Title: Tectonics on Jupiter's icy moon Europa

Author: Kerry J. Cupit

Location:

Simon Fraser University

8888 University Drive

Burnaby, B.C.

Canada V5A 1S6

Contact email: kcupit@sfu.ca

Contact address:

10543 170A Street

Surrey, B.C.

Canada V4N 5H8

Running title: Tectonics of Europa

Keywords: convergent, divergent, water ice, ice shell, polar wander, tectonics, margins

Date submitted: Dec 5, 2008

(A) Introduction

The ice surface of Europa appears unique in the solar system and exhibits small-scale features that can be interpreted as plates with terrestrial tectonic similarities. By reconstructing how these plates fit together in the past, insight into possible Europan tectonic processes can be gleaned. Tectonic models can also be conceived and tested, based on the limited data returned from this moon to date.

(B) About Europa

Europa is one of the four largest moons in orbit around Jupiter making up what are known as the Galilean moons (Fig. 1). It is remarkable in that it is the only known planetary body in the solar system to have a surface made up almost entirely of water ice floating atop a possible subsurface liquid ocean (Showman and Malhotra, 1999; Gaidos and Nimmo, 2000; O'Neill et al., 2007). This ice shell is one layer out of four that make up the composition of Europa (Fig. 2); the icy surface, a theorized subsurface ocean, a rocky mantle and a nickel-iron core.

The ice shell around Europa is suggested to be between 50 and 170km thick (O'Neill et al., 2007) and crater counting methods have indicated that most of the surface is between 30 and 80 million years old (Figueredo and Greeley, 2004). The surface exhibits large patches of different colours (Fig. 3), however the source of these colours is debated. Identified as sulfur and silicates (McCord et al., 1998; McCord et al., 1999; Showman and Malhotra, 1999), if it is assumed that the material associated with patchy colours were emplaced rather than converted from *in-situ* non-coloured material, then the source is either a hypothesized ocean below (McCord et al., 1998; McCord et al., 1999; Showman and Malhotra, 1999) or from sources external to Europa (Cupit, 2007).

A subsurface liquid water ocean layer has been inferred through observations of a dampened Jovian magnetic field around Europa (Gaidos and Nimmo, 2000) and has been suggested to be up to 100km thick (O'Neill et al., 2007). Beneath this is a rocky silicate mantle that Cupit (2007) suggested might have boundary layer interactions with the overlying subsurface ocean in the form of black smokers due to tidal heating of the mantle. A nickel-iron metallic core rests at the centre of Europa.

(C) Remote sensing

Unlike studying geology on Earth, planetary geology relies entirely upon remote observations. It is typical for observations to be made from many thousands of kilometres away. However, technology carried on new space probes has improved dramatically over forty years, changing observation styles from the acquisition of low-resolution blurry dots (Fig. 4) to multi-megapixel multi-panel images at very high resolution (Fig. 5). Advances in planetary spacecraft navigation and survivability mean that probes can approach closer to Europa than before and spend more time making more detailed observations. The earliest close-range data obtained from Europa was a fly-by in 1973 by Pioneer 10 (Jet Propulsion Laboratory, 2003). Therefore, knowledge about this moon has developed quickly since then and it is still an emergent field.

A number of probes have passed through or near the Jupiter system. However, only five have made notable observations of Europa from which the tectonic discussions in this paper are derived. They are the Pioneer 10 fly-by in 1973 (Jet Propulsion Laboratory, 2003), the Pioneer 11 fly-by a year later in 1974, the Voyager 1 and 2 fly-bys in 1979 (Hoppa et al., 1999a) and the arrival of the Galileo orbiter in 1997 (Wikipedia contributors, 2008). The Galileo orbiter has taken the highest-resolution photos of Europa to date, obtaining resolutions near 420 metres per pixel (Sullivan et al., 1998). However, Galileo was only able to photograph 20-30% of Europa at this resolution before its mission ended in 2003 (Schenk et al., 2008).

Remote sensing observations can be grouped into two types: optical and geophysical observations. Optical observations are useful to most modern studies of Europan geology, however a number of geophysical techniques are also used to characterize the environment around Europa. Equipment used in geophysical observations includes magnetometers, gravimeters, charged particle instruments, ultraviolet and infrared spectrometers, Geiger tube telescopes, and plasma analyzers (Wikipedia contributors, 2008).

(D) Evidence for tectonism

Photos of the surface of Europa taken during flybys have been used in many studies to identify features that may be indicative of tectonic processes operating on this moon. With an average surface age of 10 million years (Showman and Malhotra, 1999), any geologic processes would have been recently active or perhaps currently active, despite a noticeable decrease in resurfacing activity over the last 30 to 80 million years (Figueredo and Greeley, 2004).

Very large scale fracturing (Fig. 6) and melting has been observed on Europa's surface (Showman and Malhotra, 1999; Gaidos and Nimmo, 2000), which suggests that the forces responsible for creating them are regional and operating on a near moon-wide scale. Showman and Malhotra (1999) examine the case that tidal forces from Jupiter may be responsible, which may also be a viable contributor to other tectonic-like features observed on Europa. Regardless of tidal influence, geologic features on Europa have been grouped into craters, ridges, bands, chaotic terrain and plains (Fig. 7). Craters are typically formed from bolide impacts and thus aren't discussed further in the scope of Europan tectonics, since they rely on influences initially external to the Jovian system.

(i) Dark bands

Voyager images from 1979 reveal dark, wedge shaped bands criss-crossing the surface (Fig. 8) with roughly 50 to 100km spacing (Schenk and Seyfert, 1980) between brighter plains. It is interesting to note that the bright plains bordering the dark bands appear to match very closely with each other, with small amounts of rotation and translation applied (Sullivan et al., 1998). The rotation is generally less than 10°, is in random orientations, and isn't necessarily always present (Sullivan et al., 1998). Closer inspection of the dark bands reveal that they have parallel lineaments and pit complexes in bilateral symmetry to a central lineament ridge pair (Fig. 9a) (Sullivan et al., 1998). Figure 9b shows a brightness versus intensity graph of a dark band ridge highlighting this bilateral symmetry. However, the study in which this was produced did not take into account the illumination angle, resulting in lower troughs to the right of peaks versus to the left of those same peaks, regardless of which side of the central lineament ridge pair the data was obtained.

It can therefore be concluded that extrusion of material must be taking place at the centre of these dark bands (Sullivan et al., 1998) under varying conditions to produce symmetrical albedo characteristics. In order to produce the tens of metres of topography sometimes observed along these central ridges, Sullivan et al (1998) assumed that any extruded material must have a high viscosity or is rapidly quenched so that it is ultimately emplaced close to the central ridge.

Morphologically, these dark bands occur in linear, crescent shaped, and trapezoidal shapes (Sullivan et al., 1998). Given the bilateral symmetry exhibited, these ridges likely represent crustal extension and plate separation (Sullivan et al., 1998; Schenk et al., 2008) and the newest crustal material present on Europa.

(ii) Plates

Bright, undeformed regions with sharply defined boundaries are interpreted as plates of ice. Spaces between plates are usually dark (Sullivan et al., 1998). However, removing these spaces and fitting plates back together to develop a tectonic history is relatively trivial. On larger scales Euler poles must be used to account for plate rotation, but on scales of hundreds of kilometres this correction need not be made (Sullivan et al., 1998). A sample plate reconstruction can be seen in Figure 10. It is interesting to note that less than 1% of plate material is missing in this reconstruction, which Sullivan et al (1998) suggests was converted to dark material, covered by dark material, or somehow consumed in unobserved processes.

(iii) Chaotic terrain

Chaotic terrain covers about fifty percent of the surface of Europa (Greenberg, 2004) and is characterized by the large-scale breakup and consumption of bright coloured plate material, possibly through subsidence and/or burial (Sullivan et al., 1998). Pappalardo et al (1998) suggests that features within chaotic terrain of the Conamara area of Europa are indicative of thermally induced vertical displacement, hinting at convective cells occurring within the ice shell.

Chaotic terrain represents one possible terrain type where plate material is consumed. However, while dark bands are clearly evident of crustal extension, evidence for compensatory crustal consumption is far subtler (Sullivan et al., 1998; Greenberg, 2004; Patterson et al., 2006).

Future studies may be able to elucidate a crustal surface area budget for each terrain type, but as of now none yet exists.

(iv) Strike-slip faults

Close-up photos of the surface of Europa reveals increasingly compounded terrain types (Sullivan et al., 1998). From these some researchers have identified a number of past and currently active strike-slip faults (Fig. 11) (Hoppa et al., 1999b). One key result from the research of Hoppa et al (1999b) is that the preferential direction of strike-slip faults are dictated by which hemisphere they occur in. For the northern hemisphere, 80% of all identified strike-slip faults are left-lateral. Whereas in the southern hemisphere, 95 to 100% of all strike-slip faults are right-lateral. Europa's proximity to Jupiter means that it can be subjected to significant tidal forces that act upon the ice shell (Hoppa et al., 1999b; Showman and Malhotra, 1999; Gaidos and Nimmo, 2000). These forces appear to be the main mechanism whereby strike-slip direction is determined in each hemisphere (Hoppa et al., 1999b).

(v) Convergent margins

As of 1998, there had been no studies performed that would indicate any presence of convergent plate margins on Europa (Sullivan et al., 1998). However, studies conducted in 2003 and 2006 have since identified a few locations that are good convergent margin candidates (Greenberg, 2004; Patterson et al., 2006). A good example of a proposed convergent margin is shown in Figure 12. Greenberg (2004) made the observation that these margins do not exhibit any structures similar to what would be expected on Earth, but instead have a subtle "muscle tissue" appearance. The best method for identifying convergent margins of this type is to look for two plates separated by a band and yet do not have edges that would match with each other if they were brought together.

(E) Tectonic models

(i) Active lid verses stagnant lid

O'Neill et al (2007) suggested that planetary plate tectonic regimes could be classified as "active lid" or "stagnant lid". Active lid tectonics involves downward moving cold lithosphere, where stagnant lid tectonics involves lithosphere that is too strong to become incorporated into the mantle. More specifically, stagnant lid tectonics occur when mantle convection stresses are less than lithospheric stress, thus keeping intact a globally stable lithosphere. The average age of the surface of Europa is 10 million years old (Showman and Malhotra, 1999). However, there are no active large-scale resurfacing processes visible in observations to date. Therefore, O'Neill et al (2007) theorize that Europa has had both active and stagnant lid periods throughout its history resulting in occasional global resurfacing, similar to what has been suggested for Venusian tectonics.

(ii) Tidal stresses

Tidal influences from Jupiter can impart significant stress to the surface of Europa (Hoppa et al., 1999b) and to a lesser extent, so can the other Galilean moons (Figueredo and Greeley, 2004). Gaidos and Nimmo (2000) postulate that tidal stresses can cause displacement and friction along the edges of Europan strike-slip zones, producing warmer and more plastically flowing ice. They calculate that displacement of 0.6m could sustain temperatures of 273K within the fault zone, and that melted material would move upwards at a rate of tens of centimetres per orbit possibly resulting in the formation of dark ridge structures over time. Dark ridge structures with repeating curvilinear forms (Fig. 14) may have initially been formed as cracks created by tidal forces over a period of a few Europan days (Hoppa et al., 1999a).

It appears that tidal forces are responsible for pushing nearby plates along strike-slip faults, instead of stress release within a single plate (Hoppa et al., 1999b), therefore it may be worthwhile to investigate this same phenomenon on Earth.

(iii) True polar wander

If the ice shell is decoupled from the silicate interior and varies in thickness latitudinally, then it may be possible that polar wander is an appreciable outcome from regional stresses (Schenk et al., 2008). No moon-wide features have been observed, but 0.3 to 1.5km deep arcuate troughs hundreds of kilometres in length indicate about 80° of true polar wander through implied stresses due to the reorientation of the surface relative to the moon's spin axis (Schenk et al., 2008). These troughs appear to be at least be geographically related to the dark bands mentioned previously, suggesting that many tectonic patterns on Europa may be related to true polar wander (Schenk et al., 2008). Preferential directions of strike-slip faults noted in each hemisphere support this hypothesis.

(iv) Milankovich-like cycles

Further research is required to investigate why the surface of Europa is relatively very young compared to the ages of other planetary surfaces in the solar system. If Europa does indeed undergo periodic global resurfacing, then various factors may contribute coincidentally to either weaken lithospheric strength or strengthen the convective forces within Europa to the point that active lid tectonics can take place. Figueredo and Greeley (2004) suggest that tidal interactions between the four Galilean moons may lead to cyclic effects on Europa with a period of approximately 100 million years. Hoppa et al (2001) identified an effect of nonsynchronous rotation on the order of 250 thousand years that may also contribute to longer-term tectonic processes.

(F) Similarities to Earth tectonics

Despite very different lithospheric mediums on Europa and Earth (water ice versus silicates), there is evidence that similarities exist between the two planetary bodies. Heat generated from the decay of radioactive elements is likely a contributing factor for heat transfer in Europa (Showman and Malhotra, 1999), as it is also on Earth [textbook]. Additionally, there is evidence for convergent, divergent and strike-slip margins between plates on Europa (Schenk and Seyfert, 1980; Sullivan et al., 1998; Hoppa et al., 1999b; Figueredo and Greeley, 2004; Greenberg, 2004; Patterson et al., 2006; Schenk et al., 2008). Divergent margins processes expressed in the form of dark bands on Europa also bear a striking similarity to mid-oceanic spreading ridges on Earth (Sullivan et al., 1998).

O'Neill et al (2007) notes that despite similar tectonic features on Europa, Earth is the only known planetary body with active lid plate tectonics.

(G) Conclusion

Less than a third of the surface of Europa has been photographed at resolutions sufficient for detailed plate tectonic studies to date, yet there have been numerous studies undertaken than have produced abundant and valuable results. One obvious characteristic of this icy world is that the plates are on a much smaller scale (10 to 50km wide) than the plates making up Earth's crust, meaning that high-resolution photos are necessary for continued detailed studies of this moon. The latest probe to visit Europa, Galileo, concluded its mission in 2003. Despite significant scientific interest in Europa and the possibility that life might exist in its global subsurface liquid water ocean, financial and political interests mean that it may be many years before closer investigations are made of this world. In the meantime, data sets from Voyager and Galileo will be used for many future studies of Europa, improving upon knowledge that has been accumulated over 35 years since the days of the first Pioneer flybys.

The observation that tidal forces may play a role in Europan strike-slip faults suggests that phenomenon observed on other worlds may be worthwhile to investigate closer to home, to help fill in gaps in knowledge or suggest new lines of research on Earth. Planetary geology therefore has implications not only for the theoretical understanding of other bodies in our solar system, but for Earth-based processes as well.

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(I) Figures

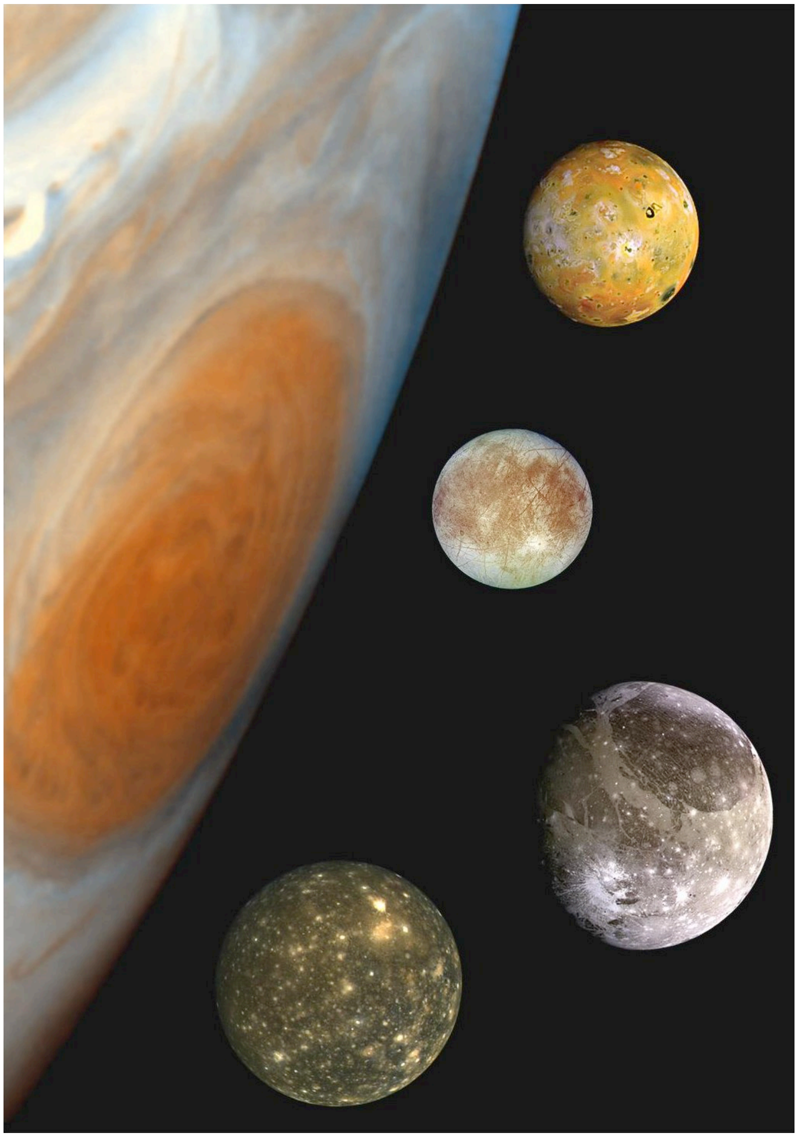

Figure 1: The four largest moons around Jupiter known as the Galilean moons, and Jupiter. Sizes are to scale, however spatial relationships are not. Wikipedia contributors (2008).

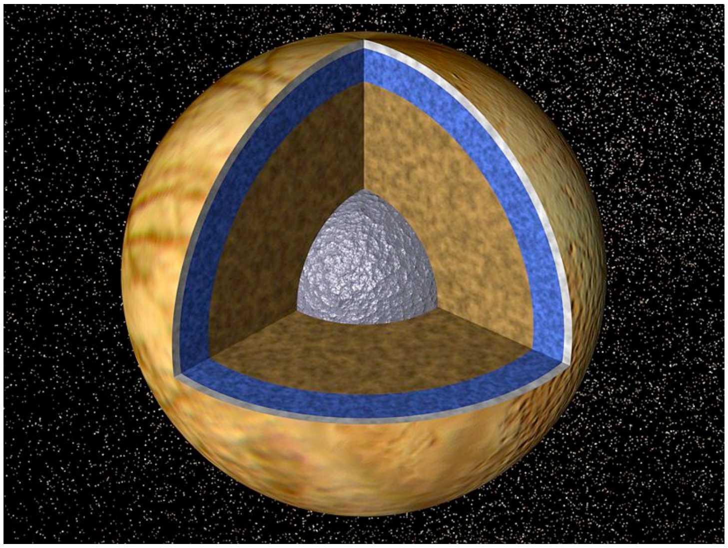

Figure 2: Cutaway view of Europa showing four proposed layers: the 20-150km thick ice shell (O'Neill et al., 2007), the subsurface ocean, the silicate mantle and the nickel-iron metallic core. Wikipedia contributors (2008).

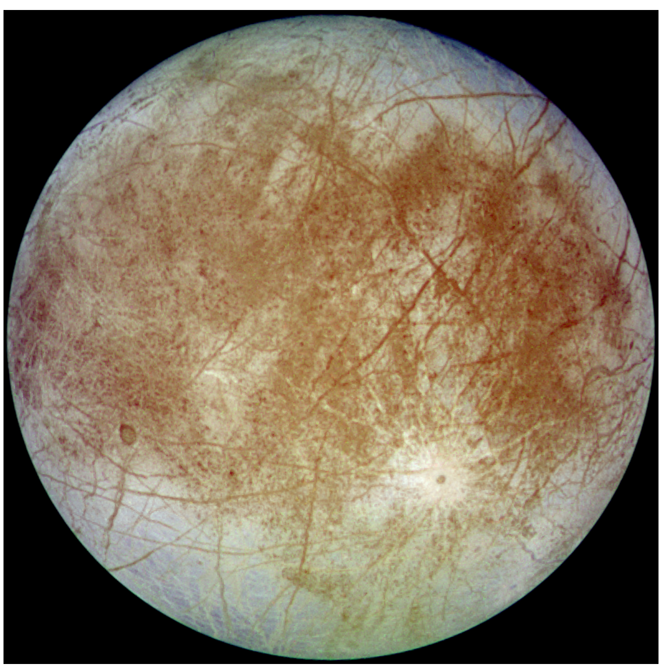

Figure 3: Global view of Europa, showing large-scale dark ridge structures, craters, and patchy colours. Wikipedia contributors (2008).

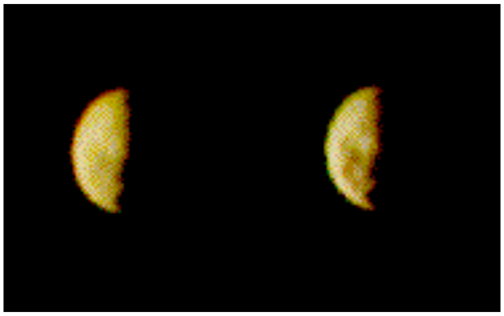

Figure 4: One of the best images of Europa taken by Pioneer 10 during its flyby in 1973, with 161km/pixel resolution. Image at left is a colour composite, whereas the image at right is a computer-enhanced version. Jet Propulsion Laboratory (2003).

Figure 5: Sample of a high-resolution photo taken from the Galileo space probe of Europa, showing dark ridges, colour variations and a prominent crater. Image is 1240km across. Wikipedia contributors (2008).

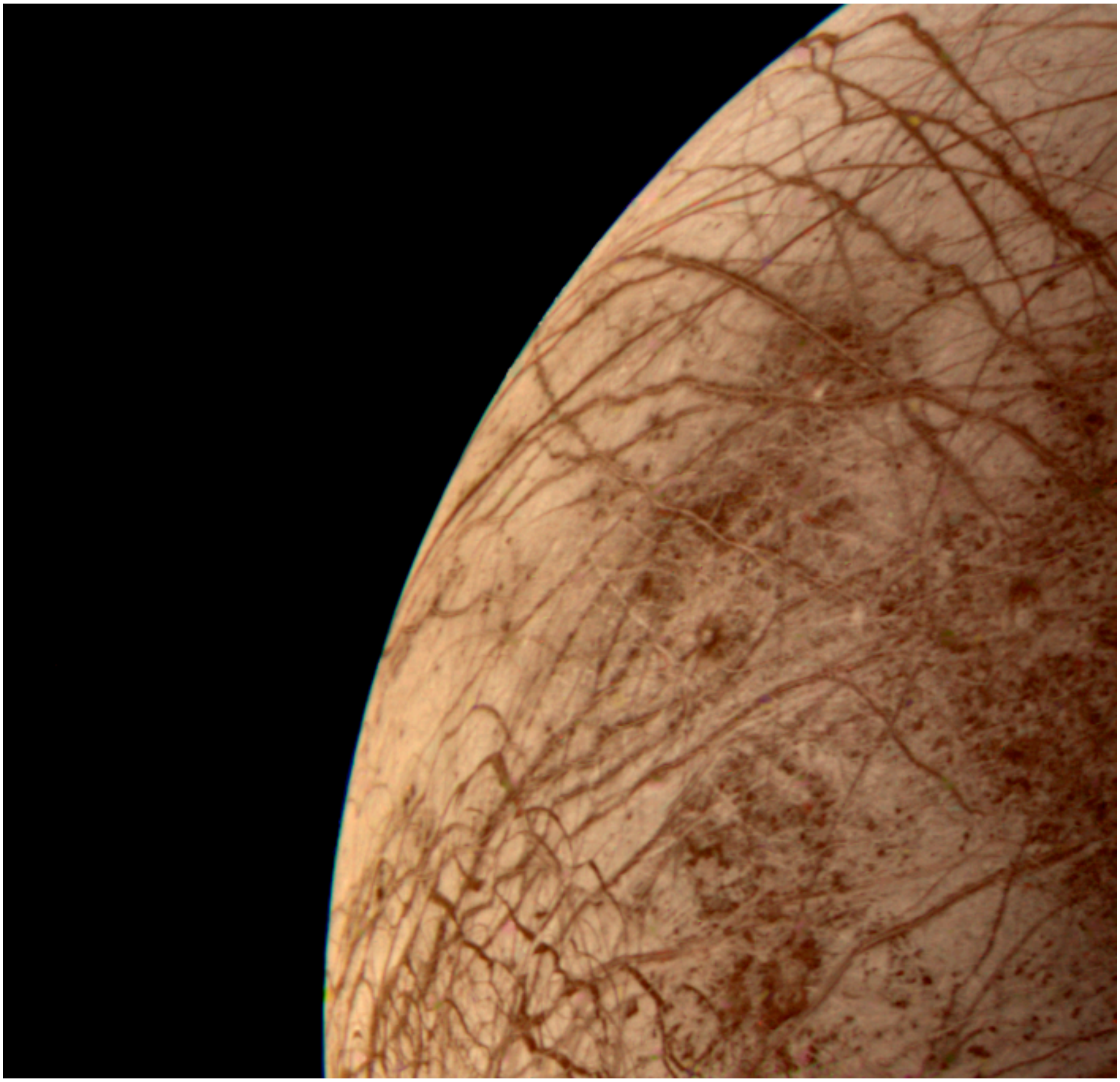

Figure 6: Dark ridges on a near global scale on the surface of Europa, possibly implying large-scale fracturing and melting. National Space Science Data Center (2008).

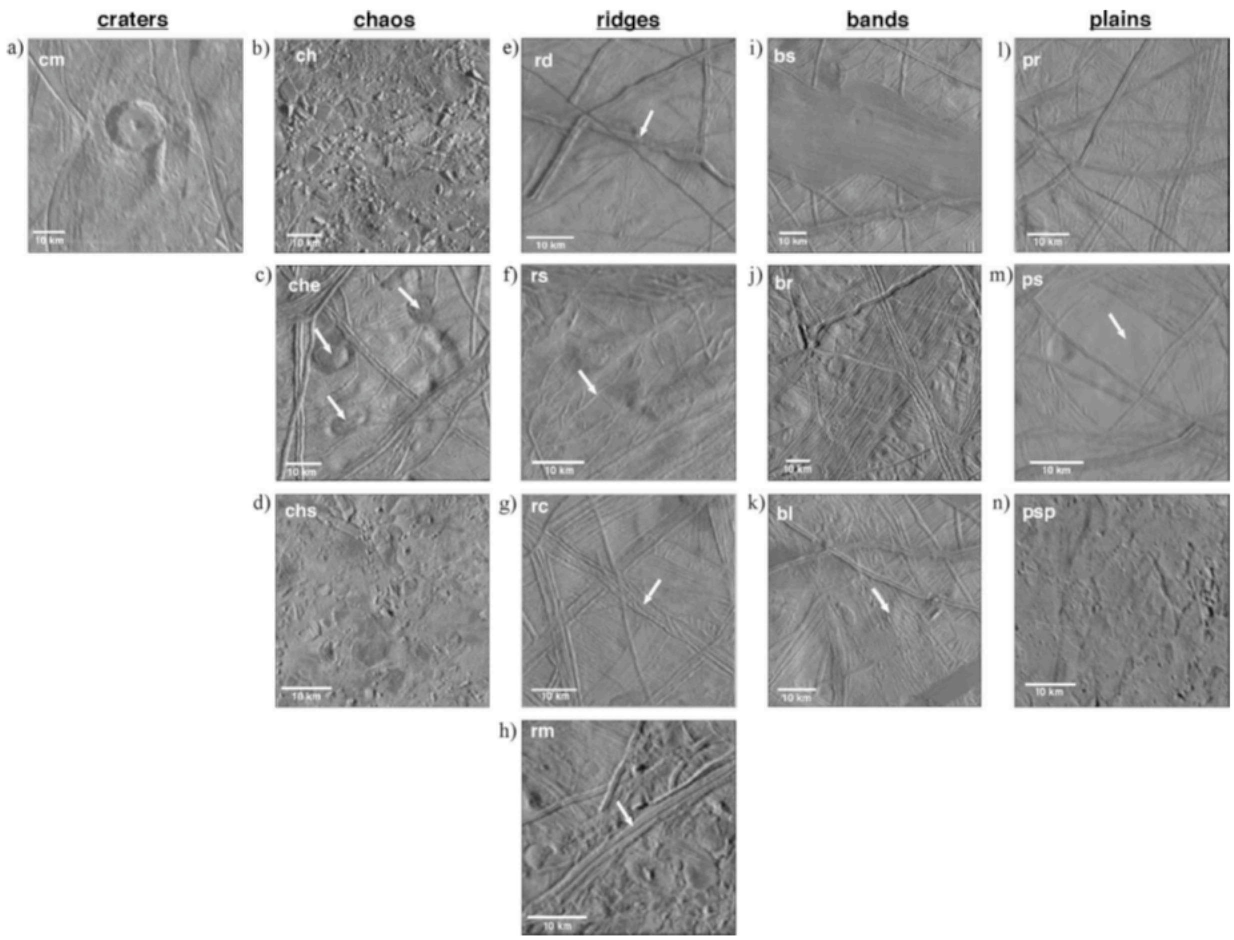

Figure 7: Features on Europa are classified into one of five broad categories: craters, chaos terrain, ridges, bands, and plains. Arrows highlight classified features in these images. Figueredo and Greeley (2004).

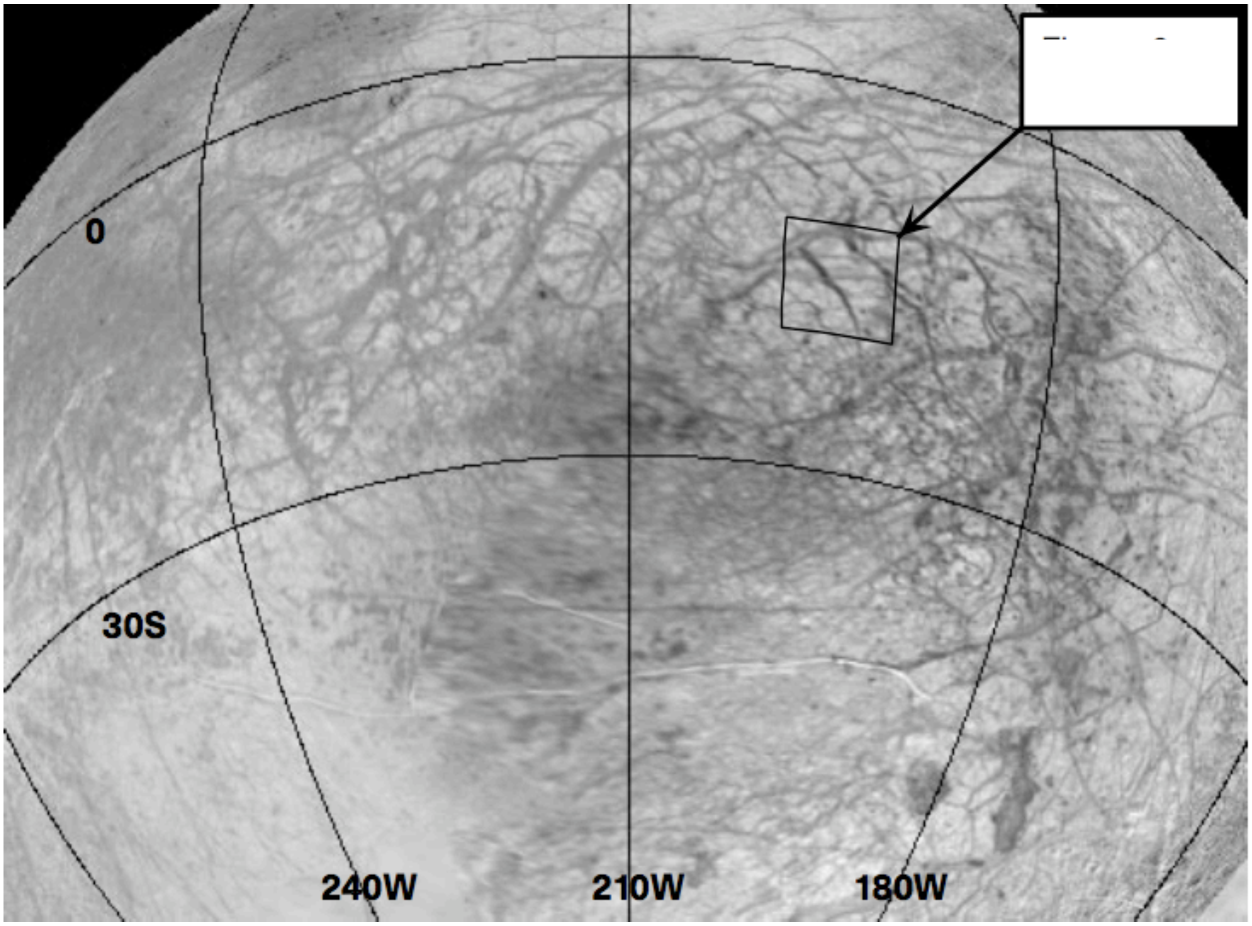

Figure 8: Lower hemisphere image of Europa taken by Voyager, showing 50-100km separations between dark bands on the surface. Sullivan et al (1998).

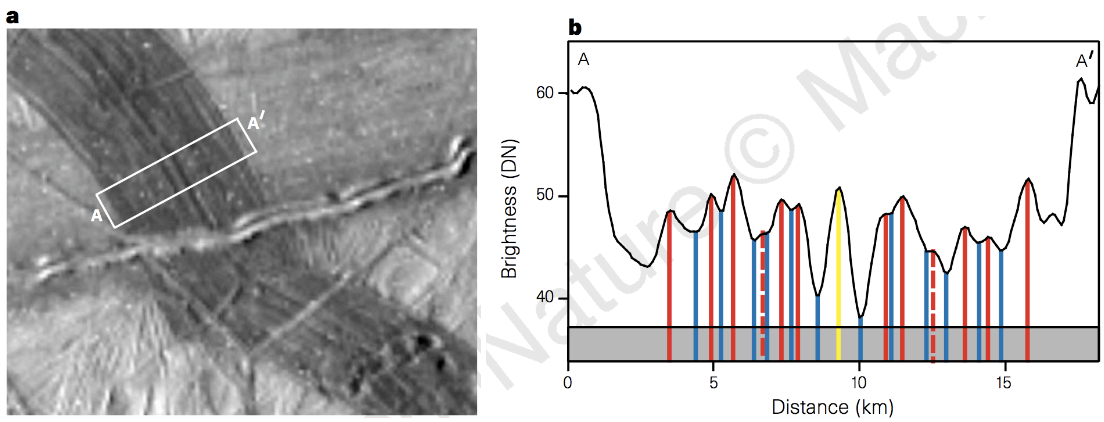

Figure 9: Close-up image of a dark ridge structure on Europa (a). Brightness versus distance graph from A to A’ (b), showing central ridge pair and bilateral symmetry. Sullivan et al (1998).

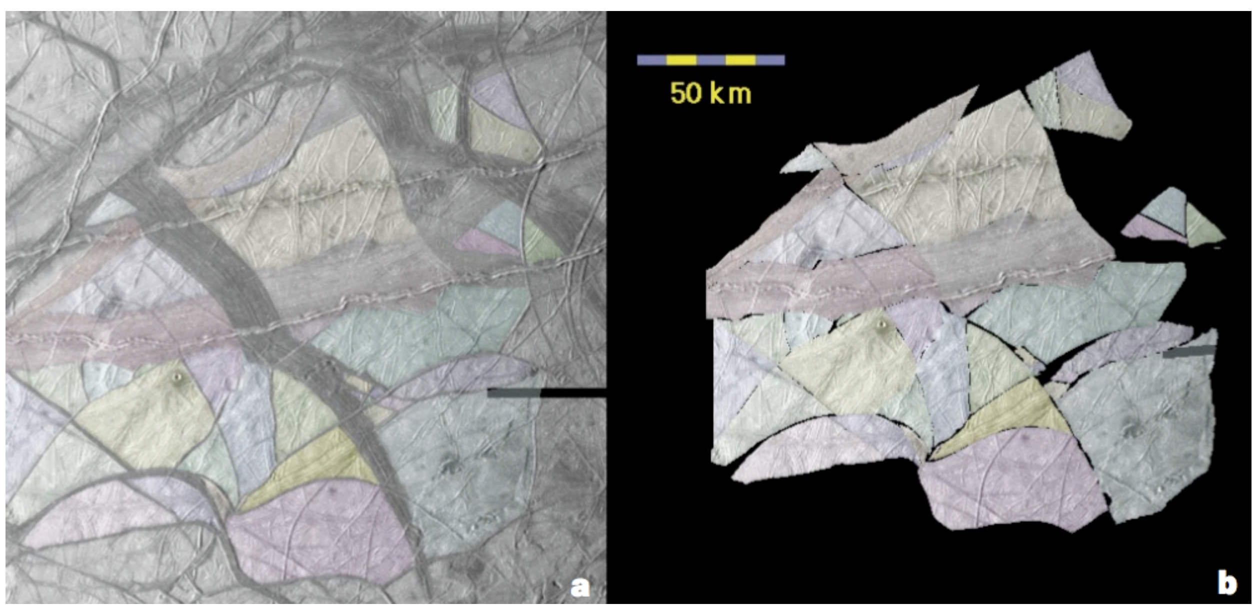

Figure 10: Sample plate reconstruction. Colours are artificial and applied simply to aid reconstruction. Sullivan et al (1998).

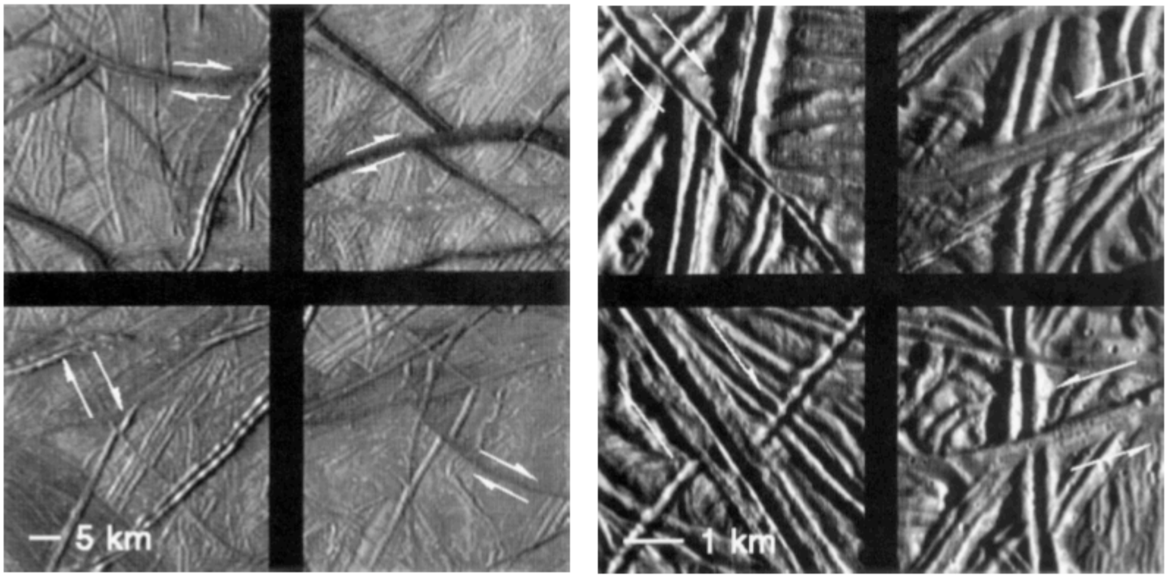

Figure 11: Examples of right-lateral strike slip motion (left panel), and left-lateral strike slip motion (right panel). Hoppa et al (1999b).

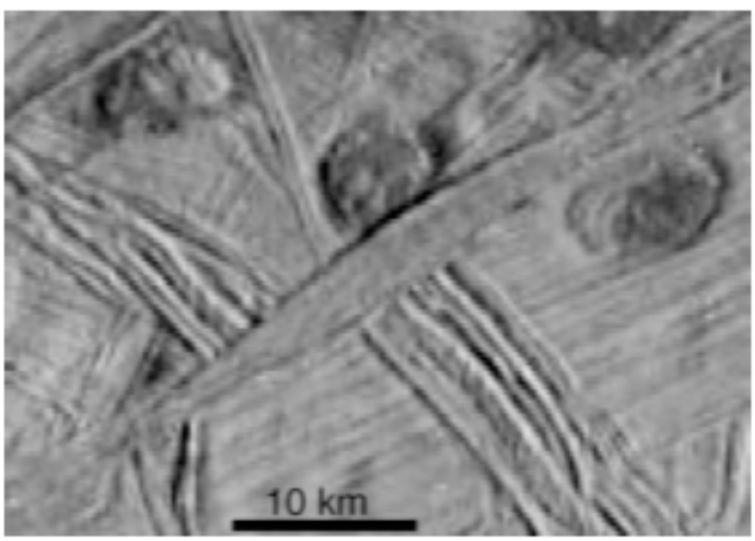

Figure 12: Example of a possible convergent margin on Europa, as evidenced by the dark circular feature being present on one side of a band and not the other, indicating some consumption of material has taken place. Also note the "muscle tissue" appearance of the central band. Greenberg (2004).

Figure 13: Curvilinear dark bands on the Europan surface. Possibly created through tidal stresses, where each arc segment is created in one Europan rotation about Jupiter. Hoppa et al (1999a).