assessing the initial conditions for surface deformation, or the mechanism controlling the formation of ridged plains, we can determine how the ice-shell has evolved from the time of ridged plains formation until today (or the past ~60 Ma).

This dissertation focuses on geological and geomorphological mapping at all available scales on Europa, from global to local, in order to determine how deformation has evolved through time and what implications this has for the evolution of the ice-shell as a whole. The global geologic map (Chapter 2) investigates surface features and their cross-cutting relationships at the global scale. A regional and local geomorphologic map (Chapter 3) located in the trailing anti-Jovian hemisphere (Fig. 1.2), investigates a transitional terrain in detail in order to refine formation mechanism hypotheses and newly-identified mechanisms operating on the finest resolvable scale (10s of meters). In order to analyze the formation of the ridged plains further (Chapter 4), we create a high-resolution Digital Elevation Map (DEM) and perform a variety of experiments with a two-layer physical analogue model.

In addition to Europa, this dissertation also explores the surface history of Enceladus, specifically in the leading hemisphere. Enceladus is a small (~500 km diameter) moon of Saturn that sits within Saturn's E-ring (Lassell, 1848; Feibelman, 1967). Its surface is divided into discrete regions of tectonized terrain and heavily cratered terrain (Fig. 1.3; Smith et al., 1982; Spencer et al., 2009; Crow-Willard and Pappalardo, 2015). The regions of tectonized terrain are hypothesized to be relatively young, ~1 Ma – 400 Ma depending on the region (Porco et al., 2006; Kirchoff and Schenk, 2009; Crow-Willard and Pappalardo, 2015), due to the lack of

apparent impact craters. The youngest of the tectonized terrains surrounds the South Pole of the satellite and contains four fractures, informally known as “tiger stripes”, which are active plume sources (Porco et al., 2006) that populate the E-ring with potentially ocean-sourced material (Postberg et al., 2011; Waite et al., 2017). However, it is not well known how Enceladus resurfaces, especially only in discreet locations, and what this implies about the presence and longevity of its sub-surface ocean. This dissertation focuses on the mapping and analysis of the southern Leading Hemisphere Terrain (LHT), an area consisting of unique features colloquially known as the “cratered islands”, in order to determine the geologic history of this unique terrain and the implications for resurfacing mechanisms on Enceladus.

1.2 Geologic Mapping of Europa (Chapters 2 and 3)

For planetary bodies, global geological mapping can allow for objective observation and interpretation of unit formation and sequence of geological events. Planetary geologic mapping has been employed as an analytical tool to decipher surface evolution of a body, beginning with the Moon (e.g., Wilhelms, 1987) and other rocky bodies (e.g., Scott and Carr, 1978; Carr, 1983), as well as the icy moons of the outer planets such as Ganymede (Collins et al., 2013). Geologic mapping on planetary bodies divides the surface into units of similar morphology (texture, albedo, shape, etc.) or composition (e.g., Wilhelms, 1990; Greeley and Batson, 2007). On these planetary bodies, a global geologic map provides a global context for any studies of specific surface features or units (e.g., Mutch, 1979) and a generalized stratigraphic column indicating the temporal relationships between different units.

In Chapter 2, I present the global geologic map of Europa which has been submitted to the United States Geologic Survey (USGS). I created this map with D. Alex Patthoff (Planetary

Science Institute) under the supervision of David A. Senske at the Jet Propulsion Laboratory (JPL) in Pasadena for the Europa Clipper Project. Past global geologic maps of Europa are either incomplete (Doggett et al., 2009) or not published. Therefore, there is no established global geologic context for the variety of regional studies that have been completed (e.g., Prockter et al., 1999; Figueredo and Greeley, 2000, 2004; Prockter and Schenk, 2005). This context is essential for comparing different regions of Europa to one another, especially because Europa is not imaged at a consistent resolution or geometry. A global geologic map of Europa will provide this geologic context and aid in analyzing the surface as a continuous whole, rather than in separate parts.

With the new global map, I show that Europa's surface features generally fall into three periods: (1) the oldest period, which is dominated by the formation of ridged plains, (2) the middle period, dominated by the formation of band features, and (3) the youngest period, dominated by the formation of chaos terrain. These three periods exhibit potential overlap, but in general the cross-cutting relationships of the units follows this progression.

The work in Chapter 2 is intended for publication with the USGS and in a journal article intended for *Icarus*. The map has been submitted to the USGS, reviewed, revised and resubmitted. The manuscript, which is in its final stages of editing, with Alex Patthoff and Dave Senske as coauthors which we plan to submit to *Icarus*.

In Chapter 3, I present the first high-resolution (< 20 m/pixel) geomorphological map and structural map of the E12 MOTTLE01 and 02 region on Europa and a geomorphological map of the context region (at 220 m/pixel). The units in the geomorphologic map are defined by surface texture, landform shape (morphology), dimension, and relative albedo. The structural map units include interpretations from the geomorphologic map units and their interpretation implies

potential kinematic processes for the formation of particular structures. This study region borders an area of chaos terrain to the west and an area of ridged plains terrain to the east, and therefore it is interesting to investigate as an area of transitional terrain (Fig. 1.2).

My primary mapping observations include the regular spacing and gentle slopes of the ridge-and-trough terrain, the sharp boundaries and preserved structures of the chaos terrain, and the symmetry but irregular size of double ridges. I then evaluate proposed formation mechanisms for these and other mapped features. I also find that the high-resolution images reveal an abundance of small (< 100 m) pits, the presence of a newly identified high-albedo smooth material, and potential tectonic fabric, all of which have possible implications for the surface history. With mapping and structural analyses, I show that local-scale resurfacing mechanisms have transitioned from distributed deformation expressed by the formation of the ridged plains to discrete deformation characterized by the formation of chaos and isolated fractures. This finding is consistent with simultaneous ice-shell thickening and cooling occurring as the ice-shell deformed.

The work in Chapter 3 has been completed and published in *Icarus* (Leonard et al., 2018) with coauthors, Robert Pappalardo and An Yin. The manuscript benefited from helpful comments from David Senske, Francis Nimmo, Paul Helfenstein, and an anonymous reviewer.

1.3 Analogue Modeling of Europa's Ridged Plains (Chapter 4)

The aforementioned three-stage development of ice-shell structures on Europa requires ice-shell deformation to have transitioned from a distributed mode to a discrete mode, possibly caused by progressive ice-shell thickening since the onset of the global resurfacing event (Pappalardo et al., 1999; Figueredo and Greeley, 2004; Leonard et al., 2018). Alternatively, the

ice-shell could be in steady state and deformation is induced by tidal stress (e.g., Greenberg et al., 1998; Greenberg et al., 2002). In this scenario, the evolution of ice-shell structures through time is not recognized and therefore requires that all surface structures can be formed at essentially the same time. Differentiating between these competing hypotheses requires better understanding of how the ridged plains formed, as they set the initial conditions for the subsequent or contemporary resurfacing processes. Although in Chapter 3, I favor a contractional origin for the ridged plains analyzed, similar structures have alternatively been interpreted as resulting from related extensional block faulting (Kattenhorn, 2002), akin to the detachment model for the grooved terrain development on Ganymede (Pappalardo and Greeley, 1995; Patel et al., 1999; Prockter et al., 1998, 2000; Figueredo and Greeley, 2000).

In Chapter 4, I present two-layer physical analogue experiments with the purpose of differentiating between the two competing models (i.e., compression versus extension) for the morphological development of the ridged plains. I also create stereo-topography data with which I test the viability of our experimental results together with the highest resolution satellite images. With this work, I show that the compression-induced morphology best explains the observed map pattern and cross-sectional shapes of the ridged plains features. Specifically, the analogue experiments with a brittle layer that has less than one-sixteenth of the underlying ductile-layer thickness best explains the morphological observations of the ridged plains on Europa. Because the ridged plains are among the oldest features on Europa and compression-induced followed by the formation of younger extensionally induced band structures, I suggest that this sequence of events can simply be explained by progressive ice-shell thickening due to secular cooling of the ice-shell and ocean system.

The work in Chapter 4 has been completed and the manuscript has been submitted to *Icarus* with Robert Pappalardo and An Yin as coauthors.

1.4 Enceladus (Chapter 5)

In Chapter 5, I shift focus to the geology of Enceladus. Recent research on the South Polar Terrain (SPT) of Enceladus has illuminated the mechanisms of active and recently active resurfacing processes (e.g., Mitri and Showman, 2008; Barr and Preuss, 2010; Patthoff and Kattenhorn, 2011; Han et al., 2012; Porco et al., 2014; Spitale et al., 2015; Yin and Pappalardo, 2015; Yin et al., 2016; Gall et al., 2017). However, it remains unclear if the same processes have operated in the geologic past in tectonically inactive regions such as the Leading Hemisphere Terrain (LHT) and Trailing Hemisphere Terrain (THT) (Fig. 1.3; Crow-Willard and Pappalardo, 2015). Specifically, if the resurfacing processes that formed the LHT and THT were dominated by resurfacing mechanisms similar to those currently acting on the SPT, it would require a cyclic evolution of the satellite possibly related to its orbital evolution around Saturn. Alternatively, if the resurfacing mechanisms differ drastically for the development of the three tectonized terrains on the icy satellite, a monotonic evolutionary trend possibly dictated by the history of the satellite could be deduced.

In Chapter 5, I present a structural map of the southern Leading Hemisphere and the results of a kinematic analysis of the evolution of the region based on the mapping observations. With this work, I show that the little-deformed blocks in ductilely sheared domains of the LHT referred to as “crater islands” by Crow-Willard and Pappalardo (2015), are most likely to have been sheared off from the neighboring ancient Cratered Terrain (see Fig. 1.3). Furthermore, I use the morphologic features around the relic cratered blocks, such as curvilinear ridges and troughs,

to deduce the structural origin and kinematic development of the isolated cratered blocks. The main result of this work is that the relic blocks have experienced vertical-axis rotation during distributed ductile strike-slip shear deformation. When combined with constraints on stress magnitude and deformation duration, I use the estimated strain rates to determine the averaged viscosity of the ice shell during the inferred strike-slip deformation and the corresponding thermal state of the shear zone. I then compare this result against the thermal regime across the active SPT, to infer that Enceladus has likely undergone periods of intense episodic heating in discrete locations which leads to the nonuniformly resurfaced state of the satellite currently.

The work in Chapter 5 has been completed and submitted to *Earth, Planetary, and Space Science Letters (EPSL)* with An Yin and Robert Pappalardo as coauthors.

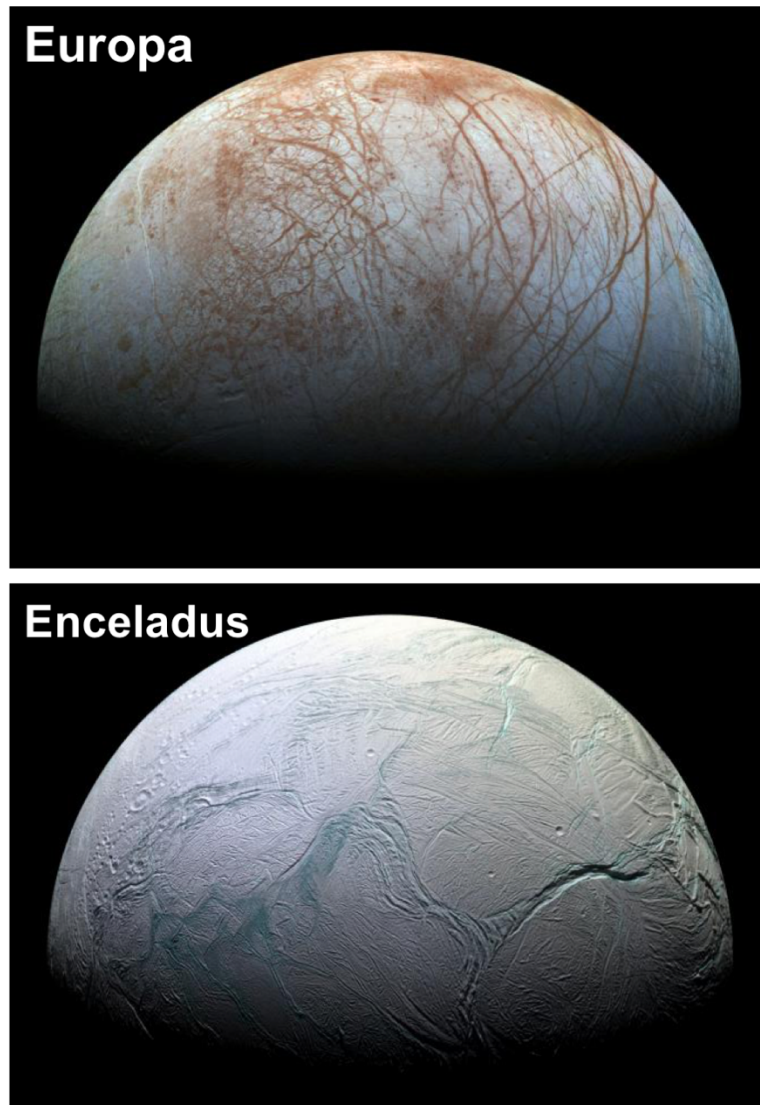


Figure 1.1 PIA19048 image of Europa (top). Note the paucity of apparent impact craters, the abundance of red-orange lineaments, and the red-orange mottled areas of chaos terrain. PIA11133 image of Enceladus (bottom). Note the contrast of tectonized terrain that lacks apparent impact craters, with the crater covered terrain (left part of image),

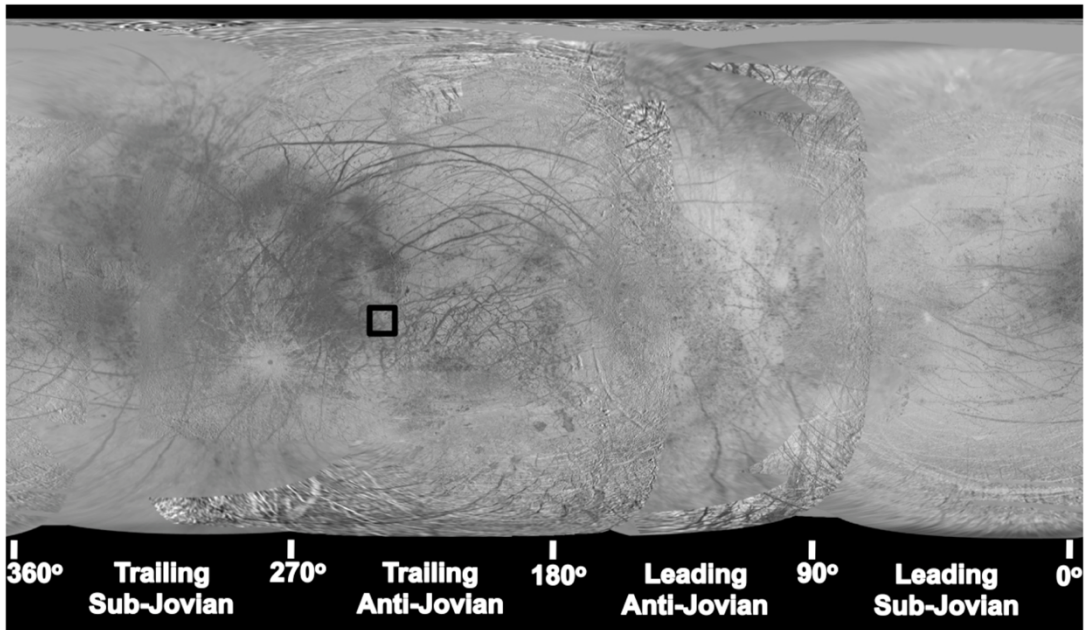


Figure 1.2 Global mosaic of Europa from the USGS. The black box indicates the approximate location of the study area for Chapter 3. Modified from Leonard et al. (2018).

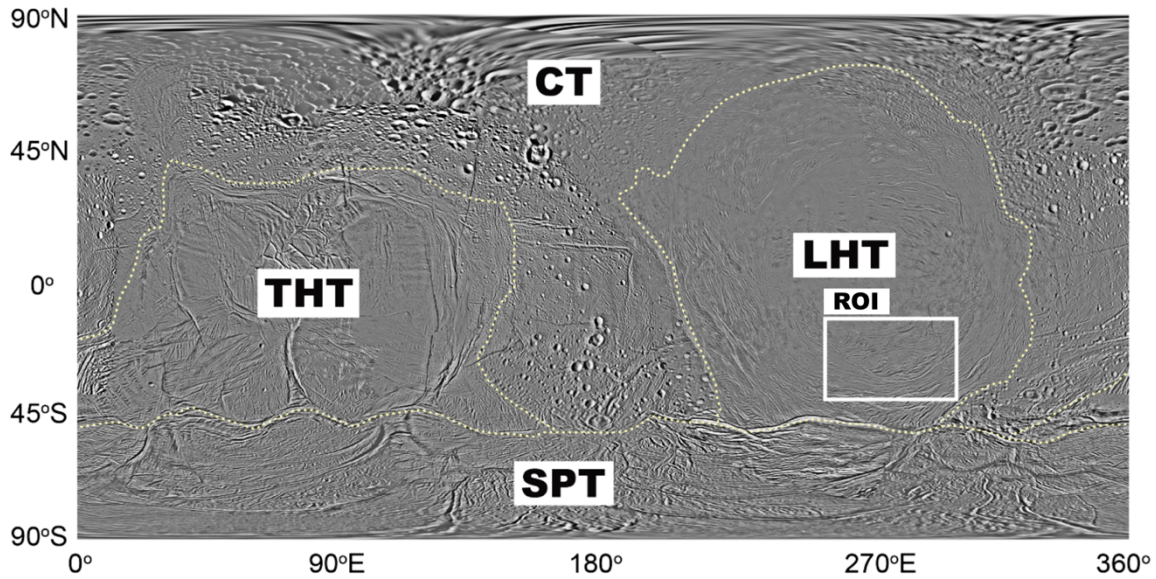


Figure 1.3 Global mosaic of Europa from the USGS. The four terrains are labeled—CT: Cratered Terrain, THT: Trailing Hemisphere Terrain, LHT: Leading Hemisphere Terrain, SPT: South Polar Terrain. The white box indicated the approximate location of the Region of Interest (ROI) studied in Chapter 5. Modified from Leonard et al., (*in review*).

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- Chapter 2 -

The Global Geologic Map of Europa

2.1 Introduction

Discovered by Galileo Galilei over 400 years ago and imaged in detail by the Voyager 2 and Galileo spacecraft, Jupiter's icy moon Europa has been a source of intrigue. A range of science investigations suggest that it contains the key ingredients for habitability, notably energy, chemistry, and liquid water (e.g., Wackett et al., 2004; Hand et al., 2009). Europa's surface is geologically complex and, based on the dearth of impact craters, interpreted to be as young as ~60 Ma (e.g., Lucchitta and Soderblum, 1982; Pappalardo et al., 1999; Bierhaus et al., 2001, 2009; Figueredo and Greeley, 2004; Prockter and Schenk, 2005; Doggett et al., 2009). The array of geologic features that characterize the surface include extensive ridged plains, regions of broad disruption termed chaotic terrain, long, quasi-linear ridges that span thousands of km, and bands up to 60 km wide and that extend 100s of km (e.g., Prockter and Patterson, 2009) (Figure 1). These features, along with other geophysical measurements (Kivelson et al., 2000), suggest the presence of a global briny liquid water ocean beneath the ice shell (Cassen et al., 1979, 1982; Anderson et al., 1998; Pappalardo et al., 1999; Kivelson et al., 2000; Kargel et al., 2000; Schubert et al., 2009; Nimmo and Manga, 2009; Zolotov and Kargel, 2009; Vance and Goodman, 2009). It was not until the arrival of the Galileo spacecraft in 1995 that the true nature and level of complexity of the surface was revealed. Although image data returned by Galileo provided insight into the structure of a variety of regions, the entire satellite has yet to be observed at a regional scale (better than 250 m/pixel) and the detailed geologic nature of much of its surface remains a mystery. Establishing the global context of the distribution and timing of European geologic units forms a basis to understand regional and local scale processes, serves as a tool for the planning of future missions, and most of all is essential to gaining insight into the potential habitability of this icy world.

Following the general procedures of planetary mapping (e.g. Wilhelms, 1972, 1990; Greeley and Batson, 1990; Tanaka et al., 2011) we have generated a global map of Europa at a scale of 1:15M (Figure 2.2). We have established four aerially extensive primary material unit types (crater material, chaos, bands, and ridge plains) that are divided into geologic subunits: (1) continuous crater ejecta (ce) and discontinuous crater ejecta (dce)—materials associated with impact craters including the primary impact crater (c) and its local deposits and farther ranging ejecta material; (2) various morphological types of chaos materials identified as high albedo chaos (chh), mottled chaos (chm), low albedo chaos (chl) and knobby chaos (chk). Disrupted terrains whose textures vary, apparent relative brightnesses range from high to low, and are too small (10-75 km in diameter) to be mapped as a unit at the 1:15M scale, but whose presence is ubiquitous and significant enough to be identified on the map as a point, are identified as microchaos (mch); (3) Linear to curvilinear zones with a distinct, abrupt albedo increase (bha) or change (b) from the surrounding region that are also greater than 15 km in width; and (4) ridge plains, high-albedo, compared to the surrounding terrain, seeming smooth at global resolution (~1 km/pixel). We also identify structures which are too small to be mapped aerially but are significant enough to be mapped linearly: depression margins (dm), troughs (t), multi-ring structures (mrs), cycloids (cy), band lineae (bl), ridges (r), and undifferentiated lineae (ul). This map provides a global stratigraphic framework for Europa and allows for future quantitative assessment of the distribution of the various geologic terrains (see Table 2.1).

2.2 Previous Mapping

The earliest efforts to map Europa on a broad scale were based on image data from the Voyager mission that was limited in spatial coverage and resolution, no better than 2 km/pixel

(Lucchitta and Soderblom, 1982). That initial mapping identified units primarily based on albedo variations. Structural feature mapping was restricted to the largest lineations and impact craters. The Galileo mission provided an improved image data set with resolutions as good as 8 m/pixel. Lower resolution, ~1 to 2 km/pixel, data revealed the broad global character of Europa. Images at scales better than 1 km/pixel revealed numerous individual ridges, fractures, domes, and the details of what became called chaos terrain. On regional to local scales these data allowed for relative ages to be constrained for individual features and classes of structures at a limited number of locations (Head et al., 1998; Senske et al., 1998; Spaun et al., 1998a,b; Klemaszewski et al., 1999; Prockter et al., 1999; Sullivan et al., 1999; Williams et al., 1999; Kadel et al., 2000; Figueredo et al., 2002; Prockter and Schenk, 2002; Kattenhorn, 2002). Based on the insight provided from the Galileo observations, Greeley et al. (2000) outlined the guidelines for mapping units, defined a naming convention for features, and suggested a color scheme for map units. Subsequently, Figueredo and Greeley (2000, 2004) produced regional scale maps of datasets that formed north to south transects along the leading and trailing hemispheres of Europa, and later Doggett et al. (2009) generated a preliminary global geologic map. However, our map contains all original line work.

2.3 Mission Data and Base Map

The suite of images used for our geologic mapping combines data sets obtained from both the Voyager and Galileo missions. The Voyager 1 and 2 spacecraft imaged Europa during flybys in March and July 1979 respectively. Voyager 1's global images ranged in resolution from 30 to 100 km/line pair (lp) while Voyager 2 provided multispectral coverage of ~20% of the surface with resolutions as high as 2-4.5 km/lp over the longitude range of ~130° and ~210°. The Galileo

mission made 12 flybys (out of a total 21 flybys of all four Galilean satellites) of Europa between June 1996 and January 2002, and acquired images primarily of the anti-Jovian hemisphere ($\sim 135^\circ - 225^\circ$). Relatively high-resolution imaging (<250 m/pixel) was possible during each targeted flyby covering $\sim 1\%$ of the surface (Doggett et al., 2009). Ultimately, approximately 36% of the surface was imaged at 1 km/px or better by the Galileo mission, a resolution adequate for a 1:15M map for all but two areas at the poles where no image data was available. For these areas of no data, a simple gray fill was applied for aesthetic purposes. Figure 2.3a shows the distribution of image coverage resolution from both Voyager and Galileo image data used to create the base map mosaic. The multiple flyby nature of the Galileo mission resulted in viewing and lighting geometries that varied significantly (Figure 2.3). Such variation is generally common for spacecraft observations of the outer planet satellites and must be considered when mapping as some regions are dominated by changes in albedo while others are dominated by topographic shadowing. While this range of emission and incidence angles allows for characterization of morphology and photometric properties, it must be carefully considered when determining surface geology. The mapping techniques section (Section 2.4) elaborates on the methods we used to maintain consistency in unit definition across various emission and incidence angles.

The cartographic base for this geologic map is a controlled photomosaic of Europa (Figure 2.1; USGS Map I-2757, 2002) which combined the highest quality images of moderate resolution generated by the Galileo Solid State Imager (SSI) and the Voyager 1 and 2 cameras (Batson, 1987; Becker et al., 1998, 1999, 2001). Due to the failure of Galileo's high-gain antenna to deploy fully, the highest-resolution imaging (10s of m/pixel) was limited number of characteristic terrain and feature types. As such, Voyager data remains the highest-resolution

coverage of some areas, (e.g., the strip centered near 150°). The global digital image map was produced using Integrated Software for Imagers and Spectrometers (ISIS2) (Eliason, 1997; Gaddis et al., 1997; Torson and Becker, 1997). Individual images were radiometrically calibrated and photometrically normalized using a Lunar-lambert function with empirically derived values (McEwen, 1991; Kirk et al., 2000). A linear correction based on the statistics of all overlapping areas was then applied to minimize image brightness variations. Although consistency was achieved where possible, different filters were included for global image coverage as necessary: clear/blue (~507 nm) for Voyager 1 and 2 (Danielson et al., 1981); clear, near-IR (757 nm), and green (559 nm) for Galileo SSI (Belton et al., 1992). The process of creating a geometric control network began with selecting control points on the individual images, making pixel measurements of their locations, using reseau locations to correct for geometric distortions, and converting the measurements to millimeters in the focal plane. These data were combined with the camera focal lengths and navigation solutions as input to a photogrammetric triangulation solution (Davies et al., 1996, 1998; Davies and Katayama, 1981).

During the creation of the USGS global mosaic, a compromise of 500 m/pixel resolution was used such that many of the higher resolution images were down-sampled and lower resolution data were up-sampled in an attempt to create a consistent portrayal of observable features. Moreover, only images of moderate emission/incidence angles were used in order to reduce contrast differences between the images. The final constructed Sinusoidal projection mosaic was then reprojected to Mercator and Polar Stereographic projections, for latitudes below and above 57°, respectively (Fig. 2.1).

2.3.1 Europa “Supermosaic”

Mapping on the anti-Jovian hemisphere has been aided by the production of an image mosaic that includes almost all images with pixel scales between 165 m and 1 km obtained by Galileo in the region from 83.5°N to 72.5°S, 70°E to 201.5°E. The entire mosaic was sampled to the resolution of the best available image, at a pixel scale of 165 m. Mosaic processing began by tying features in several lower-resolution “background” images to their geographic coordinates in the USGS global image mosaic (sampled at 500 m/pixel). The background images used in the 72 higher resolution images that were tied to the background can be found in Table 2.2.

The high-resolution images were tied to each other and to the background by selection of 568 prominent geographic control points. The points were selected by hand using the ISIS3 program `qnet`, and then the program `jigsaw` was used to update the control points so that the program `automos` could assemble the final mosaic. Because the mosaic was intended to be used for morphologic mapping and not for measurements of albedo or color, no photometric function or corrections were applied to the images beyond the basic Galileo SSI calibration. The ISIS3 program `equalizer` was used to roughly match the brightness of the images in the mosaic.

2.4 Methodology

Our geologic map was produced following the general principles of planetary mapping practices (e.g. Wilhelms, 1990; Skinner and Tanaka, 2003; Tanaka et al., 2005). We set a digital mapping scale of 1:4M to create the map and set a vertex spacing of ~10 km. We followed planetary mapping standards (e.g. Wilhelms, 1972, 1990; Tanaka et al., 2011) in order to separate observations of characteristics and interpretations, thereby ensuring that the objective descriptions of each unit and feature are valid for any future Europa dataset. Interpretations are subject to change with time, especially with future datasets anticipated from the Europa Clipper

and other missions; however, this Europa Global Map will still be relevant in the future because of the objective methods used in our mapping. Units defined here are assumed to be three-dimensional volumes of icy layers, each with a distinctive apparent relative brightness, texture, and family of structures. Due to the variation in viewing and lighting geometry as discussed above, we took great care to maintain consistent mapping practices across the images while capturing the details when possible and following established guidelines for mapping (e.g. Wilhelms, 1990; Skinner and Tanaka, 2003; Tanaka et al., 2005; Skinner et al., 2018). This is of special importance on Europa where the relative brightness and texture of particular units can vary greatly between different viewing geometries. When this was the case, we defined the unit using the most predominant appearance. The range in resolution of images used to compile the mosaic has resulted in some regions being mapped with greater certainty and density of structures, i.e. leading and trailing hemispheres, than others, i.e. sub-Jovian and anti-Jovian hemispheres. In areas where only the lowest resolution images were available for the base mosaic (~2 km/pixel or worse), units were predominantly defined based on apparent relative brightness rather than texture but matched by data number (dn) to other regions containing the same unit (e.g., Figure 2.4). Additionally, in these areas, individual structures are commonly not visible with the exception of a few wide (>20 km) linear features that have a distinctive relative brightness contrast relative to the background terrain. In areas where higher resolution images are available, we again followed the same practices of using contrasting relative brightness and textures to define units; however, we also used visible structures and morphology to define the unit and identify more distinct boundaries.

Only units of sufficient areal extent or geologic prominence have been identified on this 1:15M scale map. Features that are too small to be visible on the map are excluded individually

but are instead combined with other more extensive units. We include linear features and microchaos in our map despite their smaller size due to their importance in understanding the geologic history of the surface. However, because of their limited local aerial extent, they are mapped with line symbols instead of being identified as a separate unit.

2.4.1 Units

The units defined in this map are grouped by morphologic type and named with respect to that type. This is a practice commonly used for mapping on Europa (e.g., Prockter et al., 1999; Figueredo and Greeley, 2004; Prockter and Schenk, 2005; Doggett et al., 2009). We also based unit names and colors on previous maps of Europa as to preserve heritage and to make this map clearly comparable to other published maps of Europa (e.g., Greeley et al., 2000; Figueredo and Greeley, 2000; Prockter et al., 2002; Doggett et al., 2009). The uniqueness of a global map requires that we have additional units, and therefore new colors.

2.4.2 Contacts

Due to the mapping scale and resolution of the images that are available, many contacts on this map are marked as “approximate” as the change in surface material characteristics is often gradual, especially for the boundary between the ridged plains and chaos units. When mapping from higher resolution (10s to 100s of m/pixel) images, unit boundaries are typically quite apparent (e.g., Prockter and Schenk, 2005; Leonard et al., in preparation), which is not the case at the global scale. We reserve the “certain” contact marking for those units where a clear separation can be identified. Commonly, this occurs at the boundary of band units, or well-defined isolated chaos unit such as Murias Chaos (22° N, 83° W). Clearly defined boundaries are

only resolvable on the higher resolution images (~ 500 m/pixel) confined to the pole-to-pole mosaics on the leading and trailing hemispheres. “Questionable” contacts are used where the nature of the contact is very uncertain and determined based on albedo variations alone, usually due to low resolution imagery or an imaging geometry that washes out the terrain.

2.4.3 Linear Features

Features that are less than ~ 15 km wide are too narrow to be resolvable as units at the 1:15M scale, but can still be prominent because of their length (> 50 km) or relative brightness contrast. These structures are mapped with a line which marks the length, location, and trend of the feature. Only on the higher resolution images (better than ~ 200 m/pixel) are we able to discern ridges, troughs, bands, or other structures and categorize them as linear features. However, because much of the imaging of Europa is too low in resolution to definitively resolve and identify structures, most of the linear features have been categorized as “undifferentiated linea” suggesting they could be any of the previously mentioned structures or some other type of structure. Commonly, at image boundaries where a region has been resolved at both high and low resolutions, we categorize the feature when we are able to discern its morphological characteristics in the higher resolution images. When the structure can be traced onto the lower resolution image, we then categorize it as undifferentiated when the defining characteristics are no longer resolvable. This results in a more conservative designation of the features; however, because other linear features are observed to be complex, such as composed of multiple types of structures, e.g. ridge and band, this is the best practice for mapping.

To simplify the map, not all lineaments on Europa’s surface are identified. Those that are mapped are prominent (e.g. distinctly longer, wider than most, and > 5 km in width), useful for

constraining stratigraphy, or represent the density and distribution of the other lineaments of the area. Stratigraphic markers are those lineaments that have a broad regional extent, especially those that bridge low resolution areas or crosscut multiple units. They also have clear relative stratigraphy compared to other features or geologic units, especially if the lineament can be dated relative to other features or units. Grouped with the linear features are over ~2500 locations of microchaos that are mapped as a point feature by placing a point near the center of the outcrop to identify its location.

2.5 Geologic Units

This section describes the four primary material unit types defined for the map: craters, chaos, bands, and ridged plains. These definitions and naming scheme are based on previous maps of Europa, with some slight changes to adapt to the global resolution (e.g., Greeley et al., 1998, 2000; Senske et al., 1998; Head et al., 1999; Prockter et al., 1999; Figueredo and Greeley, 2000, 2004; Prockter and Schenk, 2005; Doggett et al., 2009). In some cases, we provide a hypothesis for the formation mechanisms of the features with the full suggested interpretations and a type image for each unit and feature provided in the Table 2.1. Units are described below in a general chronostratigraphic order—youngest to oldest.

2.5.1 Crater Units

Craters and their associated ejecta deposits cover ~2% of the surface (see Table 2.3). Commonly, the transition between the impact crater and its ejecta is not well defined and the crater rim can be difficult to discern, especially for some of the larger craters. The material units

are defined based on their apparent morphology, albedo with respect to the background material, and their relationship to the central crater structure.

2.5.1.1 Crater material

This unit is identified as a quasi-circular depression with a raised rim or complex annular structure, such as multi-ring, (see DOMU, c). Craters with diameters greater than 10 km are mapped as units. Smaller craters (<10 km diameter) are identified as point features. The crater floor can range from generally flat to bowl-shaped and is interpreted to be controlled by the size of the impacting event (crater diameter) and age of the crater (Schenk, 2002). The unit includes material within the excavated area, which may represent impact melt, r, or subsequent infilling due to a post-impact cryovolcanic processes (e.g., Moore et al., 1998, 2001; Schenk et al., 2004; Schenk and Turtle, 2009).

2.5.1.2 Continuous crater ejecta material

This unit corresponds to the area composed of the continuous swath of material, roughly radial to the central crater possessing a hummocky texture. In some cases, this material has contrasting relative brightness to the background terrain (see DOMU, ce). This is interpreted to be material excavated during an impact and deposited proximal to the impact site.

2.5.1.3 Discontinuous crater ejecta material

This material typically consists of high relative brightness patches aligned quasi-linearly and distributed radially with respect to a central crater (see Table 2.1, cde). It is interpreted to be formed by distal ejecta and secondary impact cratering (Bierhaus et al., 2001, 2009; Moore et al.,

2001). A type example is distant material associated with the crater Pwyll (88.5°E, 25.1°S). The relatively pristine nature of the deposit suggests that Pwyll may be one of the youngest craters on Europa (Bierhaus et al., 2001).

2.5.1.4 Crater ray material

This material corresponds to high relative brightness patches that are aligned quasi-linearly radiating away from a central point, the primary crater. This unit is found only around Pwyll. This unit is interpreted to be a secondary impact feature (Bierhaus et al., 2001, 2009; Moore et al., 2001).

2.5.1.5 Central peak structure

This point feature is the central structure located at the center of some craters. It can appear as a simple peak or a complex structure. Twelve craters on this map are identified to have central peak structures

2.5.2 Chaos Units

Chaos, identified from data at the 10s to 100s of meter scale, is in general, characterized by relatively higher relative brightness blocks of crustal material, ranging from 10s of meters to 10s of kilometers in size, within a lower relative brightness hummocky matrix (e.g. Greeley et al., 2000; Doggett et al., 2009; Kattenhorn and Hurford, 2009). This disrupted terrain is inferred to be associated with possible higher heat flow with respect to the surrounding terrain or perhaps are sites where the subsurface ocean is in close proximity to the surface (e.g., Greenberg et al., 1999; Pappalardo et al., 1999; Greeley et al., 2000). The lower relative brightness matrix

material associated with chaos terrain typically has been interpreted to have a higher concentration of non-ice material and is inferred to have originated through interaction with the subsurface ocean (Shirley et al., 2010; Dalton et al., 2012). The chaos units (Sections 2.5.2.1-2.5.2.3) are loosely based on relative brightness which can be verified across incidence angle and resolution. Ideally the chaos units would not be based on relative brightness alone, but at the lowest resolutions and incidence angles in the global mosaic we must resort to relative brightness for classification because no texture is discernible. As an aid to mitigate this, we quantify the designation of high vs. low vs. mottled albedo using the relative data numbers of each unit (see Figure 2.4). The total area of chaos occupies approximately 35% of Europa's surface and we marked only those that are generally $>5000 \text{ km}^2$. Smaller chaos units, microchaos, are discussed in Section 2.5.5.4.

2.5.2.1 Low albedo chaos material

This chaos unit is characterized by a smooth texture with a relatively uniform low relative brightness which remains constant over a variety of incidence angles and resolutions (see Table 2.1, chl). The boundaries of this terrain can be gradational and can range from jagged to smoothly curvilinear. This unit is found predominately in the trailing hemisphere.

2.5.2.2 Mottled chaos material

This disrupted terrain has a patchy or variegated relative brightness. On higher resolution images (200-500 m/pixel), a rough, blocky texture is visible (see Table 2.1, chm). This seemingly occurs in some locations surrounding the low albedo chaos, possibly indicating that it is a transitional terrain from ridged plains to other chaos units.

2.5.2.3 High albedo chaos

This class of chaos terrain possesses a uniform high brightness appearance relative to other chaos units. It has a relatively smooth texture with small-scale roughness (100s of meters) and occurs mostly on the leading hemisphere of Europa (see Table 2.1, chh).

2.5.2.4 Knobby chaos

The occurrence of this disrupted terrain has a rough and blocky texture. The rough texture is present at a larger scale (individual blocks are ~20-40 km across) than the other chaos units and appears to be platy. This unit also contains slightly scalloped edges in some locations at its boundary (see Table 2.1, chk). We only identify knobby chaos in one location on Europa, on the southern trailing hemisphere (70° E, 45° S at an incidence angle > 45°); however, this is likely due to a lack of widespread images with a resolution of < 500 m/pixel.

2.5.3 Band material

Bands that are defined as units are large (> 15 km in width) linear to curvilinear landforms with a range of relative brightness and lengths (up to 100s of km). The majority of bands have a lower relative brightness compared to the surrounding terrain; however, in limited places some bands do appear to have a high relative brightness. In some locations, these features are hypothesized to have formed by a process analogous to mid-ocean ridge style rifting where a rift forms and the crustal blocks separate and spread laterally by new material rising at the spreading axis (e.g., Prockter et al., 2002). This hypothesis is supported by plate reconstruction where, for some bands, separated landforms can be accurately reconstructed when the band is closed.

Recent work suggests that the varying morphologies of bands may be due to varying ice-shell rheologies and spreading rates (Howell and Pappalardo, 2017).

This unit contains linear to curvilinear zones with a distinct, abrupt relative brightness and texture change boundary with the surrounding region. The relative brightness change with respect to the background terrain can be low- relative brightness or high- relative brightness but is not necessarily constant in images with varying incidence angles (see Table 2.1, b). For the band unit, we marked only those that are greater than 15 km in width and are observed to be at least 30 km in length. Shorter and narrower bands are also identified as linear features (see Section 2.5.5.6). In some regions where there is high-resolution imaging (< 250 m/pixel), bands can be subdivided as "smooth", "lineated", or "ridged" (Figueredo and Greeley, 2004; Prockter and Patterson, 2009), but at the global scale we group them together due to the limited extent of the high-resolution image coverage.

2.5.4 Regional Plains Material

Distributed over all latitudes and longitudes, the ridged plains are the most abundant unit on Europa (see Table 2.3) where it is characterized by a relatively high- relative brightness compared to other terrain units and is cross-cut by all other units. At the global image scale ($> \sim 500$ m/pixel), this unit is seemingly smooth (see Table 2.1, pr). However, when present in higher resolution images (100 m/pixel), texture is revealed and small-scale (200-500 meters in width) complex systems of subparallel to cross-cutting ridges and troughs are identified.

2.5.5 Linear Features

Linear features on this map are identified based on the criteria outlined in Section 2.4.3. Some formation mechanisms are outlined in this section, while the full suggested interpretations can be found in the DOMU. A type image for each unit can also be found in the DOMU. Features are described below in rough chronostratigraphic order—youngest to oldest.

2.5.5.1 Depression margins

The trace of broad, shallow topographic lows are identified. Structures within the depressions appear undisrupted and well preserved (see Table 2.1, dm). Previous research suggests that these features might be indicative of recent polar wander (Schenk et al., 2008).

2.5.5.2 Troughs

Quasi-linear topographic lows with material on either side showing no apparent offset (see Table 2.1, t). Inferred to be tension cracks formed under extension. These are only identified on the northern leading to sub-Jovian hemispheres at the global resolution.

2.5.5.3 Multi-ring structures

Identified by a quasi-circular series of ridge-trough structures within a matrix of crater ejecta material (see Table 2.1, mrs). At the global resolution these structures are associated with three craters, Tyre, Callenish and Talisien. Concentric, or multi-ring structures are hypothesized to be graben formed by the collapse of the impact crater. The lack of other topography at these craters could be indicative of weak ice at depth within Europa's ice shell (Schenk, 2002).

2.5.5.4 Microchaos material

Circular to oblong 10-75 km diameter disruptions of the background terrain, which is predominately the ridged plains (Section 2.5.4) but with a lower relative brightness or different texture than the ridged plains unit (see Table 2.1, mch). The boundaries can be well defined when image resolutions are sufficient; however, on lower resolution images, the boundaries are less easily defined. These features are also referred to as pits, domes, and spots (e.g., Greeley et al., 2000); however, at this mapping scale it is not possible to distinguish among those structures. Approximately 2500 of these features are mapped globally. The morphological similarities between microchaos (also referred to in the literature as lenticulae) larger chaos areas (see Section 2.5.2) suggest a related formation process or variation of the same formation process (e.g., Pappalardo et al., 1998).

2.5.5.5 Cycloids

A series of arcs connected by at least two sharp cusps (see Table 2.1, cy). Also referred to in the literature as “flexus” (e.g., Greeley et al., 2000; Kattenhorn and Hurford, 2009). By requiring two cusps to define a cycloid, this ensures structures with just one cusp and are not cycloids are excluded from this classification. Additionally, the second cusp allows for a trend to be defined and a “chain” to become apparent, as is described in Kattenhorn and Hurford (2009). This structure can have the morphology of a band or ridge. In some instances, a single cycloid can appear to be composed of alternating segments of ridges and bands. The cycloidal shape is suggested to be controlled by a changing direction of crack propagation under the control of Europa’s diurnally rotating stress field (e.g., Hoppa et al., 1999), or tail crack propagation (Marshall and Kattenhorn, 2005). The greatest concentrations of cycloids are centered primarily around 0° and 180° longitude.

2.5.5.6. High albedo band material

Different from the general band unit, high albedo bands have an abrupt relative brightness increase from the surrounding region along with a texture change at all incidence angles. This high- relative brightness with respect to the background terrain is constant at all incidence angles (see Table 2.1, bha). We identify two such bands, both located in the southern anti-Jovian hemisphere centered around 45° S, 150° E.

2.5.5.7 Band linea

Linear to curvilinear zones less than 15 km in width with a distinct, abrupt relative brightness change relative to its surrounding terrain (see Table 2.1, bl). These structures are inferred to have the same or similar formation mechanism as the Bands unit as they appear to have similar morphological characteristics but on a smaller scale (Section 2.5.2.1). Portions of a band identified in the band unit can be represented as a Band Linea for the segments where it is too narrow (>15 km) to be represented as a unit.

2.5.5.8 Ridge linea

Quasi-linear topographic highs containing one or more crests (see Table 2.1, r). These are most commonly identified as double ridges (two ridges separated by a trough) or ridge complexes (more than two ridges separated by troughs), at higher resolution. The multiple types of morphologies suggest ridges could be formed through a variety of processes or represent different stages of the same process (Pappalardo et al., 1998). However, on the resolution for this

mapping, differentiated among ridge types is not possible; therefore, we group all ridges into a single classification.

2.5.5.9 Undifferentiated linea

Long (10s to 100s of km), linear, through-going features of contrasting relative brightness, light or dark, and texture relative to the background terrain with a width >5 km. These structures have no other discernible characteristics at the global scale or at any available image resolution (see Table 2.1, ul). These linea are most likely examples of small fractures, ridges, subdued/brightened ridge complexes, or bands that are unclassifiable due to the limits of resolution and viewing geometry constraints.

2.6. Relative Ages

The relative ages of geologic units and structures on planetary bodies are determined largely by cross-cutting, or superposition and embayment relationships along with crater statistics. The structure or unit that appears to be on top of or deforming another structure or unit is inferred to be younger. However, determining relative ages of structures or units on Europa is challenging for a variety of reasons including: (1) the overall complexity of the surface, (2) the lack of consistent image resolution at the global scale necessary to determine cross-cutting relations, and (3) the small number of impact craters for reliable crater statistics. Despite these limitations, we are able to draw general conclusions about the history of Europa's surface (see Figure 2.6).

2.6.1 Surface Complexity

Europa stands apart from most other icy satellites because it has a surface that is dominated by complex tectonic features and is geologically young (e.g., Zahnle et al., 1998; 2003). The dissected surface can make it difficult to trace a single feature for long distances because the structure will be observed to cut across and be cut by numerous other features. Commonly, a structure will abruptly terminate or not be completely imaged. However, at the local scale, the use of cross-cutting relations is ideal for determining relative ages, but projecting those relationships to a global scale is hampered by the lack of available high-resolution images.

There are limitations to dating events by relative age, for example, reactivation can occur. A specific example is shown in Figure 2.5a—feature A is older than B, which in turn is older than C, but it appears that C is older than A—a relationship that most likely involves reactivation of older tectonic features. This case, and others, commonly results in individual age relationships that can be ambiguous. Recognizing that there are limitations to using superposition and cross-cutting relations to obtain relative ages of any individual structure, we construct our stratigraphy based on relations where the stratigraphy can be established with a high degree of confidence.

2.6.2 Image Resolution and Illumination Geometry

As discussed above, the variation in resolution and illumination geometry of the images making up the global mosaic can lead to challenges in mapping (Figure 2.5b). This especially affects determining relative ages when a structure or unit spans multiple images, which is common given the length and/or extent of the linear features and geological units. In terms of illumination geometry, in particular incidence angle (Figure 2.3), this variation across the surface can lead to drastic relative brightness changes at image boundaries when the incidence angle changes from high to low or vice versa. Additionally, structural and topographic relationships,

which can aid greatly in determining relative ages of cross-cutting features or units, are subdued when the incidence angle is low. In cases where there are discrepancies, we have indicated them on the map with question marks. However, for many regions on Europa these issues can be resolved and relative ages, especially for the larger structures mapped here, can be determined.

2.6.3 Paucity of Impact Craters

Typically, when determining the age of planetary surfaces, mappers look at crater density, size-frequency distributions, and other aspects of impact structures that can be indicative of age (e.g., degradation or relaxation) (e.g., Collins et al., 2013; Tanaka et al., 2014). The young surface of Europa (e.g., Bierhaus et al., 2009) and the corresponding paucity of craters at the global scale creates limitations because we cannot use these crater observation methods to aid in dating the various units. We have mapped only 53 craters on Europa's surface at the 1:15M scale. None of the craters overlap and there are not enough craters to perform any sort of reliable statistics on how the distribution or degradation might indicate age. Our reliance is primarily on cross-cutting relationships of structures and units to determine the relative ages of the geologic units, but we can for example, use the crater Pwyll as a stratigraphic marker as its ejecta blanket is regionally widespread, forming distinct overlapping relations with other units.

2.6.4 Chronostratigraphy

Based on the relationships between our various map units, we have created a general stratigraphic column for Europa (see Figure 2.6). In the remainder of this section, we discuss the broad geology of Europa from the oldest units to the most recent.

There appear to be three general periods in Europa's visible surface history, ~60-100 Ma (e.g., Zahnle, 1998, 2003; Bierhaus et al., 2009). The first, or oldest, of these periods is dominated by the formation of the ridged plains, ridges, and undifferentiated linea indicating that this epoch was dominated by ridge building processes. We observe this to be the case as there are no units or structures that are older, i.e. are cross-cut by, the ridged plains unit. Ridges and undifferentiated linea cross-cut each other, but do not appear to be younger than any other feature, structure, or unit on the global scale.

The second, or middle, period is dominated by the formation of Band material, High-Albedo Band material, and Undifferentiated Linea formation. The Band and High-Albedo Band units generally appear younger and cross-cut the Ridged Plains unit. Cycloids also appear to have formed during this period. It is of note that cycloids can appear similar to ridge or band linea structures and even transform from one to the other along their length, potentially indicating a transition from a ridge-building to a band-forming mechanism (0°, 133° E).

The third, or most recent period, is dominated by chaos terrain formation including the emplacement of microchaos. At the global-scale, chaos terrain does not appear to have any cross-cutting units besides craters and their ejecta, the troughs in the northern leading hemisphere, and potentially depression margins. Likewise, microchaos is observed breaking up previously formed bands, ridges, cycloids and other features, indicating that as a whole it is younger. However, we assume that each microchaos is formed relatively contemporaneously with one another, but they may have been emplaced over an extended period of time. Regardless, none are older than the ridged plains unit.

Even though we have identified three periods in Europa's surface history, we emphasize that they are heavily inter-fingered with one another and are not necessarily discrete periods. This

apparent interfingering could be a result of the image resolution limitations though we believe that this will hold true even with increased resolution or other age dating techniques. This chronostratigraphy agrees with published regional maps of Europa (e.g., Greeley et al., 2000; Figueredo and Greeley, 2004).

2.7 Geologic Summary

Data provided by the Voyager and the Galileo missions have provided significant insight into the geological processes that have shaped or continue to shape Europa. Completing a global map at a uniform or high resolution (10s to 100s of m/pixel) will need to wait for the Europa Clipper mission, now in development (Phillips and Pappalardo, 2014).

The results of this mapping provide a quantitative assessment of the areal distribution of chaos terrain and its variability across Europa—all four chaos units cover ~35% of Europa's surface with some outcrops extending laterally for 100s to 1000s of km. The chaos material resides in four morphological categories which we differentiate based on texture and albedo-- High Albedo Chaos, Mottled Chaos, Low Albedo Chaos, and Knobby Chaos. Although various hypotheses have been proposed to explain the formation of chaos, there is no consensus on the mechanism for its emplacement (see Table 2.1). Mapped occurrences of microchaos, summing to ~2% of the surface area (assuming an average area of 314 km² per microchaos feature), show a relatively uniform distribution across the surface and may have resulted from a similar process as chaos formation based on their morphology and texture.

Impact craters and their associated deposits cover less than 2% of Europa's surface area. The crater material unit is divided into three morphological units, Craters, Continuous Crater Ejecta, and Discontinuous Crater Ejecta. The latter is found only around Pwyll, potentially one of the

youngest craters on Europa (Bierhaus et al, 2001). The overall paucity of impact craters, we map 53 in total, suggests Europa has a geologically young surface.

Materials forming bands are subdivided into two units—bands (b) and high albedo bands (bha). The relative albedo within the high-albedo bands unit are consistent despite the change in incidence and emission angle, whereas the albedo of the bands unit varies significantly. Though, the majority of bands appear to be low albedo with respect to the surrounding terrain. The albedo variation of a specific band in changing incidence and emission angle could be due to grain size or macro-scale roughness, implying that high-albedo bands are potentially smoother or have smaller grains than bands. Additionally, or alternatively, the relative brightness differences from band to band could be indicative of salt concentration radiation exposure, or age (e.g., Lucchitta and Soderblom 1982; Schenk and McKinnon, 1989; Geissler et al., 1998; Carlson et al., 2002; Prockter and Patterson, 2009). Altogether, Bands and High Albedo Bands take up 3.5% of Europa's surface area.

In addition to the geologic units, we have mapped structural features that include: depression margins (dm), troughs (t), multi-ring structures (mrs), cycloids (cy), band linea (bl), ridges (r), and undifferentiated linea (ul). We have mapped over 2500 occurrences of a point feature discussed above, microchaos (mch). Due to their great extent, the linear features are stratigraphic markers that allow global-scale cross-cutting relationships to be established as they can stretch for 100s of km. As such, they are essential to a global geologic map of Europa and are critical to understanding Europa's observable surface history.

Depression margins (dm) appear to be one of the youngest features on Europa's surface because they appear not to be disrupted by the interior terrain. Troughs are also relatively young structures on Europa's surface as there are no other features that appear to cross-cut them except

for limited associations with chaos terrain. The same also applies to multi-ring structures (mrs) as they are only identified at three craters, Callenish, Tyre, and Talesien. Cycloids (cy) extend across Europa's surface for 100s of km in some cases, and can vary in relative age. Band linea (bl) are found to have the same relative age as the bands unit. Ridges typically occur within the ridged plains and are crosscut by the chaos units, microchaos, craters, and other linear features. Undifferentiated linea could potentially consist of ridges, band linea, or other structures and are often unresolvable so their potential age is widely uncertain and spans much of Europa's surface history.

Based on the identifiable cross-cutting relationships between the map units and linear features, this global geologic map reveals three relatively distinct periods in Europa's surface history (see Figure 2.6). With this map we have analyzed and summarized the state of knowledge on Europa's geological history. The apparent need for resurfacing mechanisms to create Europa's current young surface is made especially clear with the lack of craters and the wide variety of units and features identified on our map. However, much of the surface will likely remain a mystery until additional imaging and compositional data becomes available through the Europa Clipper Mission.

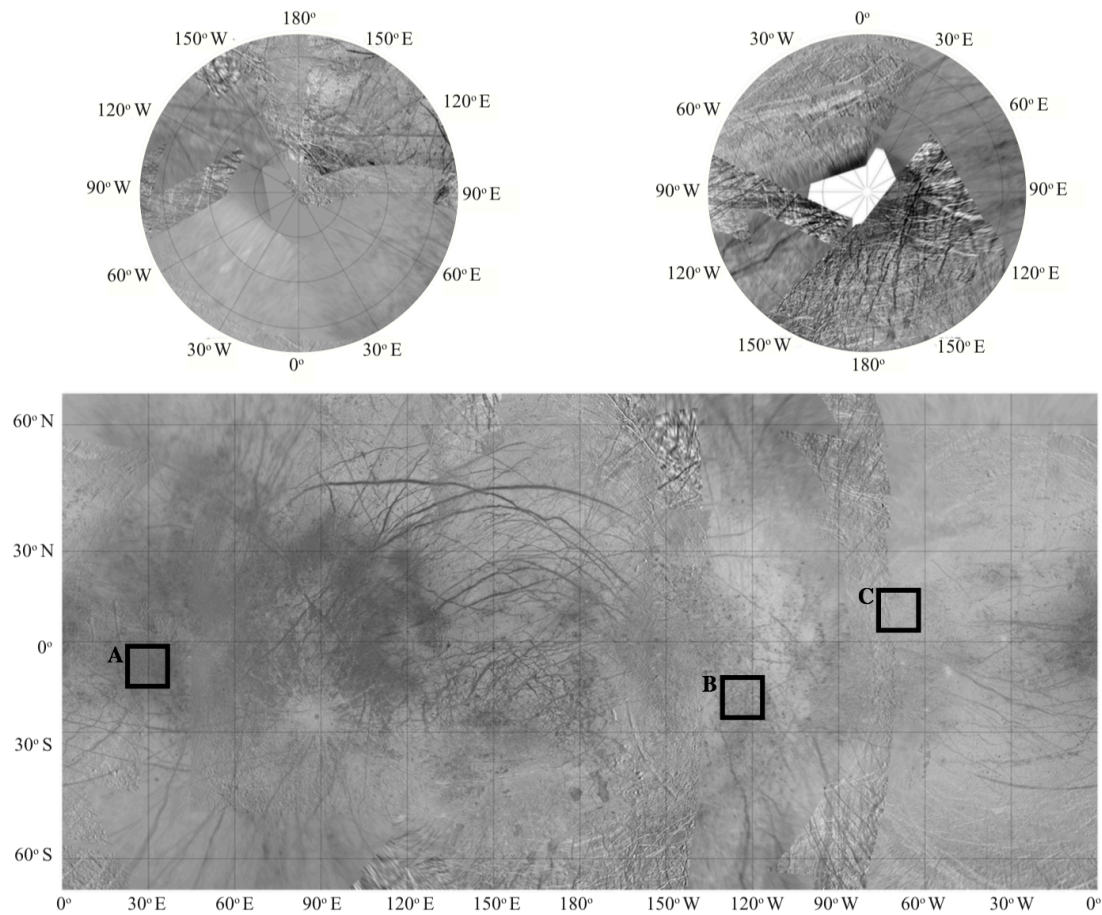
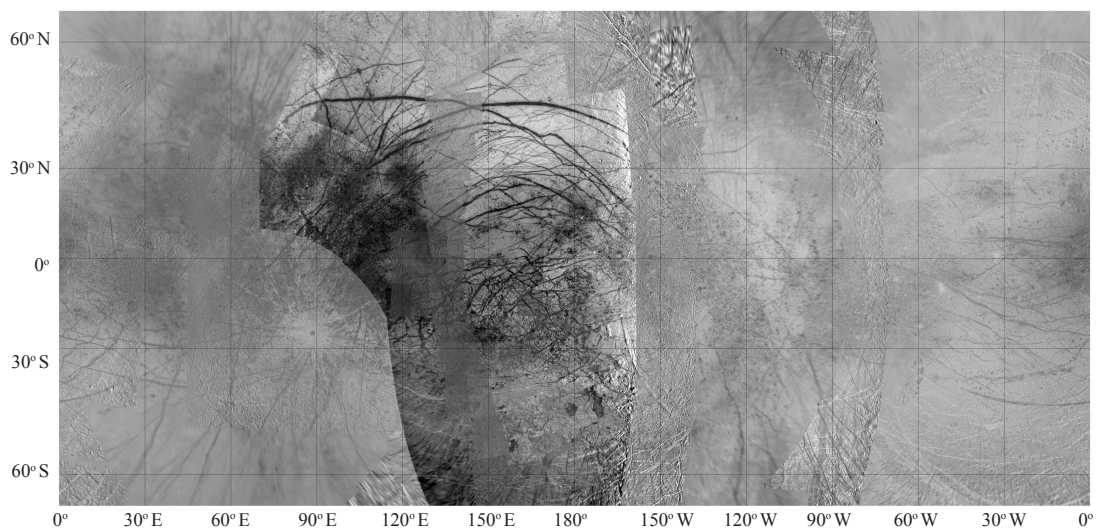
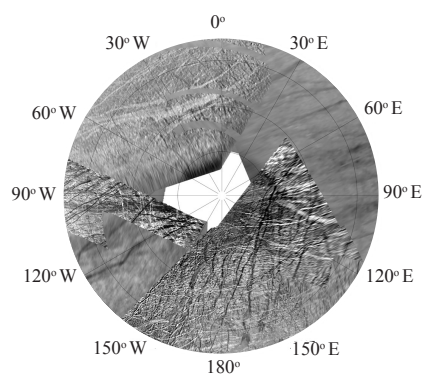
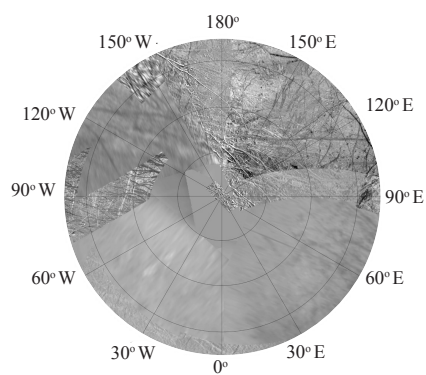
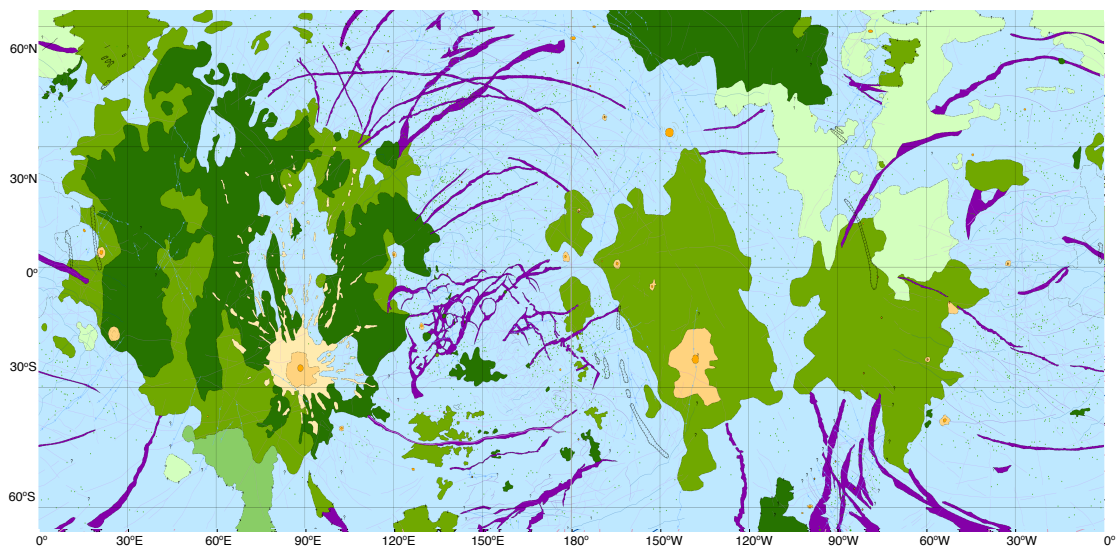
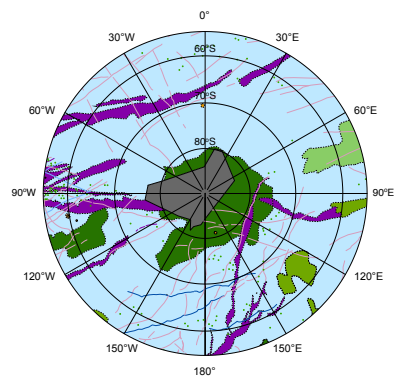
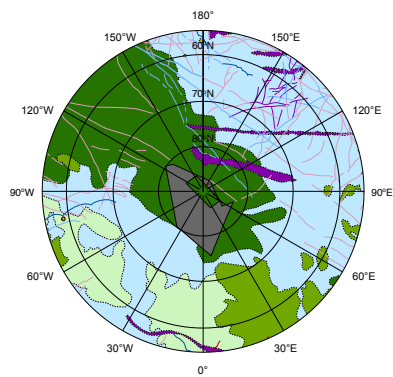


Figure 2.1. The USGS global mosaic (a), where the boxes refer to the locations of the histograms in Figure 2.4, and with the Supermosaic created by Geoff Collins overlain on the USGS global mosaic (b), next page.





Map Legend

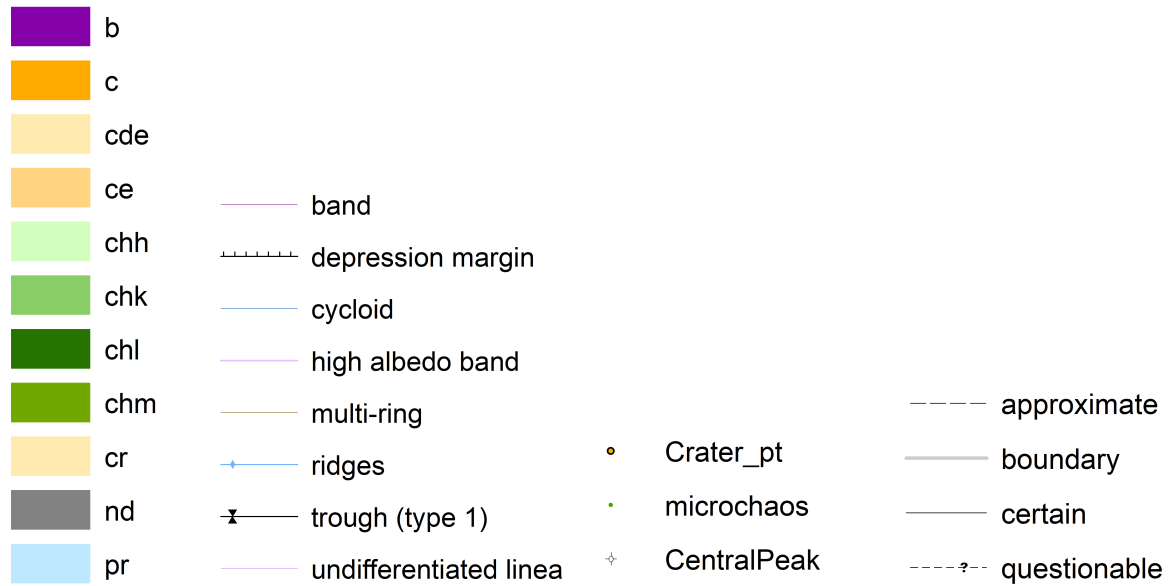
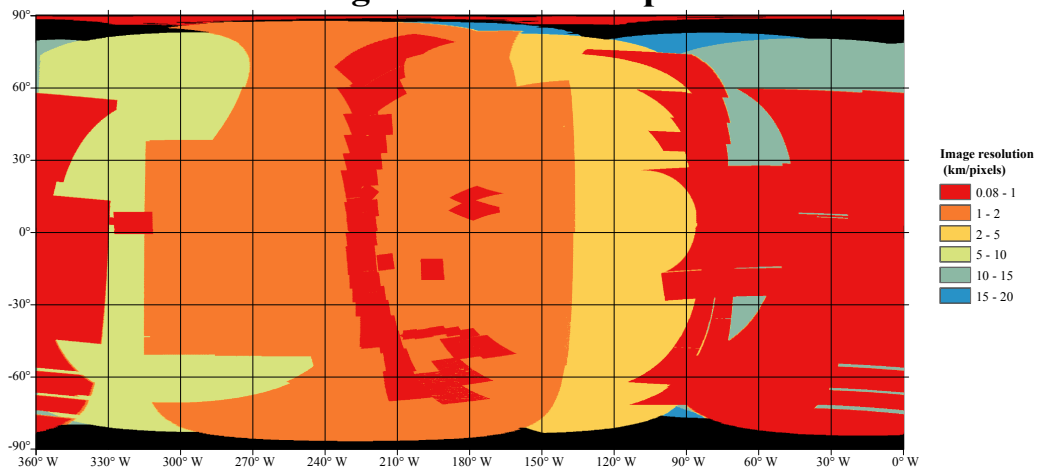
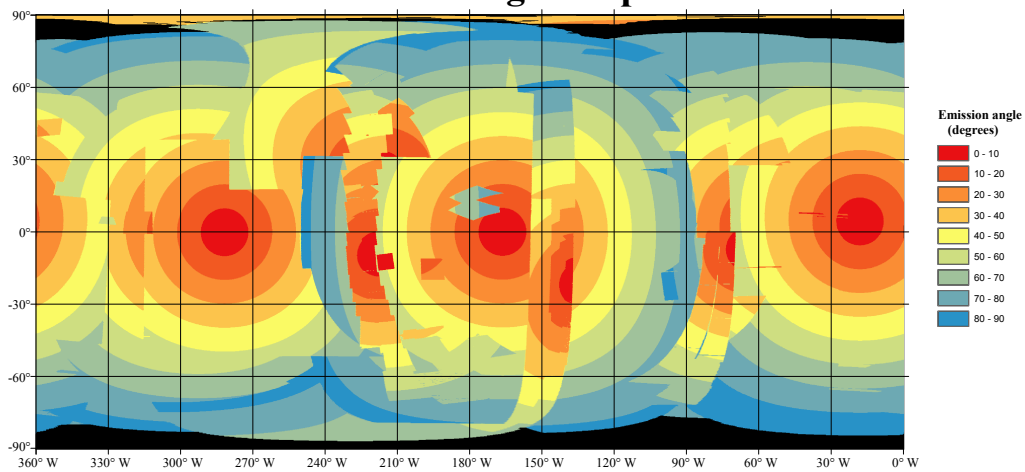


Figure 2.2. Global Geologic Map and Legend. (a) Map of Europa at 1:15,000,000 scale. (b) Seven geologic units, seven linear features and three point features are identified at this scale.

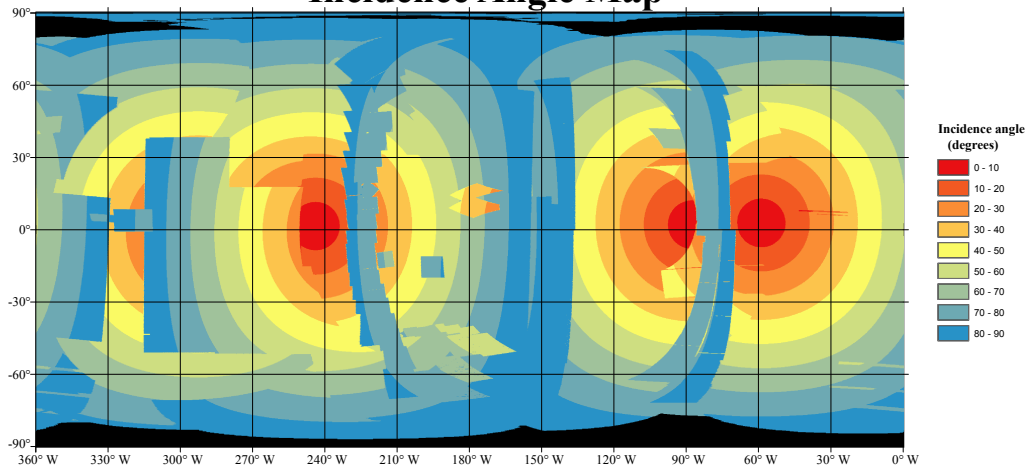
Image Resolution Map



Emission Angle Map



Incidence Angle Map



See full caption on next page

Figure 2.3. Image Resolution Map, Emission Angle Map, and Incidence Angle Map

The top map depicts the image resolution of the images used in the global mosaic, the middle map depicts the emission angle, and the bottom map depicts the incidence angle, or the angle of the lighting with respect to surface normal, of the images used in the global mosaic. Note the wide variety of resolutions (200 m to 12+ km) and incidence angles (0 to 87 degrees) of the images used in the global mosaic, making consistent mapping across the globe difficult.

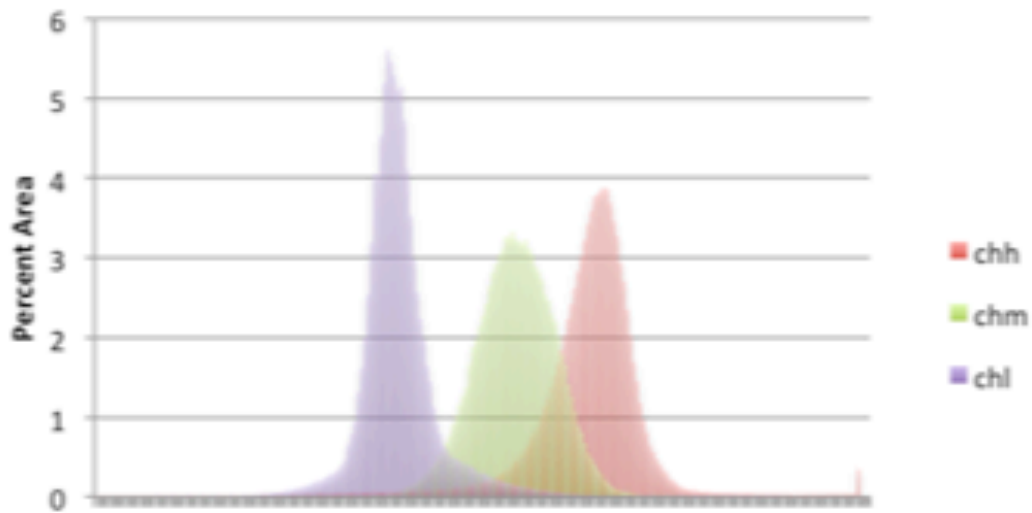


Figure 2.4. Chaos Histograms. Three of the chaos units—low albedo chaos, mottled chaos and high albedo chaos—are defined partially by relative brightness. The histogram is purple corresponds to the Data Numbers of all the pixels in box A on Figure 2.1a, an area of Low Albedo Chaos. Likewise, the green histogram corresponds to box B in Figure 2.1a and the red corresponds to box C. Note that the Low Albedo Chaos histogram is narrow, the Mottled Chaos histogram is broad reflecting the variety of relative brightnesses within this unit, and the High Albedo Chaos histogram again is narrow. The x-axis (data number) is not labelled because we do not use the precise numbers as this can vary across imaging geometry, but the shape and relative placement of the histograms.

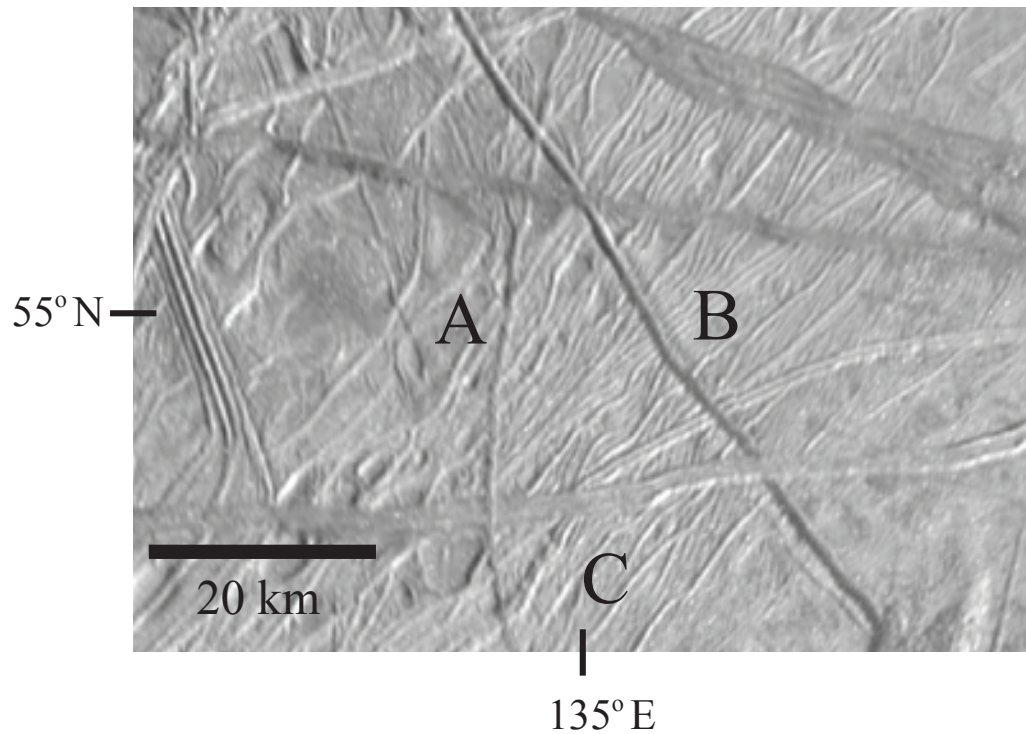
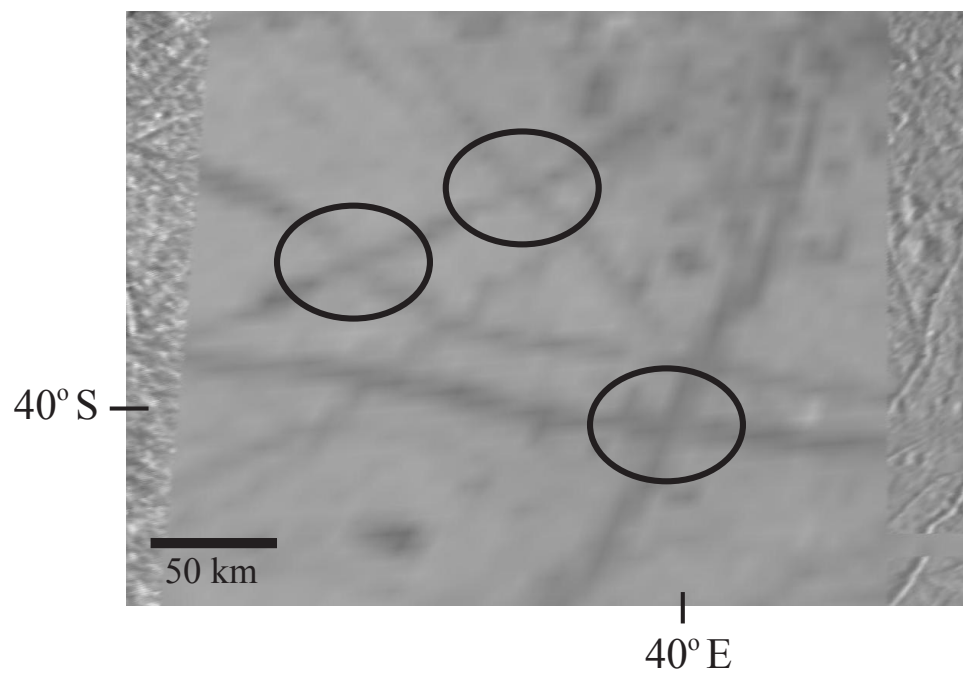


Figure 2.5. Ambiguous Relationships. Examples of why the typical practice of superposition determining relative age does not work on Europa. The three lineaments forming a triangle in (a) have conflicting superposition relationships: Lineament A is younger than C and older than B (B, A, C); Lineament B is younger than A and older than C (C, B, A); Lineament C is younger than B and older than A (B, C, A). The lineaments in (b) have indecipherable superposition relationships due to low resolution images.



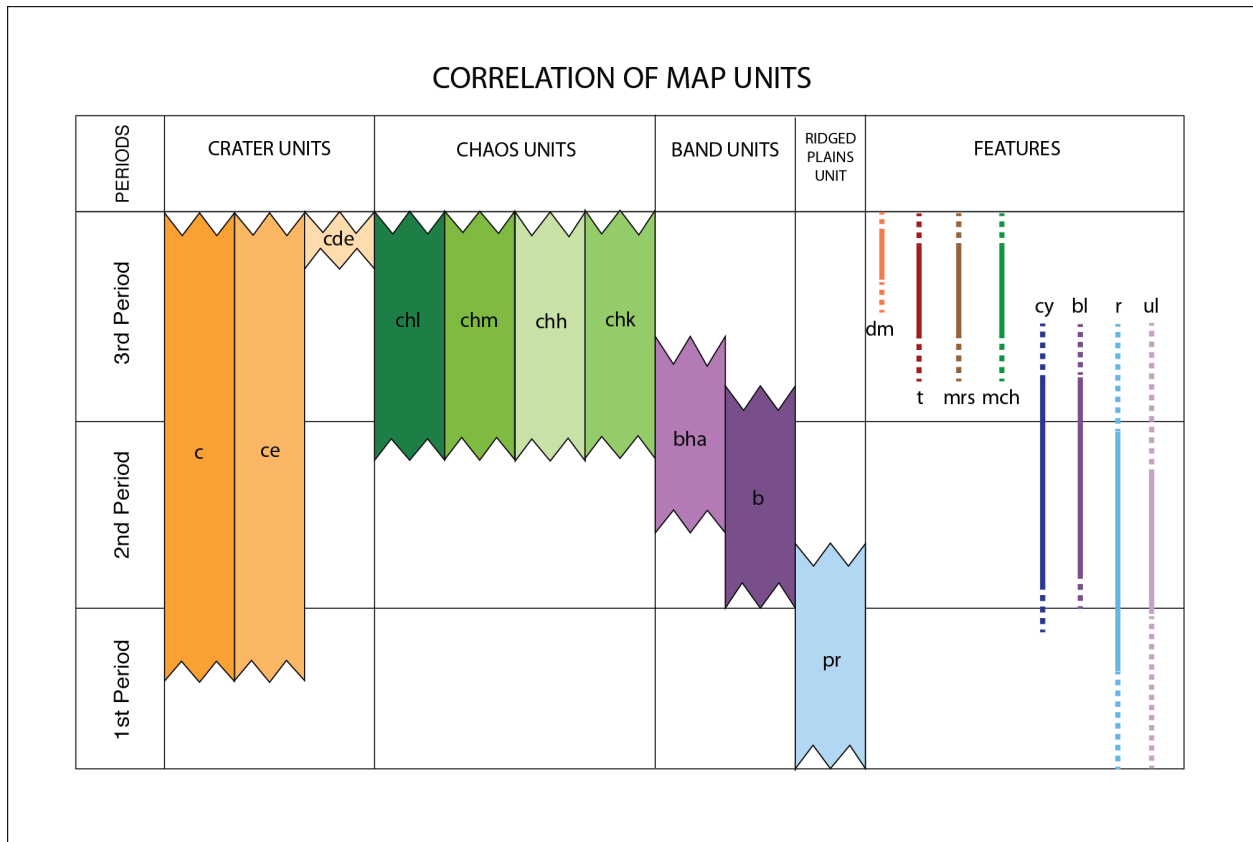


Figure 2.6. Correlation of map units (COMU). This chart is a representation of the relative ages, as determined by cross-cutting relationships, of the various global units over the visible surface history (~100 Ma). The jagged edges on each bar and dotted parts of each line represent the uncertainty and how each bar could extend forward or backward (up or down) in time. We observe that Europa's resurfacing over the past ~100 Ma can be divided up into three periods where ridged plains formation is the oldest (1st period), followed by a period of band formation (2nd period), and lastly a period of chaos formation (3rd period). Craters, are spread throughout time as we do not observe an over-printing and thus their relative age cannot be determined.

Table 2.1: Description of map units (DOMU)

DESCRIPTION OF MAP UNITS					
Unit Label	Unit Name	Unit Definition	Additional Characteristics	Interpretation	Type Example (low/high resolution)
IMPACT CRATER UNITS					
c	Crater Material	Quasi-circular depression with a raised rim or complex annular structure. Crater floors can be roughly flat to bowl-shaped.	We identify 53 craters on Europa's surface, approximately half of which have a diameter > 10 km (unit). Craters with a diameter < 10 km are represented as a point feature. All craters recognized by the IAU are identified on the map.	Crater Material is interpreted to be formed and emplaced by a hyper-velocity impact. The paucity of Crater Material observed on Europa's surface implies a surface age of ~60 Ma (Bierhaus et al., 2001, 2009).	 108°E, 1°N  E15 Frame 5000 109 mpx
ce	Continuous Crater Ejecta Material	Region around the crater material made up of proximal ejecta extending as far as ~5 crater radii from the primary impact crater with a patchy, mottled texture surrounding a central crater.	We identify 20 craters that have surrounding Continuous Crater Ejecta Material at the resolution of the global image mosaic.	Continuous Crater Ejecta Material is material emplaced as part of the impact process and can include entrained non-ice materials, potentially from the subsurface, or entrained materials distributed by the impactor (Moore et al., 2001).	 108°E, 1°N  E6 Frame 8304 56 mpx
cde	Discontinuous Crater Ejecta Material	High relative brightness material made up of distal ejecta extending >5 crater radii from the primary impact crater with a patchy, mottled texture surrounding a central crater material.	Found only around Puyvi crater.	Discontinuous Crater Ejecta Material can include non-ice materials (as described above in Continuous Crater Ejecta Materials) and consists of material deposited distally from the primary impact site. This displaced material drapes and modifies the pre-existing terrain to create the texture observed.	 108°E, 1°N  E15 Frame 4252 232 mpx
cr	Crater Ray Material	Isolated high relative brightness patches of extreme distal ejecta, >>5 crater radii from the primary crater, aligned quasi-linearly, emanating radially from a central point (crater).	Found only around Puyvi crater.	Crater Rays are distal ejecta deposits that form from secondary impactors and other corresponding ejecta (Bierhaus et al., 2001, 2009; Moore et al., 2001). Puyvi is the only crater with evident rays, indicating that perhaps it is the youngest large (>10 km) crater (Bierhaus et al., 2001).	 108°E, 1°N  E15 Frame 4252 232 mpx
cp	Central Peak Structure	A central structure within a crater that can range from a complex ray structure to a simple topographic peak.	Twelve identified craters contain Central Peak Structures. This point feature includes what is referred to as disrupted central peaks by Schenk and Turtle (2009).	Central Peak Structures form from the rebound process, exposing subsurface material uplifted during the crater forming event (e.g., Grieve et al., 1981; Pieters et al., 1982). This potentially implies that Europa's ice shell was not completely penetrated during crater formation (Schenk and Turtle, 2009).	 108°E, 1°N  E15 Frame 4252 232 mpx
CHAOS UNITS					
chl	Low Albedo Chaos Material	Disrupted terrain at the scale of 100s of meters to kilometers with a relatively uniform low relative brightness and subtle texture. Outcrops are typically found at the 100s of kilometer scale.	The relative low brightness of this chaos unit remains constant even in a variety of incidence angles and resolutions.	Proposed models for chaos formation include: diapirism, with potential partial melting of a salt-rich icy lithosphere (Pappalardo et al., 1998; Rathbun et al., 1998), ice-shell melt-through (Carr et al., 1998; Greenberg et al., 1999; O'Brien et al., 2002; Greenberg et al., 2003), and water lens collapse within the ice-shell (Schmidt et al., 2011). The low relative brightness of this unit is hypothesized to be due to a high concentration of salts or the effects of radiation on these salts (e.g., Carlson et al., 2002). This unit may contain a high percentage of matrix material relative to the highly disrupted pre-existing crustal blocks.	 108°E, 1°S  E11 Frame 8226 221 mpx E17 Frame 6713 217 mpx
clm	Mottled Chaos Material	Disrupted terrain at the scale of 100s of meters to kilometers with a patchy/variegated relative brightness and texture. Outcrops are typically found at the 100s of kilometers scale.	In the trailing hemisphere, this unit appears to be a gradual transition from the Low Albedo Chaos to Ridged Plains.	All chaos units are interpreted to be formed by the same or similar processes. Models for the formation of the Mottled Albedo Chaos include variations in salt content or the growth of chaos terrain from merging microchaos terrains (Pappalardo et al., 1998; Carlson et al., 2002; Doughty et al., 2009). This unit may contain nearly equal percentage of matrix material and highly disrupted pre-existing crustal blocks.	 278°E, 23°S  E15 Frame 4252 232 mpx
chl	High Albedo Chaos Material	Disrupted terrain at the scale of 100s of meters to kilometers with a uniformly high relative brightness with respect to the other chaos units and the surrounding terrain. Subtle textural variations. Outcrops are found at the 100s of kilometer scale.	Occurs primarily on the sub-Jovian hemisphere of Europa. The relative brightness of this chaos unit remains constant even in a variety of incidence angles and resolutions.	All chaos units are interpreted to be formed by the same or similar processes. The higher relative brightness of this chaos unit could indicate that this chaos is older or more radially processed, or irradiated, than other chaos varieties (Carlson et al., 2002). This unit may contain a low percentage of matrix material relative to the highly disrupted pre-existing crustal blocks.	 200°E, 10°N  E15 Frame 4252 232 mpx
chk	Knobby Chaos Material	Disrupted terrain with rough, blocky, and scalloped texture. The rough texture is at a larger scale (~10 km) when compared to the other chaos units. Outcrops are found at the 100s of kilometer scale.	The only identified location is in the southern leading hemisphere. Relative brightness is not used to define this unit, unlike other chaos units.	All chaos units are interpreted to be formed by the same or similar process. The large scale roughness of the knobby chaos could be indicative of the chaos formation process acting on a larger scale, or producing more (or larger) plates in this region.	 142°E, 34°S  E12 Frame 3813, 50 mpx
BAND UNIT					
b	Band Material	Linear to curvilinear zones, 15 to ~60 km in width with a distinct, abrupt relative brightness change (typically darker) than the surrounding region. The band must be >15 km wide in order to be considered a unit, if the band is <15 km wide it is considered a linear feature (see Band Lines).	In some regions where high-resolution data is available, (~250 m/pxel), bands can be subdivided as "smooth", "lineated", or "ridged" (e.g., Figureado and Greeley, 2004). We do not make this subdivision in order to maintain consistency across the globe where low resolution image coverage dominates and which render band subdivisions impractical.	Bands appear to be dilatational in origin as many can be removed allowing for reconstruction of the pre-existing terrain (Prockter et al., 2002; Schenk and McKinnon, 1989). The different morphologies of the bands are evident at higher resolution, ~250 m/pxel, where different spreading rates or material properties of the ice may be a factor in their formation (Howell and Pappalardo, 2015).	 142°E, 34°S  E12 Frame 3813, 50 mpx
PLAINS UNIT					
pr	Regional Plains Material	Composed of relatively uniform high apparent brightness material. Appears to be relatively smooth at the global resolution, kilometer scale, but significant textural variations are revealed in higher resolution data (<100 m/pxel). Thus, in areas of low resolution (> 1 km/pxel), this unit represents an undivided terrain where other units cannot be identified.	Distributed over all latitudes and longitudes and where high-resolution images (<100 m/pxel) are available, the unit is characterized by subparallel to cross-cutting ridges and troughs. These plains are cross-cut by every other unit.	Multiple (Geissler et al., 1998; Patel et al., 1999; Sullivan et al., 1999; Figureado and Greeley, 2004) or continuous (Greenberg et al., 1998), episodes of ridge building with repeated overprinting. At higher resolution, many morphologies of the ridged plains are apparent with potentially differing formation processes (Leonard et al., 2018).	 143°E, 32°E  E17 Frame 9239 50 mpx
LINEAR FEATURES					
dm	Depression Margin	Identified margin of broad, shallow topographic lows.	Pre-existing features within the depressions appear undisturbed and are typically well preserved. Some depression margins have well-defined walls while others are more subtle and subdued.	Inferred to be indicative of possible recent polar wander. When fit to stress patterns, have been interpreted to be artifacts that indicate the location of potential pole-poles because they occur on a great circle (Schenk et al., 2008).	 19°E, 8°N  E19 Frame 8726, 63 mpx
t	Trough	Linear, narrow (~5 km wide) topographic lows with crustal material on either side of the trough showing no apparent offset.	Where observed, troughs are not cross-cut by any other structure or unit. Due to the map scale, only troughs >5 km wide are mapped.	Inferred to be tension cracks and appear to be one of the youngest structures on Europa's surface (Figureado and Greeley, 2004).	 4°E, 43°N E20 Frame 6813, 45 mpx
mrs	Multi-Ring Structure	Quasi-circular to arcuate series of continuous or discontinuous ridges surrounded by material with a hummocky texture.	Associated with three large impact craters, Callisto, Tethys, and Tyre.	Concentric rings formed during the impact process and may be directly related to the ice-shell thickness (e.g., Turtle, 1998; Kadel et al., 2000; Lidzberg et al., 2006). The lack of other topography (e.g., a distinct bowl-shaped crater) at these craters could be indicative of weak ice at depth within Europa's ice shell (McKinnon and Melosh, 1980; Schenk, 2002).	 29°E, 17°S E19 Frame 8726, 63 mpx
mch	Microchaos Material	Circular to oblong 5-25 km diameter disruptions of the background terrain. Commonly occurring on the Regional Plains and often has a lower relative brightness or different texture than the Regional Plains Material.	Also referred to as pits, domes, spots, and lenticulae (e.g., Head et al., 1997; Greeley et al., 2000; Greenberg et al., 2003). Over 2000 of these features are identified globally over all latitudes and longitudes. Due to the map scale, only microchaos with a diameter > 5 km are mapped.	The morphological similarities between Microchaos Material and larger chaos areas suggest a related formation processes. Proposed models for Microchaos formation include: diapirism, with potential partial melting of a salt-rich icy lithosphere (Pappalardo et al., 1998; Rathbun et al., 1998), water lens collapse within the ice-shell (Schmidt et al., 2011; Michaut and Manga, 2014), and cryomagnetic activity (Fagents et al., 1998).	 137°E, 38°N E19 Frame 8726, 63 mpx
cy	Cycloid	A series of continuous arcs, typically 5-10 km wide, linked by at least two well-defined and sharp cusps.	Also referred to as flexus, these features can range morphologically from a band to a ridge along their length. Two or more cusps are required for characterization as a cycloid in this map distinguishing them from lineaments such as the prominent band at 167°W, 39°N.	The cycloidal shape has been suggested to be controlled by a changing direction of crack propagation under the control of Europa's diurnally rotating tidal stress field (Hoggs et al., 1999), potentially aided by non-synchronous stress (Hirford et al., 2007) or initiated as a taluscrack (Marschall and Kattenhorn, 2005).	 205°E, 16°N E17 Frame 9552, 51 mpx
bha	High-Albedo Band Linea	Linear to curvilinear zones (5-15 km wide) with a distinct, abrupt apparent brightness increase relative to the surrounding region.	High Albedo Band Linea appear to have a higher relative brightness than the surrounding terrain at the range of incidence angles observed, unlike the Band unit (b). Occurs in three locations at the global scale (Greenberg, 2004). Only HighAlbedo Band Linea > 5 km wide are mapped due to the map scale.	These bands may differ in morphological properties from the Band Material (b) due to the presence of a fine grained material (Geissler et al., 1998) or, they may be sites of young bright ice (Lancetta et al., 1981; Schenk and McKinnon, 1989). It has also been proposed that the formation mechanism for these bands could be the same as that for Band Material (b) and Band Lines (bl), or it may differ by involving significant contraction (Greenberg et al., 2004) or dextral shear (Prockter et al., 2002; Kattenhorn et al., 2004).	 147°E, 41°S E17 Frame 9552, 51 mpx
bl	Band Linea	Linear to curvilinear zones (5-15 km wide) with a distinct, abrupt relative brightness change (brighter or darker) from the surrounding region, less than 15 km in width.	Continuation of the Band Unit where the lateral extent is too small to map it as an areal unit at this map scale. Only Band Lines > 5 km wide are mapped due to the map scale.	Inferred to have the same or similar formation mechanism as the Band Material (b).	 177°E, 34°S 202°E, 16°N
r	Ridge	Quasi-linear topographic highs (~5-10 km wide) containing one or more crests.	Large length to width ratio. On average, less than 100 m high. (Greeley et al., 2000; Coulter and Kattenhorn, 2010; Leonard et al., 2018). Only Ridges > 5 km wide are mapped due to map scale.	At higher resolution Ridges commonly appear as double ridges or ridge complexes. Ridges could be formed through a variety of processes (for review, see Kattenhorn and Hirford, 2009).	 18°E, 38°S
ul	Undifferentiated Linea	Long (10s to 100s of km), linear, through-going features (5-15 km wide) of either low or high relative brightness that do not have other discernable characteristics at the global scale.	The unique characteristics of these features cannot be constrained at the global scale. With higher resolution data or more favorable viewing geometries, they likely could be characterized into other, more specific linear features with higher-resolution images or more favorable viewing geometries. Only Undifferentiated Linea > 5 km wide are mapped due to the map scale.	Undifferentiated Linea are most likely examples of Troughs, Ridges, or Band Lines that are undetectable due to resolution, lighting, and viewing geometry limitations.	 18°E, 38°S

Table 2.2: Images in the supermosaic

	Image Number	Resolution	Incidence Angle
Background	G1ESGLOBAL01_03498751.13	1.6 km	38
	G1ESGLOBAL01_03498751.26		
	G1ESGLOBAL01_03498751.39		
	G1ESGLOBAL01_03498751.78		
	I4ESGLOCOL01_04409848.65	1.45 km	75
	I4ESGLOCOL01_04409849.00		
	I4ESGLOCOL01_04409849.26		
Higher-Resolution Images	I1ESREGMAP01_04206192.00	220 m	75
	I1ESREGMAP01_04206192.13		
	I1ESREGMAP01_04206192.26		
	I1ESREGMAP01_04206192.39		
	I1ESREGMAP01_04206192.52		
	I1ESREGMAP01_04206192.65		
	I1ESREGMAP01_04206192.78		
	I1ESREGMAP01_04206193.00		
	I1ESREGMAP01_04206193.13		
	I1ESREGMAP01_04206193.26		
	I4ESWEDGES01_04409551.65	230 m	39
	I4ESWEDGES01_04409551.78		
	I4ESWEDGES01_04409552.00		
	I4ESWEDGES01_04409552.13		
	I4ESWEDGES01_04409552.26		
	I4ESWEDGES01_04409552.39		
	I4ESWEDGES01_04409552.52		
	I4ESWEDGES01_04409552.65		
	I4ESWEDGES01_04409552.78		
	I4ESWEDGES01_04409553.00		
	I5ESREGMAP01_04499618.00	228 m	81
	I5ESREGMAP01_04499618.14		
	I5ESREGMAP01_04499618.26		
	I5ESREGMAP01_04499618.40		
	I5ESREGMAP01_04499618.52		
	I5ESREGMAP01_04499618.65		
	I5ESREGMAP01_04499618.79		
	I5ESREGMAP01_04499619.01		
	I5ESREGMAP01_04499619.13		
	I5ESREGMAP01_04499619.26		
	I7ESAGENOR01_04666648.13	200 m	57
	I7ESAGENOR01_04666649.52		
	I7ESAGENOR01_04666651.00		
	I7ESAGENOR01_04666652.39		
	I7ESAGENOR01_04666653.78		
	I7ESNERTRM01_04666645.52	230 m	81
	I7ESNERTRM01_04666645.65		
	I7ESNERTRM01_04666645.78		
	I7ESNERTRM01_04666646.00		
	I7ESNERTRM01_04666646.13		
	I7ESNERTRM01_04666646.26		
	I7ESNERTRM01_04666646.39		
	I7ESNERTRM01_04666646.52		
	I7ESNERTRM01_04666646.65		
	I7ESREGMAP01_04666641.52	220 m	81
	I7ESREGMAP01_04666641.65		
	I7ESREGMAP01_04666641.78		
	I7ESREGMAP01_04666642.00		
	I7ESREGMAP01_04666642.13		
	I7ESREGMAP01_04666642.26		
	I7ESREGMAP01_04666642.39		
	I7ESREGMAP01_04666642.52		
	I7ESREGMAP01_04666642.65		
	I7ESREGMAP01_04666642.78		
	I7ESREGMAP01_04666643.00		
	I7ESREGMAP01_04666643.13		
	I7ESREGMAP01_04666643.26		
	I7ESREGMAP01_04666643.39		
	I7ESREGMAP01_04666643.52		
	I7ESREGMAP01_04666643.65		
	I7ESREGMAP01_04666643.78		
	I7ESREGMAP01_04666644.00		
	I9ESNORLAT01_04848847.00	200 m	78
	I9ESNORLAT01_04848847.13		
	I9ESNORPLN01_04848882.07		
	I9ESNORPLN01_04848882.11		
	I9ESNORPLN01_04848882.42		
	I9ESNORPLN01_04848882.46		
	I9ESNORPLN01_04848882.49		
	I9ESNORPLN01_04848882.53		
	I9ESREGMAP01_04848845.00	200 m	78
	C3ESWEDGES01_03686394.00	420 m	87

Table 2.3 Relative surface area percentages for each unit type

Unit(s)	Aerial Coverage
Crater (<i>c, ce, cde</i>)	1.5%
Microchaos (<i>mch</i>)	2% *
Chaos (<i>chh, chm, chl, chk</i>)	40%
Bands (<i>b, bha</i>)	3.5%
Ridged Plains (<i>pr</i>)	53%

*The area of each microchaos is assumed to average out to equal the area of a circle with radius ~10 km.

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- Chapter 3 -

**Analysis of very-high-resolution Galileo images and
implications for resurfacing mechanisms on Europa**

3.1 ABSTRACT

The young (<100 Ma) surface of Jupiter's icy satellite Europa raises the key questions: (1) what are the resurfacing mechanisms for creating Europa's young surface, and (2) how have these processes evolved through time? To address these questions, we analyze the nine high-resolution frames obtained by the Galileo Solid State Imager (SSI)—eight at 16 m/pixel and one at 8 m/pixel (commonly quoted at the planned 6-12 m/pixel as in Greeley et al., 2000)—during the E12 flyby of Europa in Dec. 1997. This dataset is now two decades old, but it has not been analyzed in detail until this work. Despite the largely different viewing and lighting conditions, we mosaic these high-resolution frames into the 220 m/pixel regional context frame. We then perform geomorphologic mapping of the high-resolution image mosaic and the regional image frame, for comparison, and we also create a structural map of the high-resolution image mosaic. The units in the geomorphologic map are defined by surface texture, landform shape (morphology), dimension, and relative albedo. The structural map units include interpretations from the geomorphologic map units and their interpretation implies potential kinematic processes for the formation of particular structures. Our primary mapping observations include the regular spacing and gentle slopes of the ridge-and-trough terrain, the sharp boundaries and preserved structures of the chaos terrain, and the symmetry but irregular size of double ridges. We then evaluate proposed formation mechanisms for these and other mapped features. The high-resolution images also reveal an abundance of small (< 100 m) pits, the presence of a newly identified high-albedo smooth material, and potential tectonic fabric, all of which have possible implications for the surface history. The mapping and structural analyses lead to the key finding that local-scale resurfacing mechanisms have transitioned from distributed deformation expressed by the formation of the ridged plains to discrete deformation characterized by the

formation of chaos and isolated fractures. This finding is consistent with simultaneous ice-shell thickening and cooling occurring as the ice-shell deformed.

3.2 INTRODUCTION

Voyager and Galileo Solid State Imager (SSI) images of Europa reveal complex surface features exemplified by a wide variety of crosscutting surface structures with diverse morphologic expressions (e.g., Pappalardo et al., 1999). Additionally, the paucity of recognizable craters with diameters >10 km requires that Europa's surface is young, on the order of 60 Ma (Zahnle et al., 1998). Unraveling the cause of this young surface age combined with the complexity of Europa's surface features has led to competing hypotheses for the formation of key landforms—chaos structures, double ridges, and ridge-and-trough terrain. For chaos terrain these hypotheses include melt-through (Greenberg et al., 1999; O'Brien, 2002), diapirism (Pappalardo et al., 1998; Schenk and Pappalardo, 2004), and the collapse of a melt-lens within the ice shell (Schmidt et al., 2011; Soderlund et al., 2014); for double ridges, cryovolcanism (Fagents and Greeley, 1997; Kadel et al., 1998), tidal squeezing (Greenberg et al., 1998), linear diapirism (Head et al., 1999), shear heating (Nimmo and Gaidos, 2002), compression (Sullivan et al., 1998), wedging (Melosh and Turtle, 2004; Han and Melosh, 2010; Johnston and Montesi, 2014), and compaction (Aydin, 2006); and for ridge-and-trough terrain, extensional tilt-blocks (Kattenhorn, 2002), and folding (Leonard et al., 2015).

Although these competing hypotheses make specific predictions, their validation has been hampered by the lack of definitive observations due to the generally low-resolution images at >220 m/pixel. In order to address this issue, we use the previously unanalyzed 12ESMOTTLE01 and 02 high-resolution (8-16 m/pixel, see Section 3.4.1) image strip to evaluate these hypotheses

by refining the morphologic requirements or constraints on the surface feature formation mechanisms and thus narrow down the potential hypotheses. This work allows us to construct a geomorphologic map with the map units defined by surface texture, landform shape, dimension, and albedo. The geomorphologic map forms the basis for constructing a structural map, which correlates the mapped landforms to interpreted structures. This correlation in turn allows us to infer plausible kinematic processes for the observed morphologic features, leading to a better understanding of the resurfacing processes that have kept Europa's surface young.

The key findings of this work include: (1) Europa's surface deformation has transitioned from a distributed to a discrete mode over the discernable surface history, possibly resulting from the progressive cooling and thickening of the ice shell; (2) ridge-and-trough terrain exhibit gentle, quasi-symmetric slopes and regular spacing indicating folding as a likely formation process; (3) the consistent size and shape of double ridges along their length, but variation in size as a unit suggest compaction or linear diapirism formation mechanism, though neither appear to fit perfectly; (4) chaos terrain exhibits abrupt and heavily deformed boundaries with preserved pre-existing structures on the interior, favoring a water lens collapse formation mechanism; (5) secondary cratering processes may also contribute to resurfacing (~0.5% of the surface); (6) fine lineations are prevalent in the high-resolution images and are interpreted as a tectonic fabric; and (7) the presence of a newly identified *high albedo smooth* material may be indicative of a surface process operating at even a finer scale than is resolvable by the high-resolution images.

3.3 REGIONAL GEOLOGY

During its extended mission, the Galileo spacecraft imaged less than 0.03% of Europa's surface at 8-16 meters per pixel, the highest resolution obtained of Europa's surface to date

(Doggett et al., 1999; Greeley et al., 2000). One of the highest resolution imaged areas of Europa was obtained during Galileo's E12 flyby of the Trailing Anti-Jovian hemisphere (Fig. 3.1) and overlaps with an area imaged at regional resolution (~ 230 m/pixel during the E11 flyby (Fig. 3.2A). Previous work in the anti-Jovian hemisphere has been focused on the “wedges” region, Argadnel Regio (Schenk and McKinnon, 1989; Prockter et al., 1999, 2002), an area interpreted to have resulted from extensional tectonics (Helfenstein and Parmentier, 1983; Greenberg et al., 1998).

There are five primary terrain types identified on Europa (Figueredo and Greeley, 2000, 2004; Greeley et al., 2000): ridges, plains, chaos, bands, and crater terrain. This study region borders an area of chaos terrain to the west and an area of ridged plains terrain to the east, and therefore it is interesting to investigate as an area of terrain transition (Figs. 3.1, 3.2A and 3.2B; e.g., Figueredo and Greeley, 2004). Also, this transition in terrain type presents a wide variety of morphological terrain types in high-resolution (Fig. 3.3A) that could be applicable to many different areas on Europa, given that in general, chaos and ridged plains terrain cover the majority of the surface (Doggett et al., 1999; Greeley et al., 2000; Schenk, 2009). For instance, plains terrain, also identified as “ridged plains” as mapped by other investigators or “ridge-and-trough terrain” in this work, makes up $\sim 60\%$ of Europa's surface (Doggett et al., 1999).

3.4 DATA AND METHODS

In this work, we use nine frames of the highest resolution images in the E12 “Mottle” Region from the Galileo SSI Instrument, which have not previously been analyzed in depth. With this image mosaic we create geomorphological (Figs. 3.2B and 3.3B) and structural map (Fig. 3.3C) of the region in order to analyze the surface features and infer likely formation processes.

3.4.1 Data

The high-resolution data in this region consists of nine frames—one at 8 m/pixel and eight at 16 m/pixel (a single Galileo SSI image at full resolution and eight subsequently acquired in summation mode)—all obtained at an incidence angle of 16-19° and an emission angle of 74°-76° (Table 3.1; Fig. 3.3A). The resolution of these images is typically quoted to be 6 and 12 m/pixel respectively (e.g., Sullivan and Moore, 1999; Greeley et al., 2000; Prockter, 2004). In fact, the planned, or estimated resolution was 12 m/pixel before the Galileo SSI captured the images. The actual resolution of the images, taken from the header of each image, noted in Table 3.1, is closer to ~8 and 16 m/pixel, respectively, in the vertical direction and 40-50 m/pixel in the horizontal direction. The smear in the images is negligible at less than one pixel, based on the original E12 encounter planning data from JPL (D. A. Senske, personal communication). The regional resolution image that overlaps with the high-resolution images (Fig. 3.2A), from Galileo observation 11ESREGMAP01, has a resolution of 229 m/pixel with an incidence angle of 74° and emission angle of 22°, essentially the opposite incidence and emission angles of the high-resolution observation (Table 3.1). A low incidence angle highlights albedo (reflectivity) differences, and a high incidence angle highlights structural features, and topography (Figs. 3.2A and 3.3A). Therefore, comparison between the high and regional resolution can be difficult, but provides complementary information. The images were corrected and mosaicked using the ISIS3 procedures *gllssi2isis*, *spiceinit*, *deltack*, *trim*, *cam2map*, and *mapmos*.

3.4.2 Methods

We performed geological mapping of the high-resolution mosaic (Fig. 3.3B) prior to mapping the regional resolution image (Fig. 3.2B) in order to eliminate any biases that might come from prior analysis of the low-resolution images. Following analysis of the regional-context image, a consistency check was performed between the two maps, regional and high-resolution. The differences noted—viewing geometry effects, misidentified chaos, and insights to band formation—are analyzed in Section 3.8.2. This method of mapping the high-resolution images first, without any context, is not commonly practiced in planetary mapping given that images of the same surface typically improve in resolution over time so low-resolution maps are typically followed sequentially by high-resolution maps (e.g., Lucchitta and Soderblom, 1982; Doggett et al., 1999; Doggett et al., 2007). By reducing any low-resolution mapping bias, we offer a unique perspective on the classification of geomorphologic features observed at high-resolution based on their texture and morphology, which can have implications for their formation mechanism.

Based on the geomorphologic map, we also constructed an interpreted structural map of the same high-resolution region (Fig. 3.3C). The structural map is different from the geomorphologic map in that it relates the observed landforms to specific structures, and implies a kinematic process of ice-shell deformation that can lead to the formation of the observed surface features. A key assumption in constructing the structural map is that the surface erosion is negligible, and the landforms preserve the original shape of the structures resulting from ice-shell deformation. Post-emplacement relaxation, deformation, sublimation, and down slope failure, could affect the original structure post-formation, so the assumption has limits (Moore et al., 1999; Moore et al., 2009; Section 3.8.1.5). Though it is typical to combine the geomorphologic and structural maps together, we do not do this for this region due to its tectonic complexity of

the terrain and to include details without making the maps too busy or cluttered. Unlike the geomorphologic map, the interpreted structural map integrates inferences from regional resolution map (e.g. *band ridge-and-troughs*, Section 3.6.1.7).

In order to place detailed geomorphologic and structural maps in a regional context, we also create a regional-scale geologic map (Fig. 3.2B). Comparison between the maps at different resolutions over the same area provides insights into the nature of the first-order features common on Europa. The regional map combines the geomorphologic and structural mapping techniques employed in the high-resolution maps. The image frame (9278r) from which we derive the regional map was previously mapped, but in less detail (Figueredo and Greeley, 2004) than in this study.

3.5 GEOMORPHOLOGIC MAP AND UNITS

The main focus of this work is to map European surface features at the highest resolution available in this morphologically transitional region—from chaos dominated to ridge dominated terrain—in order to analyze potential surface feature formation mechanisms and create an inferred evolutionary sequence. Creating a geomorphologic map (Fig. 3.3B) provides insight into the potential similarities and differences of surface features across the narrow high-resolution strip, and this permits direct comparison to the regional resolution data in the area.

The definition of major geomorphologic mapping units adopted for the high-resolution observations is based on the previous work done in this region using the regional resolution images (Figueredo and Greeley, 2004) but modified for the high-resolution as appropriate. The mapping units for the relevant regional resolution image and map (Fig. 3.2B) are denoted with a “*reg*” subscript (ex. *t_{reg}* for troughs in the regional resolution). Units containing a “low albedo”

description could be analogous of “dark” terrains with albedos measured between 0.17-0.6, as compared to the “bright” terrains with albedos typically >0.7 (e.g., Helfenstein et al., 1999). Examples of all of the geomorphologic units adopted can be found in Figure 3.4.

3.5.1 Ridge Units

Though there is much variation in specific expression, ridge material generally consists of a topographically high quasi-linear landform. There may also be an associated trough or troughs running sub-parallel to the ridge or ridges. Different sub-units of ridge materials can grade into one another along a ridge’s length, making it difficult to classify and further complicating the inferred origin of these landforms.

3.5.1.1 Double Ridge Unit (rd , rd_{reg})

Double ridges consist of two subparallel quasi-linear topographically high landforms of relatively high-albedo. The landforms are rounded to triangular in cross-section and separated by a trough that commonly contains low albedo material. The width of each ridge pair can vary from ~ 400 to ~ 1200 meters, making double ridge width relatively consistent on the regional scale, but variable on a local scale. This identified morphology is the same in the high-resolution (rd , Fig. 3.4d) and regional-resolution maps (rd_{reg} , Fig. 3.4c). An important additional note is that structures that appear to be *double ridges* in the regional resolution (rd_{reg}) are actually identified differently, e.g. revealed as *ridge complexes* (see Section 3.5.1.2), in the high-resolution images.

3.5.1.2 Ridge Complex Unit (rc , rc_{reg})

Ridge complexes are intricate and varied landforms that consist of a series of irregularly spaced ridges and troughs (Fig. 3.4f). The ridges may vary from linear to curvilinear and bifurcate along their lengths in some cases. As a sub-unit, *ridge complexes* still carry great diversity in size (from ~500 m to >10 km in width) and shape (ridge flanks range from steep and straight to gently convex). In the regional resolution data (rc_{reg} , Fig. 3.4e), part of the *ridge complex* can split or join along its length (e.g., Head et al., 1999; Figueredo and Greeley, 2000).

3.5.1.3 Low Albedo Ridge Unit (*rl*)

The low albedo ridge unit is similar to double ridges (Section 3.5.1.1) and *ridge complexes* (Section 3.5.1.2) but consists mostly or completely of a low albedo material. In contrast to *double ridges* and *ridge complexes* where low albedo material is confined to the troughs, a *low albedo ridge* is either made of or coated in a similar low-albedo material. Though similar in morphology, the *low albedo ridges* are smaller in size than *ridge complexes*; its ridge surfaces are also characterized by a ropy texture or more rounded ridge tops. These ridges have been identified only in the high-resolution region (Fig. 3.4g), though this could be due to the incidence angle differences between the regional and high-resolution images: The low incidence angle of the high-resolution images highlights albedo differences, causing the *low albedo ridges* to appear prominent or could be due to limb darkening, whereas the high incidence angle of the regional resolution image highlights topography and conceals the albedo differences between different landforms. The phase angle between the regional and high-resolution images, which could also influence albedo variations, remains relatively constant (59° to 61°) so this is likely not the source of the appearance of the *low albedo ridges*.

3.5.1.4 Trough Unit (t_{reg})

Troughs are topographically low quasi-linear landforms that have a low albedo appearance in the images. These depressions appear to have steep sides and v-shaped cross sections, though they are on the border of what is resolvable in the regional resolution. They are identified in the geomorphological map at regional resolution (Fig. 3.4a) and in the structural map at high resolution (Section 3.6.2.2).

3.5.1.5 Single Ridge Unit (rs_{reg})

Single ridges consist of one high-albedo topographically high landform with a lack of central topographic low or trough (Fig. 3.4b). These features tend to be linear and rounded in cross-section. *Single ridges* can transition into other types of ridge terrain along their length including *double ridges* (Section 3.5.1.1) or *ridge complexes* (Section 3.5.1.2).

3.5.2 Plains Units

The plains units are 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. The individual ridges do not exceed ~100 m in topographic relief, and average closer to 60 m from trough to ridge crest (Leonard et al., 2015). The most striking characteristic of plains material (also known as ridged plains, background plains, and ridge-and-trough terrain) is that it is one of the oldest units on Europa's surface because it falls in the stratigraphic background relative to essentially every other feature (Greenberg et al., 1998; Doggett et al., 1999; Pappalardo et al., 1999; Prockter et al., 1999; Greeley et al., 2000; Figueredo and Greeley, 2004). Plains material covers ~60% of Europa's surface (Doggett et al.,

1999; Greeley et al., 2000), but has not been examined in detail as the ridges within it are at a sufficiently small scale and very high-resolution data (< 40 m/pixel) covers $< 0.03\%$ of the surface.

3.5.2.1 Subparallel Ridge-and-Trough Unit (rt)

The ridge-and-trough unit consists of systematic, quasi-linear sets of ridges, topographically high landforms, alternating with troughs, or topographically low regions (Fig. 3.4i). The ridges are rounded to triangular in cross-section, and have a topographic wavelength of ~ 300 - 500 m. The limited extent of the high-resolution data does not allow us to observe the exact number of ridges within this unit. The ridges are also observed to be curvilinear and pinch and swell in width along trend (for example, Fig. 3.5, left panel). In various areas, the ridges or associated troughs bifurcate along their lengths and in this way add another ridge or trough to the system.

3.5.2.2 Convex Ridge-and-Trough Unit (rtc)

The convex plains unit has smaller ridge spacing than *subparallel ridge-and-trough* unit (see Section 3.5.2.1), ~ 300 - 350 m, and these ridges are exclusively rounded in cross-section (Fig. 3.4j). Ridges can pinch and swell and bifurcate in some cases. This unit has been previously identified by Patel et al. (1999a) in the Galileo 12ESWEDGES 01/02 observation within Argadnel Regio (Fig. 3.5).

3.5.2.3 Lineated Ridge-and-Trough Unit (rtl)

This lineated unit contains ridges and troughs that are roughly subparallel to one another with a topographic wavelength varying from ~100-300 m (Fig. 3.4k). The ridges are sharply chevron shaped in cross-section and have steep sides compared to the other ridged plains units.

3.5.2.4 Hummocky Ridge-and-Trough Unit (rth)

The hummocky plains unit (Fig. 3.4l) is characterized by small-scale ridges and troughs which commonly pinch and swell along their length (Fig. 3.5; Patel et al., 1999a). They are on the verge of what is clearly identifiable in this high-resolution image mosaic, but they have a topographic wavelength of ~50-100 m.

3.5.2.5 Mélange Ridge-and-Trough Unit (rtm)

The mélange ridge-and-trough unit (Fig. 3.4m) consists of crosscutting ridges and troughs in various directions (Fig. 3.5; Patel et al., 1999a). The ridges typically are rounded in cross-section and do not exceed ~300 m in topographic wavelength and are typically closer to ~150 m in topographic wavelength.

3.5.2.6 Ridged Plains, undivided (pr_{reg})

The undivided ridged plains are only termed and mapped as such at the regional resolution, where it is usually used as a general term for any bright region containing small crosscutting lineaments, which are barely resolvable (Fig. 3.4h). Undivided *ridged plains* could consist of various crosscutting double ridges or systematic subparallel to curvilinear sets of ridges and troughs.

3.5.3 Chaos Units

Chaos, in general, is characterized by blocks of crustal material, ranging from tens of kilometers to tens of meters in size, within a low albedo hummocky matrix (Doggett et al., 1999; Greeley et al., 2000; Kattenhorn and Hurford, 2009). It is a disrupted terrain inferred to be associated with higher heat flow with respect to the surrounding terrain or perhaps in contact with the subsurface ocean (e.g., Greenberg et al., 1999; Pappalardo et al., 1999; Greeley et al., 2000). Lower albedo material on Europa typically has a higher concentration of non-ice material and is commonly inferred to have originated in the subsurface ocean (Shirley et al., 2010; Dalton et al., 2012).

3.5.3.1 Low Albedo Smooth Chaos Unit (*chs*, *las_{reg}*)

The low albedo smooth unit is identified in the high resolution (*chs*, Fig. 3.4p) as a unit with lower albedo than the surrounding features and with unresolvable roughness within the chaos terrain. The material appears smooth down to the scale of a few high-resolution pixels (~20-40 meters).

Occurring primarily near the chaos regions in the regional resolution, *low albedo smooth* (*las_{reg}*, Fig. 3.4o) refers to a terrain that retains the structure of other units but appears to be embayed by a low albedo material. It can occur near identified chaos terrain or independently, which is why we do not label this unit with the “ch” abbreviation typically associated with chaos (e.g., Greeley et al., 2000; Figueredo and Greeley, 2004; Doggett et al., 2009). This unit could be related to what is referred to as Low Albedo Plains in other texts (Prockter et al., 1999; Prockter and Schenk, 2005).

3.5.3.2 Subdued Ridge Unit (*rts*)

The subdued ridge unit (Fig. 3.4q) occurs within the chaos terrain, as observed in the high resolution. They have an indistinguishable morphology from the *ridge-and-trough* unit (Section 3.5.2.1), but consist partially to completely of a low albedo material (e.g., Section 3.5.3.1).

3.5.3.3 Discontinuous Unit (*rtd*)

Discontinuous chaos (Fig. 3.4r) consists of dissected, variegated albedo ridges that are morphologically similar to more pristine units including *ridge-and-trough* (Section 3.5.2.1) and *double ridge* (Section 3.5.1.1). This unit is interpreted to be pieces of pre-existing units, which are isolated or rotated from their original emplacement.

3.5.3.4 Variegated Albedo Chaos Unit (*chv*)

Within the chaos region as observed at high resolution, variegated albedo terrain (Fig. 3.4s) is a hummocky, pockmarked, and rough terrain containing material with a heterogeneous albedo. There are no identifiable remnants of pre-existing structures (as in Section 3.5.3.3). It is found mostly near, but within, the borders of the chaos terrain.

3.5.3.5 Chaos, undivided (*ch_{reg}*)

Identified as such at the regional resolution because subdivision is difficult at this resolution, chaos terrain (Fig. 3.4n) in this setting includes a combination of what has previously been referred to as platy chaos and knobby chaos (Greeley et al., 2000). Generally, chaos terrain sits at a lower elevation than surrounding terrain but in some cases is elevated (e.g. Schmidt et al.,

2011). Contact with other units in this region varies, but mostly appears gradational at the regional resolution.

3.5.4 Band Material

Usually associated with large (> 10 km in width) linear to curvilinear landforms occurring in a range of albedos, band material is subdivided here based on texture (e.g., *smooth band* material or *ridged band* material) and internal morphology (e.g., *medial trough band* or *lineated band*). Bands are identified at regional resolution in this case because of their scale (>10 km wide). Only one band is captured in the high-resolution, a *lineated band* (Section 3.5.4.4), but is initially identified as a plains unit (Section 3.5.2.3). The implications of this identification are discussed in Section 3.8.2.6.

3.5.4.1 Smooth Band Unit (*bs_{reg}*)

Identified at the regional resolution after Figueredo and Greeley (2004), the smooth band unit (Fig. 3.4t) is a low albedo feature made up by a material with roughness unresolvable at the regional resolution and bounded by two distinct ridges. The edges can be linear to curvilinear and sub-parallel to each other. These bands can extend over 100s of km and have a typical width of 10 km, but can be larger, and commonly pinch-out near their termini.

3.5.4.2 Medial Trough Band Unit (*bm_{reg}*)

The medial trough band unit (Fig. 3.4u) is similar in appearance to the smooth band but has a fine lineated texture with a wide central trough which runs lengthwise along the band (Pappalardo et al., 1998b). Around this central trough, the band exhibits a rough symmetry.

Medial trough bands appear relatively low in topographic relief and they are also typically more narrow than *smooth bands*, only reaching ~2-7 km in width but can be ~50-100 km in length.

3.5.4.3 Ridged Band Unit (br_{reg})

A ridged band (Fig. 3.4v) consists of a subparallel set of ridges and troughs contained within a linear to curvilinear band. Within the band, ridges and troughs can terminate or bifurcate along their length. These bands are ~7-15 km in width in this region and can be > 150 km in length. Differences between a *ridged band* and a *ridge complex* (Section 3.5.1.2) include scale and ridge spacing; ridges in a *ridged band* appear to be more evenly spaced and equally sized compared to the varying size and spacing of ridges in a *ridge complex*.

3.5.4.4 Lineated Band Unit (bl_{reg})

A lineated band (Fig. 3.4w) is similar to a ridged band (Section 3.5.4.3) at regional resolution but exhibits more of a pinch and swell along the individual ridges within the band, especially on the borders. The ridges that make up the borders of the *lineated bands* unit appear to have a braided texture, as they are curvilinear and can pinch and swell, and can cross cut each other.

3.5.5 Other Units

Material units not directly associated with Ridges (Section 3.5.1), Plains (Section 3.5.2), Chaos (Section 3.5.3) or Bands (Section 3.5.4) are here grouped as Other Units. Both of these units are mapped in the high-resolution mosaic geomorphologic map (Fig. 3.3B).

3.5.5.1 High Albedo Smooth Unit (*has*)

Crosscutting all other local units, except for a few prominent fractures, high-albedo mantling material (Fig. 3.4y) appears to overlay and obscures other pre-existing structures or materials. Non-uniform in shape and diffuse in nature, the high-albedo smooth unit is observed in patches with an area of $\sim 10\text{-}25\text{ km}^2$. There appears to be no spatial correlation with any other unit in the high-resolution images.

3.5.5.2 Mass Wasted Material Unit (*mw*)

The mass wasted material (Fig. 3.4z) identified in the high-resolution images consists of a mostly high albedo material on a slope. There is also an apparent low albedo material distinctly downslope of the higher albedo material and streaks of low albedo material trending downslope. This material occurs adjacent to chaos regions, on *scarps* (Section 3.6.2.2), and within structural *troughs* (Section 3.6.4.3).

3.6 STRUCTURAL MAP AND UNITS

The three major structural units identified in the high-resolution region are Ridges, Troughs, and Craters. We include the *chaos material* (Sections 3.5.3.1 through 3.5.3.4) on the structural map (Fig. 3.3C) in order to highlight the structure, or lack thereof, within the chaos regions. Within this section, we use the term “subdued” to describe structures that do not appear fresh because they have been: (1) severely dissected by other structures, (2) extensively pitted, or (3) have gentler slopes or are topographically diminished in comparison their well-preserved, potentially less degraded, counterparts.

3.6.1 Ridge Structures

Here, ridges are sub-divided by their apparent preservation of the original formation structure (e.g., *ridge-and-trough* and *subdued ridge-and-trough*), the number of ridge peaks within the structure (e.g., *double ridge* and *ridge complex*), and insights from the regional resolution (e.g., *band ridge-and-trough*).

3.6.1.1 *Ridges-and-Trough Structures (rt)*

Ridge-and-trough structures are defined by a systematic subparallel ridge-and-trough repeating sequence, which lack the characteristics of being subdued.

3.6.1.2 *Subdued Ridges-and-Trough Structures (rts)*

Subdued ridge-and-trough structures are defined by a systematic subparallel ridge-trough sequence (Section 3.6.1.1) but appear degraded due to heavy dissection by the post-dating *fine lineations* (Section 3.6.2.4) structural unit. Additionally, these structures are topographically subdued compared to the well-preserved *ridge-and-trough* structures (Section 3.6.1.1).

3.6.1.3 *Double Ridge Structures (dr)*

Double ridge structures are defined by a pair of ridges separated by a single trough, usually containing low-albedo material. These *double ridge* structures are observed to have minimal apparent degradation with smooth slopes and quasi-symmetric ridges. Each ridge is ~300-500 m wide, with heights measured in other works to be 100-300 m (e.g., Head et al., 1999 and Dombard et al., 2013).

3.6.1.4 *Subdued Double Ridge Structures (rds)*

Subdued double ridge structures are identified the same way as well-preserved *double ridge* structures (Section 3.6.1.3), except in that *subdued double ridge* structures are topographically subdued as well as heavily pitted.

3.6.1.5 Ridge Complex Structures (*rc*)

Ridge complex structures contain ridges that are topographically higher (>100 m) and individually wider (>500 m) but contain fewer and less regular ridges than a set of *ridge-and-trough* structures (Section 3.6.1.1). The ridges within a *ridge complex* can range from subparallel to curvilinear with respect to each other and can bifurcate. These *ridge complex* structures appear slightly or not at all subdued.

3.6.1.6 Subdued Ridge Complex Structures (*rscs*)

Subdued ridge complex structures have the same definition as *ridge complex* structures (Section 3.6.1.5), but have been broadly subdued by pits and dissection. Additionally, *subdued ridge complex* structures have gentler slopes and less prominent topography.

3.6.1.7 Band Ridge-and-Trough Structures (*rtb*)

At the regional resolution, a *lineated band* (Section 3.5.4.4) crosses through the high-resolution region. In the high resolution, this band consists of small-scale (~50-200 m) curvilinear ridges and troughs that appear to be triangular in cross-section.

3.6.1.8 Ropy Ridge Structures (*rr*)

Ropy ridges are similar structurally to *complex ridges (rc)* but are more rounded in cross-section, have gentler slopes, and the overall width of the structure is narrower (< 3 km wide). *Ropy ridge* structures are also typically low albedo and are observed to be roughly subparallel. *Ropy ridges* appear relatively well preserved, with little to no evidence of being subdued.

3.6.2 Troughs and Associated Structures

This structural category contains types of scarps and troughs, and other linear structures with negative topography.

3.6.2.1 Scarp Structures (*sc*)

A scarp expressed as a quasi-vertical topographic displacement of a geologic unit or structure. It is identified by where the pre-existing terrain was continuous before the formation of the *scarp* and inferred associated fault. The area between the *scarp* and the presumed fault has been exposed due to the relative motion of the footwall with respect to the hanging wall. The area between the *scarp* and the fault thus probably consists of heavily fractured and *mass-wasted* material (Section 3.5.5.2).

3.6.2.2 Trough Structure (*t*)

Trough structures generally encompass sharp topographic lows that crosscut pre-existing structures. They do not appear to be associated with other ridge structures and can occur independently or in sets. *Troughs* lack significant raised edges, which differentiate them from ridge types. In general, *troughs* make up the stratigraphically youngest structures on Europa's surface. *Troughs* appear to have steep, near-vertical, sides. They appear to contain a low albedo

material, but this could represent shadowing if the slopes are $> 80^\circ$, based on the low incidence angle of the high-resolution images. The typical length of a major *trough* varies from ~ 4 -15 km in this region and have associated widths of ~ 50 -100 m

3.6.2.3 Minor Trough (tm)

A minor trough is identified by its small size (< 50 m in width) or if it is significantly subdued by dissection or shallow topography.

3.6.2.4 Fine Lineaments

Not shown in the structural map figure to reduce clutter, but identified in Figure 3.6, these linear features are identified by apparent striations or fine troughs (< 30 m wide). The fineness and multitude of these structures results in an overall linear trend or texture that transects other observed structures.

3.6.3 Craters (c_{reg})

Circular to quasi-circular depressions are identified as pits or craters in the high-resolution images. Because the incidence angle highlights albedo over morphology, it is difficult to see the rim topography and ascertain whether the observed features are truly impact craters, let alone whether they represent primary or secondary impacts. An important note regarding these pits identified in the high-resolution images is their concentration in the eastern portion of the study region. This spatial correlation will be discussed further in Sections 3.7.6 and 3.8.1.6.

3.6.4 Materials

These material or morphologic units are included on the structural map for spatial reference, including *high albedo smooth* (*has*, Section 3.5.5.1) and *chaos* (Section 3.4.3) units.

3.7 RESULTS: NOTABLE MORPHOLOGICAL AND STRUCTURAL MAPPING OBSERVATIONS

In this section, we discuss the observations from the geomorphological and structural mapping of the high-resolution images resulting from comparing the high-resolution and regional resolution geomorphologic maps. The analysis of these observations is in the Discussion (Section 3.8).

3.7.1 Ridge-and-Trough Systems

Focusing on ridge-and-trough systems (e.g. *subparallel ridge-and-trough* unit, Section 3.5.2.1), there are four observations which are relevant to potential formation mechanisms from the high-resolution images and the geomorphologic and structural maps: (1) the presence of symmetric, shallow slopes, (2) a curvilinear to sinuous shape of the individual ridges along their length, (3) the presence of ridges bifurcating along their length, and (4) a systematic trend in the orientation of the ridge-and-trough sets (Table 3.2, Fig. 3.7). Another notable characteristic includes the relatively consistent widths of individual ridges at 300 +/- 100 m and a width to length ratio of the individual ridges of < 0.1. The total width or the length of a ridge-and-trough system is not determinable using these high-resolution images because of the limited extent of the images. The troughs separating each ridge contain a low albedo material, potentially emplaced by ice sublimation or downslope movement (Spencer, 1987).

3.7.2 Double Ridges

The observations to especially note of the *double ridges* in this region are: (1) the ability to be generally constant in uniform shape and size along the length of the ridge at this scale (Fig. 3.8), (2) the range of sizes and scales exhibited (from 500-1200 m in total width in this high-resolution mosaic alone), (3) the symmetric ridges on either side of the central trough (Fig. 3.8A), (4) that a *double ridge* can join or split from a *single ridge* or *ridge complex* (Fig. 3.8B), (5) that *double ridges* can crosscut other units or be crosscut (Fig. 3.8C) indicating these structures have formed throughout the surface history, and (6) that the structures are not significantly affected by any observable pre-existing topography. These observations from the high-resolution images could differentiate among and evaluate the proposed formational mechanisms (Table 3.3, Fig. 3.8), which is discussed in detail in Section 3.8.1.2. In this region, *double ridge* width varies locally from 500-1200 m as seen in this high-resolution mosaic (Fig. 3.3A), similar to previous analyses from other regions (e.g., Head et al., 1999). At the regional or global resolution, this range in widths is considered to be negligible and *double ridge* width is essentially constant (e.g., Greeley et al., 2000). At the high-resolution however, we take this to be a sizeable local variation in width that must be taken into consideration when analyzing potential formation mechanisms.

Though there is only one example in this high-resolution strip, *double ridges* can transform into other feature types along their length, including *ridge complexes*, *ropy ridges*, or *troughs*. It is not surprising that this observation is limited in this high-resolution, given the orientation and limited extent of the images. In this case, the *double ridge* abruptly includes a medial ridge along its length, transforming it into a *ridge complex* (Fig. 3.8B). Thus, this ability to transform along its length becomes a requirement for the formation process of a *double ridge*. Additionally, there

is one example where a *double ridge* abruptly ends and there is no observed medial fracture (Fig. 3.8C), providing another potential indicator for formation mechanism.

3.7.3 Chaos

There are a few different theories for the formation of chaos terrain (Section 3.5.3), including: melt-though (Greenberg et al., 1998; O'Brien et al., 2002), diapirism (Pappalardo et al., 1998; Schenk and Pappalardo, 2004), and melt-water lens collapse (Schmidt et al., 2011; Soderlund et al., 2013). The key aspects of the mapped region are: (1) the abrupt border between chaos and other terrains (Fig. 3.9B), (2) the heavily deformed border regions, (3) the preservation of pre-existing structures (Fig. 3.9A, see Sections 4.3.2 and 4.3.3, *subdued* and *discontinuous chaos* terrain respectively), (4) the presence of a *low albedo smooth* material (Section 3.5.3.1), (5) the lack of visible plates and likewise, (6) the overall scale of the chaos terrain (Table 3.4).

3.7.4 High Albedo Mantling Material

The high-resolution images revealed a surface morphology not noted on Europa previously: a relatively smooth, *high-albedo smooth* material (Section 3.5.5.1) that appears relatively flat and is contained within a small ($< 1 \text{ km}^2$) area in multiple locations across the high-resolution region. This unit is inferred to be rough at a smaller scale than the image resolution. This material is pitted and appears to subdue crosscutting structures (Fig. 3.10).

3.7.5 Small Pits and Craters

One of the features unmarked in the structural map considering their number (> 1700) and unrecognized in the regional resolution due to their size (30-75 m in diameter) are the small pits

and craters (Fig. 3.11). These pits and craters are quasi-circular structural features that tend to be high albedo at the rim and contain low albedo material within a bowl-shaped depression.

3.7.6 Fine Lineaments

Another observation revealed only by this high-resolution and detailed mapping is the pervasive linear feature trending N75E-N81E. This feature was not included on the structural map to avoid clutter (Fig. 3.3C), but when observed alone (Fig. 3.6) it is evident that these *fine lineaments* (Section 3.6.2.4) are pervasive across the high-resolution image. Additionally, these structures are not parallel to the image projection (or elongation of the pixels) and change direction slightly across the mosaic, indicating that these features are not an artifact of image processing. In the images, the *fine lineaments* consist of spatially grouped (~50 m spacing), thin fractures or troughs. Particular features in this class appear to be related to prominent structures (Fig. 3.6A), while others appear to be related to slopes or mass wasting of topographically high structures (Fig. 3.6B), whereas others still appear to be unaffected by the presence of these prominent structures at all and simply crosscut them (Fig. 3.6C).

3.7.7 Comparison Between High-Resolution and Regional Resolution Maps

Unsurprisingly, there are a few clear differences between the regional resolution image and the high-resolution images. What is unexpected is that these differences go beyond simply greater detail and the enhanced ability to discern different morphologies. These noted differences include: (1) potential surface changes, (2) misidentification of chaos terrain, and (3) constraints for the formation of morphologically different bands. Each of these noted observations are explored in detail in Section 3.8.2. In particular cases, the differences in the high-resolution

images provide caution for maps at regional resolution and can help us understand how certain features form.

3.8 DISCUSSION

Herein, we evaluate the observations from the high-resolution mapping (see Section 3.7) using previously proposed formation hypotheses, or our own hypotheses as appropriate.

3.8.1 Surface Feature Formation Mechanisms

The E12 Mottle high-resolution region is structurally intricate and tectonically complex. While we cannot unravel its entire surface history considering the limited extent of the high-resolution strip, there are multiple observations gained from the mapping that will aid in constraining formation mechanisms and relative ages of different structures. In this section, we will address whether our observations (Section 3.7) agree or disagree with observations made from the regional resolution mapping or from predictions made by different formation models for a variety of structures and materials, including: *ridge-and-trough*, *double ridges*, *chaos*, *high albedo smooth*, *craters*, and *fine lineaments*.

3.8.1.1 Ridged Plains

As stated in the unit description, not much is certain about the ridged plains or ridge-and-trough material, besides that it can appear in various different forms or sub-units in the highest resolution images (Head et al., 1999; Patel et al., 1999a and b; Kattenhorn, 2002). The existing proposed formation mechanism, specifically for the subunit of *subparallel ridge-and-trough* material, is a type of normal faulting that would produce tilt-blocks (Kattenhorn, 2002), akin to

the grooved terrain on Ganymede (Pappalardo and Greeley, 1995; Prockter et al., 1999, 2000; Figueredo and Greeley, 2000). However, a high-resolution analysis of Europa's ridge-and-trough terrain has not been performed prior to this work. The tilt-block hypothesis likely does not support most of our observations from the high-resolution region (Section 3.7.1, Table 3.2). If the ridge-and-trough systems were formed via an extensional tilt-block mechanism, the ridges would not bifurcate as commonly observed in the high-resolution images (Fig. 3.7C, Table 3.2, Pappalardo and Greeley, 1995; Head et al., 1998; Leonard et al., 2015). The slopes of the individual ridges in the ridge-and-trough systems are relatively symmetric in cross-section, additionally indicating that the tilt-block mechanism is likely not the formation mechanism for ridge-and-trough terrain as this would preferentially produce asymmetric slopes, with only a special case producing symmetric ridges (Fig. 3.7A and 3.7B, Pappalardo and Greeley, 1995; Kattenhorn, 2002; Leonard et al., 2015). In order to produce a symmetric cross-section, the slopes of a tilt block must be $\sim 45^\circ$, which is not observed and neither is the necessary mass-wasting to make the slopes shallower (Fig. 3.7B).

If the *subparallel ridge-and-trough* terrain formed via a compressional folding mechanism, as proposed in Head et al. (1999) and explored by Leonard et al. (2015), the observed characteristics could be produced. Folds allow for slopes ranging from symmetric to asymmetric, with no particular preference. Additionally, the slopes of folds are dependent on the amount of applied stress to some extent, and therefore can be anywhere from shallow, like we observe (Fig. 3.7B), to quasi-vertical, or isoclinal. Folding can also create ridges that bifurcate along their length (Leonard et al., 2015). Thus, we conclude that a folding mechanism best fits the observed characteristics of the *subparallel ridge-and-trough* structure and morphology of ridged plains in this region. This could be the case for the other ridged plains morphologies, but we do not have

cross-sectional information for *convex*, *hummocky*, or *mélange ridge-and troughs*, so we verify cannot verify this hypothesis for those units.

3.8.1.2 Double Ridges

There are multiple hypothetical models for the formation of *double ridge* structures including cryovolcanism (Fagents and Greeley, 1997; Kadel et al., 1998), tidal squeezing (Greenberg et al., 1998), linear diapirism (Head et al., 1999), shear heating (Nimmo and Gaidos, 2002), compression (Sullivan et al., 1998), wedging (Melosh and Turtle, 2004; Han and Melosh, 2010; Johnston and Montesi, 2014), and compaction (Aydin, 2006). We compare these different hypotheses to our observations from the high-resolution mapping (Section 3.7.2, Table 3.3, and Fig. 3.8).

Cryovolcanism, as proposed by Kadel et al. (1997), requires repeated or continuous expulsion of material from below the surface along a central trough vent such that the material piles up on either side to form the ridges. Cryovolcanism could take place in an explosive or effusive manner (Fagents, 2003). While this model explains the local variation in size and shape of the *double ridges* fairly well, it is difficult to explain how the majority of observed *double ridges* would end up fairly uniform in width and height along their length (Fig. 3.8).

Cryovolcanism is likely an intermittent process along a series of trough vents that would lead to irregular *double ridges* that pinch and swell more often than observed in the high-resolution images. Flanking fractures associated with double ridges are not observed in this region and thus cannot be used to support cryovolcanism as the primary mechanism for forming *double ridges* (Dombard et al., 2013). As such, cryovolcanism as a formation mechanism for *double ridges* is

unlikely as is cannot produce symmetric (Fig. 3.8A) and regionally consistent structures with only small-scale variations.

The tidal squeezing model involves a fracture opening and closing repeatedly from the effects of diurnal stresses generated as the satellite travels its slightly eccentric orbit around Jupiter. When the crack opens, water from below or warm ice flows up to the surface; when the crack closes, the material is pushed up to form the flanking ridges (Greenberg et al., 1998). However, the mechanism for the fluid or slush to reach the surface is tentative (Crawford and Stevenson, 1988) and whether or not diurnal stresses would have the ability to crack the ice shell is unclear (Greenberg and Geissler, 2002). Additionally, like the cryovolcanism hypothesis, the tidal forces and the amount of material squeezed out would not remain constant along the *double ridge* and spread evenly to both sides, especially with observed pre-existing topography present (Fig. 3.8A). One of the appealing aspects of this model is that it could explain how one type of ridge might transition into another along its length (Fig. 3.8B, Geissler et al., 1998). For example, if the crack was closed, it might appear to be similar in structure to a *single ridge* or if, in response to the changing nature of the surface stresses, a *double ridge* underwent only extensional stress for a time, the ridge might widen to form a *ridge complex*. However, the small-scale variation in size of the *double ridges* that we observe is also not well explained by this model, as it appears the ridges would continue to grow for as long as the stress conditions allowed, leading to significant variations in size not observed in the high-resolution images. Overall, these first two hypothesized methods of formation have similar problems because they involve a mobile material rising and extruding directly onto the surface likely causing width and height variations along the length of the ridge (Fig. 3.8), but such is not observed.

Linear diapirism, a model proposed by Head et al. (1999), is related to the sparse examples of linear diapirism that takes place in Earth's crust. On Europa, the authors propose that an initial crack is formed by tidal stresses and a buoyant, ductile material exploits this weakness in the brittle upper crust and upwells. This upwelling pushes the brittle crust up around the linear diapir forming the two symmetric ridges of the *double ridge* (Head et al., 1999). Though it is debated whether this mechanism would be able to produce such a linear ridge (Greenberg et al., 1998), the size of the ridge would relate to the size of the diapir and the thickness of the lithosphere, making the *double ridges* potentially consistent in size (Fig. 3.8). Linear diapirism would not be affected by pre-existing topography, only depending on where the ice shell was weakest. Additionally, this would allow for preservation of pre-existing terrain observed on a few ridge flanks (Pappalardo et al., 1998b; Greenberg and Sak, 2014), even though we do not observe this feature in this high-resolution region. The greatest weakness of this hypothesis is that this mechanism might not produce the relative regularity in width and height of a *double ridge* along its length and there is no definitive example on Earth to demonstrate this model (Fig. 3.8A).

Similar to the idea that heated ice would cause an upwelling or upwarping of the brittle top layer, Nimmo et al. (2002) propose that tidally forced movement along a strike-slip fault would cause an upwarping and, if melting occurs, a collapse of the center, which would form the *double ridge*. The linearity of the feature in this case is due to the idea that a *double ridge* is a strike-slip fault created by tidal stress, as opposed to the melt-water lens collapse hypothesis that is proposed to form chaos terrain (see Section 3.8.1.3). The heating and upwarping could result in symmetric ridges as long as physical properties of the ice shell were locally constant (e.g., prominent structural obstacles or changes in material properties). However, the shear heating mechanism proposed by Nimmo et al. (2002) is unlikely to produce enough heat to produce the

observed features (Han and Showman, 2008). The process could potentially preserve the pre-existing topography or cover it with mass wasting. The size and shape of the *double ridges* in this model would relate to the magnitude of the stress acting on the particular ridge, bringing into question whether a consistent width ridge along its length could be produced (Fig. 3.8).

The wedging model, similar to linear diapirism, involves material rising from the subsurface but unlike linear diapirism, this material does not reach the surface in the wedging model. If a linear liquid water dike forms underneath the European surface, Melosh and Turtle (2004) argue that the imposed stresses could create a *double ridge* on the surface, supported by the later work of Han and Melosh (2010). However, modeling performed by Johnston and Montesi (2014) concluded that the circumstances for this model to work and match the observed structure of a *double ridge* were unlikely at best due to size limitations. Thus, most likely, the wedging model cannot reproduce the size or consistent shape we observe (Johnston and Montési, 2017).

Sullivan et al. (1997) suggest that the formation of a *double ridge* would occur when a fracture opens and then is compressed together repeatedly to cause the area around it to bulge upward. This model is attractive, given that there is a lack of identified contractional features to match the proposed extensional features on the European surface (Sullivan et al., 1998; Prockter et al., 2002). However, compression does not explain how *double ridges* can transform along their length into other features like bands or *ridge complexes* (Fig. 3.8B), with the exception of *single ridges*. The symmetry of each ridge is also unlikely in a compressive stress field with a brittle material, where it is more likely that one side would dominate (as in the case of thrusting on Earth) instead of being relatively equal. The idea that *double ridges* could accommodate some of the missing surface contraction on Europa does not end with Sullivan's compression model

(Aydin, 2006; Culha et al., 2014), and while there is observational support (e.g., Patterson et al., 2006; Kattenhorn and Prockter, 2014), it is not present in these high-resolution images.

The compaction band model, proposed by Aydin (2006), requires the *double ridges* to have formed by localized strain where a porous material is compressed. Because the porosity of the surface materials is not well constrained and could vary greatly in space and time, owing to variations in surface history, this mechanism may have operated at a local scale and particular time of *double ridge* evolution. Assuming the surface materials have the necessary properties, Aydin's model provides a medium to allow contractional surface features with the needed symmetry and theoretical ability to develop into other features (Aydin, 2006). In the high-resolution images however, the *double ridges* are rounded in cross-section and have gentle flanking slopes (Fig. 3.8A), whereas the Earth analog examples provided by Aydin (2006) display steeper ridge limbs and rounded ridge tops. Thus, in order for compaction to form the *double ridges*, the slopes must have mass wasted or viscously relaxed to make their slopes shallower, an unlikely mechanism because viscous relaxation preferentially degrades long-wavelength features. We see no direct evidence for mass wasting along the *double ridge* flanks in the high-resolution images, but it has been observed in association with *double ridges* in other regions (e.g., Head et al., 1999; Spaun et al., 2003). Nonetheless, this model succeeds where most others do not, in creating a viable mechanism for producing symmetric and consistently sized *double ridges* across the surface.

The observations from the high-resolution images, particularly the consistent and symmetric ridge morphology, and the ability to be unaffected by previous topography, reveal strengths and weaknesses in all the current formation theories. The high-resolution images cause us to place emphasis on symmetry and consistency for *double ridge* formation, leading us to interpret that

linear diapirism and compaction are best fit to the observations. Because these hypotheses do still contain weaknesses, it is important to consider the possibility that a combination of processes could be at work to form the *double ridges*, or that there is a completely different process producing *double ridges*.

3.8.1.3 Chaos

There are multiple hypothetical models for the formation of chaos regions, including: melt-through (Greenberg et al., 1999; O'Brien, 2002), diapirism (Pappalardo et al., 1998; Schenk and Pappalardo, 2004), and the collapse of a melt-lens within the ice shell (Schmidt et al., 2011; Soderlund et al., 2014). We compare these different hypotheses to our observations from the high-resolution mapping (Table 3.4 and Fig. 3.9).

The melt-through model of chaos formation involves direct contact, or melt-through, of the underlying ocean with the surface of the ice shell. This melting is suggested to take place over time as tidal heating occurs in the subsurface ocean and within the ice shell. This model requires a thin ice shell in order for the heat flux required to produce the melt-through of the ocean to be reasonable for Europa (Greenberg et al., 1999; O'Brien et al., 2002) and for the ice shell to resist rapid flow which would prevent melt-through (O'Brien et al., 2002). The idea of a thin-shell (< 5 km) in general is not favored for the present epoch, considering the numerous lines of evidence indicating the presence of a thicker shell (e.g., Pappalardo et al., 1999; Prockter et al., 1999; Schenk, 2002; Nimmo et al., 2003; Figueredo and Greeley, 2004; Prockter and Schenk, 2005). The melt-through model of chaos terrain formation predicts a down-sloping “beach” (Greenberg et al., 1999) rather than the abrupt boundary of the chaos unit observed in the high-resolution images (Table 3.4). The model also predicts features just outside of the chaos region, especially

ridges, to sit upon a relatively thicker shell and withstand the melting and chaos formation. There are no peninsulas or such formations in the high-resolution chaos, but there are preserved features within the chaos that might have withstood the melting preferentially (Fig. 3.9A). Thus, the melt-through model could potentially explain the apparent embayment of pre-existing and preserved structural features in the chaos region. The Greenberg et al. (1999) model explains the variation in sizes of chaos terrain by the limited heat flow in the specific region. The region of chaos directly to the west of the high-resolution region (Fig. 3.2) could help contribute to smaller areas of thinning in neighboring areas. While a few of the observations fit fairly well, the transition from other terrain to the chaos terrain does not, and it is unclear how this mechanism could produce the amount of tectonic modification observed within the chaos region.

The melt-water lens collapse model proposes that as thermal activity causes ice to melt (in response to impacts, shear heating, or endogenic heat sources), melt water lenses form. These lenses are sealed off from their surroundings and therefore cause a down-warping of the surface due to volume conservation. The subsequent collapse of these pressurized lenses is suggested to be responsible for the chaos terrain (Schmidt et al., 2011; Soderlund et al., 2013). During collapse of the lens, it is suggested that water could be injected through fractures that when refrozen and volume increases, would cause an upwarping in the area. Thus, depending on where the chaos region is in its development, it could be topographically high or low (Michaut and Manga, 2014). Differential water injection and refreezing within the chaos region lends itself well to the variety of topographic features in the high-resolution chaos region and could possibly explain why some units appear flooded, or embayed, with a low albedo material. This model could explain the observed heavily modified terrain near the edges of the chaos region, as due to episodes of downward warping and upward warping as the lens forms, then collapses, and finally

refreezes (Fig. 3.9B). A new observation from the high-resolution images is the preserved structures within the chaos region. Though embayed features have been inferred previously (e.g., Carr et al., 1998; Prockter and Schenk, 2005), they are outside of the deformed chaos terrain or on floating or tilted blocks. The structures we observe in this region are completely embayed, but the basic structures are still preserved, and are well within the broken-up border regions of the chaos terrain. The melt-water lens collapse hypothesis fits this observation, as the center of the chaos region could potentially be one of the better-preserved areas in this model (Fig. 3.9A).

Chemically or thermally driven solid-state diapirism has also been suggested as a possible model for the chaos terrain formation. Convective diapirs are proposed to transport tidal heat produced deep in the ice shell to the surface (Pappalardo et al., 1998a). When the diapir rises underneath the brittle portion of the ice shell it first upwarps the ice, potentially hundreds of meters (Pappalardo and Barr, 2004), before possibly down-warping if there is extrusion or collapse (Schenk and Pappalardo, 2004). In this region, the latter would be the case because the topography is depressed compared to the surroundings (Fig. 3.9B). The heavily modified edges of the chaos in the high-resolution images agree with this model because this is where the topographic changes would be breaking up material, while the middle would contain sections that could potentially be more preserved (Fig. 3.9A). Extrusion around the edges of the chaos region might explain the *low albedo smooth* material, but it is not clear whether this could cause the material that we see embaying units near the center of the chaos region, especially because it is not a topographic low.

With respect to the high-resolution observations, none of the chaos formation models are a perfect fit. Each has observations that agree and potentially disagree with the high-resolution mapping such as degree of modification, placement of modification, or the presence of a low

albedo material (Table 3.4). The abrupt and heavily modified boundaries of the chaos region and the preserved structures are the defining features in the high-resolution images and therefore the observations in the high resolution favor the melt-water lens collapse hypothesis. It is unclear whether any of the models allow for a lack of broken-up plates within the chaos region. Thus, more high-resolution data in other chaos regions is necessary to make observations and determine the role of platy chaos versus the knobby texture and preserved, but embayed, structures we observe in this high-resolution region.

3.8.1.4 High Albedo Smooth Material

The high albedo material (Fig. 3.10) on Europa has not been discussed or analyzed prior to this work. We identify a few possibilities for the origin of this material: (1) emplacement by a cryovolcanic or frosting process, (2) destruction of structures by secondary impact or other impact process, or (3) it is a terrain that is shaped by processes resolvable only below the scale of these high-resolution images.

The first mechanism that we suggest for the creation of the *high albedo smooth* terrain is the possibility of an overlain high-albedo material, potentially covering whatever pre-existing structures might have been present. Because we do not know the nature of the structures that might have predated this terrain, we cannot analyze how much overlying material would be required to cover the pre-existing terrain. In terms of the plausibility of this process however, we can assess the two potential mechanisms for depositing material on top of the surface, cryovolcanism and thermal migration. In order for mantling to occur via cryovolcanic deposits, we would expect to observe a potential source vent, which we do not. This overlain material could also be from a frosting process, which is suggested to occur on colder surfaces which are

topographically higher and have higher albedo on Europa (Spencer, 1987). This process is akin to water-ice thermal migration which is proposed to occur on the Moon and Mercury (e.g., Vasavada, 1999). However, there is no observational evidence indicating that this region is standing topographically high compared to the surrounding regions. Without further data, topographic or thermal, we cannot comment further on the plausibility of this process.

Another possibility for the formation of this terrain involves effectively destroying potential pre-existing structures by impacting the terrain, either a primary impact or many secondary impacts. A primary impact is unlikely as this terrain is morphologically unlike any observed craters on Europa (Schenk and Turtle, 2009). Secondary craters tend to occur in groups (e.g., Bierhaus et al., 2001) and have the potential to destroy terrain (see Section 3.8.7.2). However, this terrain occurs in relatively small ($< 1 \text{ km}^2$), uniform regions with abrupt transitions to other terrain types, suggesting that the secondary impacts is unlikely.

When Europa was first mapped using Voyager data, the rough terrain of the ridged plains that we observe in the high-resolution images was identified simply as “plains,” implying a smooth terrain (Lucchitta and Soderblom, 1982). Likewise, when mapping the regional resolution images ($> 200 \text{ m/pixel}$) on Europa, it is unclear that a terrain like the ridged plains would be present in all the seemingly smooth high albedo regions. As such, the high albedo unit (*has*, Section 3.5.5.1) we mapped based on the high-resolution images may disguise even finer scale structures, which could be resolved with higher resolution data from future missions such as the Europa Clipper mission.

Without further information, we cannot reliably differentiate among these three possibilities for the formation of this *high albedo smooth* terrain. Nonetheless, this terrain deserves note because of its comparable smoothness to other “smooth” terrains on Europa (Prockter and

Schenk, 2005), potentially relevant to landing sites for a possible future lander mission (2016 Europa Lander Science Definition Team Report).

3.8.1.5 Small Pits and Craters

We mapped the location of each of the small (< 100 m diameter) pits across the high-resolution mosaic, ~ 1700 in total (Fig. 3.11A). To account for the size and ubiquity of the small pits, the mapping was performed twice in some frames to verify consistency in what was being marked as a small pit. Overall, it is evident that these features are quite abundant (Fig. 3.11A).

The three possible formation mechanisms we propose for these small pits are: (1) devolatilization or sublimation, (2) regolith drainage or pit chains, and (3) secondary craters.

Devolatilization or sublimation pits are hypothesized to form in association with recently overturned or uncovered material containing volatiles that then, potentially violently, degas. Because this hypothesis involves material that is overturned or uncovered quickly, devolatilization pits are typically associated with impact craters and ejecta or mass wasting (e.g., Moore et al., 2009). To date, such pits have been identified on Mars, Mercury, Vesta, comets such as 67P, and Pluto (e.g., Gillis-Davis et al., 2009; Boyce et al., 2012; Denevi et al., 2012; Tornabene et al., 2012; Vincent et al., 2015; Moore et al., 2017). On Mars, the pits range from 10 m to 3 km in diameter (Tornabene et al., 2012) and the pits we observe on Europa within this range. However, the pits observed on Mars can range in shape from circular to polygonal (Boyce et al., 2012), whereas we only observe these small pits on Europa to be relatively circular. While this shape difference could be an effect of viewing geometry or image resolution (image resolution on Mars is at least 5 times better at ~ 3 m/pixel), it could also indicate a different formation mechanism. Additionally, the small pits we observe in the high-resolution images are

not associated with any mass wasting or other obviously overturned material (see Fig. 3.11A), and there is no observational evidence for heating across this entire region that could have potentially released volatiles. Thus, the origin of these small pits on Europa as devolatilization pits is unlikely.

Another potential formation mechanism for the small pits is regolith drainage pits or pit chains. Different from a catena, pit chains are typically associated with extensional faults that are overlain by a regolith or quasi-cohesionless material that drains into the subsurface void. Pit chain formation has been identified on terrestrial bodies, including Earth (e.g., Okubo and Martel, 1998; Ferrill et al., 2011), Moon (e.g., Watters et al., 2012), Phobos (e.g., Thomas et al., 1979), and Mars (e.g., Banerdt et al., 1992; Wyrick et al., 2004), as well as on icy satellites such as Enceladus (Martin et al., 2017). As implied by the name however, pit chains are aligned with each other and can merge to form a quasi-linear structure. The small pits that we observe on Europa do not align in this fashion, but instead they appear in a more random distribution (Fig. 3.11A) and thus are unlikely to form via this mechanism.

Our favored hypothesis is that these features are secondary craters because of their clear increase in abundance with proximity to the 17 km diameter crater, Amergin (Fig. 3.11B). There is limited information regarding secondary cratering on icy satellites, but it is predicted that secondaries dominate the population of smaller (< 100 m diameter) surface craters on Europa (Bierhaus et al., 2001, 2005; McEwen and Bierhaus, 2006). The suggested primary crater for the secondaries in this region, Amergin, is located off the southeast corner of the regional image, about 75 km from the center of the high-resolution mosaic. We find that the number of small pits falls off exponentially (Fig. 3.11C) with distance from Amergin, indicating that these pits are secondary craters originating from the Amergin impact.

Two dips in the spatial distribution of small pits occur where chaos terrain dominates the high-resolution image mosaic (Fig. 3.11C). While this could indicate that these chaos regions are younger or have been modified since the primary impact, it is quite plausible that the secondary impacts are more difficult to recognize in the already disrupted, lower albedo material as opposed to the more pristine, high albedo material. Alternatively, it is possible that the material properties of the chaos regions may be responsible for degrading or relaxing the secondary craters to the point where they are no longer recognizable.

The identification of such numerous secondary craters has implications for impact physics on icy satellites. Additionally, the immense range of these secondary craters could be responsible for spreading material over large distances (100s of km) across the surface. This may have important implications for spreading radiation processed oxidants, of importance to potential subsurface biology when the surface is recycled (Kadel et al., 1998).

3.8.1.6 *Fine Lineaments*

The origin of these pervasive *fine lineaments* is unclear (Fig. 3.6). There appear to be potentially three types: (1) those related to prominent structures, (2) those associated with slopes or mass wasting of prominent, topographically high structures, and (3) those unassociated with other structures.

The *fine lineaments* we observe that appear to be associated with prominent structures, such as those that run sub-parallel to *ridge complexes* (Fig. 3.6A), could have formed as a result of lithospheric loading (e.g., Hurford et al., 2005; Collins et al., 2009). This mechanism involves: (1) the formation of the prominent *ridge complex*, causing (2) the lithosphere to flex due to the

load of this structure, and eventually (3) cracking to form the *fine lineaments*. Topographic data to find evidence for the potential flexure in the lithosphere could confirm this hypothesis.

The lineaments that are quasi-perpendicular to the trend of other prominent structures and sub-parallel to the slope of these structures, such as the lineaments associated with the *double ridge* in Figure 3.6B, could be formed by mass wasting of a low albedo material. In this case, the lineaments would not be fine cracks, but surficial deposits that mimic fine fractures.

The third proposed type of *fine lineaments*, which crosscut prominent structures and have affected the cross-section of that structure (see Fig. 3.6C), we hypothesize could be the expression of a tectonic fabric. “Fabric” is a term employed in structural geology to describe a linear organization within a rock, usually referring to alignment of minerals or crystals. Here, we use it to describe a relatively consistent, subparallel linear feature within the icy surface. On Earth, fabric in a rock can form by a range of processes and at variable scales. We note that *the fine lineaments* on Europa appears to be planar, another feature of a tectonic fabric, due to its representation by joints or cracks. This implies that this fabric most likely originated from strain (referring to cleavage or foliation) and possibly related to the platy shape of large (meter-size) ice grains (e.g., Schmidt and Dahl-Jensen, 2003). This formation mechanism would imply that the lineations are the result of a tectonic fabric formed in Europa’s ice over potentially millions to >100s of millions of years of tectonic deformation. The previously described surficial deposit-related *fine lineaments* could also originate as a fabric that causes the change in albedo. Overall, we predict that tectonic fabric should become apparent across Europa once image resolution improves with the Europa Clipper Mission. Additionally, fabrics that include differences in grain size, crystal structure, and apparent albedo could be responsible for roughness on small scales, due to differential sublimation or other weathering effects (Fig. 3.6C).

3.8.2 Regional Resolution Comparison

We compare the regional resolution geomorphologic mapping (Fig. 3.2B) to the high-resolution geomorphologic mapping (Fig. 3.3B), in order to identify discrepancies when mapping at the more spatially extensive regional resolution (200+ m/pixel). We include the analysis of a possible effect of varying emission angle, a region that appeared to be chaos at regional resolution and plains in the high-resolution, and insights into band formation.

3.8.2.1 Viewing Geometry Effects

When comparing the regional map (Fig. 3.2B) with the high-resolution structural map (Fig. 3.3C) we notice that a feature present in the regional resolution image does not seem to appear in the high resolution (Fig. 3.12A). Thus, there are two possible explanations: (1) The apparent change is an artifact of different viewing angles (emission angles) and lighting (incidence angles) or (2) it is an actual change in the surface.

The first explanation is more likely; the differences in lighting and observation angle between the regional and high-resolution images are extreme (cf., Malin and Pieri, 1986). The *ridge complex* that the fracture apparently crosses through could be hiding the feature in the high emission angle of the high resolution; the surrounding chaos could be similar to the albedo of the fracture or could also be hiding the walls of the fracture from observation. The issue with this explanation is that other, directly adjacent and similarly oriented fractures are visible in both the regional and high resolution (Fig. 3.12B and C). Additionally, the fracture that appears to have changed is the most prominent of the surrounding fractures (Fig. 3.12A). Despite the size and orientation of ridge A compared to B and C (Fig. 3.12), we suspect that this discrepancy is

explained by the substantial difference in viewing geometry ($\sim 60^\circ$). This is important to note because the planned Europa Clipper mission is a flyby mission, meaning the images from this mission will have a wide variety of emission and incidence angles, making this an example of the type of discrepancies we might find.

If it were the case that this feature is an indication of surface change, it would not necessarily imply that there is active resurfacing on Europa. For instance, the change in the surface could be a result of mass wasting at that scale; Perhaps the fracture was partially filled in by material from the *ridge complex* or chaos and therefore is no longer visible in this particular region. This idea appears plausible especially given the short amount of time passed (~ 2 months) between when the Galileo SSI captures the two images and any other change would greatly exceed resurfacing rate predicted by Phillips et al. (2000) of $< 1 \text{ km}^2/\text{year}$. Whether the feature is an indication of surface change or an artifact of differing observation conditions, it would be interesting to investigate further to see if these types of small-scale changes occur elsewhere when more high-resolution data is made available by the Europa Clipper mission.

3.8.2.2 *Misidentified Chaos Terrain*

Mapping chaos regions at regional resolution matches the units mapped in the high-resolution images with one exception, the mapping of a chaos unit at regional resolution that is not mapped as a chaos unit at the high resolution. This area is located at the easternmost frame of the high-resolution (Fig. 3.13). In the regional resolution, this terrain closely matches other knobby chaos material, but in the high resolution is clearly different and closely matches the plains terrain morphology.

It is evident that this region may have been undergoing a form of morphological modification. The preponderance of small (30-75 m in diameter), dark, quasi-circular features and larger (100-300 m in diameter) dark spots in this region may have led to this misidentification (Fig. 3.11A). The possibility that these dark features are secondary craters is explored in Section 3.8.1.5. Because we conclude that the small pits are most likely secondary craters, this leads to the idea that chaos identified at the regional resolution might actually be modified by secondary cratering. Thus, we suggest that secondary cratering, within 50 km of the primary crater, could have aided in resurfacing by destroying pre-existing structures. Given that there are ~20 observed craters on the surface of Europa of the same approximate size or larger than Amergin (Schenk and Turtle, 2009), and taking a conservative estimate of 50 km radius around the primary, secondary craters would be responsible for altering ~0.5% of the surface to the level observed in Figure 3.13. Thus, while this process evidently is not the main contributor to Europa's resurfacing, it could provide a supplement and aid in destroying pre-existing structures, especially when viewed at a small scale.

3.8.2.3 *Smooth Band Formation*

The most prevalent hypothesis for the formation of *smooth bands* involves fracture initiation followed by extension and infilling similar to the formation of mid-ocean ridges on Earth (Prockter et al., 2002). *Smooth bands* have also been often associated with movement, primarily extension and slip, by matching terminated features on either side of the band (Sullivan et al., 1998; Prockter et al., 2002). Whether these bands can also accommodate contractional movement is still up for debate (Figueredo and Greeley, 2000). The *smooth band* identified in

the regional resolution image does not cross through the high-resolution image, so it remains unverified if the structure at regional resolution is similar to that in the high-resolution images.

3.8.2.4 Medial Trough Band Formation

One suggested formation mechanism for *medial trough bands* is spreading centered around the axial trough, in a similar fashion to that proposed for the formation of *smooth bands* (Prockter et al., 2002). A small piece of *medial trough band* material runs through the high-resolution region (eastern edge), where it appears to consist of 3-4 steep-sided ridges. Nothing about the *medial trough band* appears smooth at this higher resolution. However, it is important to note that this area appears to have been disrupted and may not accurately represent how a pristine medial trough ridge would appear at high resolution. However, when the high-resolution image is mapped independently, this structure is grouped with the *ridge complexes* (Section 3.5.1.2) based on its size, the irregularly spaced ridges and troughs, and the steepness of the ridge flanks. The appearance in the high-resolution images indicates these structures may be an artifact of resolution, only appearing to be smooth because they are a smaller version of a *ridge complex*.

3.8.2.5 Ridged Band Formation

Ridged bands are hypothesized to be a version of *smooth bands*, but with the formation mechanism operating at a different rate (Tufts et al., 2000; Prockter et al., 2002). Similarly, it is also hypothesized that *ridged bands* form through a tilt-block normal faulting mechanism (Kattenhorn, 2002). This may be the case, however it is important to note implications of the observations from the high-resolution images. Though the *ridged band* material that runs through the high-resolution strip in this region is partially disrupted, it is classified in the high-resolution

map as part of the *ridge complex* material (see Section 3.5.1.2). This implies that the two structures are not as different as previously thought and may indicate a similar, if not evolutionary, formational mechanism between the two units. Likewise, similarly steep and relatively symmetric ridge flanks and chevron-shaped cross section of the individual ridges within the *ridged band* suggest that the *ridged bands*, like *ridge complexes*, require a unique formation mechanism instead of being evolved phases of a *double ridge* (Head et al., 1999).

3.8.2.6 Lineated Band Formation

Part of a *lineated band* identified in the regional map is exposed in the high-resolution is identified as *lineated ridge-and-trough* or a subunit of plains material (Section 3.5.2.3). At high resolution, a *lineated band* is dissimilar to a *ridged band*, as the topographic relief of the individual ridges is significantly smaller and the morphology of the ridges differs greatly (Section 3.5.2.3). Additionally, the spacing and size of the ridges between the observed *ridged bands* (~500 m wide) and the *lineated bands* (~100-200 m wide) are too different to reconcile with proposed degradation. As such, the high-resolution observations suggest that the formation mechanism for *lineated band* material is not the degradation of a *ridged band* as previously proposed (Figueredo and Greeley, 2004). However, because this is the only *lineated band* imaged at this resolution at present, we cannot rule this hypothesis out completely.

3.8.2.7 Single Ridges

The one *single ridge* that was identified in the regional resolution that crosses through the high-resolution frames is identified as a *double ridge* in the high-resolution image. We suspect that *single ridges* are artifacts of the lower, regional resolution, as there are no *single ridges*

identified in the high-resolution images. In general, *single ridges* are also thought to either evolve to or from *double ridges* (Section 3.5.1.1, Greeley et al., 2000), though there is no evidence to support this in the limited high-resolution area, given there are no *single ridges* to observe.

3.8.3 Surface Evolution from Inferred Stratigraphy

Understanding of the evolution of Europa's surface from direct observation is limited by its surface age, or the past ~60 Ma +/- a factor of 3 (Zahnle et al., 2003). By determining how the visible surface has evolved, we constrain how the resurfacing processes have changed with time by investigating crosscutting structures. Figure 3.14 contains examples of analyzing crosscutting relationships to determine relative age.

The purpose of mapping the high-resolution images with both geomorphological and structural focus is to investigate surface morphology and the kinematic origin of structures (thus, resurfacing processes). Part of analyzing the formation of the surface is to investigate how it evolved into what it is like today. We do this by determining crosscutting relationships; however, this method is non-ideal in this region given its limited extent and considering the possibility of reactivation of some structures by tidal forcing. Moreover, comparing the relative ages of structures at the opposite ends of the high-resolution strip is difficult (i.e. we cannot ascertain relative ages for features along the strip because they never come into contact with each other). Thus, we create an evolution of the high-resolution surface that depicts a possible sequence of events, but requires further investigation and comparison to other high-resolution regions. It is important to note that not all features within an inferred "step" necessarily formed contemporaneously, but in the same general timeframe (Fig. 3.15).

The inferred stratigraphic column (Fig. 3.16) of this region is, from oldest to youngest: ridged plains, bands and other lineaments, chaos, and fractures. This sequence matches closely with those inferred in other regions of Europa at the regional scale (Pappalardo et al., 1999; Prockter et al., 1999; Figueredo and Greeley, 2000, 2004; Greeley et al., 2000). These time periods of formation blend into one another, but there are a few exceptions to this stratigraphy, especially in the relative ages of some lineaments (Geissler et al., 1998). In general, however, this progression of surface features holds. In terms of landscape degradation is some evidence of segregation (Spencer, 1987; e.g. Fig. 3.7, dark material in troughs) but no apparent sublimation features (Moore et al., 1999; 2009). Thus, our results support the possibility that this evolution of features is an indication of possible changes in the thickness of the ice shell (Pappalardo et al., 1999). Whether this is a cyclical process (Husmann and Spohn, 2004) or not remains unclear.

The high-resolution images do confirm how the relative ages inferred from regional resolution images may not be accurate. For example, a few works have used lineaments and bands crossing through chaos region as an indication that these lineaments are younger than the chaos terrain (Greenberg et al., 1999; Figueredo and Greeley, 2000). If we had only analyzed the regional resolution, we may have thought this as well because there exist features that cross through the chaos. However, it becomes evident in the high-resolution images that these structures have weathered the formation of the chaos region around them (Fig. 3.9; Prockter and Schenk, 2005). Thus, considering the high-resolution data is crucial to the accurate determination of what we are actually observing at the regional resolution. Further high-resolution data is needed to confirm these findings though, as we only directly observe local relationships with this single, narrow strip of high-resolution images.

3.8.4 Distributed to Discrete Deformation

As previously alluded to, the structural relationships summarized in Figures 3.14-16 evolve from small-scale ridge-and-trough systems to scarp and chaos terrain formation, with features like double and complex ridges occurring mostly in the middle of the stratigraphic column and rarely throughout. Thus, the high-resolution surface is consistent with the hypothesis that Europa resurfacing has changed through time (Pappalardo et al., 1999). We concur, as previously concluded by Figueredo and Greeley (2004), that the style of deformation has changed from distributed to discrete. From this, we infer that Europa's icy lithosphere has strengthened with time, presumably due to cooling and thickening. This hypothesis can account for the observed structural relationships and the surface structure formation hypotheses that we favor based on the high-resolution mapping. *Ridge-and-trough* terrain forming by folding is a distributed deformation mechanism (Section 3.8.1.1), bands could be formed by a combination of distributed and discrete deformation (e.g., Patterson et al., 2006), *double ridges* formed by compaction or linear diapirism (Section 3.8.1.2), chaos formed by lens collapse or diapirism (Section 3.8.1.3) are all forms of discrete deformation. Additionally, ice shell thickening would initially result in compressive forces before extensional forces dominate (Nimmo, 2004) which would explain the transition from compressional folds to extensional bands. Whether this activity is cyclic or occurred recently (within the age of the surface), we cannot say from this analysis.

3.9 CONCLUSIONS

Through key high-resolution observations obtained by mapping the E12 Mottle region in detail, we constrain the formation mechanism for structures on Europa. Our findings include:

1. Ridge-and-trough systems are observed to be multi-generational, and to have regular spacing and symmetric, gentle slopes, favoring the folds formation hypothesis.
2. *Double ridges* are remarkably consistent in size and shape along their length, favoring the compaction or linear diapirism hypotheses, though neither fits perfectly.
3. Chaos terrain has sharp boundaries, preserved pre-existing structures and heavily deformed border regions, suggesting that the water lens collapse hypothesis is the most likely formation mechanism.
4. Different morphological types of bands could have different formation mechanisms, not necessarily related to the evolution of *double ridges* or to the same mechanism operating at different rates. If they are formed by the same mechanism, the significant morphological differences need to be explained (cf, Howell and Pappalardo, in prep).
5. The *high albedo smooth* morphological terrain unit may originate from frosting due to cryovolcanic deposits, thermal processes, or impact ejecta. However, we propose that this is likely a new material not identified previously, which appears smooth at 8-16 m/pixel but likely has structure on a smaller scale only visible at a higher resolution.
6. This region of Europa's surface is covered in small (< 50 m diameter) pits, which we interpret, based on their distribution, as secondary craters. The high-resolution region closest (~50 km) to the primary crater appears to have undergone modification (not associated with chaos as identified in the regional map), and the pre-existing structures are heavily degraded compared to the surrounding terrain, possibly indicating that secondary craters could aid in resurfacing small patches of Europa.
7. *Single ridges* are not observed in the high-resolution mosaic despite identification in the overlapping regional resolution image. This could indicate that *single ridges* are an

artifact of low resolution and will be reclassified when higher-resolution images become available.

8. At the scale of the high-resolution images, Europa's surface has numerous *fine lineations*, possibly a result of tectonic loading or the presence of a tectonic fabric.

Resurfacing on Europa has transitioned from distributed deformation, seen in the multiple generations of ridge-and-trough systems, to discrete—including ridges, chaos features, scarps, and troughs. We predict that remnants of the distributed deformation, such as a tectonic fabric, will become apparent with higher resolution images from Europa Clipper. Ultimately, the shift in deformation from distributed to discrete may be driven by ice-shell thickening over the visible surface age.

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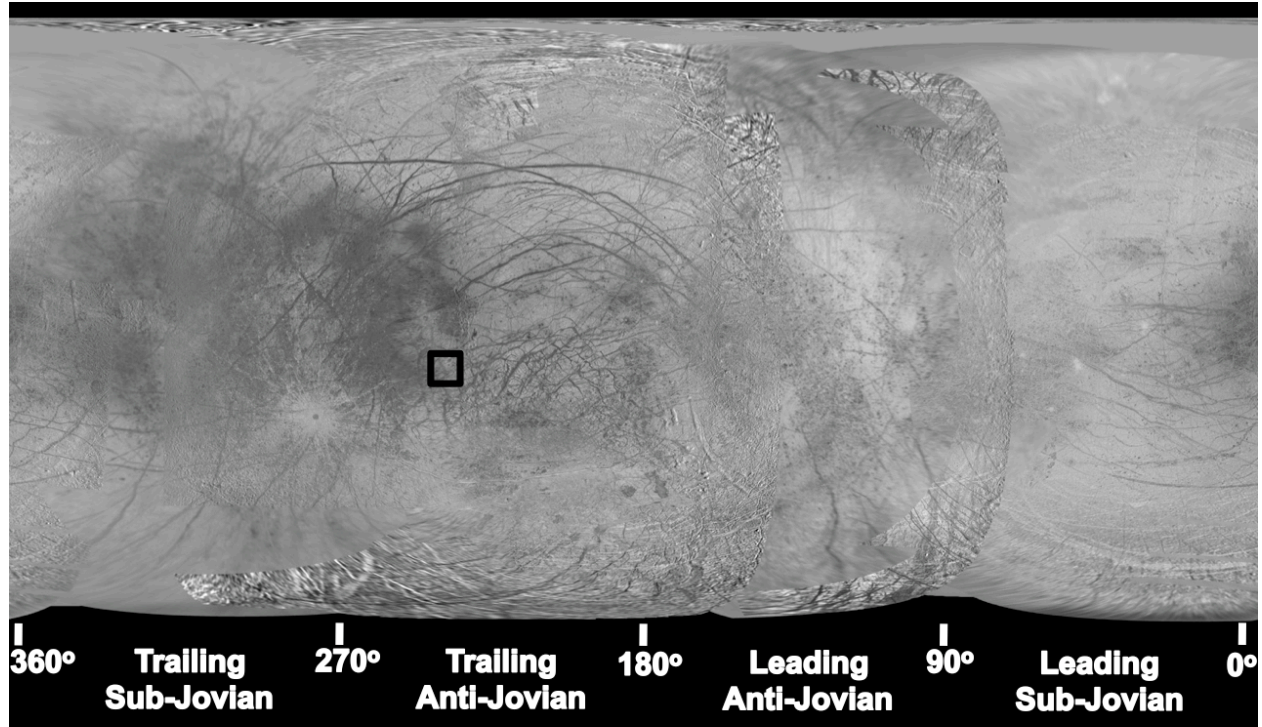


Figure 3.1 The USGS Global mosaic of Europa in West positive coordinate system. The black box indicates the approximate location of the regional resolution image in Fig. 3.2A. This area occurs between a chaos region (to the west) and a region characterized by bands and ridged plains (to the east, also known as the wedges region).

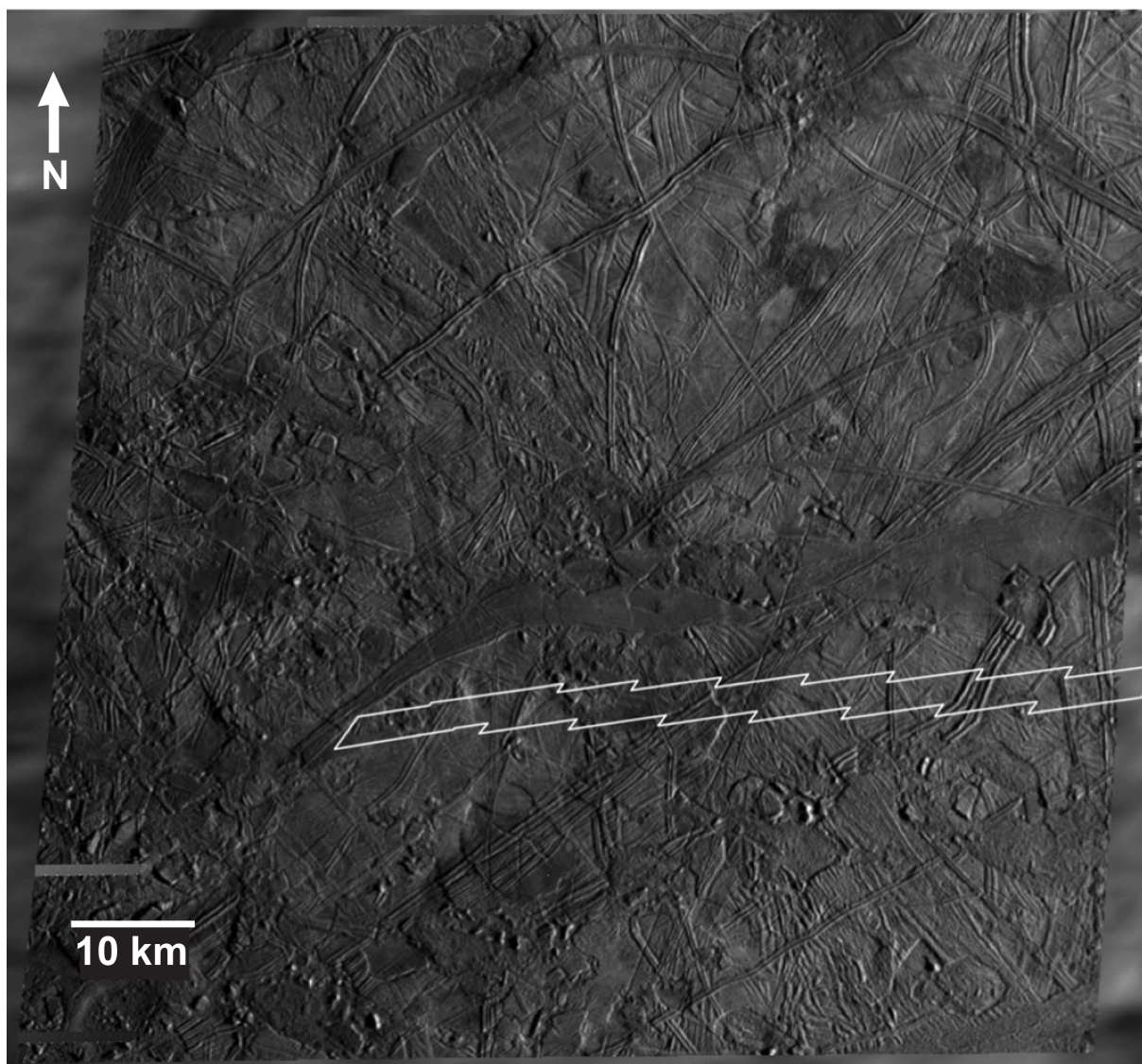


Figure 3.2A. Regional resolution image (220 m/px) taken by Galileo SSI (11ESREGMAP01 or 11E0017) with white outline indicating location of the high-resolution image mosaic (Fig. 3.3A). The image was taken at an incidence angle of 74° and an emission angle of 23° . Simple cylindrical projection, north is up.

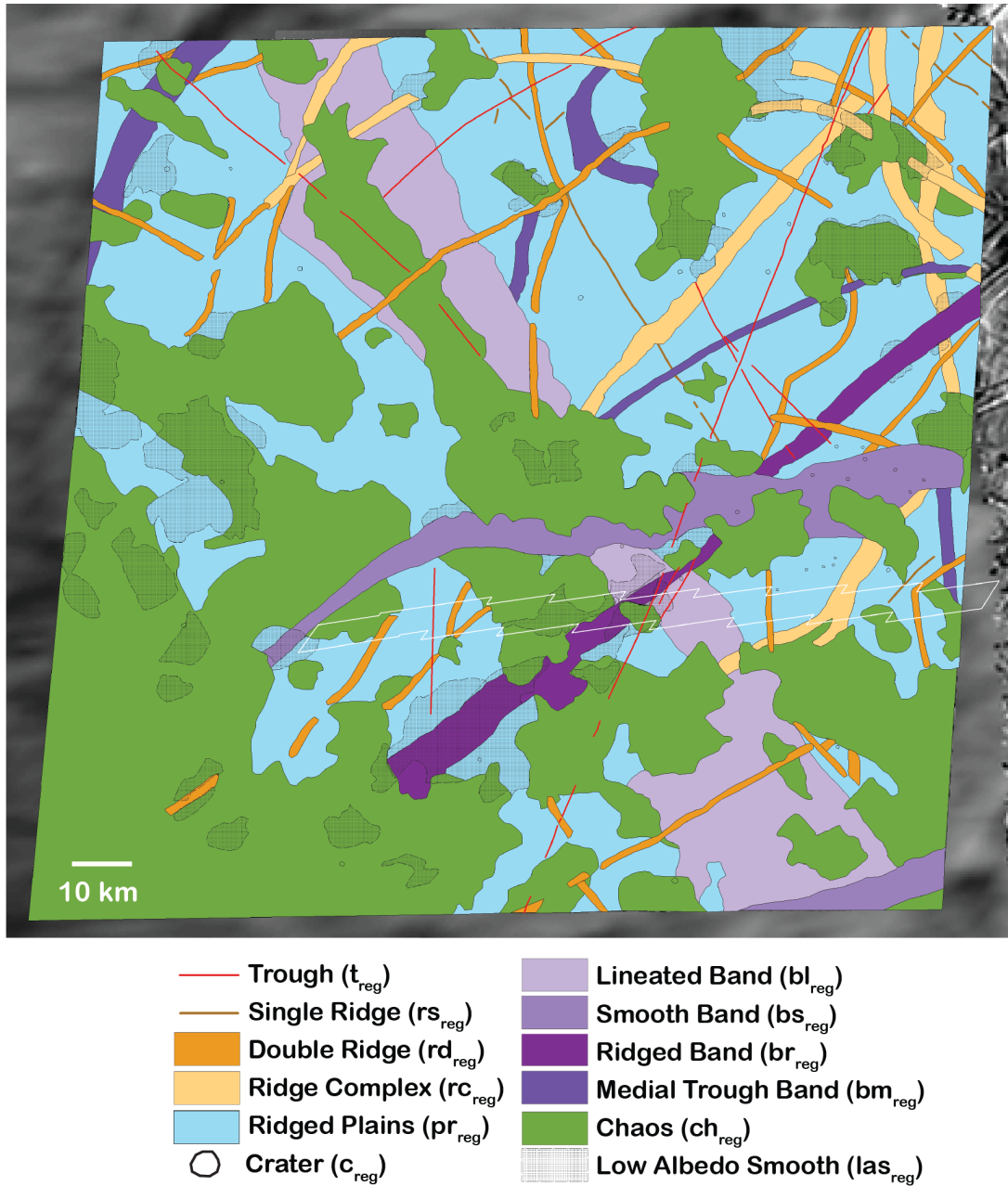


Figure 3.2B. Geomorphologic map of the regional resolution image (Fig. 3.2A) and corresponding key. The unit descriptions are in Section 3.5 and pictured in Fig. 3.4. The white outline indicates the location of the high-resolution image mosaic (Fig. 3.3A). Note the *lineated band* identified in the regional image that crosses through the high-resolution image mosaic (Section 3.8.2.6).

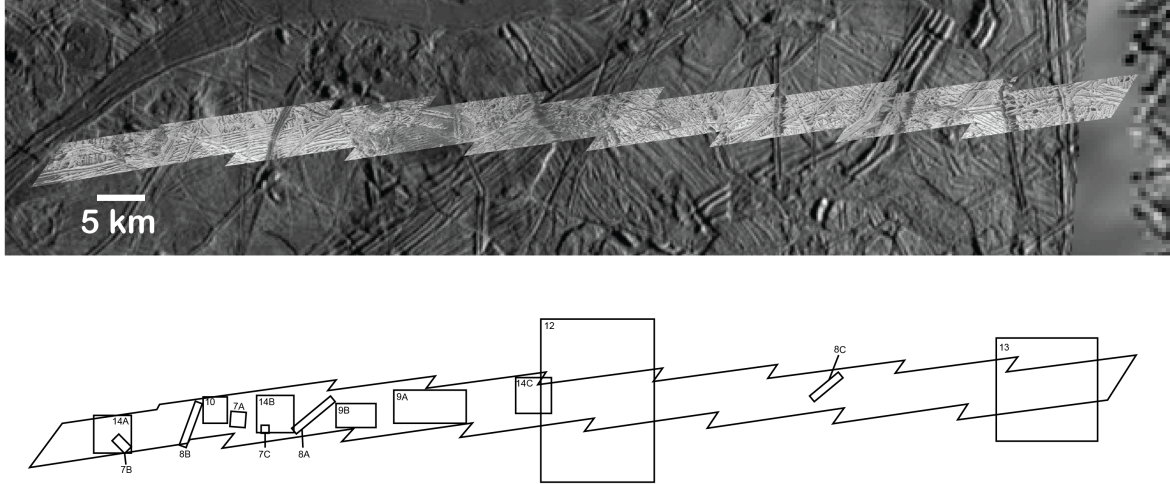


Figure 3.3A. High-resolution image mosaic (top) made up of nine Galileo SSI frames (12ESMOTTLE01 and 02, images 2378r, 2400r, 2404r, 2407r, 2411r, 2418r, 2421r, and 2425r), the westernmost (2378r) at ~ 8 m/pixel and the others at ~ 16 m/pixel (see Table 3.1). The frames were imaged at an incidence angle of $\sim 18^\circ$ and an emission angle of $\sim 77^\circ$. Simple cylindrical projection, north is up. Note that these images are not photometrically corrected. Outline of the mosaic (bottom) serves as a map of the locations of the other figures in this paper.

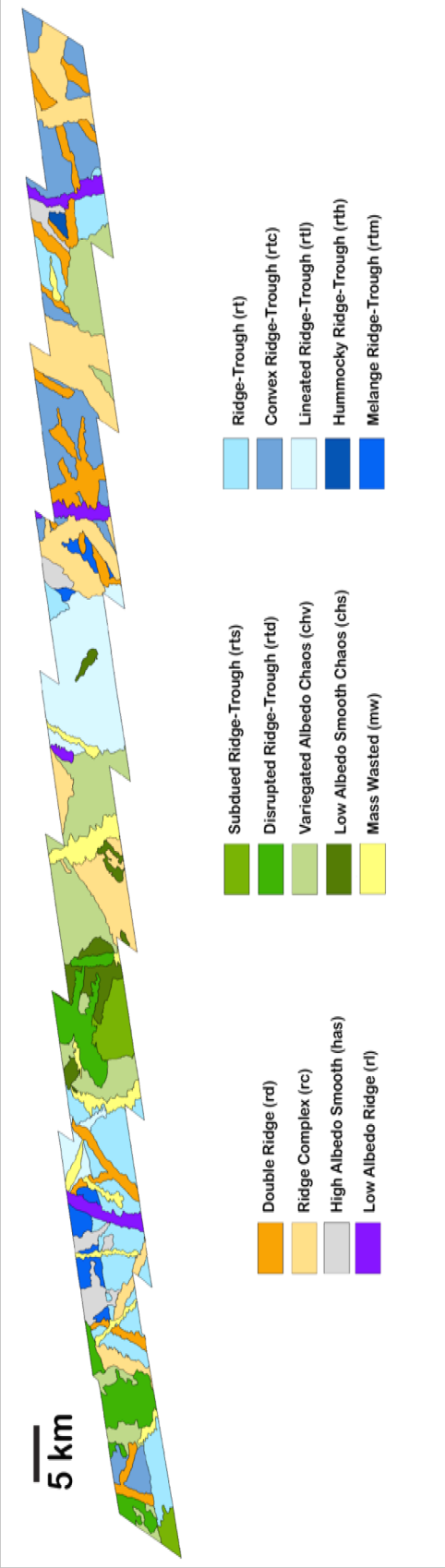


Figure 3.3B. Geomorphologic map of the high-resolution mosaic (Fig. 3.3A) and corresponding key. The different material units identified are based on albedo, texture, apparent degradation, size and general morphology. The units are described in Section 3.5 and pictured in Fig. 3.4.

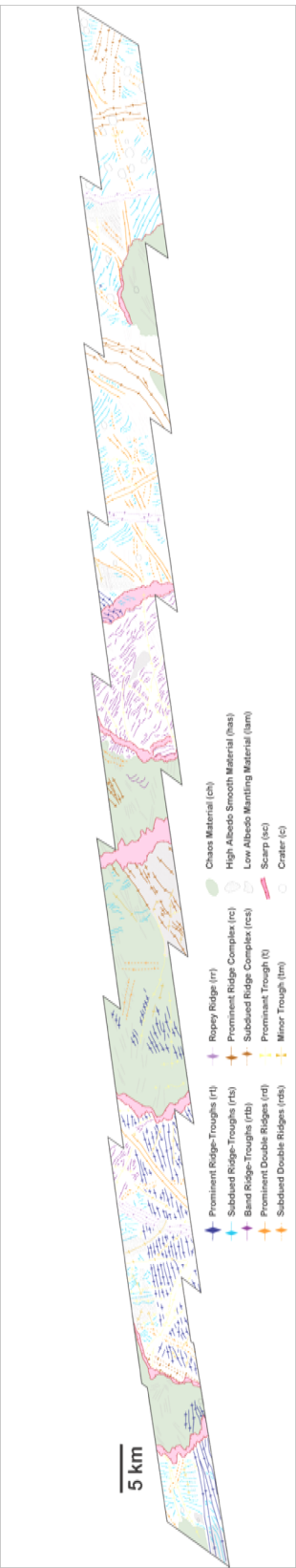


Figure 3.3C. Structural map and key. For structural unit descriptions see Section 3.6. Multiple types of ridges and troughs are highlighted with different colors depending on the context in which they occur (e.g., within a band, as a set, or independently as a *double ridge*) as this have potential ramification for formation mechanism and causes the ridges to vary in overall structure. Fault scarps are mostly contained to the border of chaos material regions, highlighting the sharp transition between chaos and surrounding terrain. Note the increasing number of potential craters as we move East. Symbols are based on Federal Geographic Data Committee Digital Cartographic Standard for Geologic Map Symbolization—Planetary Geology Features.

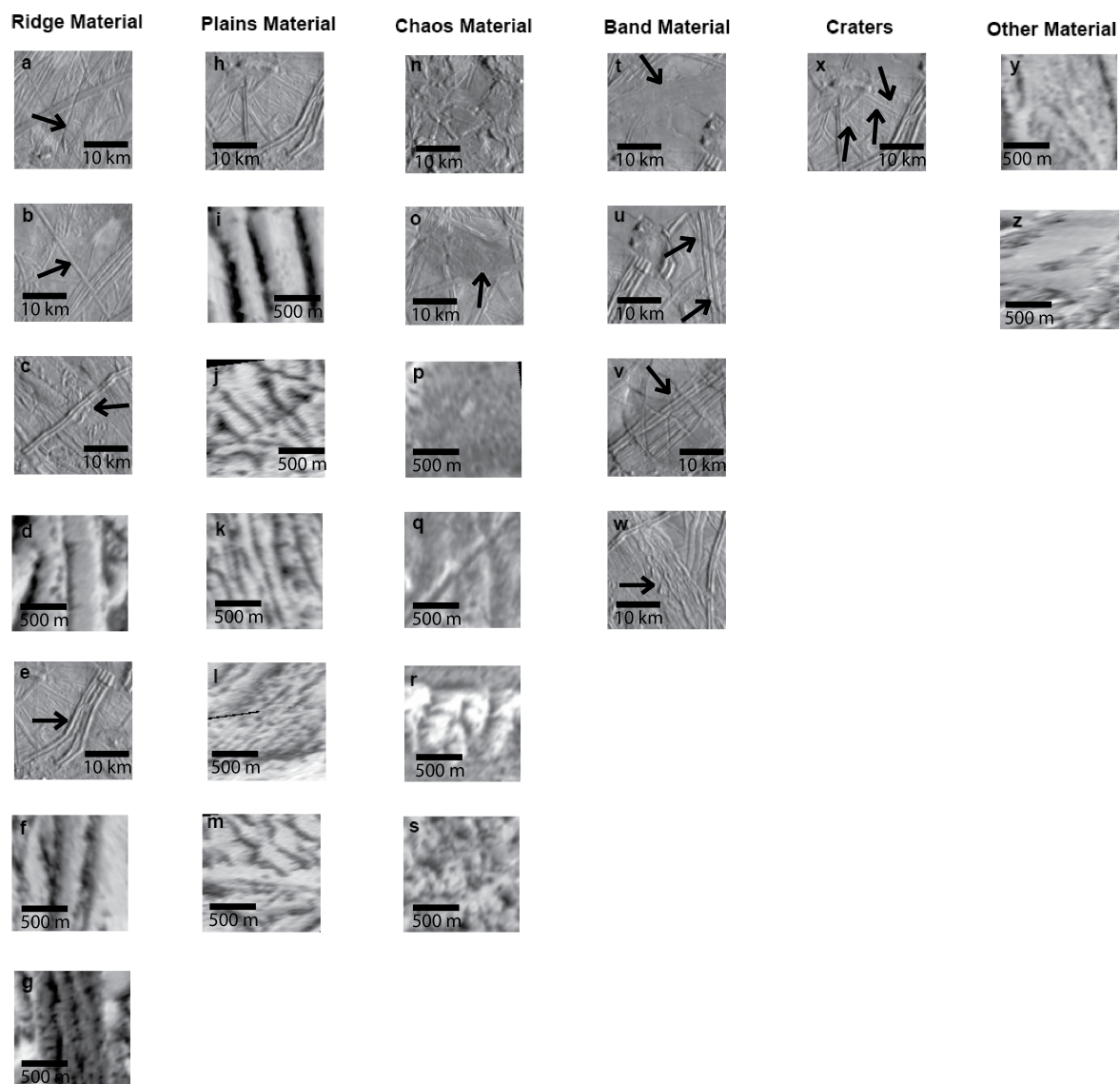


Figure 3.4 See next page for full caption

Figure 3.4. Classification of material units based on geomorphology, texture, albedo and size. For unit descriptions and interpretations see Sections 3.5-8. Both regional resolution and high-resolution units for the geomorphologic maps are included (see corresponding scale bars). For the Ridge Material or material associated with ridges that were not a part of a set or system, there are *troughs* (a), *double ridges* at regional resolution (b) and high resolution (c), *ridge complexes* at regional resolution (d) and high resolution (e), and *low albedo ridges* (f). For the Plains Material, or ridge-and-troughs material, there are *ridged plains* (h), *subparallel* (i), *convex* (j), *lineated* (k), *hummocky* (l), and *mélange* (m). For the Chaos Material, there is a general *chaos* unit for regional resolution (n) as well as a *low albedo mantling* (o), and for high resolution, *low albedo smooth* (p), *subdued ridges* (q), *discontinuous* (r), and *variegated* (s). Band Material is identified only in the regional resolution and includes *smooth* (t), *medial trough* (u), *ridged* (v) and *lineated* (w). There are a few *craters* in the regional resolution (x) and other units, which do not fall under the main five categories including *high albedo smooth* (y) and *mass wasted* material (z).

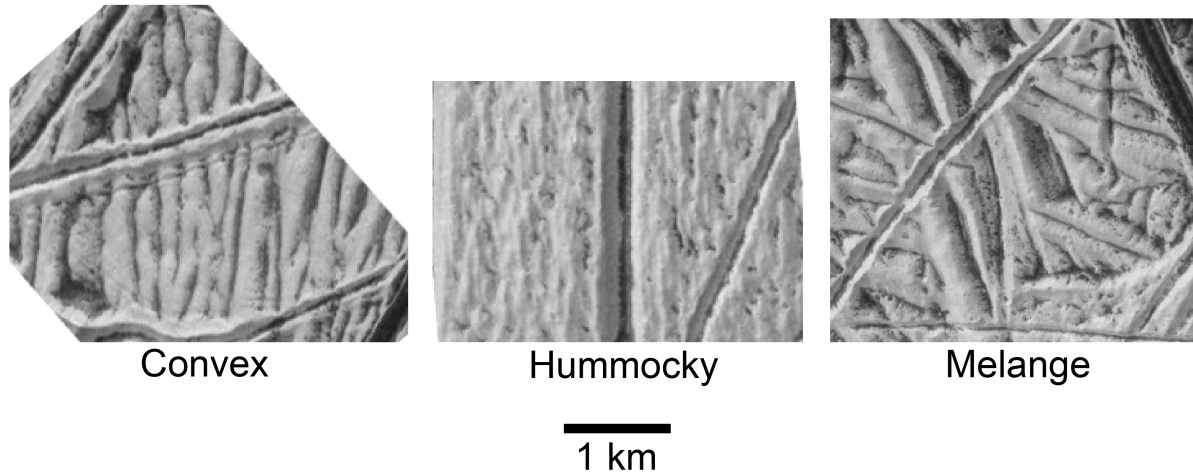


Figure 3.5. These three ridged plains sub-units—*convex*, *hummocky*, and *mélange*—were first identified by Patel et al. (1999a). These results were never published in a peer-reviewed journal, but we choose to recognize this work here, as it is the only other work to analyze the varying morphologies within the broad European ridged plains unit using high-resolution (<50 m/pixel) images provided by the Galileo mission. For these units, we adopt or slightly modify Patel et al.’s material and structural description. The other ridge-and-trough units described in this work are heavily modified or unique compared to those in Patel et al.

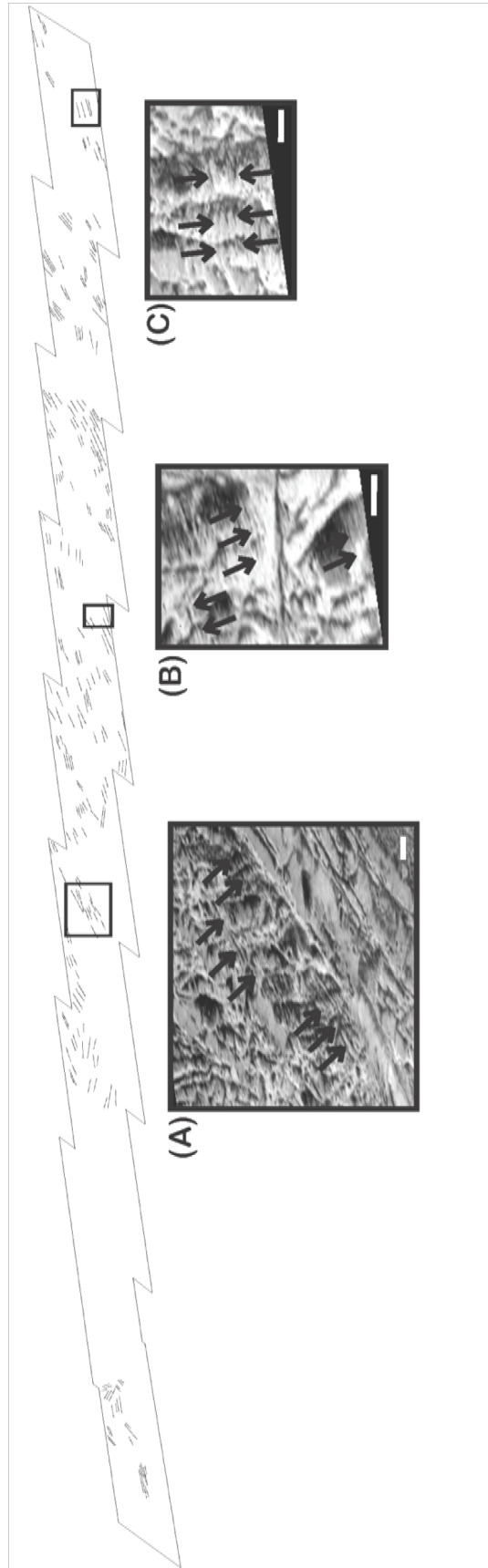


Figure 3.6. Examples of the *fine lineaments* structural unit defined in Section 3.6.2.4. Note the possible differences in structural origin. In the bottom left panel, the *fine lineaments* orientation and location suggest a loading origin. In the bottom middle panel the *fine lineaments* are potentially tectonic in origin, related to the formation of the ridges as a tectonic fabric. The *fine lineaments* in the bottom right panel appear independent of the *ridge complex* it crosses and does not have an apparent loading origin. The *fine lineaments* here also may have accelerated sublimation as we see slight topographic effects on the ridge where the lineations occur. White scale bar in all panels is 500 m.

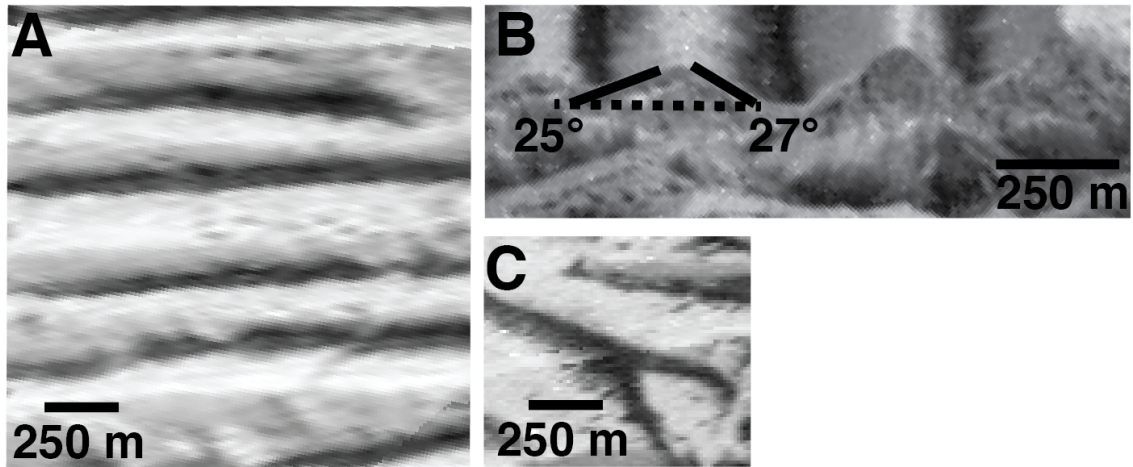


Figure 3.7. Examples of ridge-and-trough attributes as listed in Table 3.2. (A) An example portraying the sub-parallel, linear and regularly spaced nature of the ridge-and-trough terrain. (B) A cross-section of the ridge-and-trough terrain displaying the apparent angle of the slopes of the individual ridges (ranging from 20 to 35 degrees). (C) An example of a y-junction or a bifurcating ridge.

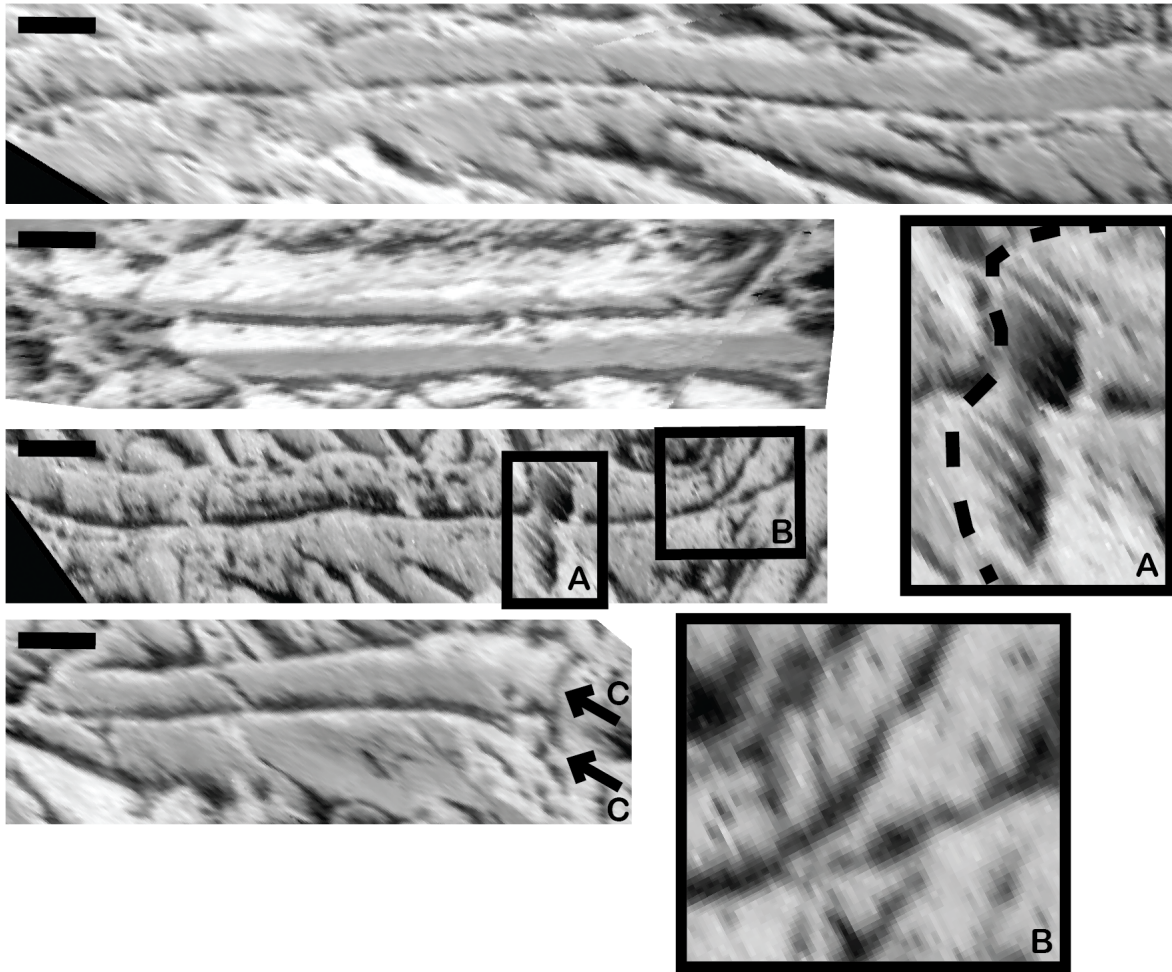


Figure 3.8. Example of *double ridge* attributes as listed in Table 3.3. (A) A cross section of *double ridge* reveals that the individual ridges are relatively symmetric. (B) An example in the high-resolution strip of where a *double ridge* evolves along its length into a potential *ridge complex*. (C) In some cases, *double ridges* appear strong and coherent, enough so to be unaffected (in shape) by pre-existing topography and post-formation deformation (second image from top) while in other cases (C, arrow) ridges appear easily fractured across. (D) The only example of a *double ridge* ending without evolving into another feature or being crosscut by newer structures. Scale bars indicate 500 m.

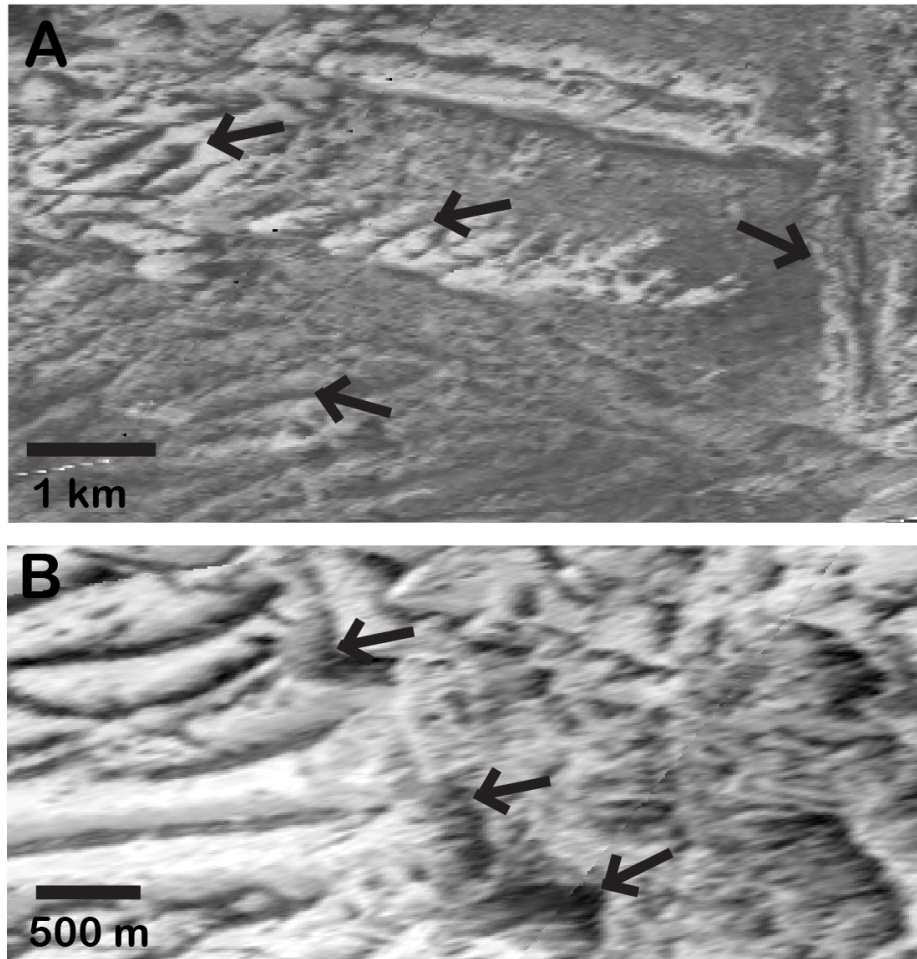


Figure 3.9. Examples of chaos attributes as listed in Table 3.4. (A) Surviving structures in chaos region. The red box indicates a slightly modified but mostly intact *double ridge*. Arrows indicate part of what is interpreted to be a ridge-and-trough and *double ridge* unit completely embayed by the *low albedo smooth* material (see Section 3.5.3.1). The preservation of these units has implications for chaos formation, as the mechanism must allow for embayment and mild modification in addition to the heavy modification of other nearby units. (B) The sharp boundary between well-preserved ridged-trough terrain and chaos terrain. North is up.

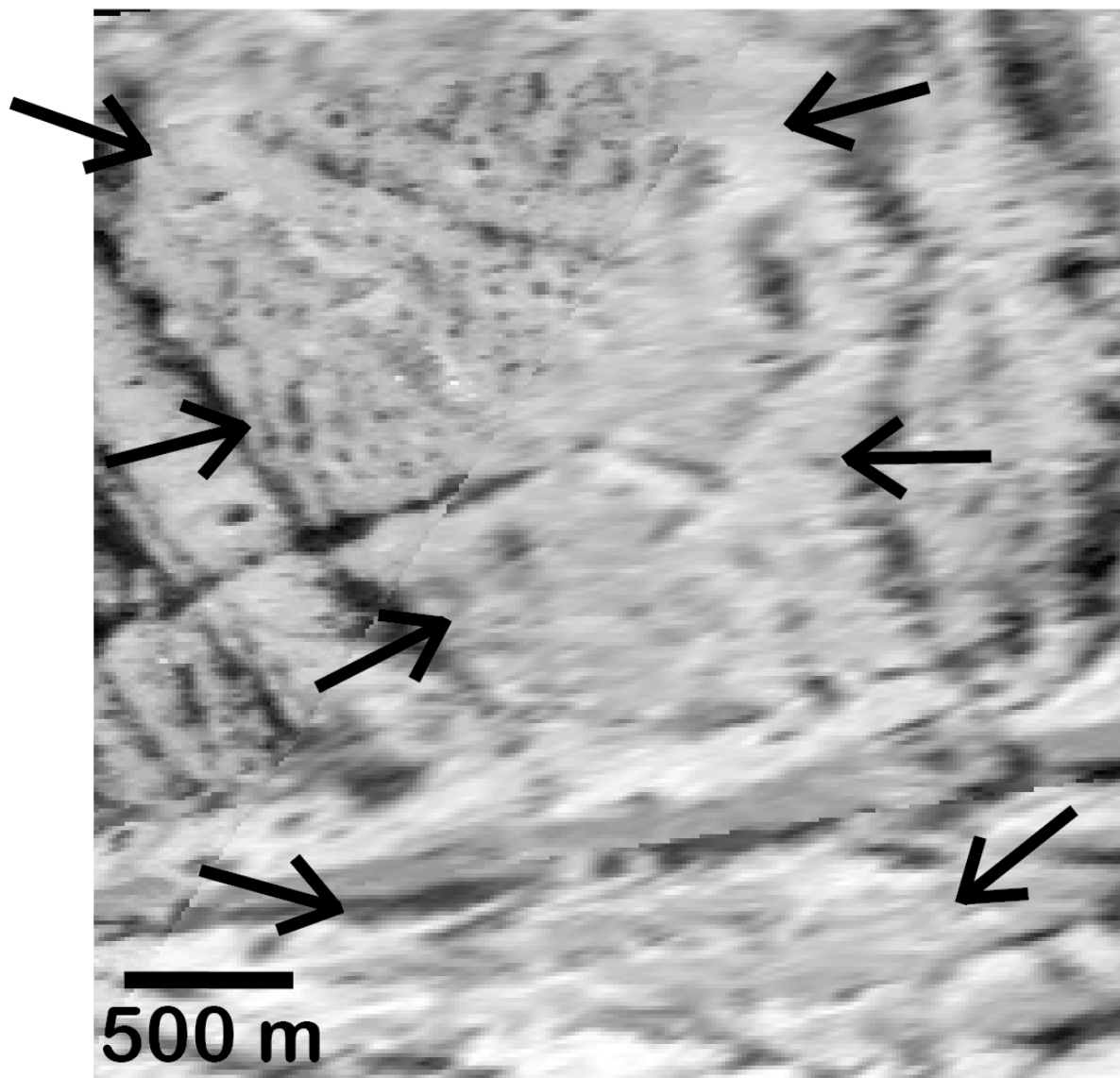


Figure 3.10. The arrows denote the edges of the *high albedo smooth* material. Note how the features around the high albedo region have troughs and ridges, but the area within the arrows consists mostly of small (~10 m) pits, subdued troughs and smooth material. This material also appears to have degraded the *subparallel ridge-and-troughs* at the bottom of the image.

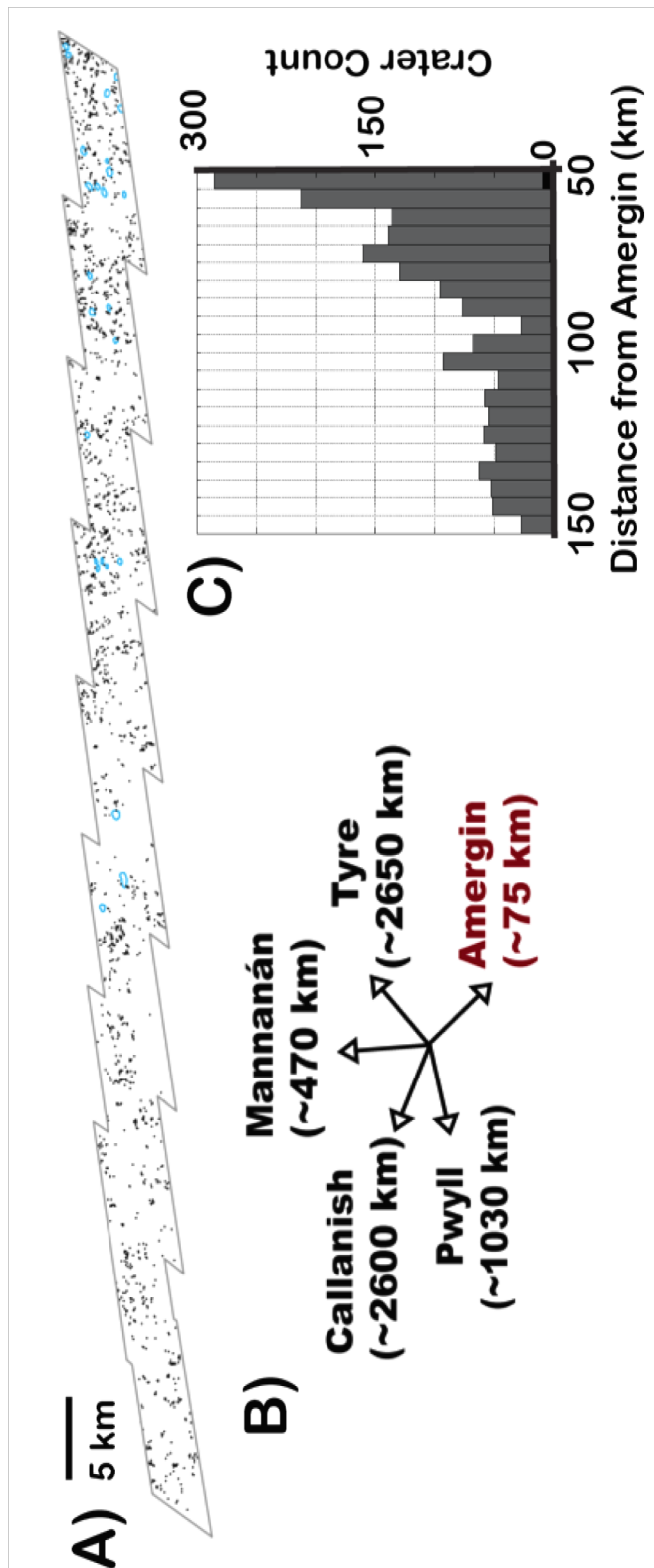


Figure 3.11. (A) Map of each small pit (black dot) and dark spot (light blue) in the high-resolution image. North is up. (B) An indication of the closest or largest primary craters on Europa and their distances to this region. (C) Plot of number of pits (grey) and spots (black) with increasing distances from Amergin, the closest primary crater. Note the exponential fall off thus indicating that these spots are likely secondary craters.

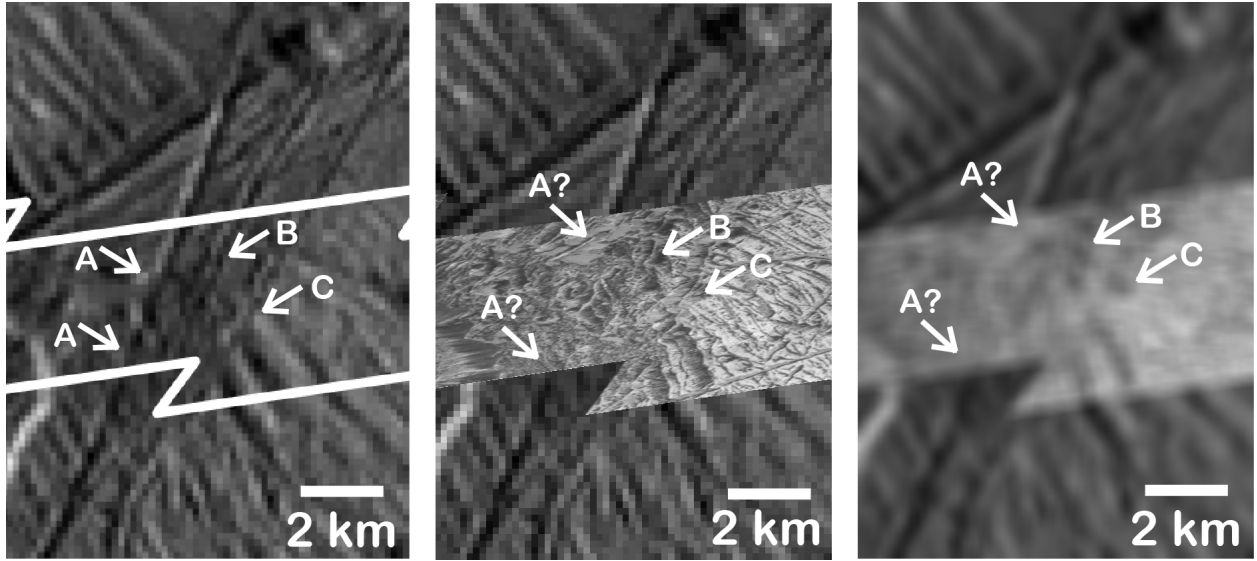


Figure 3.12. (A) Denotes the ridge observed in the regional resolution image (left) that appears to disappear in the high-resolution image (middle). (B) and (C) denote two other ridges of similar orientation to ridge (A) in the regional resolution (left) that are still observed in the high-resolution images (middle). Note that when the high-resolution image is resampled to approximately match the resolution of the regional image (right), the ridges (B) and (C) are again visible, but the ridge (A) is still not visible. The high albedo feature near the top (A, middle and right) appears to be the *ridge complex* trending NE and not the ridge (A), as it trends ~N. This is reinforced by the lack of structure at the bottom of the images (A, middle and right).

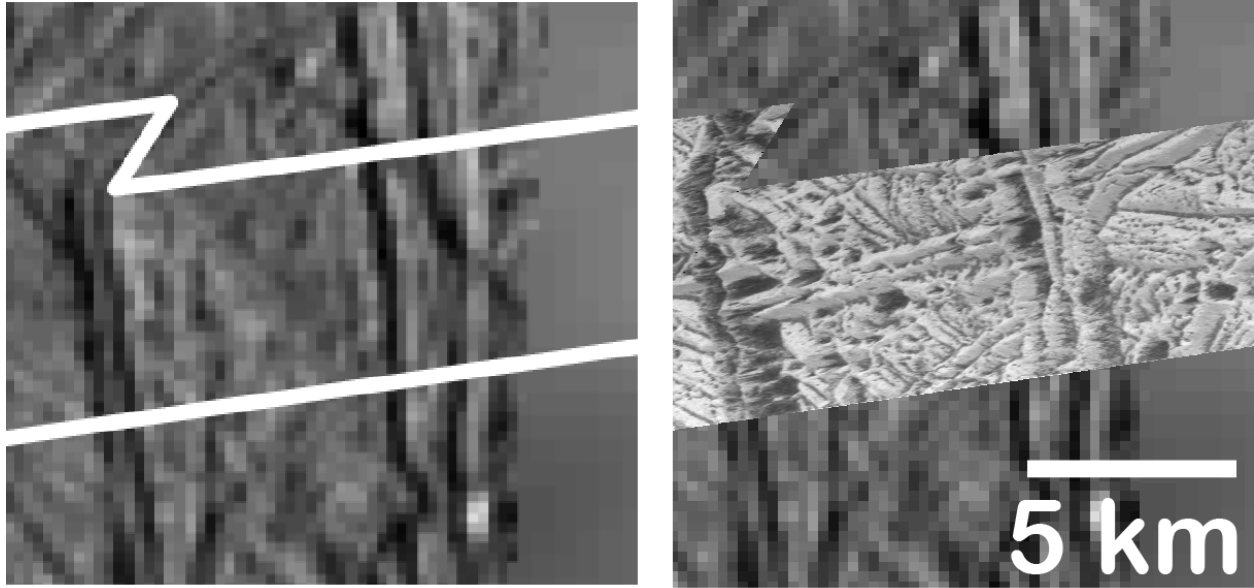


Figure 3.13. This region is identified as chaos at the regional scale (left), but in the high-resolution image (right), we can see that it does not resemble chaos terrain, but instead, the terrain appears to be modified by a different process. We interpret that this region has been modified by secondary craters (see Fig. 3.11), even though it is near other chaos terrain. Common scale, North is up.

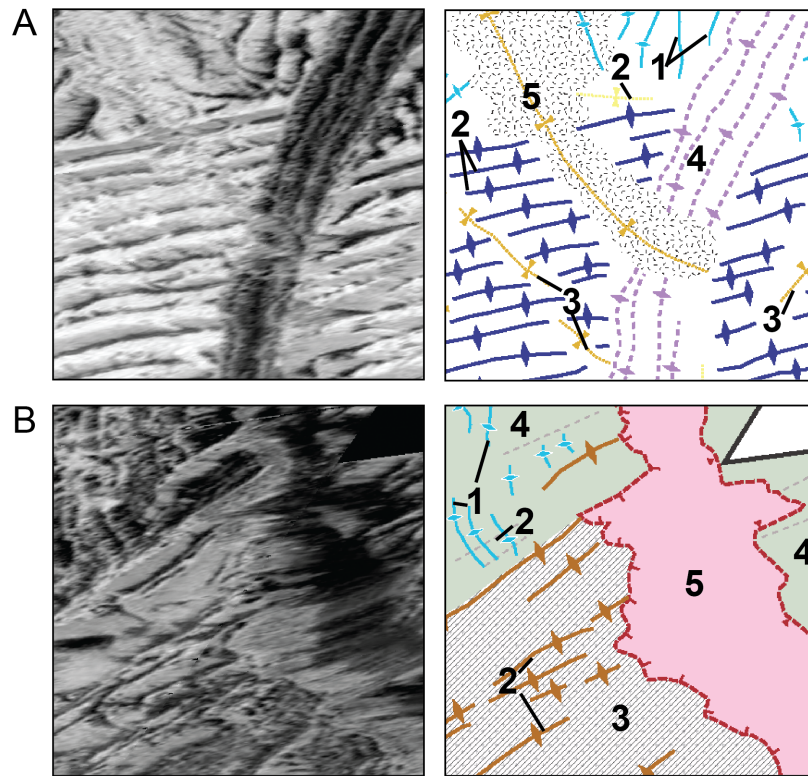


Figure 3.14. Examples of crosscutting relationships used to determine relative ages, as labeled by the numbers where 1 is the oldest event and 5 is the youngest event. In frame (A) the relationships are as follows: (1) the *subdued ridge-and-trough* terrain is cut by (2) the *ridge-and-trough* terrain which is cut by (3) a few *minor troughs* which are intersected by (4) the *ropy ridge* which is cut by (5) a *minor trough* and *high albedo smooth* material. In (B) the cross-cutting relationships are as follows: (1) the *subdued ridge-and-trough* terrain is cut by (2) *fine lineaments* and *subdued ridge complex* structure covered by (3) a *low albedo smooth* material which is modified by (4) *chaos formation* which is cut by a (5) *scarp structure*. While these two areas do not overlap, we can draw general inferences on the overall history of the region as a whole by observing the trends in the local crosscutting relationships—for example, *subdued ridge-and-trough* terrain is always the oldest and *scarps* are some of the youngest features—which lead to the stratigraphic history displayed in Figures 3.15 and 3.16.



Figure 3.15. Inferred history of this region determined by crosscutting relationships to determine the relative age of the structures.

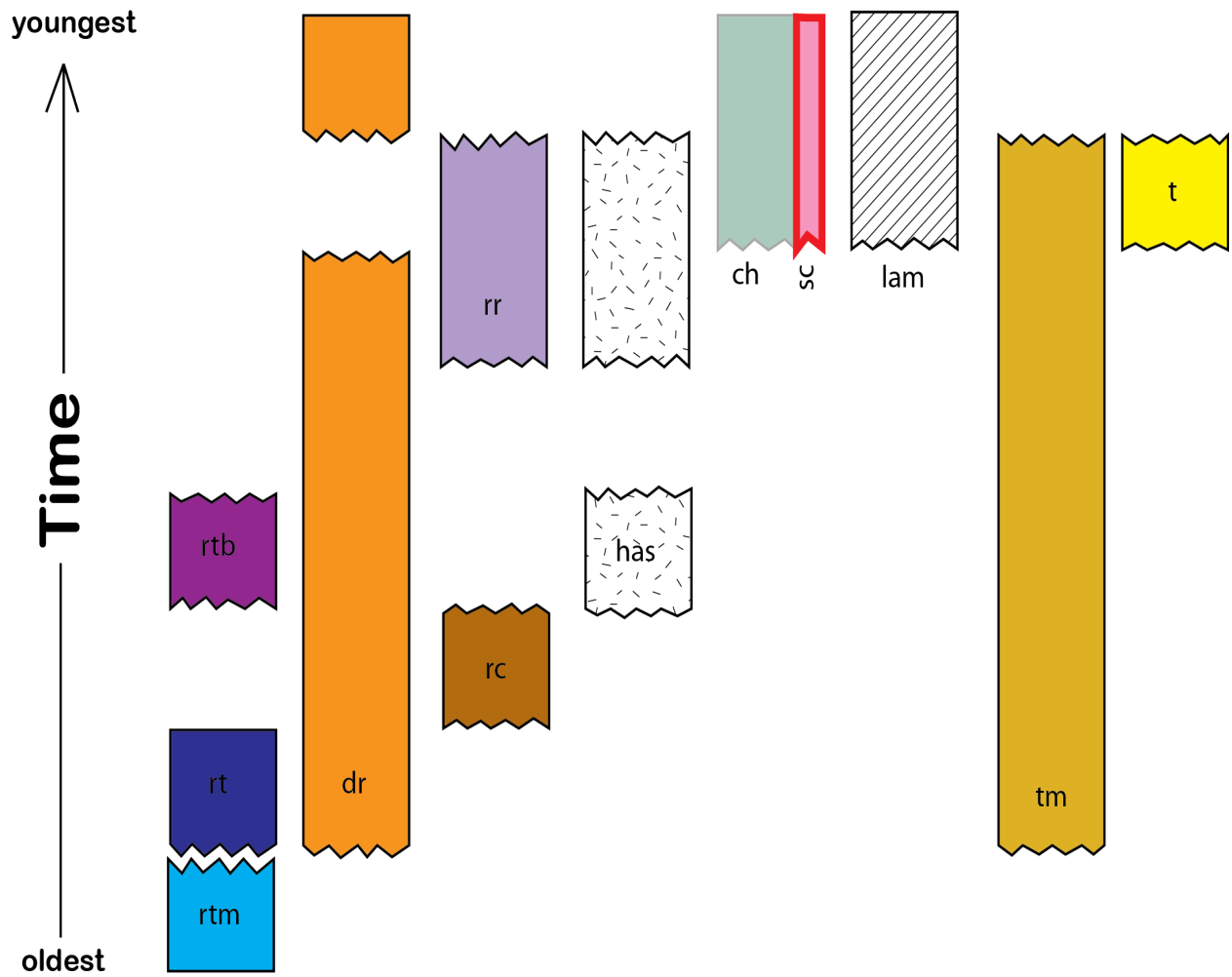


Figure 3.16. Stratigraphic column determined by crosscutting relationships among units from the evolutionary sequence (Fig. 3.14). Unit abbreviations from Structural Map (Fig. 3.3C)

Table 3.1: Image data and information from all the images used in this study.

Orbit	S-clock	Observation ID	Incidence Angle (°)	Emission Angle (°)	Vertical Resolution (m/pixel)	Horizontal Resolution (m/pixel)
E11	s0420619278	11ESREGMAP01	74.617	22.338	229	228
E12	s0426272378	12ESMOTTLE01	19.917	76.307	8.0	23.4
E12	s0426272401	12ESMOTTLE02	19.130	76.505	16.8	49.2
E12	s0426272404	12ESMOTTLE02	18.836	76.444	16.6	49.6
E12	s0426272407	12ESMOTTLE02	18.502	76.125	16.6	48.0
E12	s0426272411	12ESMOTTLE02	18.164	75.915	16.4	47.6
E12	s0449962415	12ESMOTTLE02	17.834	75.544	16.3	46.4
E12	s0426272418	12ESMOTTLE02	17.5	75.275	16.3	45.6
E12	s0426272421	12ESMOTTLE02	17.171	74.843	16.0	44.3
E12	s0426272425	12ESMOTTLE02	16.850	74.529	15.5	43.5

*Note the phase angle is relatively constant between the images ($\sim 60^\circ$).

Table 3.2: Comparison of *subparallel ridge-and-trough* formation mechanisms against observations in the high-resolution mosaic.

	Tilt-Blocks	Folds
Symmetric Ridges		
Systematic		
Shallow Slopes		
Can Bifurcate		
Linear or Curvilinear		

*Green indicates where theory satisfies the observation, and red indicates where it is unclear or not satisfied.

Table 3.3: Comparison of *double ridge* formation mechanisms against observations in the high-resolution mosaic

	Cryovolcanism	Tidal Squeezing	Linear Diapirism	Shear Heating	Wedging	Compression	Compaction
Uniform height/shape along length							
Symmetric Ridges							
Small-scale variation in size							
Morphs into other structures							
Younger or older stratigraphically							
Not inhibited by previous topography							
No apparent central “crack” or vent							

*Green indicates where theory satisfies the observation, and red indicates where it is unclear or not satisfied.

Table 3.4: Comparison of Chaos formation mechanisms against observations in the high-resolution mosaic.

	Melt-Through	Lens	Diapirism
Abrupt Boundaries			
Heavily Modified Edges			
Preservation of Structures			
Low Albedo Smooth material			
Lack of large plates			
Scale			

*Green indicates where theory satisfies the observation, and red indicates where it is unclear or not satisfied.

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- Chapter 4 -

Ridged Plains on Europa Reveal a Compressive Past

4.1 Abstract

Europa's seemingly young surface implies relatively recent resurfacing. Ridged plains, which make up >50% of Europa's surface, have yet to be fully analyzed to interpret a potential formation mechanism. Because this feature dominates Europa's surface, it is key to understanding how Europa has resurfaced and how this resurfacing may have evolved through time. Thus, in this work we create a new high-resolution topographic model and a two-layer physical analogue model to investigate the formation of ridged plains. We find that the ridged plains most closely resemble the compressional physical analogue experiments which generate folds. Specifically, the analogue experiments with a brittle layer that has less than one-sixteenth of the underlying ductile-layer thickness best explains the morphological observations of the ridged plains on Europa. Based on the scaling relationships, we find that at the time of the ridged plains formation, the brittle part of the ice shell of Europa's ice shell was ~200 m thick and the total ice-shell thickness, including both the ductile and brittle parts, was ~ 3000 m. Compared to the predicted current ice shell thickness, this would imply that Europa's ice-shell has thickened through the visible surface history.

4.2 Introduction

Unlike most planetary surfaces in our Solar System, Europa is largely devoid of impact craters. Instead, its surface consists of several enigmatic features ranging from pervasive occurrences of regularly spaced ridges and troughs to chaotic terrain resembling broken pieces of the ice shell. Although the paucity of impact craters requires the surface age of Europa to be ~60 Ma (e.g., Schenk et al., 2003; Zahnle et al., 2003; Bierhaus, 2009), the exact processes and mechanisms responsible for the resurfacing remain poorly understood. Current hypotheses addressing this issue vary from cryovolcanism, to plate tectonic processes (e.g., Crawford and Stevenson, 1988; Greenberg et al., 1998; Pappalardo et al., 1999; Greeley, 2000; Greenberg and Geissler, 2002; Figueredo and Greeley, 2004; Doggett et al., 2009; Kattenhorn and Prockter, 2014).

Observationally the surface of Europa appears to have been shaped by a three-staged development: (1) the initial formation of ridged plains, followed by (2) the development of band-like structures, and finally (3) the creation of chaos features (Figueredo and Greeley, 2004; Leonard et al., 2018; Senske et al., 2018; Leonard et al., *in prep*). The formation of the ridged plains may result from folding (Head et al., 1998; Patel et al., 1999; Leonard et al., 2018) or extensional faulting (Kattenhorn, 2002), but has not been widely investigated. The formation of band-like structures has been attributed to juvenile ice-shell accretion similar to mid-ocean-ridge spreading on Earth (e.g., Prockter et al., 2002; Prockter and Patterson, 2009). The spreading hypothesis is consistent with predicted band morphology and reconstructions of pre-band-formation structures that require significant ice-shell separation (Schenk and McKinnon, 1989; Sullivan et al., 1998; Prockter et al., 2002; Prockter and Patterson, 2009). The formation of chaos structures has been intensely debated since their initial recognition, with end-member hypotheses

including melt-through, sill formation and collapse, and diapirism induced by thermal and/or chemical buoyancy (Greenberg et al., 1999; Pappalardo et al., 1998; O'Brien et al., 2002; Collins and Nimmo, 2009; Schmidt et al., 2011; Michaut and Manga, 2014). Ridges form throughout the stratigraphic sequence (e.g., Figueredo and Greeley, 2004; Senske et al., 2018) and in regional scale maps are noted to gradually increase in size and become more prominent with time (Figueredo and Greeley, 2004).

The aforementioned three-stage development of ice-shell structures on Europa requires ice-shell deformation to have transitioned from a distributed mode to a discrete mode, possibly caused by progressive ice-shell thickening since the onset of the global resurfacing event (Pappalardo et al., 1999; Figueredo and Greeley, 2004; Leonard et al., 2018). Alternatively, the ice-shell could be in steady state and deformation is induced by tidal stress (e.g., Greenberg et al., 1998; Greenberg et al., 2002). In this scenario, the evolution of ice-shell structures through time is not recognized and therefore requires that all surface structures can be formed at essentially the same time. Differentiating between these competing hypotheses requires better understanding of how the ridged plains formed, as they set the initial conditions for the subsequent or contemporary resurfacing processes: ice-shell thickening would require the ridged plains to be contractional in origin (Nimmo, 2004), whereas diurnal tidal forcing would predict the ridged plains to have been mainly generated by combined extensional and strike-slip deformation (Hoppa et al., 1999a, cf. Rhoden et al., 2002.).

Some of the best imaged ridged plains features are those mapped by Leonard et al. (2018) using the highest resolution images available for this type of terrain. In this work, we use the term “ridged plains” to refer to four of the five morphologies identified in high-resolution images of Europa (Patel et al., 1999; Leonard et al., 2018) which are all variations of a subparallel,

systematic ridge-and-trough terrain. Although Leonard et al. (2018) favored a contractional origin for the ridged plains analyzed in their study (Table 4.1), similar Europa structures were alternatively interpreted as resulting from related extensional block faulting (Kattenhorn, 2002), akin to the detachment model for the grooved terrain development on Ganymede (Pappalardo and Greeley, 1995; Patel et al., 1999; Prockter et al., 1998, 2000; Figueredo and Greeley, 2000). One possible way of differentiating between the two competing models (i.e., compression versus extension) is to explore the mechanical controls for the morphological development of the ridged plains. Specifically, a rigorously scaled analogue experiments under contrasting boundary conditions create surface morphology and its evolution that can be compared against the detailed shapes and spatial arrangements of ridges documented from the high-resolution images and the resulting topographic data.

In this study, we first developed a two-layer physical analogue model using an experimental setup constructed at the University of California, Los Angeles. We then created stereo-topography data with which we test the viability of our experimental results together with the highest resolution satellite images. A key result of the work is that the compression-induced morphology best explains the observed map pattern and cross-sectional shapes of the ridged plains features. Specifically, the analogue experiments with a brittle layer that has less than one-sixteenth of the underlying ductile-layer thickness best explains the morphological observations of the ridged plains on Europa. Because the ridged plains are among the oldest features on Europa and compression-induced followed by the formation of younger extensionally induced band structures, we suggest that this sequence of events can simply be explained by progressive ice-shell thickening due to secular cooling of the ice-shell and ocean system.

4.3 Data and Methods

4.3.1 Topographic Data and Morphologic Observations

We produce stereo-topography data from the image frame overlaps of the Galileo SSI E12 Mottled terrain region (i.e., frames 2400 and 2404) using the Ames Stereopipeline software (Broxton and Edwards, 2008; Moratto et al., 2010). From the height and spacing of the ridges, we calculate the linear strain assuming the undulating surface started as a perfect plane later deformed by extension as tilted blocks or compression as folds. The small angle change between the images is non-ideal for constructing the digital topographic models. To minimize this effect, we average three topographic profiles spaced at 100 m (Fig. 4.2C), which shows the amplitudes of individual ridges to be 50-80 m (Fig. 4.2D).

The ridged plains subunits display the following characteristics (Leonard et al., 2018) (Table 4.1): (1) the presence of symmetric shallow slopes, (2) curvilinear to sinuous traces of individual ridges along their length, (3) ridge bifurcation along the general ridge trend, and (4) a sub-parallel trend for an individual ridge-and-trough set. In the limited high-resolution area mapped by Leonard et al., (2018), the individual ridges are relatively consistent at 300 ± 100 m wide and a length-to-width ratio of >10 . The total width or length of a ridge-and-trough set cannot be determined with the current data due to the limited extent of the high-resolution images (e.g., Fig. 4.1D). Some of the troughs separating each ridge contain a low albedo material, potentially emplaced by ice sublimation or downslope mass wasting processes (Spencer, 1987).

4.3.2 Experimental Setups and Procedures

Although analogue models have been widely applied for tectonic studies on Earth (e.g., Davy and Cobbold, 1988; Malliot and Koyi, 2004; Cruz et al., 2008), they were rarely used for the

studies of ice-shell deformation (cf., Manga and Sinton, 2004; Sims et al., 2014). In this work, we model the ice-shell of Europa consisting of lower ductile warm ice and upper brittle cold ice. We use a ductile putty layer to simulate the lower-crustal ductile deformation and a sand layer to simulate the upper-crustal brittle deformation. The experimental ductile material is a therapeutic putty with a viscosity of $\sim 10^4$ Pa s, and the fine-grained (< 200 μm) dry sand for our brittle layer has a cohesive strength of ~ 60 Pa and a frictional angle of 22 - 27° (Zuza et al., 2017). Using the ratio between the cohesive strengths of ice on Europa (Beeman et al., 1988) and of the dry sand (Zuza et al., 2017) used in the experiments, we obtain a length scaling factor of $1:10^5$ based on the scaling law of Hubbert (1937) (also see its application by Cruz et al., 2008 for analyzing terrestrial structural deformation):

$$\frac{h_{ice}}{h_{mod}} = \frac{C_{ice}}{C_{mod}} \cdot \frac{g_{mod}}{g_{ice}} \cdot \frac{\rho_{mod}}{\rho_{ice}} \quad (4.1)$$

where the subscript *ice* refers to Europa and the subscript *mod* refers to the analogue model values, h is the thickness of the brittle layer, C is the cohesion of the brittle layer, g is the gravity, and ρ is the density of the brittle layer material. This scaling law implies that a 1-cm thick sand layer in our model on Earth represents an about 2-km thick ice shell on Europa. The time scaling factor was obtained by using the ratio between the putty viscosity and average viscosity of warm ice assumed to be 10^{14} Pa s (e.g., Poirer, 1982; Showman and Han, 2004; Mitri and Showman, 2005) using the relationship proposed by Davy and Cobbold (1988):

$$\frac{t_{ice}}{t_{mod}} = \frac{\mu_{ice}}{\mu_{mod}} \cdot \frac{h_{mod}}{h_{ice}} \quad (4.2)$$

where the subscript *ice* refers to Europa and the subscript *mod* refers to the analogue model values, t is the duration of deformation, and μ is the viscosity of the ductile layer. This leads to a scaling factor of $1:10^9$, where a 24-hour experiment corresponds to a deformation episode of $\sim 10^6$ years on Europa. The boundary between the brittle and ductile layer in our experiment is

discreet, as opposed to the likely more gradual transition on Europa, which means we are modelling the end-member behavior of this system.

To set up an experimental run, we first place the putty into an analogue experimental box with movable walls used for imposing bounding conditions (Fig. 4.3). We let the putty relax to a flat surface over the course of 3-7 days before adding the desired amount of sand on top. Finally, we scatter coffee grounds over the surface of the sand that act as tracking particles of surface deformation during the experiment (after Riller et al., 2012). In order to run an experiment, we employ a step motor to move a wall to either compress or extend the layered experimental materials at a constant rate, which is calculated from the ratio of the length and time scaling factors as shown in Table 4.2.

4.4 Experimental Results

The brittle sand layer thicknesses used in the experimental runs are 0.25 cm, 0.5 cm, and 1.0 cm whereas the ductile-layer thicknesses are 2 cm, 6 cm, and 8 cm, for a total of nine variations. The moving wall simulating the horizontal boundary induces an averaged strain rate of 10^{-6} s^{-1} , which scales to a strain rate of $\sim 10^{-15} \text{ s}^{-1}$ on Europa (Eq. 4.2). We run each experiment for 24 hours, resulting in $\sim 30\%$ total strain (Fig. 4.4). Prior to deformation, the surface of the analogue model is generally smooth with coffee grounds scattered on top to act as strain markers (Fig. 4.4, first row). Ridges, in both compression and extension, begin to emerge across the deformation region within the first 8 hours of the experiment, or around 10% strain (Fig. 4.4, second row). As deformation proceeds, the ridges become increasingly well-defined and closely spaced (Fig. 4.4, third and fourth row).

After the duration of the compressional experiment, we observe that the ridge traces

generated are linear to curvilinear, spaced regularly, bifurcated, and bounded by narrow troughs. The resulting morphologies of our compressional ridges agree well with results of similar experiments scaled for Earth (e.g., Dubey and Cobbold, 1977). Interestingly, the region proximal to the moving wall in the compressional experiments does not show any surface deformation. In the extensional experiments, the ridges (horsts) are wide with flat tops (Fig. 4.4) and the troughs (graben) between each ridge are wide and generally evenly spaced.

4.4.1 Varying Brittle Layer Thickness

The first variation we test in the experiments is different brittle layer thicknesses, while holding the ductile layer thickness constant at 2 cm. In the experiments with a compressional boundary condition, the wavelength of the resulting folds and the spacing of the resulting thrusts increase with the brittle-layer thickness (Figs. 4.5 and 4.6). The ridges that formed in such experiments display a square to rounded cross-sectional shape (Fig. 4.7). However, the emergence of the rounded geometry depends critically on the thickness of the ductile layer when the thickness of the brittle layer is fixed (see Section 4.4.2 below).

In the extensional experiments, the spacing of the resulting normal faults increases with brittle-layer thickness (Fig. 4.5 and 4.6). This result is consistent with the predictions of the infinitesimal-strain instability models (e.g., Fletcher and Hallet, 1983; Yin, 2000). However, we could not run the extensional experiments with a brittle layer thickness of 0.25 cm because the resulting structures are below a visible resolution (< 2 mm) and likely have strong influences from the grain size of the sand. None of the extensional experiments produce tilt blocks, possibly due to insufficient basal shear to create the detachment fault within the sand layer (e.g., Wainwright and Brun, 1999).

4.4.2 Varying Ductile Layer Thickness

We systematically change the ductile-layer thickness to determine its effect on surface structures. This set of experiments was motivated by the work of Stewart (1996) who proposed that the thickness of a ductile substrate determines whether folds or thrusts occur in the overlying brittle layer. Using a 2 cm thick layer of the putty places the experiments in the regime of mixed folds and thrusts according to the empirical relationship proposed by Stewart (1996) model (Fig. 4.8). Thus, this work not only assesses how ductile layers affect the surface development of ice-shell structures, but also will independently test the postulation by Stewart (1996).

The extensional experiments show that the surface morphology of the resulting structures does not change with the ductile-layer thickness. This indicates that even increasing the potential shear between the brittle layer and the ductile layer, does not produce enough shear to form the listric fault or decollement needed to produce tilt-block style extensional deformation. Therefore, we conclude that tilt-blocks cannot be formed under the conditions imposed by this experiment and will not form on Europa unless other deformational mechanisms are invoked (e.g., uplift or topographic induced sliding).

The compressional experiments, however, transition from thrust-dominated structures to fold-dominated structures as the ductile layer thickens (Figs. 4.9 and 4.10). This is accompanied by a change in the cross-section shape from asymmetric, to box-fold like, to a cylindrical syncline as the ductile layer thickens (Fig. 4.9). The spacing of the ridges decreases initially with increasing ductile-layer thickness (2 cm to 6 cm) and plateaus during the continued thickening (6 cm to 8 cm) (cf., Martinod and Davy, 1994)

4.5 Discussion

In addition to the morphological characteristics of ridged plains identified by Leonard et al., (2018), our newly generated topographic data (Fig. 4.2) show that individual ridges have amplitudes varying from 50 m to 80 m. Observed ridge flanks are symmetrical, with an average angle of 10-20° (Fig. 4.2). These particular ridges have a wavelength of 400-600 m. Erosion, via sputtering for example, of the ridges is thought to be negligible (e.g., Pappalardo et al., 1999) so this topography represents the formational state of the ridges. Therefore, from these values, we calculate the linear strain, $\varepsilon [\%] = 100 * \frac{L-L_0}{L_0}$ where L is the final length (half-wavelength of the ridge) and L_0 is the original length or ridge slope length. We find a compressional strain associated with the ridged plains formation of 3-7%. This is a first-order calculation because it assumes an original flat surface folded into a ridge that is triangular in cross-section, pure-shear shortening (perpendicular to the ridge), and does not consider other mechanisms (e.g., thickening, cleavage formation, etc.).

The thickness of the ductile layer has an effect on the resulting structures generated within the analogue model (Fig. 4.9). From our set of experiments, we generate a regime diagram (Fig. 4.10) indicating when folds (F) versus when thrusts (T) dominate the surface structures, as observed in cross-sections produced from each experiment. Increasing the ratio of the ductile-layer to brittle-layer thickness ratio changes the structural mechanism that results in the ridges, and it changes the cross-sectional shape (Fig. 4.9). As folding begins to dominate, the ridges become increasingly rounded in cross-section, which matches the observed morphology of ridged plains on Europa (Fig. 4.11; Table 4.3).

Because the observed morphology of ridges in the thick ductile layer compressional experiments more closely match the observations of ridged plains on Europa (Table 4.3; Fig. 4.11) when compared to the extension-generated ridges, we find that folding is likely the formation mechanism for the ridged plains. In particular, while the ridges generated in the extensional experiments can appear rounded in cross-section as the brittle layer thickness decreases, we interpret this as an effect of the grain size of the sand due to the scale of the ridges. Additionally, the extension experiments do not produce ridges with shallow slopes or narrow troughs, like the observed ridges in the ridged plains on Europa. Thus, we interpret the ridged plains to be formed through folding. In order for folding to dominate, we find that the brittle layer must be thinner than one sixteenth of the combined brittle-ductile layer thickness (Fig. 4.10). When scaled to Europa (Eq. 4.1), the result requires the corresponding brittle ice layer to be ~200 m thick and the total thickness of the ice shell to be greater than ~3000 m during the development of the ridged plains.

The linear strain produced in the physical analogue experiments under compression with a thick ductile layer (Fig. 4.9) is 4-9%, similar to that observed in the ridged plains. Note that the total shortening of the experimental materials consists of two components: (1) uniform shortening and accompanied layer thickening without surface folding (i.e., basic strain as described by Smith, 1975), and (2) shortening accommodated in folds generated from instabilities between the brittle and ductile layer (Smith, 1975). When compared against the observations, only the second component can be determined using the topographic profiles and assuming the ground surface before deformation was a flat plane. Therefore, it is likely that the folds generating the ridged plains on Europa require more than the observed strain from topography, as there was likely ductile layer thickening as well.

Folding as a possible mechanism of ridged plains formation has important implications for the evolution of Europa, as they are the oldest features on the icy moon and their history provides key information about the initial conditions of the latest global resurfacing event. For example, the fold origin requires compression dominates ice-shell tectonics at the onset of the resurfacing event. The current prevailing thought that the more recent ice deformation (e.g., band formation) is dominated by extension (e.g., Prockter et al., 2002; Prockter and Patterson, 2009) indicates that there must have been a transition time when the ice-shell deformation changed from compression to extension. We suggest that this change in the mode of deformation results from progressive cooling and thickening of the ice shell originated from a global ocean. Specifically, the early but brief volume contraction in the shallow part of the ice shell (Nimmo, 2004) leads to uniform contraction and folding; later and protracted volume expansion created the younger extensional structures. It is possible that the surface of the satellite had extensional and compressional tectonics operated simultaneously during the transition stage, which allows the high shortening strain expressed by the formation of the ridged plains to have been accommodated by local extension elsewhere. Alternatively, the strain produced during ice shell thickening (Nimmo, 2004) could be underestimated and further modelling efforts are required to understand the behavior of ice in these conditions.

The above hypothesis may be tested by the new data to be returned by the planned Europa Clipper mission (Phillips and Pappalardo, 2014). For instance, detecting the presence of a saltier layer in the near-surface of the ice-shell could indicate that the ice shell was thinner before re-freezing (Leonard and Howell, 2019). Additionally, high-resolution (< 50 m/pixel) images would allow for further characterization of the ridged plains at a global rather than local scale.

4.6 Conclusions

Comparing the observations of ridged plains on Europa to the surface structures generated by our analogue experiments, we find that the resulting ridge-trough systems in the compressional experiments match best the observed cross-sectional shape and map-view patterns of the structures. This result leads us to suggest that the ridged plains result from global cooling associated with an initial volumetric expansion of the ice crust at the onset of the latest resurface event starting at ~60 Ma. This is followed by ice-shell extension expressed by the formation of band structures. A major requirement for our model is that the last global resurfacing process started from the entire satellite covered by a global ocean, and its progressive cooling (and possibly with the perturbation of tidal stresses) has led to the three-state evolution of the surface structures on Europa. Our results imply that the initial brittle layer of the ice shell during the development of the ridged plains was ~200 m and the total ice-shell thickness is > 3000 m. This prediction is consistent with our proposed ice-shell thickening hypothesis as the current ice crust is likely 20-30 km thick (e.g. Pappalardo et al., 1999; Schenk, 2002) implying a likely brittle layer thickness >1 km (e.g., Carr et al, 1998; Nimmo and Manga, 2002; Nimmo and Schenk, 2006). Eventually, as the ice shell continued to thicken, extensional stresses dominate and ridged plains formation stops. If this were the case, we would expect to observe signatures of an ice-shell that has thickened through time with the data returned by the Europa Clipper mission.

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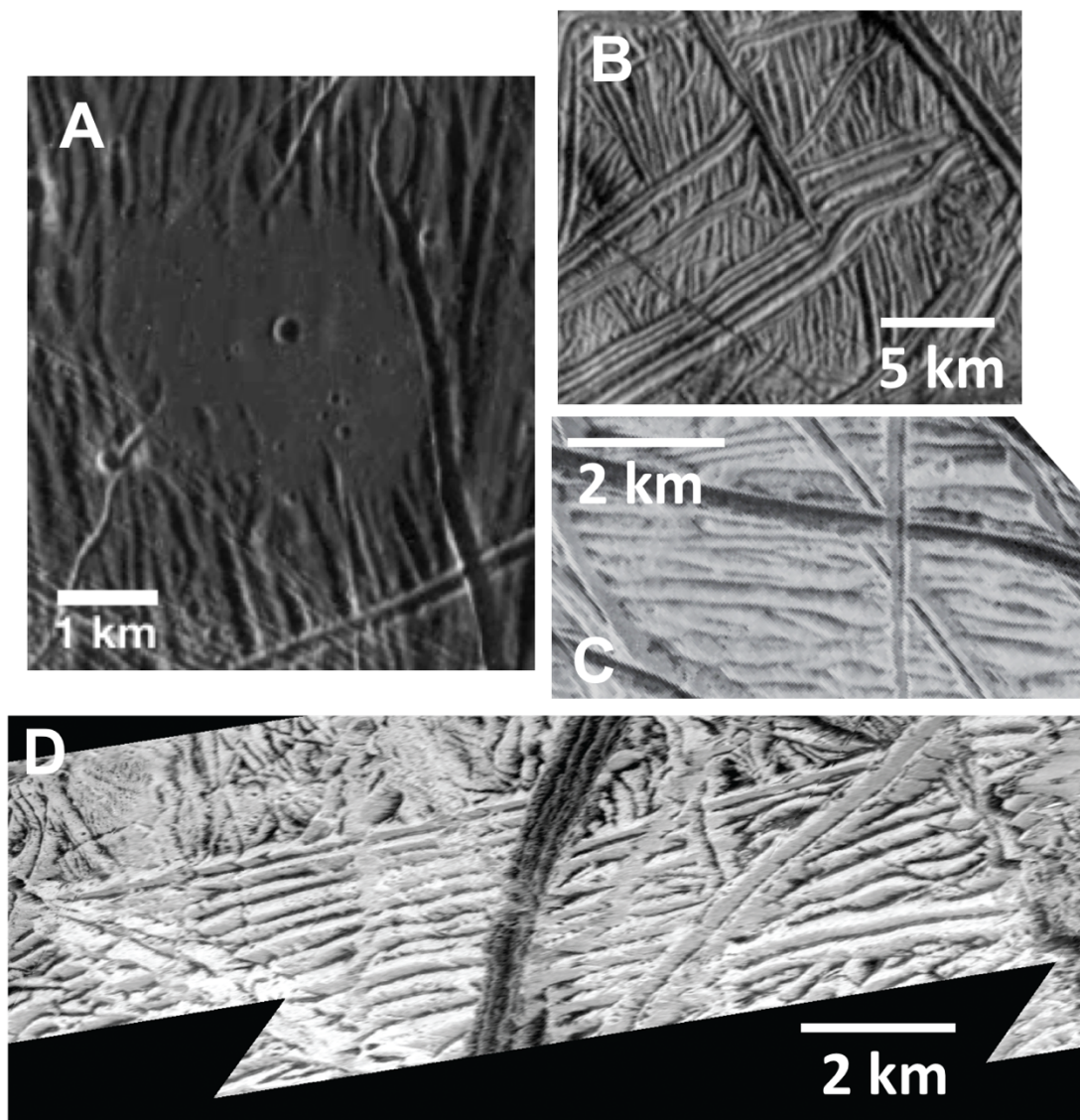


Figure 4.1 A variety of examples of ridged plains on Europa. Note the linear to curvilinear systematic ridge traces in all examples: (A) frame 5452 at 26 m/pixel from the Galileo E4 flyby of Europa, (B) frame 8700 at 66 m/pixel from the Galileo E19 flyby of Europa, (C) frame 2821 at 29 m/pixel from the Galileo E12 flyby of Europa, and (D) frames 2400-2405 at 16 m/pixel from the Galileo E12 flyby.

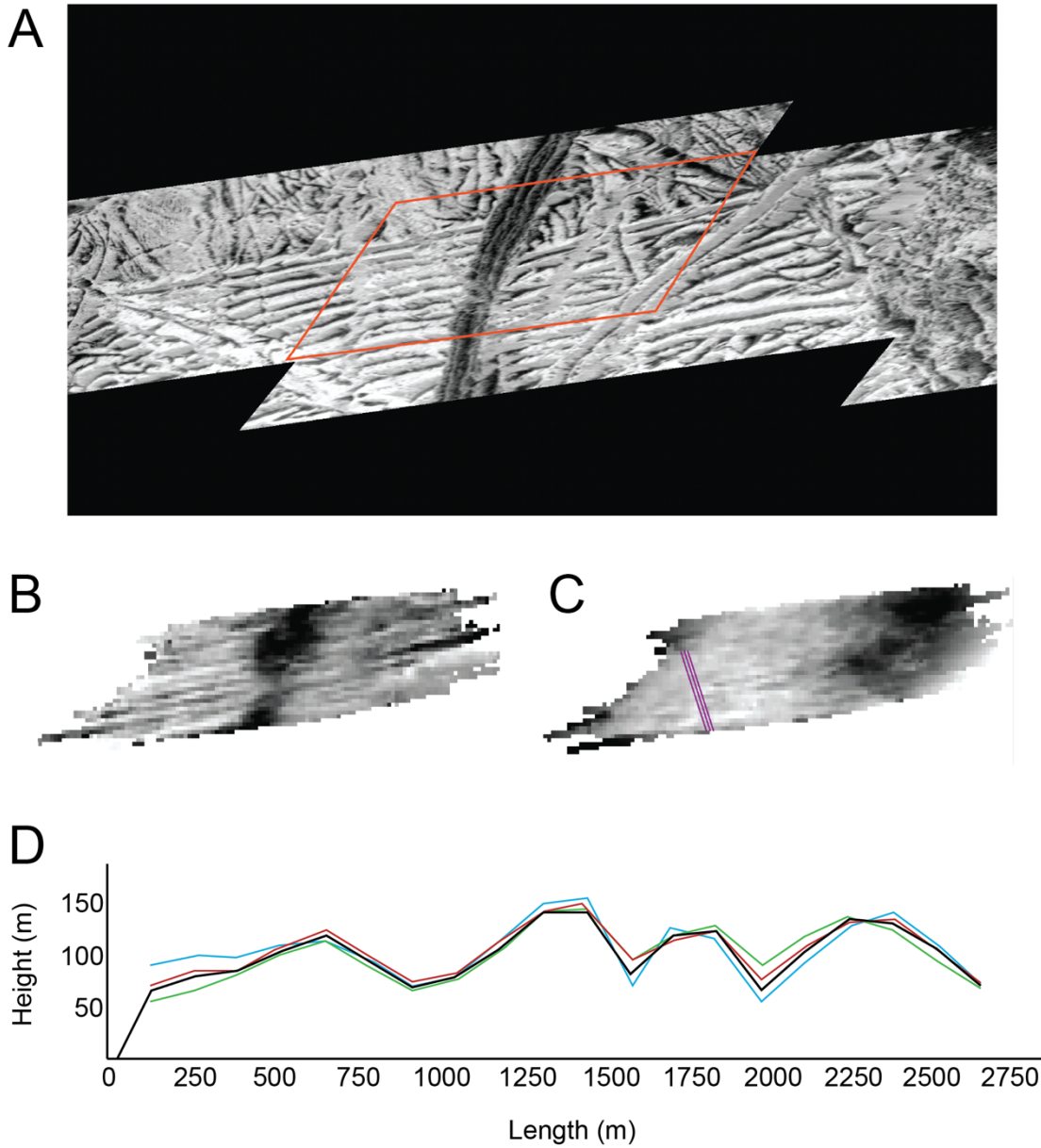


Figure 4.2 (A) Location of stereo-topography outlined in a red box, frames 2400-2405 from the Galileo E12 flyby. (B) Image overlain with topographic product. (C) Digital elevation model with lines indicating the approximate location of topographic profiles in (D) where white shades are topographically high and darker shades are topographically low. (D) displays the topographic profiles from (C) where the black line in is the average of the three topographic profiles.

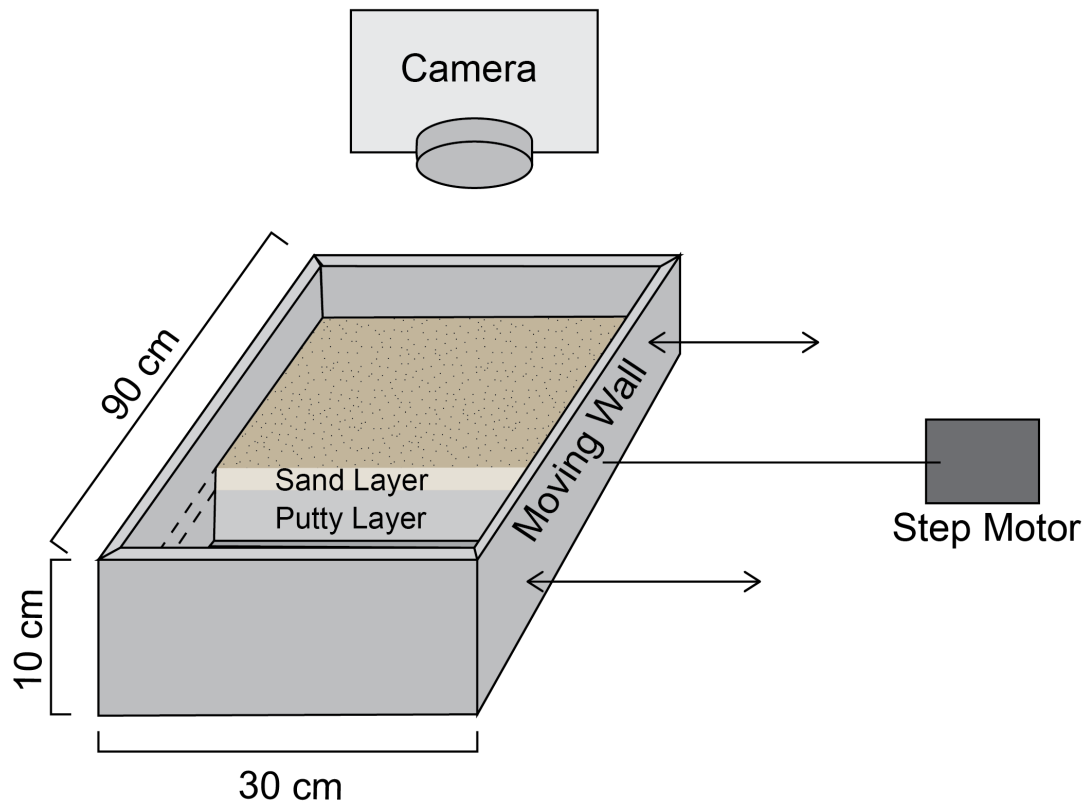
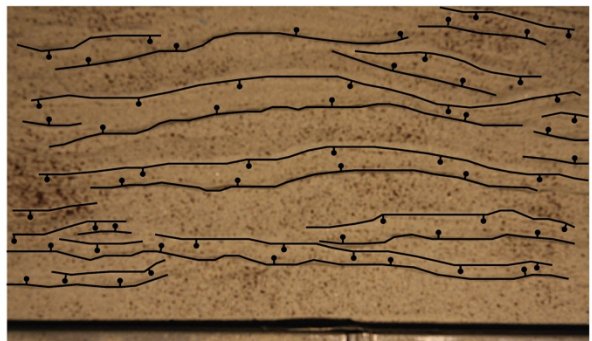
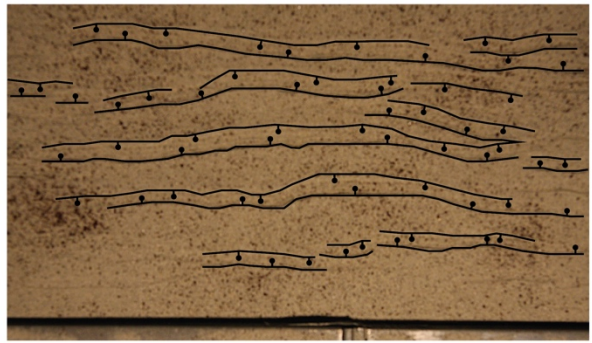
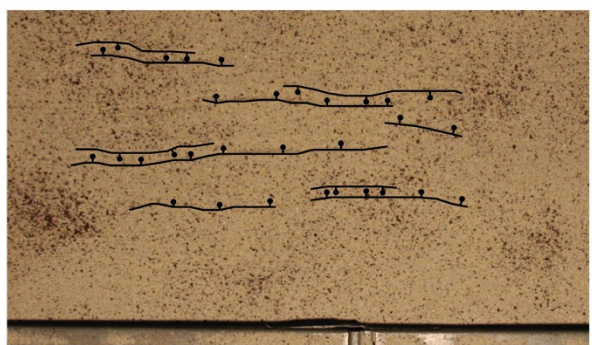


Figure 4.3 Schematic of the physical analogue model set-up. The moving wall on the right is controlled by a step-motor that we control using the LinControl computer software. The camera above the experimental set-up takes pictures of each experiment at 2-minute intervals.

Compression



Extension



See next page for full caption

Figure 4.4 Images and interpretations of compressional (0.5 cm brittle layer, 2 cm ductile layer) and extensional (1.0 cm brittle layer, 2 cm ductile layer) experiments over the course of 24-hour deformation period. The moving wall, which will compress or extend the experiment, is at the top of each image. The top row of images is the initial analogue model set-up, prior to any deformation. The second row is 8 hours into deformation. The third row is 16 hours into deformation. The last row is after 24 hours of deformation, at the end of the experiment period. Note how between the third and last row, the only significant difference is in the spacing of the resulting structures.

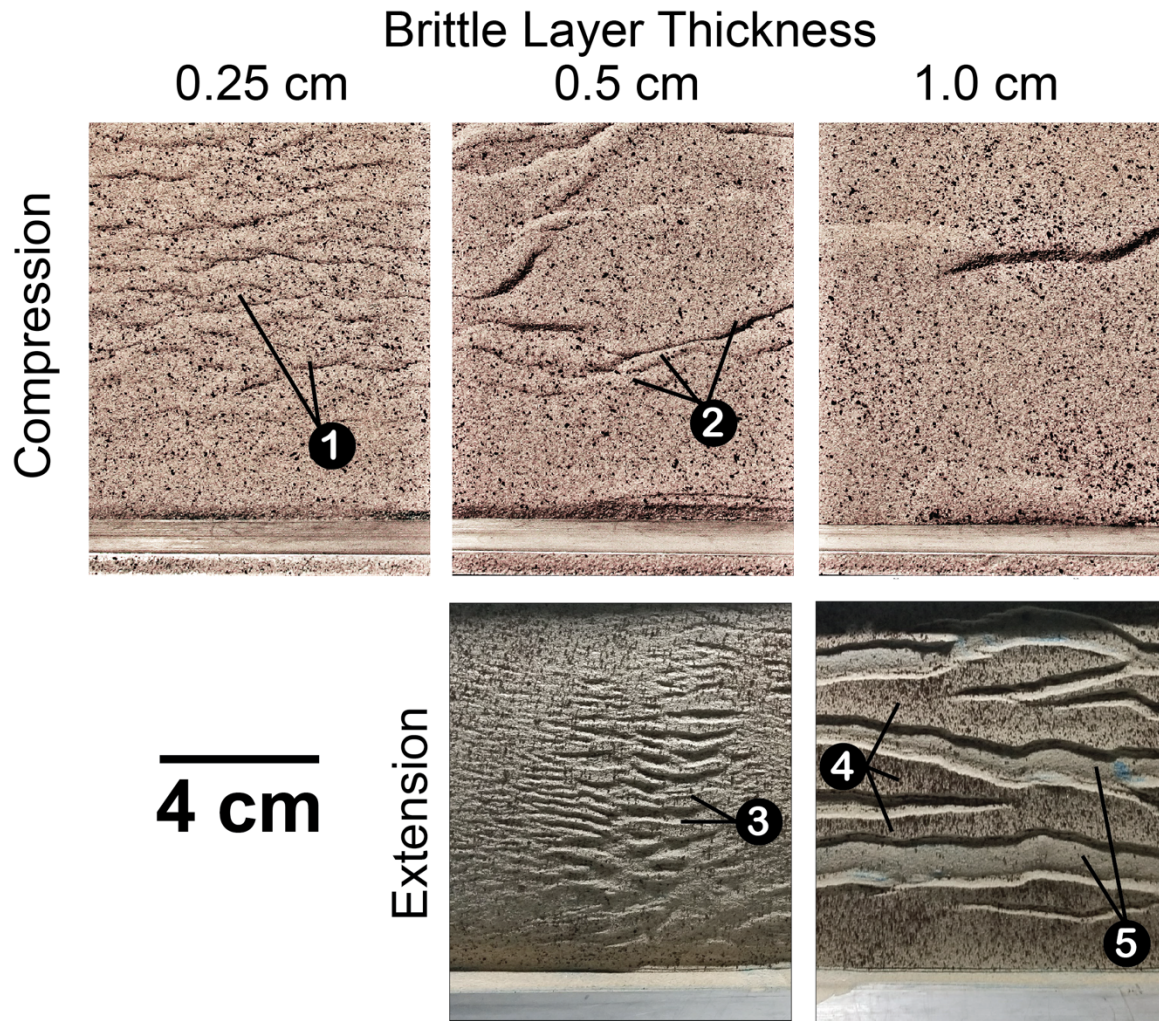


Figure 4.5 Experiment results with constant ductile layer thickness at 2 cm and varying brittle layer thickness of 0.25 cm, 0.5 cm, and 1.0 cm. The numbers indicate key features of the experimental results: (1) the rounded geometry of the compressional ridges, (2) the curvilinear trace of the features, (3) the steep slopes and flat-top geometry of the extensional ridges, (4) the horsts, and (5) the graben.

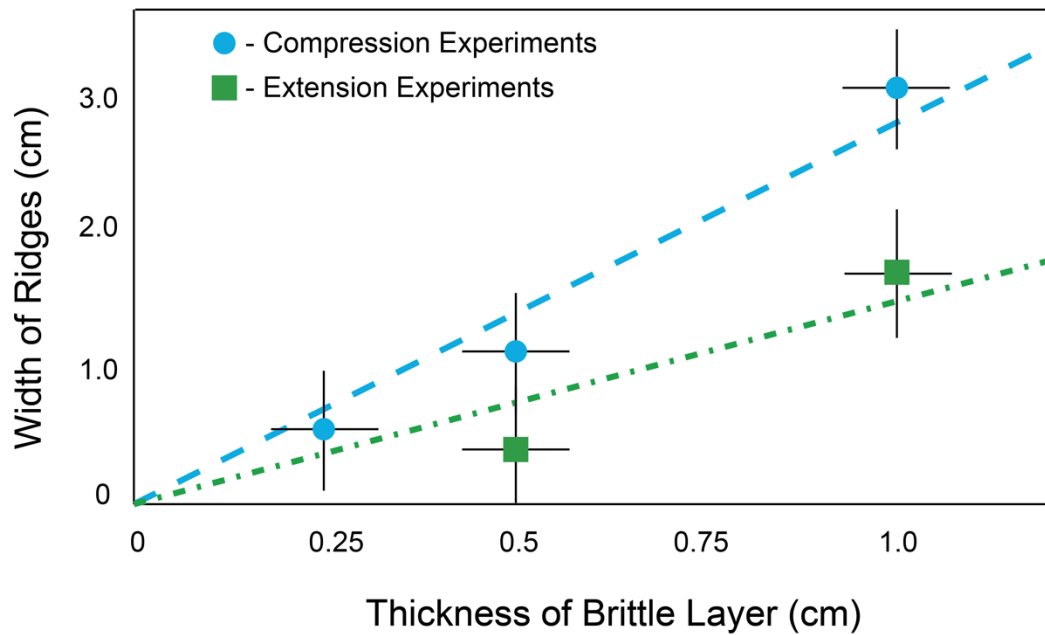


Figure 4.6 Graph of the experiment results showing how the width of ridges behaves with the thickness of the brittle layer. The blue circles are the data points from the compression experiments. The green squares are the data points from the extension experiments. There error bars are set at ± 0.5 cm to capture the varying widths of the ridges across a single experiment.

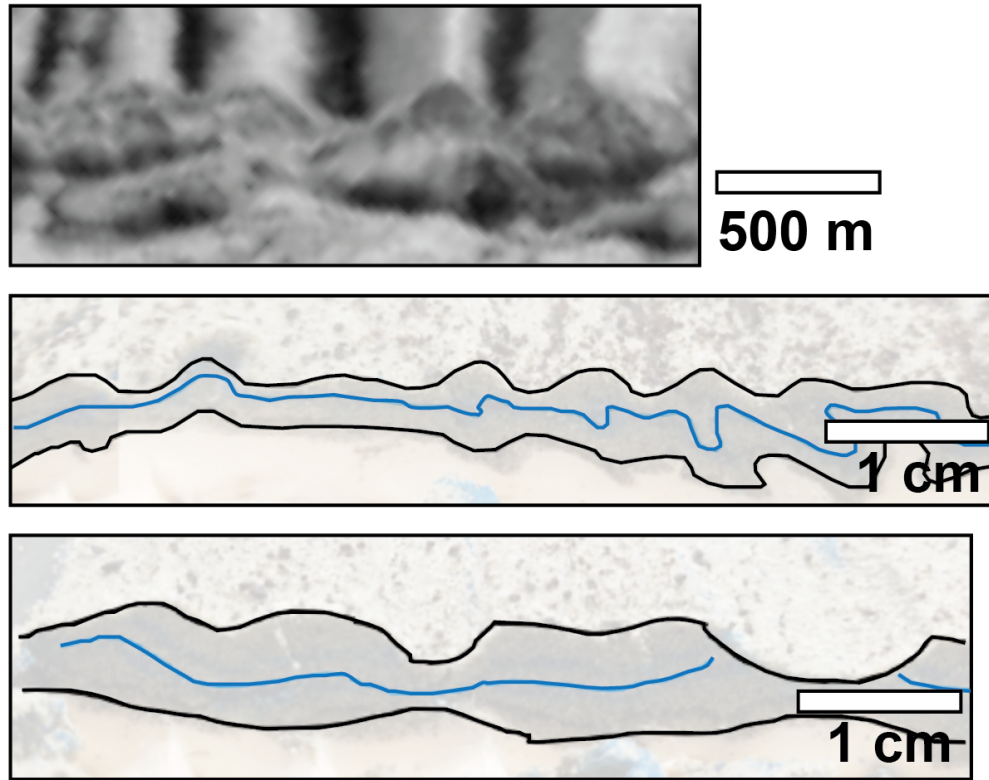


Figure 4.7 Experiment results compared to ridged plains terrain in cross-section view. The top panel is part of Frame 1989 from the E12 Mottle mosaic of the subparallel ridge-and-trough morphology of the ridged plains cut by a scarp so that we see the ridges in cross-section. The middle panel shows the cross-section of a compression experiment with 0.5 cm brittle layer and 8 cm ductile layer. The bottom panel shows the cross-section of an extensional experiment with 0.5 cm brittle layer and 2 cm ductile layer.

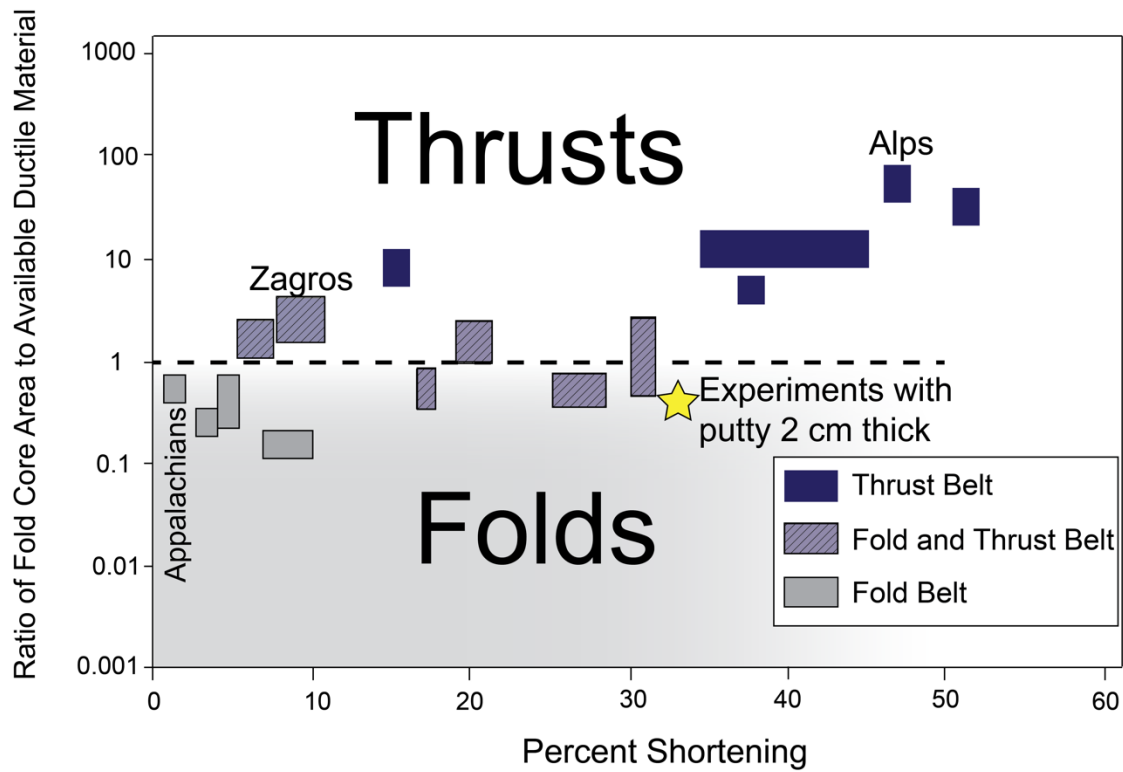
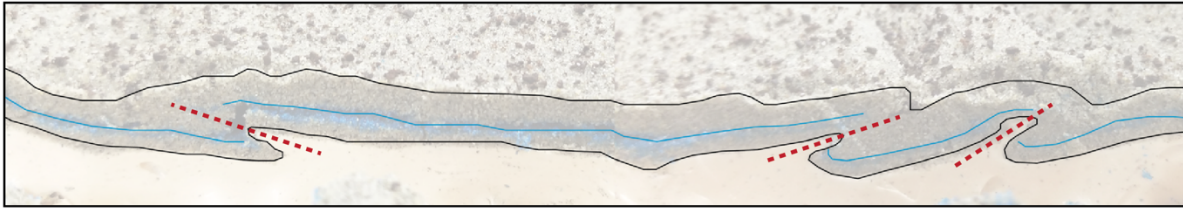


Figure 4.8. Modified from Stewart (1999), the regime diagram for the formation conditions for folds versus thrust faults. The yellow star shows where our experiments sit when the ductile layer is 2 cm thick. In theory, when we increase the ductile layer thickness (to 6 cm and 8 cm), the star would move down further into the folds regime resulting in more folds and less thrusts in our experiments.

0.25 cm Brittle Layer; 2 cm Ductile Layer



0.25 cm Brittle Layer; 6 cm Ductile Layer



0.25 cm Brittle Layer; 8 cm Ductile Layer



1 cm

Figure 4.9 Cross-sections of different compressional experiments with constant brittle layer thickness (0.5 cm) and varying ductile layer thickness (2 cm - top two boxes, 6 cm - third box, and 8 cm - bottom box). Note how the dominate ridge formation mechanism transitions from thrusting to folding as the ductile layer increases. The red dashed lines indicate the approximate location of a thrust fault.

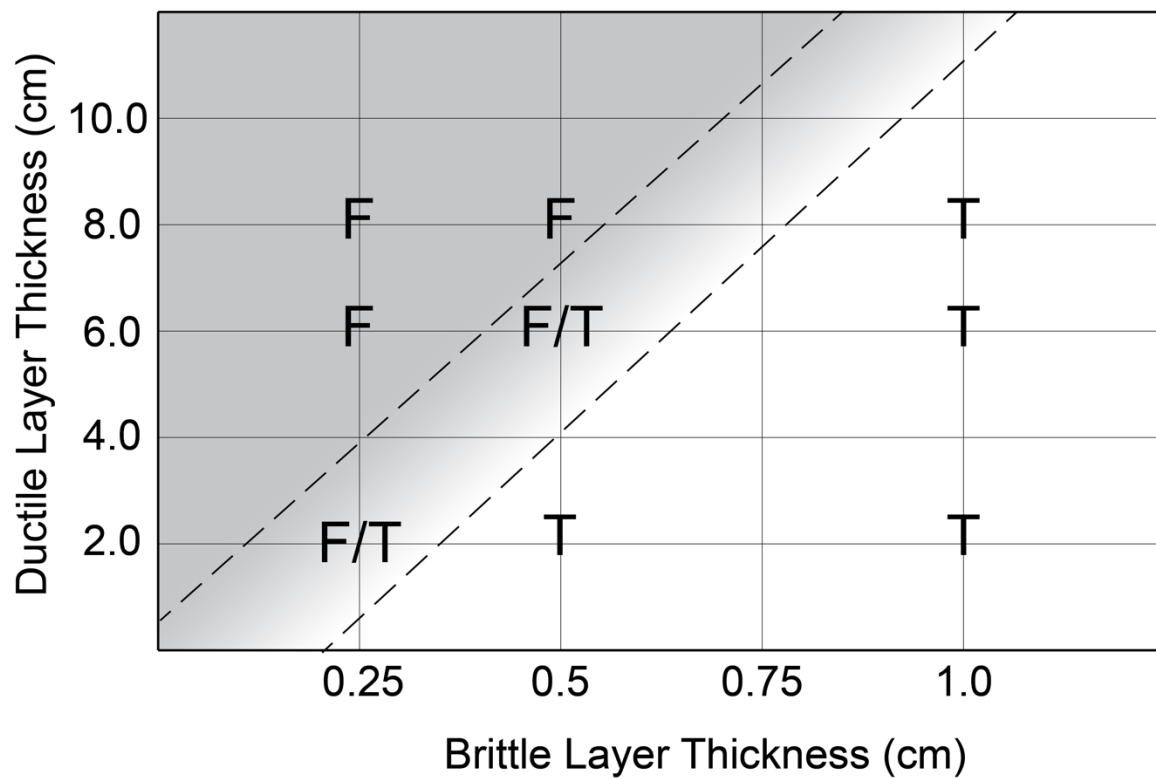


Figure 4.10 A regime diagram for our experiments showing where the brittle layer thickness to ductile layer thickness ratio will result in a transition from a thrust-dominated to fold-dominated environment.

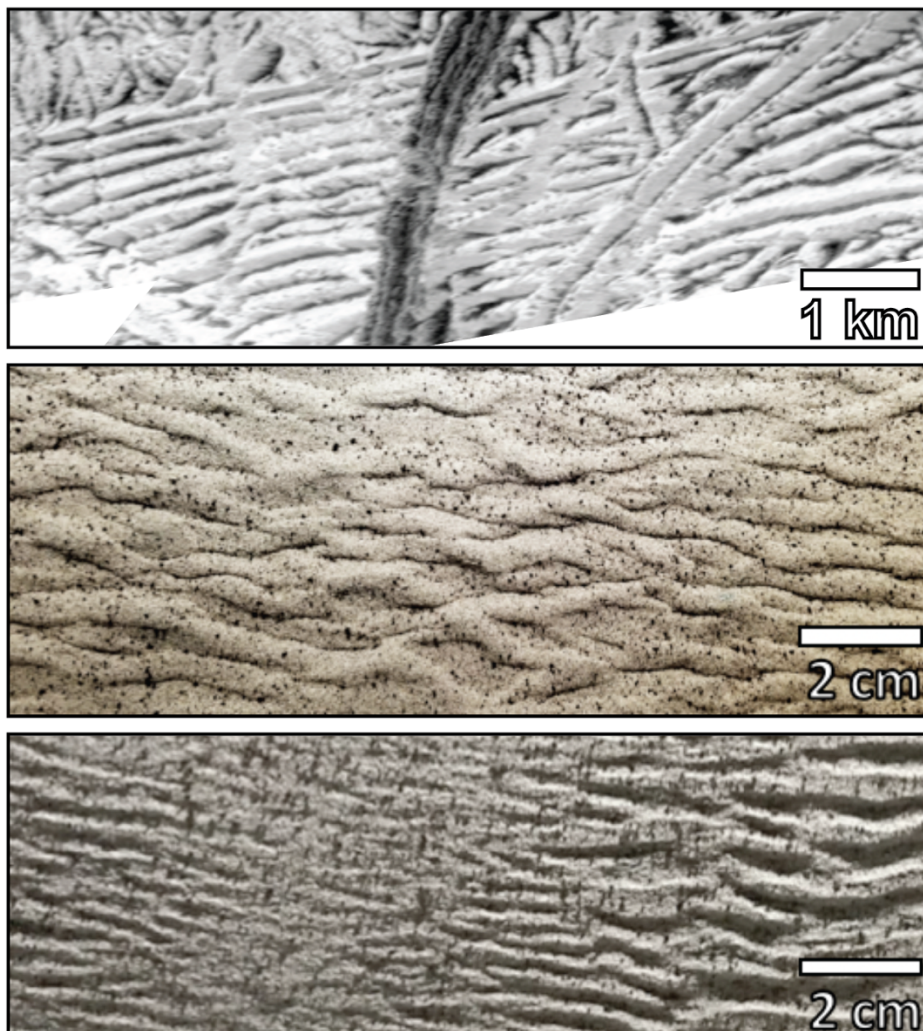


Figure 4.11 Experiment results compared to ridged plains terrain in map view. The top panel includes two frames (2400 and 2404) from the E12 Mottle mosaic of the subparallel ridge-and-trough morphology of the ridged plains. The middle panel shows the results of a compression experiment with 0.5 cm brittle layer and 8 cm ductile layer. The bottom panel shows the results of an extensional experiment with 0.5 cm brittle layer and 2 cm ductile layer.

Table 4.1: Comparison of *subparallel ridge-and-trough* formation mechanisms against observations in the high-resolution mosaic.

	Tilt-Blocks	Folds
Symmetric Ridges		
Shallow Slopes		
Linear or Curvilinear		
Can Bifurcate		
Systematic		

*Green indicates where theory satisfies the observation, and red indicates where it is unclear or not satisfied. Modified from Leonard et al. (2018)

Table 4.2: Material values for the analogue experiments, and Europa

Material Property**	Experiment Value	Europa Value*
Cohesion, C	60 Pa	10^6 Pa
Density, ρ	1700 kg/m ³	920 kg/m ³
Gravitational acceleration, g	9.8 m/s ²	1.31 m/s ²
Height Scale, h $\frac{h_{ice}}{h_{mod}} = \frac{C_{ice}}{C_{mod}} \cdot \frac{\rho_{mod}}{\rho_{ice}} \cdot \frac{g_{mod}}{g_{ice}}$	1 cm	2 km
Viscosity, μ (ductile)	10^4 Pa s	$10^{17} - 10^{18}$ Pa s
Time Scale, t $\frac{t_{ice}}{t_{mod}} = \frac{\mu_{ice}}{\mu_{mod}} \cdot \frac{C_{mod}}{C_{ice}}$	24 hours	10^6 years

*values found in: Beeman et al. (1988); Pappalardo et al. (1999); Prockter and Pappalardo (2000); Zuza et al. (2017)

**equations from Hubbert (1937) and Cruz et al. (2005)

Table 4.3: Europa Ridged Plains Observations Compared to Analogue Model Results

Analogue Model	Compression Experiments	Extension Experiments
Rounded in cross-section		
Linear to curvilinear along length		
Large length to width ratios (>10)		
Narrow troughs		
Shallow (<25°) slopes		
Quasi-symmetrical slopes		

4.7 References

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- Chapter 5 -

Past thermal state of Enceladus inferred from ice-shell deformation in the Leading Hemisphere

5.1 Abstract

The Leading Hemisphere Terrain (LHT) of Enceladus has experienced distributed deformation expressed by the pervasive development of >100 km wide and >100s km long ductile strike-slip shear zones and sparsely distributed craters. Within the zones are locally preserved little-deformed semirigid blocks up to 10-20 km in size with surfaces dominated by impact craters. The edges of these relic blocks display ductile drag folds and smeared tails of rigid fragments, which are indicative of vertical-axis rotation associated with ductile strike-slip shear. Kinematic analysis requires the development of the LHT to have been driven mainly by toroidal flow of the ice-shell material. Additionally, the structural mapping quantifies the shear strain magnitude. If the observed deformation occurred within 10 Ma and was induced by tidal stress, the estimated ice-shell viscosity—based on strain determination and the available age data—requires a high heat flux ($> 0.3 \text{ W/m}^2$) and a thin brittle layer ($< 1.5 \text{ km}$) during the development of the LHT.

5.2 Introduction

Enceladus, a small icy satellite of Saturn with a diameter of ~500 km, displays a wide range of morphologic features that include active linear fractures emitting vapor jets, curvilinear ridges interpreted as folds, isolated zones of linear to curvilinear tensile cracks, and heavily cratered regions that have not experienced significant tectonic deformation in the past ~4 Ga (Fig. 5.1; Porco et al., 2006; Spencer et al., 2009; Spencer and Nimmo, 2013; Crow-Willard and Pappalardo, 2015; Yin and Pappalardo, 2015). Recent research on the South Polar Terrain (SPT) of Enceladus has illuminated the mechanisms of active and recently active resurfacing processes (e.g., Mitri and Showman, 2008; Barr and Preuss, 2010; Patthoff and Kattenhorn, 2011; Han et al., 2012; Porco et al., 2014; Spitale et al., 2015; Yin and Pappalardo, 2015; Yin et al., 2016; Gall et al., 2017). However, it remains unclear if the same processes have operated in the geologic past in tectonically inactive regions such as the Leading Hemisphere Terrain (LHT) and Trailing Hemisphere Terrain (THT) (Fig. 5.1; Crow-Willard and Pappalardo, 2015). Specifically, if the resurfacing processes that formed the LHT and THT were dominated by resurfacing mechanisms similar to those currently acting on the SPT, it would require a cyclic evolution of the satellite possibly related to its orbital evolution around Saturn. Alternatively, if the resurfacing mechanisms differ drastically for the development of the three tectonized terrains on the icy satellite, a monotonic evolutionary trend possibly dictated by the history of the satellite could be deduced. It is with this motivation that we examine the deformation processes in regions outside the SPT where past geologic records are preserved and their implied mechanical and thermal states can be ascertained (e.g., Bland et al., 2007, 2012; Patthoff et al., 2015; Lucchetti et al., 2017; Martin et al., 2017). The focus of this study is to show from detailed photogeologic mapping that the LHT (Fig. 5.2a) has experienced distributed strike-slip ductile-shear

deformation that occurred possibly as early as ~ 10 Ma (Spencer and Nimmo, 2013; Crow-Willard and Pappalardo, 2015), soon before the formation of the SPT in the past few million years (e.g. Porco et al., 2006).

As shown below, our mapping efforts establish the structural relationships around little-deformed blocks in ductilely sheared domains of the LHT; the heavily cratered blocks, referred to as “crater islands” by Crow-Willard and Pappalardo (2015), are most likely to have been sheared off from the ancient Cratered Terrain (see Fig. 5.1). Furthermore, we use the morphologic features around the relic cratered blocks, such as curvilinear ridges and troughs, to deduce the structural origin and kinematic development of the isolated cratered blocks. The main result of our work is that the relic blocks have experienced vertical-axis rotation during distributed ductile strike-slip shear deformation (Fig. 5.2b). When combined with constraints on stress magnitude and deformation duration, we are able to use the estimated strain rates to determine the averaged viscosity of the ice shell during the inferred strike-slip deformation. The estimated viscosity is, in turn, used to assess the corresponding thermal state of the shear zone, which we then compare against the thermal regime across the active SPT.

5.3 Data and Methods

The photogeologic mapping methods in this work are similar to the approach presented in Yin and Pappalardo (2015) and Leonard et al. (2018) that consists of two steps: (1) document the attributes of major morphological features, and (2) relate the morphologies and spatial distribution to plausible deformation causes and strain paths. The details of the data sources and

the methods of mapping are briefly described below.

5.3.1 Data

We conducted our photogeologic mapping using a Cassini ISS mosaic product that is publicly available from United States Geological Survey (USGS) Astropedia (PDS Annex) at <astrogeology.usgs.gov>. The global mosaic used in Figure 1 and the photogeologic mapping has a spatial resolution of ~100 m/pixel. The images used in this mosaic have a spatial resolution between 50 m/pixel and 500 m/pixel and phase angles of $< 120^\circ$, in order to create consistency across the global mosaic. The region where we conducted photogeologic mapping in this work (Fig. 5.2a) is taken from a portion of the global mosaic.

5.3.2 Methods

We perform photogeologic mapping in the southern LHT region (Fig. 5.2a) in order to investigate the structural origin and kinematic evolution of the region. The features are mapped based on the morphologic appearance interpretable from the satellite images such as cross-sectional geometry of ridges and troughs, surface textures, and landform shapes. Assuming negligible erosion and deposition after the formation of the mapped morphologic features and assuming their origins were induced only by ice-shell deformation, we are able to use the tectonic-geomorphology mapping methods (e.g., Burbank and Anderson, 2009) to relate the mapped landform features to assign a structural origin and the related kinematic evolution of a mapped feature (Table 5.1). Observationally, we identify four main types of morphological units (Fig. 5.3): (1) sharp-crest ridges (Figs. 5.3a and 5.3b), (2) round-top ridges (Figs. 5.3c and 5.3d), (3) troughs (Figs. 5.3e and 5.3f), and (4) craters (Fig. 5.3g). We further divide the ridge and

trough units into “major” (> 2 km in width) and “minor” (< 2 km in width) subunits. The few craters mapped in the study area have diameters generally < 10 km and are concentrated exclusively on the surfaces of the relatively undeformed relic blocks.

5.4 Structural Origin and Kinematic Evolution of Morphological Units

In contrast to the development of parallel strike-slip and/or tensile fractures in the SPT (e.g., Porco et al., 2006; Patthoff and Kattenhorn, 2011; Yin and Pappalardo, 2015; Yin et al., 2016), the Leading Hemisphere Terrain of Enceladus is dominated by zones of narrow ($< a$ few km in width) but long (> 10 s to 100 s km) curvilinear ridges and troughs (Fig. 5.1 and 5.2). The ridges—locally affected by sparsely distributed impact craters—merge, diverge, and surround semi-square and semi-elliptical blocks which are heavily cratered on the surface (Fig. 5.2b). We illuminate the structural relationships among curvilinear ridges/troughs and the little deformed relic blocks through detailed systematic mapping. The results are displayed in Fig. 5.2b.

5.4.1 Structural Interpretations

Correlation between the observed morphologic features and their structural interpretations are listed in Table 5.1. The structural interpretations provided below assume that deposition and erosion have not altered significantly the surface shape of the mapped morphologic features (i.e., the shape of the observed morphological feature can still be related to its structural origin). This assumption is reasonable given the range of estimated sublimation rates of water ice in the Saturnian system in general and the low deposition rates for regions away from the South Polar Terrain on Enceladus in particular (e.g., Sieveka and Johnson, 1982; Prockter et al., 2000; Prockter et al., 2002; Patterson et al., 2010; Spencer and Nimmo, 2013; Yin and Pappalardo,

2015; Leonard et al., 2018). Research based on Cassini data indicates that space weathering, another possible modifier of the surface morphology, is also negligible at Enceladus (e.g., Paranicas et al., 2012). Additionally, we do not observe any evidence of post-emplacement relaxation or downslope mass wasting, which could affect the original shape of mapped morphological features after their formation (e.g., Moore et al., 1999; Moore et al., 2009). Our structural analysis allows us to recognize the following key geologic features (Table 5.1): (1) tensile cracks that are expressed as linear and narrow troughs bounded by steep walls with a v-shaped cross-section geometry, (2) normal faults characterized by sharp-crested ridges flanked with asymmetric slopes; (3) thrust faults that are closely associated with irregular or discontinuous ridges and have both linear to curvilinear traces, and (4) folds that are ridges with either circular and box-like cross-section geometry.

5.4.2 Kinematic Interpretations

Structural mapping (Fig. 5.2b) suggests that except the late north-trending tensile cracks on the east side of the mapped area, all the morphological features dominated by curvilinear ridges and troughs were generated during a single episode of deformation. This is indicated by the absence of offsets and cross-cutting relationships of the geologic structures having different orientations and morphological expressions. Instead, we find that ridges and troughs are merging, diverging, and even folded concordantly (Fig. 5.2b). Based on these observations, we suggest that the mapped features are parts of a single structural system generated by distributed left-slip shear deformation. Left-slip shear deformation is indicated by the presence of giant sigma-clasts (Fig. 5.4a), en echelon folds (Fig. 5.4b), rotation of ridges towards a relic block indicating the sense of block rotation (Fig. 5.4c), and trains of asymmetric drag folds within

shear zones (Fig. 5.4d). The giant sigma clasts are expressed by the shapes of the relic blocks, which are analogous to semi-brittle sigma clasts in ductile shear zones on Earth (Simpson and Schmid, 1983; Passchier and Simpson, 1986; Passchier, 1994). The sigma clast tails are most apparent for the easternmost block in the study area (Fig. 5.4a). The strain-shadow regions of the rotated blocks created local extension, which in turn caused inward warping of foliation and progressive tightening of folds towards the rotated block (Fig. 5.4c). The *en echelon* folds (Fig. 5.4b) and the asymmetric folds (Fig. 5.4d) indicate the left-lateral sense of shear. The kinematic development of the distributed left-slip shear zone is conceptualized in Fig. 5.5. Specifically, it illustrates how the coherent cratered terrain was broken up by shear zones, the development of asymmetric folds, and the formation of foliation. These processes were responsible for erasing the craters in ductilely deformed regions surrounding the little deformed relic blocks of the Cratered Terrain.

5.5 Quantitative Model and Results

In this section, we quantify our observations in the context of rheology and thermal state of Enceladus's ice shell during the deformation of the Leading Hemisphere Terrain. We estimate the average viscosity, heat flux, and the thickness of the ice shell of our study area assuming a Newtonian rheology and using the finite strain estimated from the rotated relic blocks. Following Fossen and Cavalcante (2017), the strain measured from the rotated blocks can be obtained by

$$\varepsilon = \cot(\alpha_0) - \cot(\alpha) , \quad (5.1)$$

where α_0 is the initial orientation of the rotated blocks, α is the final orientation of the rotated blocks, and ε is the strain. We assume that the deformation is homogeneous, which implies that

the rotation angle can be derived from a passive marker—in this case, deflected ridges in the stress shadow region. This angle ranges from 30-45°. From the original 15° orientation of the ridges (see Fig. 5.5), to rotate the blocks an additional 30° implies a total 70° of shear, resulting in a strain of ~2.8 (Fig. 5.4).

In order to estimate the average strain rate associated with the development of the studied shear zone, we need to know the duration of deformation. The crater-based age for the development of the Leading Hemisphere Terrain is estimated to be ~10 Ma (Spencer and Nimmo, 2013; Crow-Willard and Pappalardo, 2015). Because the region lacks deformed craters which are apparent in other regions on Enceladus, it is possible that the duration of formation is less than the age of the terrain. However, we assume that the duration of formation to be 10 Ma in order to obtain a conservative estimate for the strain rate (see Section 5.6 for discussion on relaxing this assumption). Assuming Newtonian fluid behavior for the ice shell, this duration allows us to estimate the average viscosity of the shear zone, η , from the following relationship:

$$\eta = \frac{\sigma}{\dot{\epsilon}} = \frac{\sigma \Delta t}{\epsilon} \quad (5.2)$$

where η is the viscosity of the shear zone surrounding the rigid clasts, σ is the average shear stress, Δt is the duration of shear zone formation, $\dot{\epsilon}$ is the average strain rate, and ϵ is the total shear strain as calculated in Eq. 5.1. The shear stress magnitude is estimated to be between 10 kPa and 100 kPa, which is considered to be the plastic strength of the ice shell of Enceladus (e.g., O'Neill and Nimmo, 2010) and the maximum stress generated by warm-ice convection, diurnal tides, and gravitational spreading of uneven ice-shell thickness under thermal perturbation (e.g., Hurford et al., 2007; Smith-Konter and Pappalardo, 2008, O'Neill and Nimmo, 2010; Yin et al.,

2016). We list all the model parameters in Table 5.2.

In order to calculate the heat flux during the development of the shear zone, we adopted the approach by Bland et al. (2015) that relates the average ice-shell temperature T_{int} to the average ice-shell viscosity by the following relationship (Fig. 5.6):

$$T_{int} = \frac{T_{bot}}{\left(\frac{RT_{bot}}{E} \ln\left(\frac{\eta}{\eta_{bot}}\right) + 1\right)} \quad (5.3)$$

Here, R is gas constant, E is the activation energy, T_{bot} is the temperature at the base of the deforming layer, and η_{bot} is the viscosity of the base of the conductive and brittlely deforming ice shell. As brittle-ductile transition occurs when the ice viscosity is in the range of 10^{13} - 10^{17} Pa s (Poirier, 1982), we assign $T_{bot} = 10^{15}$ Pa s in our calculation (see Table 5.2).

The presence of both ductilely deformed ice expressed as curvilinear ridges and brittlely deformed relic blocks indicates that stress in the shear zone has a magnitude that is capable of driving coeval ductile and brittle deformation. In other words, the viscous and frictional stress must be continuous across the edge of the relic blocks. The vertically averaged frictional stress, σ_f can be estimated by:

$$\sigma_f = \frac{1}{z} \int_0^z (\mu \rho g z) dz = \frac{1}{2} \mu \rho g z, \quad (5.4)$$

where z is the brittle ice thickness (see Fig. 5.6), μ is the frictional coefficient for ice, ρ is the density, and g is the gravitational acceleration on Enceladus. The Newtonian viscous shear stress can be expressed as $\sigma_v = \eta \dot{\epsilon}$. Equating σ_f to σ_v allows to estimate the ice-shell thickness by

$$z = \frac{2\sigma_v}{\mu \rho g}. \quad (5.5)$$

Using an experimentally determined value of friction coefficient of $\mu \sim 0.5$ for ice (Dempsey et al., 1999; Dempsey, 2000; Schulson and Fortt, 2012) and assuming that σ_v is on the order of 10-

100 kPa, we find that $z = 0.15$ to 1.5 km.

From the average temperature obtained from Eq. 5.3 and the ice-shell thickness determined in Eq. 5.5, we obtain the heat flux F during the shear-zone development from the following relationship after Petrenko and Whitworth (1999):

$$F = \frac{k\Delta T}{z} \ln\left(\frac{T_{int}}{T_{surf}}\right), \quad (5.6)$$

where k is the thermal conductivity, T_{surf} is the temperature of the surface, T_{int} is the average temperature of the ice shell, and $\Delta T = T_{surf} - T_{int}$. This calculation assumes a constant thermal conductivity throughout the deforming ice shell.

We can then solve for the heat flux from Eq. 5.6 by taking the surface temperature, T_{surf} , to be ~ 70 K. We calculate the layer thickness $z \sim 0.15 - 1.5$ km resulting in a heat flux from the surface of $0.8 - 6.9$ W/m², depending on the magnitude of stress invoked.

5.6 Discussion

The formation of the relic cratered terrain in a regional left-lateral shear zone has implications for the evolution of Enceladus including past heating events, or episodic resurfacing, and global tectonics. From the calculated ice viscosity and brittle layer thickness (Table 5.2), we can infer the heat flux in this region when the structures formed, or the paleo-heat flux. Additionally, from a global perspective, we hypothesize that the regional left-lateral

shear zone may extend around the Leading Hemisphere of Enceladus, possibly indicative of a hemispheric scale toroidal flow.

5.6.1 Paleo-heat Flux

Based on our calculations, the relic cratered terrain formed at a time when the heat flux measured from the surface was $>0.8 \text{ W/m}^2$, depending on the magnitude of stress invoked (Fig. 5.7). This is greater than the heat flux measured at the SPT today, $0.15 - 0.24 \text{ W/m}^2$ (Spencer et al., 2009; Howett et al., 2011; Spencer and Nimmo, 2013), the range of paleo-heat fluxes ($0.1 - 0.27+ \text{ W/m}^2$) calculated by previous work in other places on Enceladus (Bland et al., 2007, 2012; Giese et al., 2008), and that is predicted by resurfacing models (e.g., O'Neill and Nimmo, 2010; Barr and Hammond, 2014) (Fig. 5.7). The mechanisms to produce the heat flux emitting from the SPT today are debated (e.g., Mitri and Showman, 2008; Roberts and Nimmo, 2008; O'Neill and Nimmo, 2010; Behoukova et al., 2012; Shoji et al., 2013), and cannot easily reproduce the heat flux observed there, let alone be invoked for the higher heat fluxes we calculate in the leading hemisphere. Thus, while it appears that the observations and calculations in this study as well as other recent studies (e.g., Bland et al., 2007, 2012; Giese et al., 2008) find that even more heat flux than is currently observed in the SPT was required in the past, it is difficult to justify without a mechanism to produce the currently observed heat flux measured in the SPT.

We can constrain the maximum duration of formation to be, at most, the approximate age of the LHT. However, we can also look at the case of relaxing the assumption that deformed craters should be present in a surface that deformed slower than its surface age. Based on observations by other work, the LHT is younger than the THT (Crow-Willard and Pappalardo, 2015). Therefore, we know that the LHT cannot have a shorter duration of formation than the total age

of the THT, estimated by crater counting statistics to be < 2 Ga (Kirkoff and Schenk, 2009). In this relaxed version of the calculation, the age and therefore the duration of formation we use is an extreme upper limit, which results in a minimum possible heat flux. Implementing a duration of formation of ~ 2 Ga results in a calculated minimum heat flux of $0.6 - 5.1 \text{ W/m}^2$, depending on the stress value invoked. Increasing the duration of formation even to the age of the satellite (~ 4 Ga) would not decrease the calculated heat flux more than a factor of two. Thus, our calculated heat flux is robust to increasing the duration of formation, as it does not fall below what is currently observed in the SPT, and the high value must be explained in another way.

If we constrain the paleo-heat flux to a thermal event of a similar magnitude to what is occurring in the South Polar Terrain today (Spencer et al., 2009), we require a layer of regolith to insulate the surface and raise the effective surface temperature to $\sim 110\text{K}$ (Fig. 5.7). The presence of a regolith layer, or a low conductivity porous layer, has been suggested previously (Squyres et al., 1983; Bland et al., 2012; Martin et al., 2017) to lower the required heat flux for relaxing landforms on the surface of Enceladus and to explain the presence of pit chains. In order to obtain a heat flux similar to what is observed in the SPT today and still produce the observed relic cratered terrain features, the low conductivity layer must be 1-10 m thick (following Bland et al., 2012) and the duration of formation must be ~ 2 Ga. This regolith layer could be a result of porous plume deposits blanketing the surface, though the current plume orientations do not favor this (Kempf et al., 2010) as the modeled deposition over 10 Ma is negligible. If the plumes have been sustained in the current orientation over the past ~ 2 Ga, a layer of ~ 2 m of plume fallout (Kempf et al., 2010) may have accumulated. Though, it is unclear if the lifetime of the plumes could be this long or maintain the current orientation.

The leading hemisphere as a whole has an anomaly in microwave emission at around 3.88

microns (Ries and Janssen, 2015). The microwave emission indicates an anomaly at a shallow, 1-5 m, depth interpreted to be due to the young age of the terrain and thus lack of micrometeorite bombardment (Ries and Janssen, 2015). This seems coincident with our prediction for the presence of regolith or, at least, the presence of a layer of low thermal conductivity near the surface.

5.6.2 Hemispheric-scale Toroidal Flow

Incorporating the idea that the southern leading hemisphere formed in response to a left-lateral shear zone into the broader global context, we propose that the leading hemisphere has experienced toroidal flow. Hemispheric clockwise toroidal flow could be responsible for the southern left lateral shear zone and the apparent circular feature that dominates the hemisphere (Fig. 5.1). The plausibility of this large-scale toroidal flow could be investigated further with future detailed mapping of the remainder of the leading hemisphere. There is new evidence suggesting that the SPT could have also formed under this sort of toroidal flow (Schoenfeld and Yin, 2018), but the work is preliminary. The source of the potential toroidal flow is unknown but could be related to the orbital mechanics of the moon and the dissipation of energy into the ice shell and ocean.

5.7 Conclusions

Based on our calculations, to obtain the heat flux measured today ($\sim 0.3 \text{ W/m}^2$) at the South Polar Terrain, the surface must be insulated to create an effective surface temperature of $\sim 110 \text{ K}$ and the duration of formation must be $\sim 2 \text{ Ga}$. However, we propose that the resurfacing event that formed the Leading Hemisphere terrain resulted in a heat flux of $> 0.8 \text{ W/m}^2$, due to the

apparent intensity of tectonic activity and the amount of shear as evidenced by the relic cratered terrain and the inferred shorter duration of formation (~ 10 Ma). This apparent heat flux could be reduced if the effective surface temperature is increased by adding a layer of insulating material ~ 1 -10 m thick. The orientation of the shear zone and its apparent continuation around the remainder of the Leading Hemisphere may indicate that it was driven by clockwise toroidal flow in the ductile subsurface ice. The origin of this hemispheric-scale flow is beyond the scope of this work, and its plausibility could be explored further in future detailed mapping of the entire LHT and physical analogue modeling work. However, this high-heat, ductile resurfacing event has implications for the formation of the SPT, the episodic nature of Enceladus resurfacing, and the dynamics and rheology of the ice shell.

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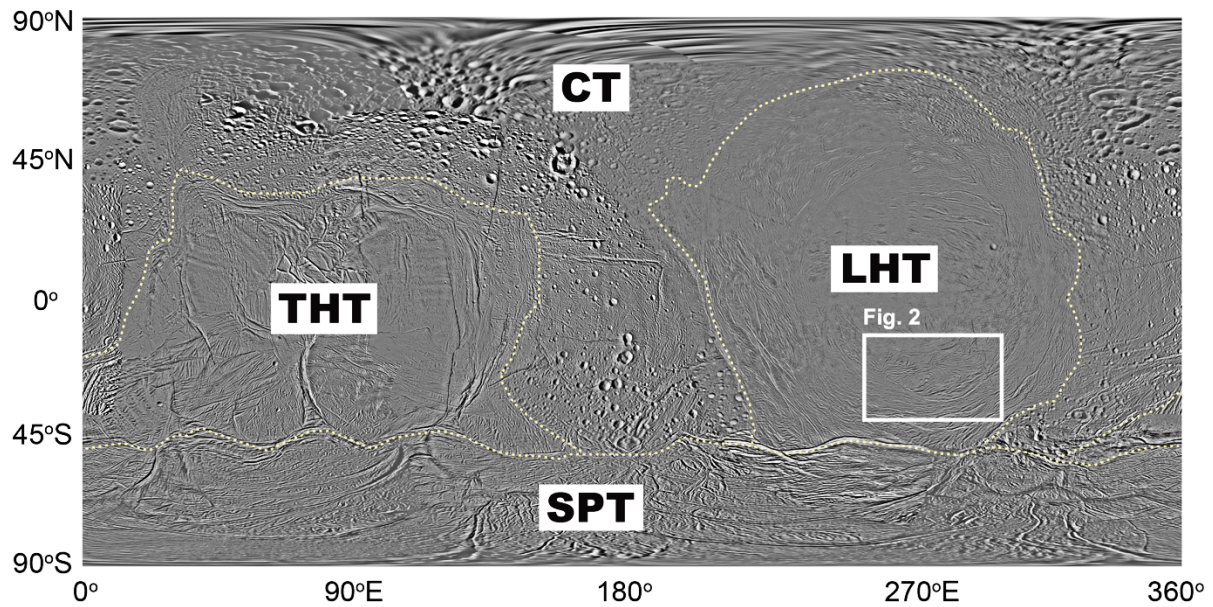
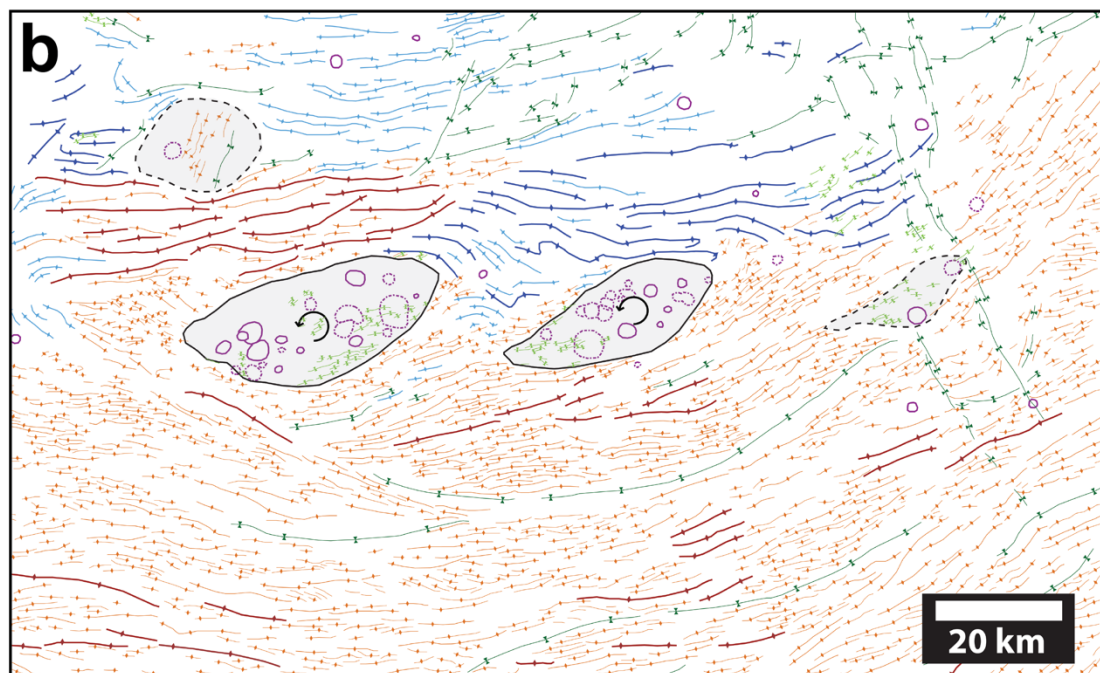
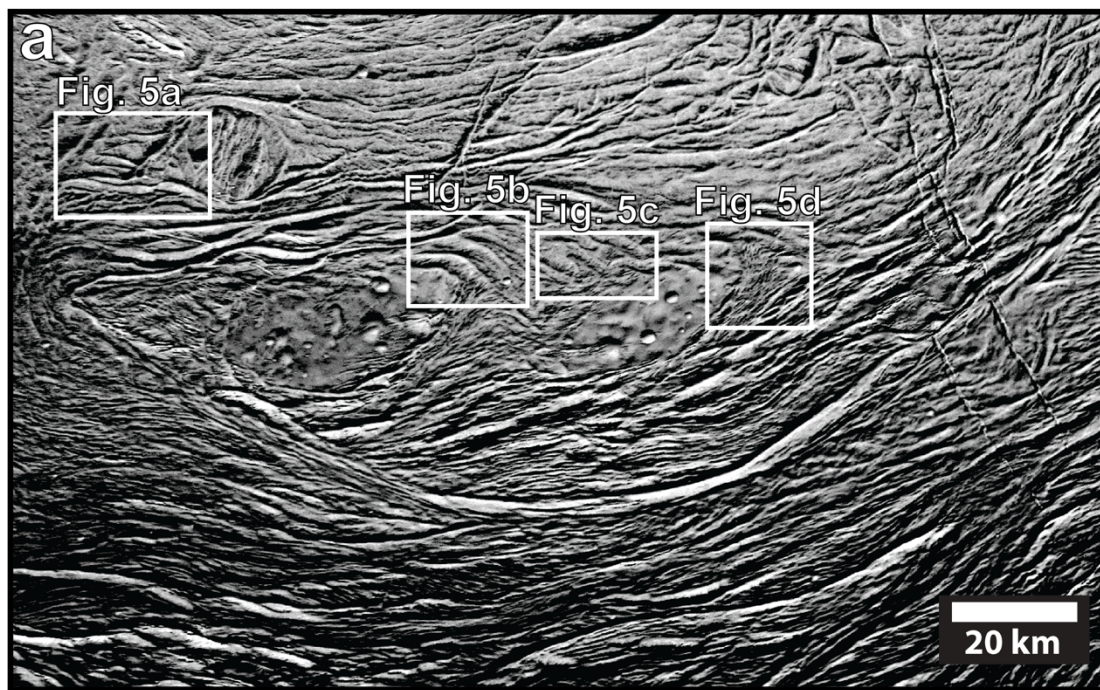


Figure 5.1 Global map of Enceladus in cylindrical projection and base map for geologic mapping (see text for the source of the image mosaic). The globe is divided into four general terrains after Crow-Willard and Pappalardo (2015): CT, Cratered Terrain; SPT, South Polar Terrain; THT, Trailing Hemisphere Terrain; LHT, Leading Hemisphere Terrain. The white box indicates the location of Fig. 5.2.



- | | |
|--|---------------------------|
| — Sharp-crested ridges, major (>2 km wide) | ○ Crater |
| — Sharp-crested ridges, minor (<2 km wide) | ○ Possible Crater |
| — Rounded-top ridges, major (>2 km wide) | ◻ Cratered Block |
| — Rounded-top ridges, minor (<2 km wide) | ◻ Possible Cratered Block |
| — Troughs, major (>2 km wide) | |
| — Troughs, minor (<2 km wide) | |

Figure 5.2. See next page for full caption

Figure 5.2. Image mosaic (a) of the region in the southern leading hemisphere of Enceladus that we map. The location of this image is indicated by the white box in Figure 5.1 and the location of Figs. 5.5a-d are shown by the white boxes. A structural map (b) of region in Fig. 5.2a highlighting the types of ridges and the extent of the relic cratered terrain. Note how the craters (purple) are concentrated on the relic cratered blocks.

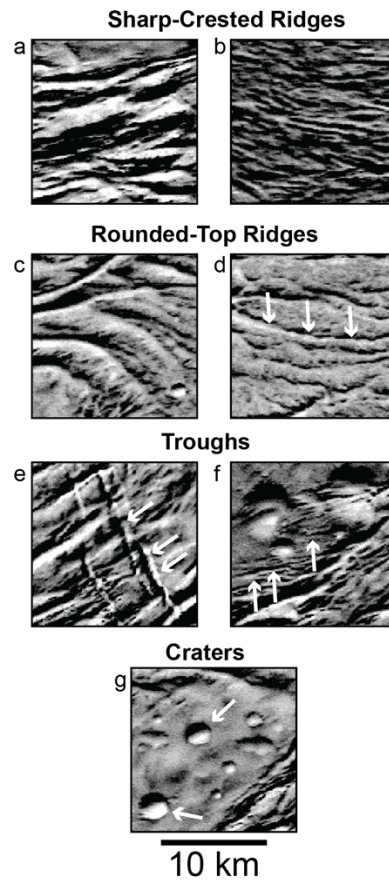


Figure 5.3. Index of structural units identified in Figure 2B, with type examples. The unit descriptions are as follows: Sharp-Crested Ridges, Major (a) and Minor (b), are quasi-linear topographic highs that are roughly triangular in cross-section with large length to width ratios and asymmetric slopes; Rounded-Top Ridges, Major (c) and Minor (d), are linear to curvilinear topographic highs that are rounded to boxy in cross-section with large length to width ratios, roughly symmetric slopes, and some pinch and swell along their length; Troughs, Major (e) and Minor (f), are linear topographic lows that are v-shaped in cross-section and have steep walls with a large length to width ratio; and Craters (f) are roughly circular, bowl-shaped topographic lows with raised rims.

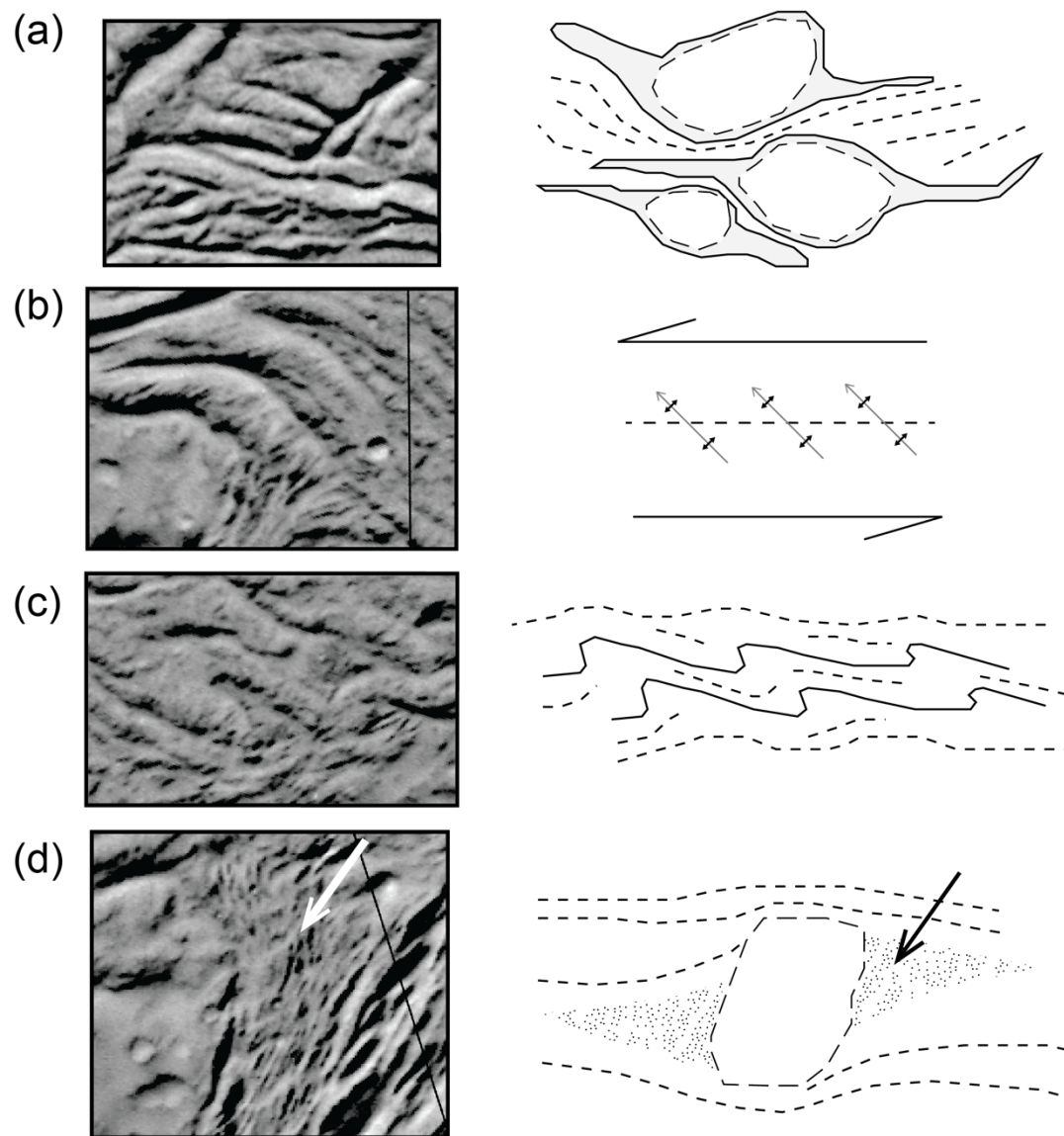


Figure 5.4. See next page for full caption

Figure 5.4. (a) tail region of the rotated relic block, and schematic (right) traced and modified from Figure 3 in Passchier and Simpson (1986) indicating the formation of tails on sigma clasts in centimeter scale samples on Earth; (b) en echelon folds in proximity to the rotated block, and a schematic (right) depicting the expected orientation of en echelon contractional structures that form in a left-lateral shear zone. Note the similar trend directions. (c) the strain shadow region containing ridges that gradually change direction with proximity to the block, and a schematic (right) traced and modified from Figure 4 in Simpson and Schmid (1983) indicating where this strain shadow forms with respect to a rotated clast; (d) portion of the structural map showing proposed asymmetrical folds, and a schematic (right) traced and modified from Figure 12 in Ghosh and Sengupta (1987) noting the trend of asymmetrical folds expected in a left-lateral shear zone. All of the images from Enceladus in this Figure are in a Mercator projector (from <CICLOPS.org>) in order to allow for accurate angle measurements and comparisons.

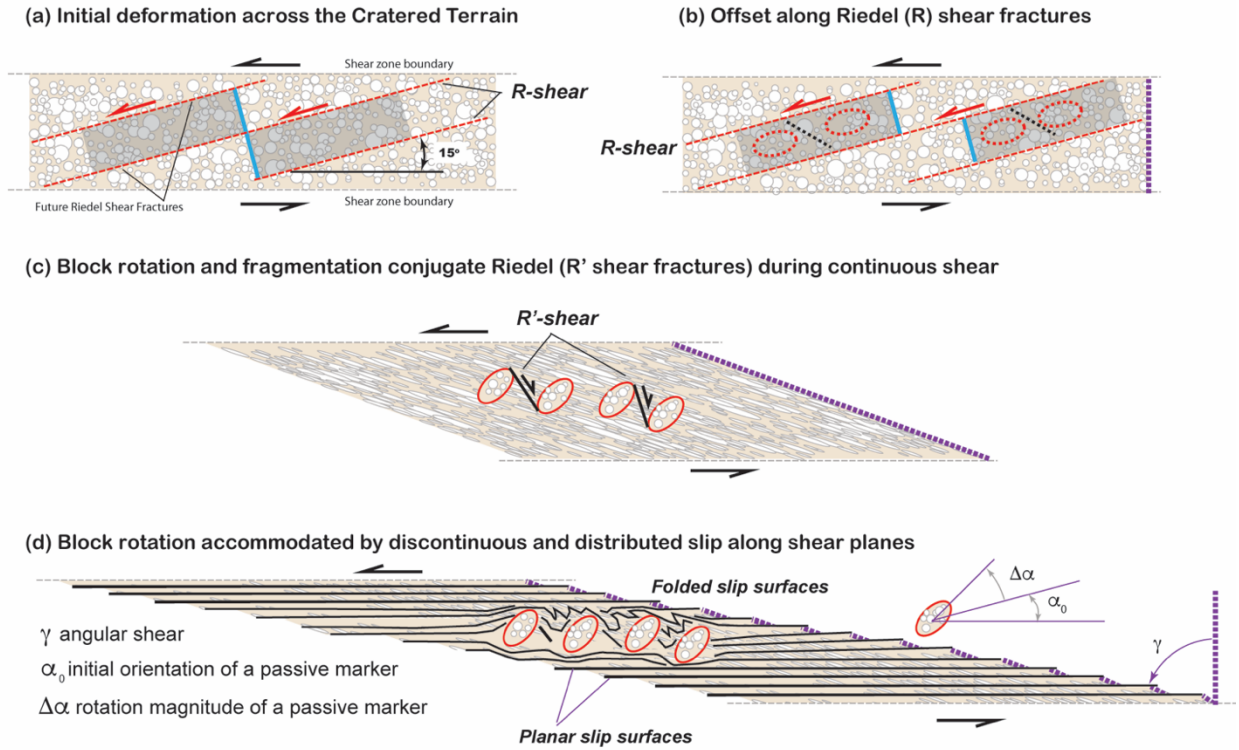


Figure 5.5. Block diagram of the proposed evolution of the relic cratered blocks. (a) the initial deformation of the terrain where left-lateral shear causes the formation of Riedel shear fractures (R-shears) at an angle of $\sim 15^\circ$ with respect to the shear zone. (b) Offset along the R-shear fractures and the formation of conjugate Riedel fractures (R' shear fractures). (c) Block rotation and fragmentation due to the conjugate Riedel fractures during continuous shear. (d) Block rotation accommodated by discontinuous and distributed slip along shear planes. From analysis of the rigid cratered blocks, we find that they have rotated from an initial 15° orientation to $\sim 45^\circ$, implying 30° of rotation ($\Delta\alpha$). In order to achieve 30° of rotation, the shear zone must undergo $\sim 70^\circ$ of angular shear (γ).

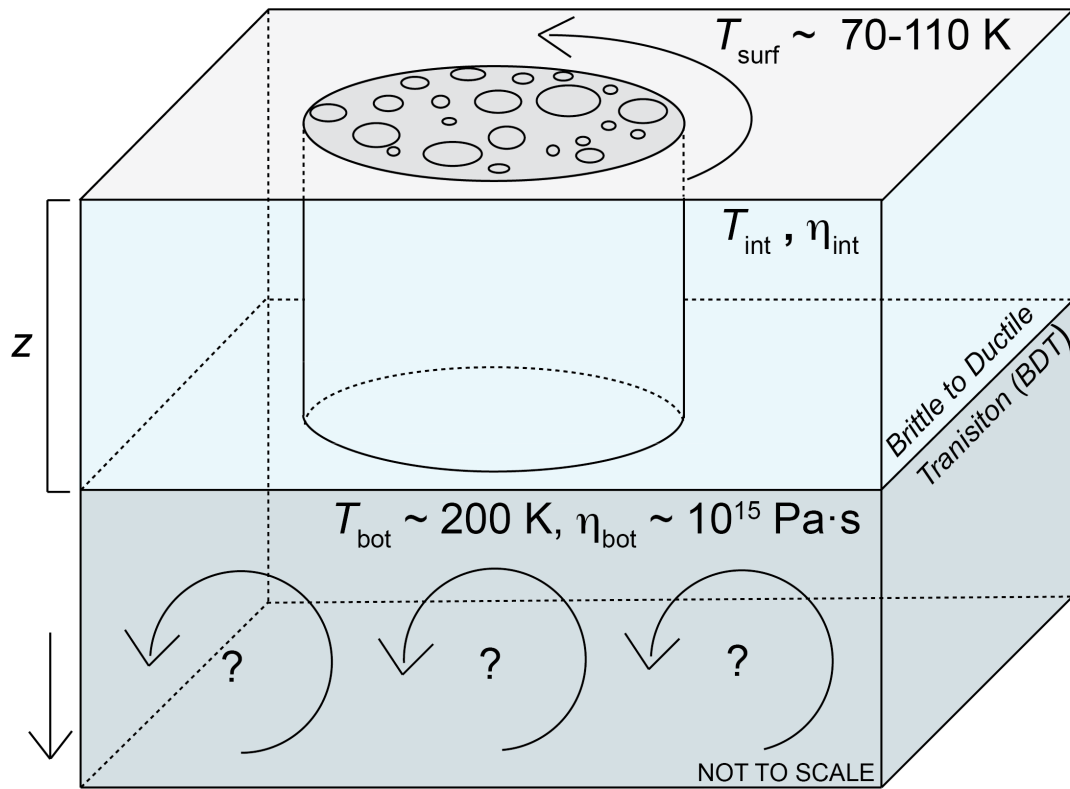


Figure 5.6. Block diagram of the relic cratered terrain and associated subsurface. The top layer, indicated by z , is the layer in which the relic cratered terrain is embedded, where z is the thickness of that layer. The bottom layer represents the ductile ice, which is potentially convecting.

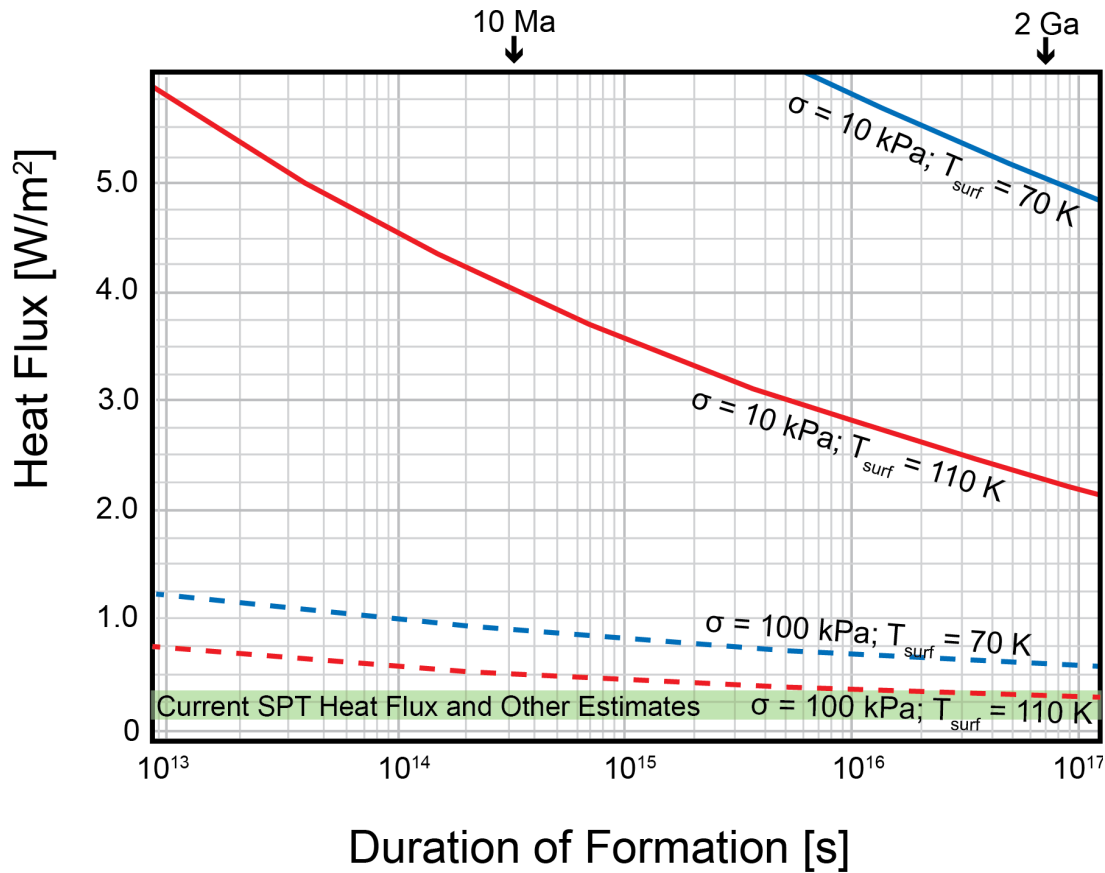


Figure 5.7. The heat flux required to produce the calculated ice viscosity (10^{18} - 10^{19} Pa s), using a surface temperature of 70 K (blue lines) with a range of stress values (10 kPa and 100 kPa). Note that independent of the duration of formation (discussed in Section 5.6.1), the heat flux does not reach values predicted by other studies or what is observed at the SPT currently (green box). This indicates that in order to reach heat flux values hypothesized to have occurred on Enceladus (e.g., Giese et al., 2008; Bland et al 2012) and the heat flux observed in the SPT today (0.1 - 0.3 W/m^2), the effective surface temperature must be raised to 110 K (red lines). Therefore, a layer of insulating material (~ 1 - 10 m thick) must be present in order to reduce the expected heat flux to values known to be produced on Enceladus. See Section 5.6 for further discussion.

Table 5.1. Criteria for identifying various types of structures

	Tension cracks	Normal faults	Thrust faults	Circular Folds	Box Folds
Ridge morphology in cross section view	Commonly not associated with ridge formation.	(a) Sharp ridge crest; (b) one side of the ridge displays high-angle planar scarps.	(a) Irregular ridge crests; (b) symmetric or asymmetric ridge slopes with the steep side above fault traces	(a) Semi-circular, rounded ridge crest in cross section view; (b) Smooth and symmetric ridge slopes but without planar scarps.	(a) Flat ridge tops; (b) Steep to vertical ridge flanks defining vertical fold limbs.
Trough morphology in cross section view	Steep walls bounded by high-angle fractures.	Depression correlates with the extent of the bounding faults.	Irregular shaped basins induced by thrust loading in the footwalls.	Troughs are synclinal folds with circular cross section geometry.	Steep walls bounded by draped limbs from flat fold top. This differs from extensional cracks where bounding normal faults truncate footwall layers.
Scarp shape and fault-induced depression geometry	Relatively constant height for scarps. Constant width of depression.	Scarp height decreases laterally. Induced trough width decreases towards fault tips.	Variable scarp heights and trough width.	No sharp scarps; synclinal depressions do not have flat floors common for graben basins.	Sharp scarps, flat trough floors, and constant trough width.
Map-view geometry of mapped structures	Straight traces and parallel sets with even spacing.	Relatively straight fault trace.	Highly curved, wavy fault traces. More discontinuous than fold traces.	Both straight and curvilinear traces.	Steep walls bounded by high-angle fractures.
Termination structures	Cracks die out along strike.	Normal faults could be linked with strike-slip faults or die out along strike.	Thrusts could be linked with strike-slip faults at fault tips or die out along strike.	(a) Folds and thrusts can occur in the same belt. (b) Folds can terminate at strike-slip faults.	(a) Folds and thrusts can occur in the same belt. (b) Folds can terminate at strike-slip faults.
Secondary structures	None.	Parallel normal faults near main fault.	Parallel thrusts and folds near main fault.	Parallel folds.	Parallel folds.

Modified from Yin and Pappalardo (2015)

Table 5.2. Corresponding values for each variable and quantity calculated in Equations 5.1-5.5.

Quantity	Value
α_0 , initial orientation of blocks	15°
α , final orientation of blocks	45°
γ , angular shear	70°
ε , shear strain	2.8
σ , stress	10-100 kPa
η_{bot} , viscosity at base of deforming layer	10 ¹⁵ Pa s
T_{bot} , temperature at base of deforming layer	200 K
R , gas constant	8.314 J/mol/K
E , activation energy	60 kJ/mol
T_{surf} , effective surface temperature	70-110 K
μ , frictional coefficient	0.6
ρ , density	960 kg/m ³
g , gravitational acceleration	0.113 m/s ²
k , thermal conductivity	4.3 W/m/K

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- Chapter 6 -

Conclusions

6.1 Summary and Conclusions

In this dissertation, I have explored the formation mechanisms for structures observed on the surfaces of Europa and Enceladus, and the implications of these mechanisms for the evolution of their ice-shells over the visible surface history. Specifically, I address (1) the global distribution of surface features and relative timing of their formation across Europa, (2) the criteria for the formation of different European surface structures observed at the highest available resolution, (3) the formation mechanism for Europa's ridged plains, and (4) the formation of the southern LHT on Enceladus.

With the Europa global geologic map, I provide a quantitative assessment of the areal distribution of chaos terrain and its variability across Europa—all four chaos units cover ~35% of Europa's surface with some outcrops extending laterally for 100s to 1000s of km. Based on the cross-cutting relationships between the map units and linear features in the global geologic map, I identify three relatively distinct periods in Europa's surface history—the oldest period is dominated by the formation of ridged and ridged plains, the middle period is dominated by the formation of bands, and the most recent period is dominated by the formation of chaos terrain. This finding generally matches that of past regional maps (e.g., Prockter et al., 1999; Figueredo and Greeley, 2004; Doggett et al., 2009) The apparent need for resurfacing mechanisms to create Europa's current young surface is made especially clear with the lack of craters and the wide variety of units and features identified on this map.

Zooming in to the local scale, I constrained the formation mechanism for structures on Europa through key high-resolution observations obtained by mapping the E12 Mottle region in detail. The findings include that ridge-and-trough systems are observed to be multi-generational, and to have regular spacing and symmetric, gentle slopes, favoring the folds formation

hypothesis. The analysis of double ridges show that they are remarkably consistent in size and shape along their length, favoring the compaction or linear diapirism hypotheses, though neither fits perfectly. For chaos terrains, I showed that the sharp boundaries, preserved pre-existing structures and heavily deformed border regions, suggest that the water lens collapse hypothesis is the most likely formation mechanism. Additionally, I speculated that the high albedo smooth morphological terrain unit may originate from frosting due to cryovolcanic deposits, thermal processes, or impact ejecta. However, I proposed that this is likely a new material not identified previously, which appears smooth at 8-16 m/pixel but likely has structure on a smaller scale only visible at a higher resolution. I also found that this region of Europa's surface is covered in small (< 50 m diameter) pits, which I interpreted, based on their distribution, as secondary craters. The high-resolution region closest (~ 50 km) to the primary crater appears to have undergone modification (not associated with chaos as identified in the regional map), and the pre-existing structures are heavily degraded compared to the surrounding terrain, possibly indicating that secondary craters could aid in resurfacing small patches of Europa. In addition to numerous secondary craters, at the scale of the high-resolution images, Europa's surface has numerous fine lineations, possibly a result of tectonic loading or the presence of a tectonic fabric. Finally, I synthesized the observations to show that resurfacing on Europa has transitioned from distributed deformation, seen in the multiple generations of ridge-and-trough systems, to discrete—including ridges, chaos features, scarps, and troughs. Also, I predicted that remnants of the distributed deformation, such as a tectonic fabric, will become apparent with higher resolutions images from Europa Clipper. Ultimately, the shift in deformation from distributed to discrete may be driven by ice-shell thickening over the visible surface age.

Focusing in on Europa's ridged plains, I compared the observations of ridged plains on Europa to the surface structures generated by our analogue experiments and found that the resulting ridge-trough systems in the compressional experiments match best the observed cross-sectional shape and map-view patterns of the structures. From this, I suggested that the ridged plains result from global cooling associated with an initial volumetric expansion of the ice crust at the onset of the latest resurface event starting at ~60 Ma. This is followed by ice-shell extension expressed by the formation of band structures. A major requirement for this model is that the last global resurfacing process started from the entire satellite covered by a thin ice-shell (<3 km), and its progressive cooling (and possibly with the perturbation of tidal stresses) has led to the three-state evolution of the surface structures on Europa. In order for the ridged plains to be formed through folding, I found that the initial brittle layer of the ice shell during the development of the ridged plains was ~200 m and the total ice-shell thickness is > 3000 m. This prediction is consistent with my proposed ice-shell thickening hypothesis as the current ice crust is likely 20-30 km thick (e.g. Pappalardo et al., 1999; Schenk, 2002) implying a current brittle layer thickness >1 km (e.g., Carr et al, 1998; Nimmo and Manga, 2002; Nimmo and Schenk, 2006). Eventually, as the ice shell continued to thicken, extensional stresses dominate and ridged plains formation is halted (e.g., Nimmo, 2004).

Shifting focus to Enceladus, I proposed that the resurfacing event that formed the Leading Hemisphere terrain resulted in a heat flux of $>0.8 \text{ W/m}^2$, due to the apparent intensity of tectonic activity and the amount of shear as evidenced by the relic cratered terrain. Based on my calculations, to obtain the heat flux measured today ($\sim 0.3 \text{ W/m}^2$) at the South Polar Terrain (e.g. Spencer et al., 2006), the surface must be insulated ($\sim 1\text{-}10 \text{ m}$ of insulating material; Bland et al., 2015) to create an effective surface temperature of $\sim 110 \text{ K}$ and the duration of formation must be

~2 Ga. The orientation of the shear zone and its apparent continuation around the remainder of the Leading Hemisphere may indicate that it was driven by clockwise toroidal flow in the ductile subsurface ice. The origin of this hemispheric-scale flow is beyond the scope of this work, and its plausibility could be explored further in future detailed mapping of the entire LHT and physical analogue modeling work. However, I showed that this high-heat, ductile resurfacing event has implications for the formation of the SPT, the episodic nature of Enceladus resurfacing, and the dynamics and rheology of the ice shell.

Overall, this dissertation demonstrates the ability of relatively simple physical analogue experiments and thermo-mechanical models to aid in exploring questions of surface feature formation mechanisms on icy satellites. The insights provided by these experiments can be powerful, but also should be treated with care and validated by observations and other numerical or analytical modeling when available. In future work, this two-layer physical analogue model could be applied to a range of icy moons displaying tectonic deformation, such as Enceladus, Tethys, Dione, Ariel, Miranda, and Triton, and rocky worlds, such as Mercury, Venus, the Moon, and Ceres.

The results presented in this dissertation coalesce to tell a story of evolving ice-shells on icy satellites as revealed by geomorphological observations and physical analogue experiments. On Europa, I showed that the general progression of the deformation of the surface implies ice-shell cooling and thickening as the driving force. However, it remains unclear if sufficient strain will be produced by this process to produce the observed features (Nimmo, 2004), so more modeling is needed. On Enceladus, I showed that the LHT formed during a past period of high (>0.3 W/m²) heat flux, implying that the satellite and its ice-shell have undergone multiple periods of discrete heating that result in the surface deformation we observe today. The broader implication

of this dissertation is that the ice-shells of Europa and Enceladus should not be thought of as being in steady-state, but rather, as evolving with time and that this evolution is represented in the geology observed on the surface. Finally, the possible lack of thermal and chemical stability of the underlying ocean, as effected by the evolution of the ice-shell, could impact the potential habitability of these environments.

6.2 References

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