Evidence for a subsurface ocean on Europa

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10 eininga ritgerð sem er hluti af
Baccalaureus Scientiarum gráðu í jarðeðlisfræði

Leiðbeinandi
Þorsteinn Þorsteinsson

Jarðvísindadeild
Verkfræði- og náttúruvísindasvið
Háskóli Íslands
Reykjavík, maímánuður 2010

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Hér með lýsi ég því yfir að ritgerð þessi er samin af mér og að hún hefur hvorki að hluta né í heild verið lögð fram áður til hærri prófgráðu.

Abstract

Europa is one of the four Galilean satellites orbiting Jupiter. It was discovered by Galileo Galilei in 1610 and has since intrigued scientists and amateurs alike. Its location in the outer solar system permits water ice to exist in abundant form and beneath the icy shell of Europa scientists believe water to exist in liquid form. The formation of ridges, cycloids and other linear features crisscrossing the surface suggest the presence of a liquid water layer underlying the crust. Calculations of the magnitude of tidal stress needed to break the frozen surface show that sufficient stress to overcome the strength of the crust is only attained if a liquid layer is present under the moon's ice cover. The strongest evidence comes from measurements of the magnetic field around Europa. The results require a conductive layer of liquid water with dissolved salts underlying the ice crust at shallow depths. The presence of liquid water makes Europa one of the few places in our solar system that could harbour life. To confirm or refute this the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have joined forces to send two spacecrafts to the Jupiter system. The two crafts are scheduled for two seperate launches in 2020 arriving at the Jupiter system in 2025.

Ágrip

Evrópa er eitt hinna svokölluðu Galíleó tungla á braut um Júpíter. Galíleó Galílei á heiðurinn af uppgötvun þeirra, en hann beindi hinum nýuppgötvaða stjörnusjónauka að plánetunni árið 1610 og sá tunglin fjögur ganga um Júpíter. Vísindamenn og almenningur hafa síðan velt vöngum yfir furðuveröldinni á Evrópu. Vegna legu Evrópu í ytra sólkerfinu er H_2O-ís til staðar á tunglinu í miklu magni og benda rannsóknir til þess að vatn finnist í vökvaham undir gaddfreðnu yfirborðinu. Víðáttumiklir hryggir, bogadregnar myndanir sem kallast *cycloids* og önnur línuleg yfirborðsfyrirbæri liggja þvers og kruss um yfirborðið. Myndun þessara fyrirbæra hefur verið útskýrð með tilvist undirlags af fljótandi vatni. Þá hafa vísindamenn komist að því að lag af vatni á fljótandi formi er nauðsynlegt til þess að hægt sé að kalla fram nægilega spennu til þess að yfirvinna styrk íssins og brjóta upp yfirborðið. Ennfremur leiða niðurstöður mælinga á segulsviði í kringum Evrópu til þeirrar niðurstöðu að leiðandi lag af fljótandi vatni blandað uppleystum söltum sé að finna undir yfirborðinu. En ein forsenda lífs eins og við þekkjum það er vatn á vökvaformi. Evrópa kemur því til greina sem einn af fáum stöðum í sólkerfinu þar sem líf kann að þrífast. Bandarísku og evrópsku geimferðarstofnanirnar (NASA og ESA) hafa tekið saman höndum og ætla sér að senda tvö geimför til Júpíters gagngert til þess að staðfesta eða hrekja tilvist lífs í Júpíterkerfinu. Áætlað er að senda förin af stað árið 2020 og ætti ferðin að taka fimm ár.

Contents

List of Figures

Acknowledgements

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Evidence for a subsurface ocean on Europa

1 Introduction

Europa is one of the four Galilean satellites orbiting Jupiter and discovered by Galileo Galilei in 1610. The other three are Io, the most volcanically active body in the solar system, Ganymede, the largest moon in the solar system and Callisto, whose cratered surface is as old as the solar system. The true nature of Europa eluded researchers for centuries. Earth-based observations in the 20^{th} century, mainly spectroscopic studies, indicated that the surface was composed predominantly of water ice, as had been predicted from its position in the outer solar system. Images from the Voyager spacecrafts in 1979 revealed a young and possibly active surface and Galileo images taken during the Galileo mission in the years 1995 - 2003 showed prominent ridge systems and dark patches where the icy surface seemed to have melted (Fig. 1). Subtle variations in the spacecrafts' trajectories implied a differentiated body subdivided into a metallic core of radius 700 km, a silicate mantle and an outer layer as thick as ∼150 km with the density of water (Greenberg, 2005). Further details are listed in Table 1.

Table 1: Details of Europa (NASA, 2010)

Radius	1,565 km
Orbital radius	671,000 km
Orbital eccentricity	0.009
Mean density	2.94 g/cm^3
Orbit period	3.55 Earth days

Early in the exploration of Europa scientists realized that tides would play a major role in the forces at work on the moon. Ordinarily, because of the frictional dissipation of the gravitational potential energy, Europa should have settled into a circular orbit around Jupiter long ago. In fact, as noted in Table 1, Europa's orbital eccentricity is $e = 0.009$. This is the result of Europa rotating around Jupiter in resonance with Io and Ganymede. The satellites are locked into a ratio of 1:2:4, i.e. Europa's period is twice as long as Io's and Ganymede's four times the period of Io. This was discovered by Galileo in the early 1600s and explained by Pierre-Simon Laplace nearly two centuries later. He showed that the periodic repetitions of the conjunctions of the galilean satellites enhances their mutual gravitational effects and thus reinforces and maintains tidal heating in the innards of Europa (Laplace, 1805). The tidal heating may be enough to withhold a layer of liquid water beneath the surface. One of the strongest evidence for a liquid water layer on Europa comes from magnetic measurements of Jupiter's magnetic field. An induced magnetic field generated by electric currents is detected around Europa. The required conductivity can not be met by water ice, but requires liquid water with dissolved salts. This, and other evidence for a subsurface ocean, is the subject of this essay.

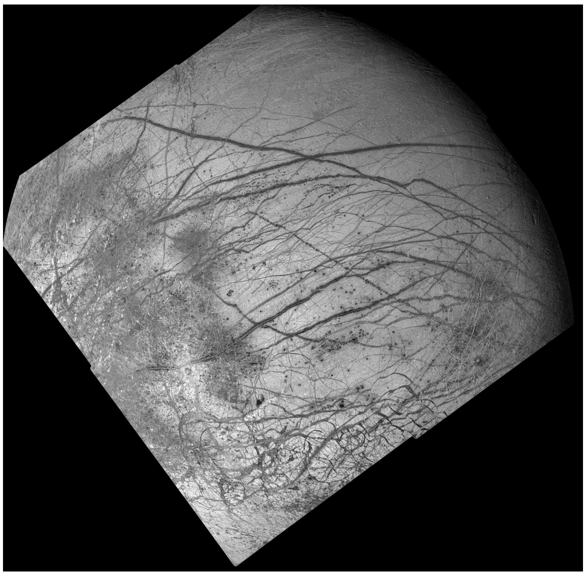

Figure 1: Surface of Europa as seen from the Galileo spacecraft. Notable are dark ridges criss-crossing the surface, many more than 1,600 km long, and dark patches which scientists believe are the result of melting of the icy surface. The mosaic covers a large part of the northern hemisphere. It is centered on 20 degrees north and 220 degrees west and is about as wide as the United States west of the Mississippi River (NASA/JPL/USGS, 1998).

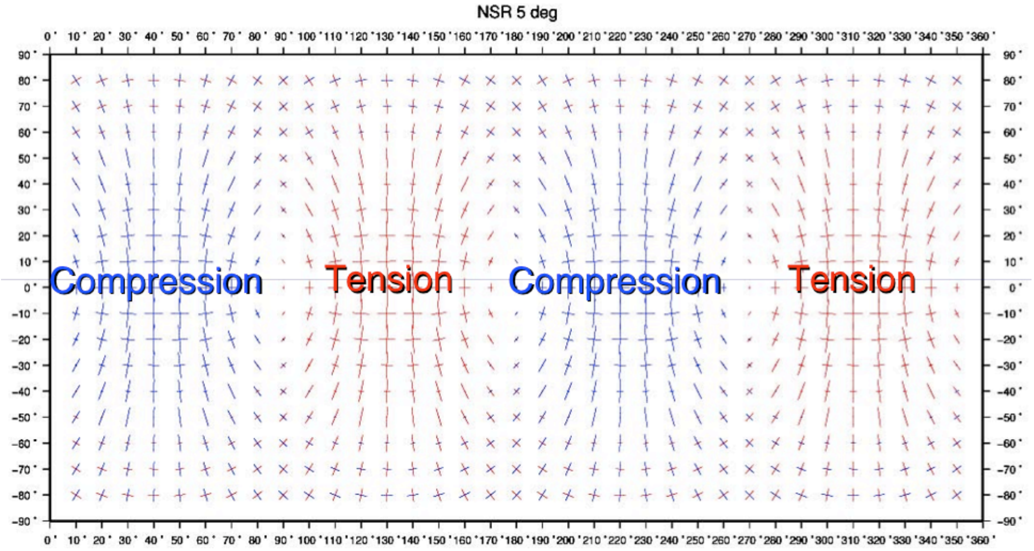

Figure 2: Stress pattern on Europa resulting from diurnal and non-synchronous stress (Pappalardo).

2 Surface features

Two distinctive features characterize the surface of Europa: a complicated network of ridges and fractures and dark patches where the surface seems to have melted. The first images of Europa taken by the Voyager spacecrafts showed a smooth surface devoid of craters. Higher resolution images taken by NASA's Galileo spacecraft revealed a low crater density confirming earlier views from Voyager. This scarcity of impact craters suggests that Europa's surface is young and possibly active today. Zahnle et al. (2003) estimate the age of the surface to be between 30 and 70 Myr, which is only about one percent of the age of the solar system.

Europa's young surface has been transformed countless times by tectonic activity. The evidence of this activity gives us clues about the inner structure of the moon and the processes that have transfigured it. Of the surface structures, linear features are the most prominent ones. They vary widely in size and shape as they crisscross the entire surface of the globe. Their origin lies in the tidal stress field on the moon generated by the moon's interaction with Jupiter (Greenberg, 2005). The tidal stress is made up of two components: a background stress which builds up as a tidal bulge migrates across Europa's surface due to non-synchronous rotation[1] and the diurnal stress formed as the moon circles Jupiter. However, neither diurnal stress nor non-synchronous stress alone would suffice to explain the crack patterns observed on Europa. Fig. 2 shows the stress pattern on Europa resulting from diurnal and non-synchronous stress. Scientists hypothesize that cracks form perpendicularly to the tensional stress. Fig. 3 shows indeed

[1]See further discussion of non-synchronous rotation in section 2.7.

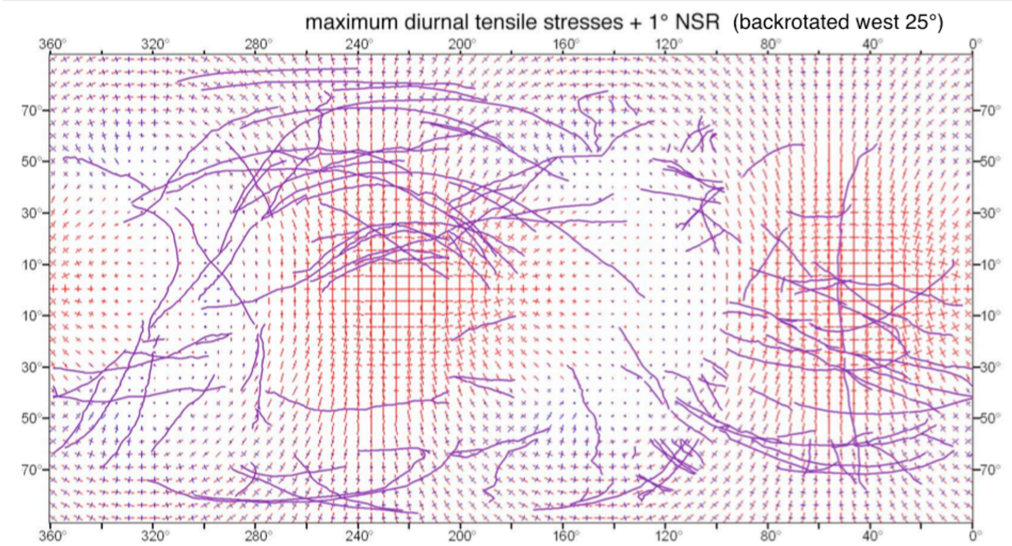

Figure 3: Lineaments on the surface of Europa fitted with the global stress pattern. A 25° backrotation of the non-synchronous rotation gives the best results (Pappalardo).

how the global distribution of lineaments fits with the stress pattern if it is backrotated 25°. According to Greenberg (2005) this stress field theory requires a global ocean layer beneath the icy crust to provide a tidal amplitude large enough to overcome the strength of the crust. A closer look at these lineaments crisscrossing the surface of the moon provides a better understanding of the processes at work. Five categories comprise the set of linear and arcuate features visible on Europa according to appearance or formation: Double ridges, cycloids, dilational bands, strike-slip faults and converging bands.

2.1 Double ridges

Double ridges are so called because they generally appear in pairs. They comprise a significant part of the surface and range from a few kilometers in length to hundreds of kilometers. Fig. 1 shows a mosaic of images taken from NASA's Galileo spacecraft. The mosaic covers a large part of the northern hemisphere including the north pole at the top of the image. Noticable are dark bands lying roughly east-west in the central latitudes, dark patches towards the west and arcuate lineaments in the south. Some of the dark bands, among them Udaeus and Minos Linea intersecting in a striking figure X at the top, stretch for over 1,600 km. Although there is a general consensus that these dark bands are ridges scientists differ on how they formed. When high resolution images are studied closely it is evident that processes creating ridges have continuously rewritten the history of Europa's surface (Fig. 4).

Fig. 4 also shows the general structure of the double ridge. Two ridges run parallel to each other seperated by a trench. Darker material flanks the ridges and in earlier

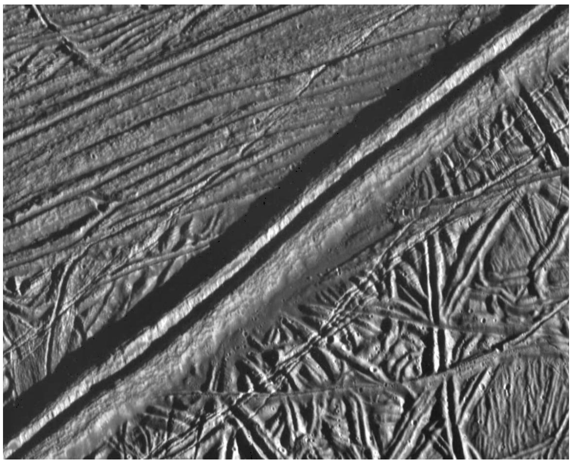

Figure 4: This high resolution image of Europa's surface shows in great detail the general structure of a double ridge running from the lower left hand corner to the upper right hand corner. It also demonstrates how ridge formations have continuously rewritten the history of the surface (NASA/JPL/ASU, 1998).

low resolution Voyager photographs, ridges appeared as a bright band lined with darker material on each side and hence they were called “triple band”. This effect can clearly be seen in Fig. 5 in the upper part of the image. Higher resolution images revealed the true form of the double ridges. Several models have been proposed to explain the formation of these ridges. Of the various models five will be considered here.

Greenberg (2005) suggests that ridges form when cracks are repeatedly opened and closed during diurnal changes in the stress field (a europan day constitutes 3.5 Earth days and represents the time of one revolution around Jupiter). Crushed ice is squeezed upon the surface as the crack closes on a thin film of frozen water. Head et al. (1998), Head and Pappalardo (1999) and Pappalardo et al. (1998) propose that linear diapirs rise up buoyantly pushing into preexisting cracks and tilting upward the brittle-elastic lithosphere along the sides of the crack. Kadel et al. (1998) suggest that double ridges represent volcanic debris deposited ballistically by gas-driven fissure eruptions of frost, ice, water and some minor silicate fraction. Others have suggested that ridges are the result of compression or the injection of melt into shallow cracks (Pappalardo et al., 1999). These models have different implications for the presence and distribution of liquid water in Europa's subsurface. The first model requires a liquid water ocean at most several kilometers under an icy shell. The diapirism model, as well as the compression model, requires that subsurface materials deform ductily in response to the stresses involved in moving this material several kilometers or more to the surface. These two models do not require a liquid water layer. The remaining two models, the volcanic model and injection model, both require liquid water at or very near the surface. Figuring out which of these models represents best how ridges are formed would certainly help to answer the question of the thickness of the ice crust.

Figure 5: In this enhanced color image taken by Galileo, “triple” bands are clearly visible in several places, most notably in the upper part. The striking crater feature near the center of the image is the Pwyll crater, considered one of the youngest features on Europa (NASA/JPL/UA, 1998a).

2.2 Cycloids

Among some of the most fascinating and enigmatic features discovered on Europa are the so-called *cycloids* (Fig. 6). First discerned in Voyager images, the arcuate ridges puzzled scientists for years. They are most often observed as double ridges but their most primitive form is observed as a crack or trough. Previous models for the formation of cycloidal and other arcuate features depended on compression and thrust faulting. Galileo observations of these features show no evidence of compression or subduction along them. Hoppa et al. (1999c) propose that cycloidal cracks form in response to Europa’s tides. Their model suggests that the arcuate pattern forms when cracks propagate across an ever-changing stress field as Europa revolves around Jupiter. The propagation follows a curved path until it reaches a critical value where the tensile stress is insuffi-

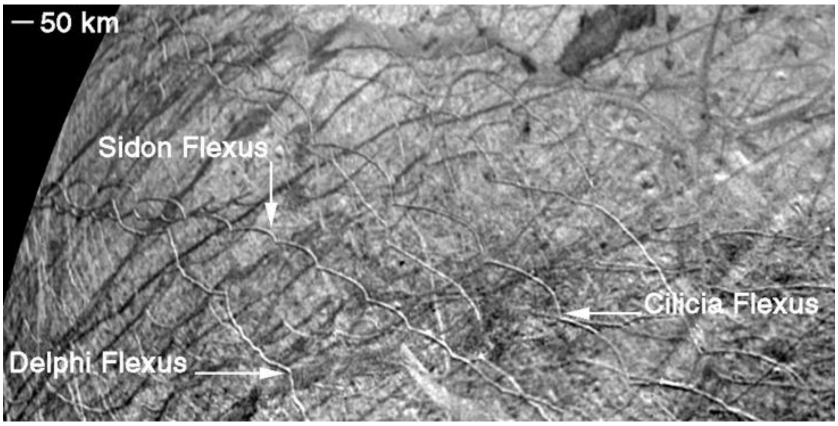

Figure 6: Cycloidal ridges near the Europa's south pole as viewed by the Voyager spacecraft (cyc, 1979).

cient to continue the propagation (Fig. 7). When cracking commences again the stress field has changed and the crack propagates in a new direction creating a cusp. Thus, one arc is created in one Europan day. This implies that cycloidal cracks form very rapidly, on the order of weeks. This model also explains several other characteristics of cycloidal features. It explains how cycloids with arcuate segments opening northward can be formed next to features that open southward. The former form when cracks propagate westward in the southern hemisphere, whereas the latter would form when cracks propagate eastward in the southern hemisphere. The opposite effect would take place in the northern hemisphere. Most arcuate features are skewed, so that there is a systematic change in the radius of curvature along the length of some cycloidal ridges. Hoppa et al.'s model cycloidal cracks are similarly skewed if the crack propagation speed varies as a function of the tension, which is reasonable to expect. This model also provides a mechanism for terminating the propagation of these cracks after several hundred kilometers. If a crack propagates into a region where the diurnal stress never reaches the strength of the ice, then cracking stops. Finally, this model explains the large-scale curvature of cycloidal chains. This overall curvature results as a crack propagates to different longitudes. Hurford et al. (2007) have made improvements to this model. By allowing material parameters to vary for each arc of an observed cycloid they get an improved fit when applying their model to actual cycloids (Hoppa et al. had used a fixed set of material parameters). Refining their new model even further, accounting for stress accumulating during non-synchronous rotation, in addition to diurnal stress, Hurford et al. got an even better fit.

2.3 Dilational bands

Dilational bands may have started out as fine cracks in the surface of Europa just like double ridges. The dilational bands seen on Fig. 8 even seem to have started out as cycloidal cracks. But instead of material building up on each side of the crack tensional

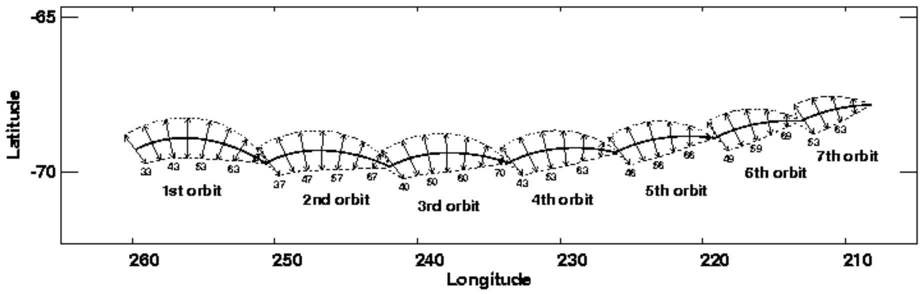

Figure 7: Model of cycloidal crack formation on Europa by Hoppa et al. The arrows represent the amplitude and orientation of the tensile stress. The numbers below the arrows indicate the hours of the orbit (Hoppa et al., 1999b).

stress has pulled it apart. Their greatest characteristic is that the landscape can be reconstructed by closing the bands and restoring structures on either side that had been separated when the band formed. The interior is generally smooth and flat, although some dilational cracks evolve into wide ridges.

Dilational bands are thought to form in a similar manner to terrestrial mid-ocean ridges (Prockter et al., 1999; Stempel et al., 2005). This is supported by the general morphology of the bands. Centered in most bands lies an axial trough and on either side linear morphological units have built up, indicating a symmetrical development. The linear units can be divided into a hummocky textured zone closest to the central trough and subparallel ridges and troughs further out. The boundaries may be marked by a sharp discontinuation or ridges. Stereo imaging has provided evidence of a dilational band that stands topographically higher than the surrounding ridged plains, consistent with emplacement of relatively buoyant material (Pappalardo et al., 1999). The observation that the band stands high today implies that topographic relaxation has not occurred as the ice cooled, or that this band formed very recently (Prockter et al., 1999). Slow non-synchronous rotation and rapid diurnal tidal flexing are the most likely sources of the tensile stress allowing for buoyant, ductile ice to rise toward the surface (Stempel et al., 2005). This is consistent with Greenberg's conclusion that the driving forces of dilation operate over large regions (Greenberg, 2005). He also concludes that dilation bands are the result of a very mobile icy crust, which is able to slide readily over a slippery liquid layer. Furthermore, his vision of the formation of dilational bands requires the crack to penetrate through the whole crust to a liquid ocean underneath. This enforces the theory of a liquid ocean beneath the surface as well as implying a thin crust. Others point out that bands do not provide direct evidence for a liquid water ocean, but may have opened above warm ductile ice (Pappalardo et al., 1999).

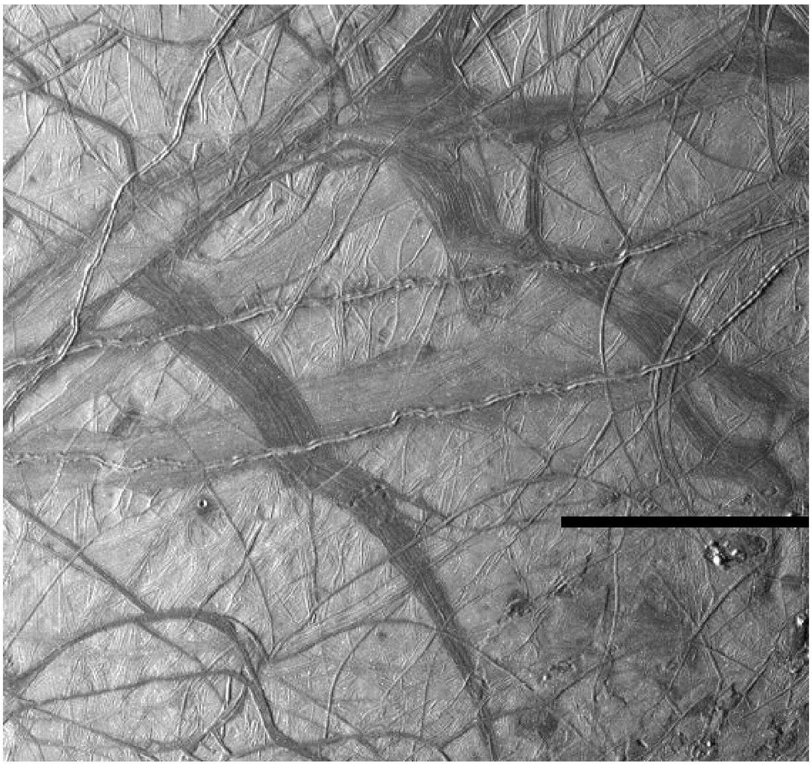

Figure 8: The broad dark features seen here are believed to be dilational bands formed by tensional stress pulling the crust apart. The arcuate shape suggests they started out as cycloidal cracks (NASA/JPL, 1997).

2.4 Converging bands

One of the unsolved problems of the formation of dilational bands is the question of surface area budget. Little evidence has been found of converging zones although Greenberg and his team believe Agenor Linea in the southern hemisphere of Europa to be a convergence feature. To support this they point out that Agenor has resisted efforts at reconstruction excluding the explanation that it is a dilational band. Furthermore, Agenor Linea's proximity to the Wedges region suggests that Agenor is the site for surface removal to balance out the surface created at the Wedges region. Other examples of convergence have been located when dilation bands and strike-slip faults have been reconstructed (Greenberg, 2005). One example can be seen in Fig. 9 where a strip of material seems to have been removed by convergence of adjacent plates.

2.5 Strike-slip fault

Strike-slip displacement along cracks in the surface ice is common and widely distributed on Europa. The first predominantly strike-slip displacement, Astypalaea Linea, was identified by Randy Tufts in 1996 (Tufts et al., 1999). Hoppa et al. (1999a) propose

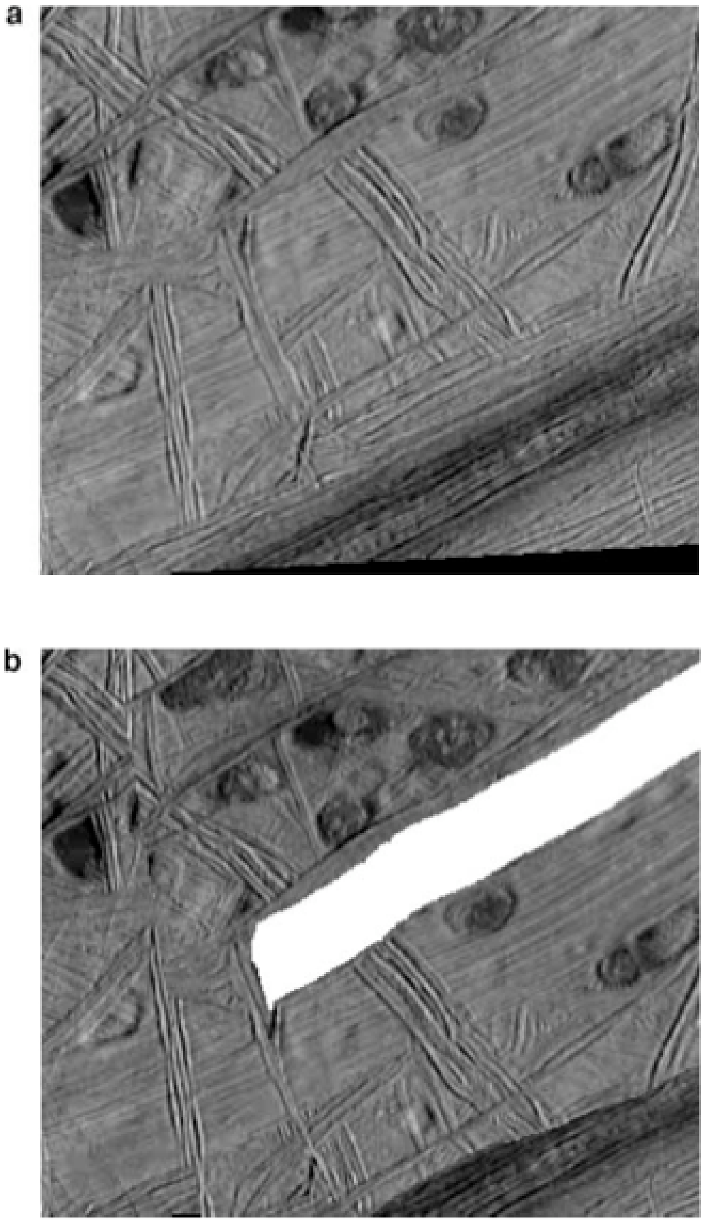

Figure 9: An example of surface convergence seen on the trailing hemisphere of Europa. The top image shows the current appearance of the region. In the lower image strike-slip faults in the surrounding area have been reconstructed resulting in an 8 km gap represented by the white section. Scientists suggest this area was removed by convergence of the adjacent plates (Sarid et al., 2002).

that diurnal tides due to orbital eccentricity may drive strike-slip motion on Europa through a process they call "tidal walking" in which faults open and close out of phase with alternate right- and left-lateral shear. As an example, a right-lateral strike-slip fault would be formed in this sequence: 1) Tensional stress opens a crack 2) The stress field shifts so that shear stress is applied and one side moves to the right compared to the other 3) The stress field shifts again closing the crack 4) The stress becomes shear stress once again but it is now applied to a closed crack and no displacement occurs. Thus, this sequence can "walk" the fault in a manner closely analogous to actual walking. Preblich et al. (2007) have modelled the process of "tidal walking" using a finite-element numerical simulation of the behaviour of viscoelastic materials. For material parameters that are plausible for the water ice composing Europa's crust, the simulation confirms earlier analytic results for strike-slip displacement along a crack that penetrates down to the liquid water substrate.

The study of strike-slip displacement has provided valuable evidence regarding the physical processes at work on Europa. Reconstruction of strike-slip fault displacement delivered the first evidence of convergence bands that compensate for the dilation that has gone on elsewhere (Sarid et al., 2002). Strike-slip study has also provided further evidence of non-synchronous rotation. Furthermore, the distribution of strike slip in both hemispheres provides evidence for polar wander. In general, right lateral shear is predicted to predominate in the far southern hemisphere, and left lateral in the north, with a mix depending on azimuth within $\sim 30^\circ$ of the equator (Hoppa et al., 1999a). When the distribution of strike slip is compared with predictions of the theory of tidal walking, the crust of Europa appears to have slid as a single unit relative to the spin axis (Sarid et al., 2002). The theory of tidal walking indicates that the top layer of the crust is decoupled from a lower layer. This enforces the idea that underneath the surface lies an ocean. In addition, the theory requires that cracks penetrate to the lower decoupling layer indicating that the ice must be quite thin, less than 10 km (Greenberg, 2005).

2.6 Chaotic terrain

We now turn our attention to the other prominent feature on the surface of Europa, chaotic terrain. In earlier Voyager images these areas appeared as dark patches but images obtained by Galileo revealed chaotic regions where ice blocks bearing marks of preexisting terrain lie stranded in a rough and hummocky texture. Greenberg et al. (1999) found by extrapolation that 18% of Europa's surface is covered by fresh chaotic terrain, another 4% is covered by modified terrain and still more older terrain has been overprinted by tectonic structures.

High-resolution images of the Conamara Chaos, the most intensily studied chaotic region, show in great detail small scale blocks of ice that have been mobilized and possibly tilted (Fig. 10). This indicates local melting where the ice blocks are analogous to buoyant icebergs on Earth. Different models have been proposed for the formation of chaotic terrain. Greenberg et al. (1999) suggest that local or regional heating melts through the icy crust, starting at the bottom at its interface with a global ocean, and continuing until the crustal thickness is reduced to essentially zero over some portion

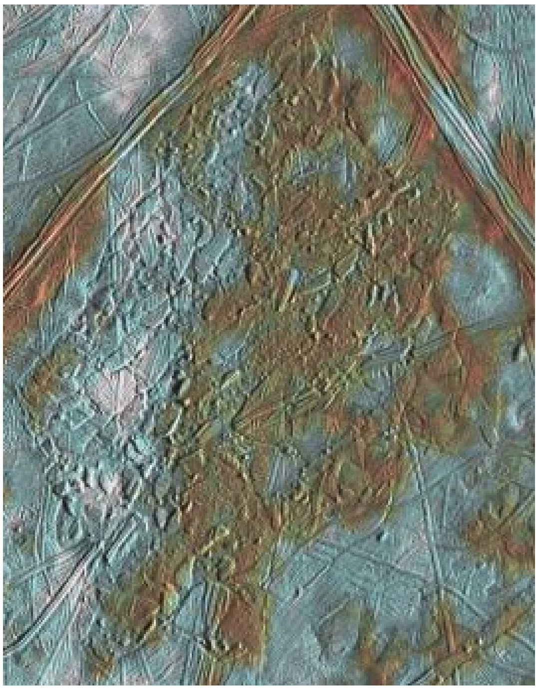

Figure 10: The Conamara chaos. Visible are blocks of ice that seem to have been broken from the crust and displaced. Some of them still bear markings of the previous terrain. Scientists differ in opinion on the formation of chaotic terrain (see text). (NASA/JPL/UA, 1998b).

of the surface. However, Pappalardo et al. (1999) point out that this model requires more heat than is available at one particular point over a period of time. Pappalardo et al. (1998) propose that chaotic terrain is the result of solid-state ice rising diapirically toward the surface. However, solid-state diapirism is inconsistent with the observed size range of chaos blocks (Collins et al., 2000). The timescale of block movement in warm ductile ice is expected to be longer than the timescale of thermal diffusion causing blocks to cool in place (Greeley et al., 2004).

2.7 Non-synchronous rotation

Like most other moons in our solar system, the Galilean satellites were long thought to rotate synchronously with their orbital motions around Jupiter, i.e. always presenting the same face to the planet. Non-synchronous rotation was predicted by Greenberg and Weidenschilling in 1984 by considering the orbitally averaged torque exerted by Jupiter on the satellite's tidal bulges (Greenberg and Weidenschilling, 1984). Tidal torques rapidly drive spin rates toward exact synchronous rotation if the orbit is circular. However, Europa's orbit is slightly eccentric ($e = 0.009$) due to its dynamical interaction with Io and Ganymede and tides tend to increase the spin rate. If Europa's ice shell is decoupled from the interior by a layer of liquid or ductile ice the outermost shell could slip over the lower layer rotating gradually relative to the direction of Jupiter. Evidence for non-synchronous rotation can be found in Europa's geological history. As the surface reorientates relative to fixed global patterns of tidal stress, systematic changes in the orientation of lineaments with age may be expected (Geissler et al., 1998). Geissler et al. analyzed the orientation and distribution of lineaments in multispectral images of Europa's northern high-latitude region performed during Galileo's first orbit of Jupiter. They found at least three distinct classes of linear features in false-colour composites made up from those images. Their distribution are shown in Fig. 11. One can see that the orientation has gone from roughly northwest-southeast in the ancient bands and bright wedges in Fig. 11a to roughly northeast-southwest orientation of the youngest fractures in 11c, i.e. a clockwise rotation of stress direction has taken place in this region over time. Other scientists have found other examples of lineaments orienting clockwise with age (Kattenhorn, 2002). Geissler et al. suggest that the reorientation can be explained by non-synchronous rotation. They do not assume that Europa's lineaments necessarily formed in response to the stresses associated with rotational reorientation, but rather that as the surface rotates it carries the lineaments with it. However, Greenberg et al. (1998) found that tidal stress results from a combination of diurnal and non-synchronous effects. More recent research has cast doubt on the argument that the observed reorientation of

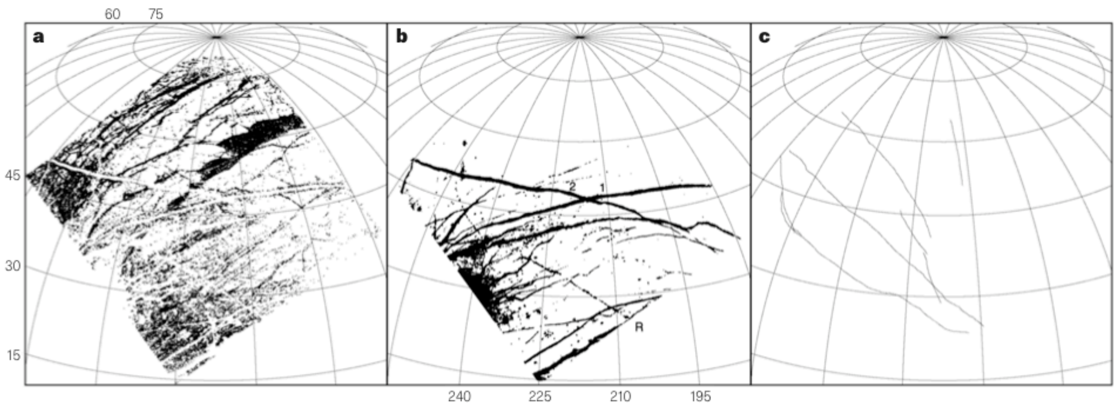

Figure 11: Distribution of lineaments of different ages. (a) shows ancient bands and bright wedges oriented northeast-southwest, (b) shows intermediate-aged triple bands and similarly coloured materials oriented west-east, and (c) shows young fractures which cross-cut the triple bands oriented northwest-southeast (Geissler et al., 1998).

lineaments results from non-synchronous rotation (Sarid et al., 2004, 2005). Sarid et al. show that the sequence of reorientation would fit as well into an arbitrary model with rotation in the opposite sense from that predicted by theory. Nevertheless, the changing orientation of lineaments observed on the surface is consistent with the theory of non-synchronous rotation, but does not provide compelling evidence for it. In addition, other evidence has been found that support theoretical predictions. Firstly, the crust is expected to expand west of the sub- and anti-jove point as the surface stretches over the tidal bulges. Geissler et al. report a large region near Europa's equator to the west of the anti-jove point to be characterized by relatively short, dark wedge-shaped bands, thought to be extensional bands. Secondly, if Europa rotated synchronously with respect to Jupiter, an asymmetry in crater density should be seen in the trailing and leading hemisphere. Indeed, no such asymmetry has been observed. Thirdly, Hoppa et al. (2001) produced a model of the formation of cycloidal ridges which requires non-synchronous rotation.

Future exploration carries the task of confirming with direct measurements the rate of rotation of Europa's crust. From the limit of less than one cycloidal crack forming per 180° of rotation relative to the direction of Jupiter, and the estimated age of the surface of 50 Myr, Europa's non-synchronous rotation period has been estimated as $<$ 250,000 years. A rotation rate in this range is fast enough to be directly observed in the not-too-distant future (Hoppa et al., 2001). The confirmation of non-synchronous rotation is an important step in verifying the existence of global subsurface ocean on Europa.

3 Inner structure

From spectroscopic measurements in the 1960's it was evident that Europa's surface consisted mostly of water ice and gravitational measurements from both Voyager and Galileo spacecrafts indicate a differentiated body (Greeley, 1999). Detailed analysis of the data reveal a dense metallic core of radius 700 km, a silicate mantle 700 km thick and an outer layer of H_2O as thick as ∼150 km. The extreme cold temperatures on the surface of Europa and the lack of a dense atmosphere eliminate the possibility of water existing in liquid form on the surface. However, tidal dissipation resulting from Europa's eccentric orbit and Jupiter's enormous tides may provide enough frictional heat to keep the water in liquid form in a subsurface layer (Greenberg, 2005; Peale et al., 1979). Magnetic field measurements strongly support this hypothesis and as described in previous chapters the formation of many surface features can be explained by the existence of an interior liquid ocean (magnetic field measurements are the subject of Chapter 4).

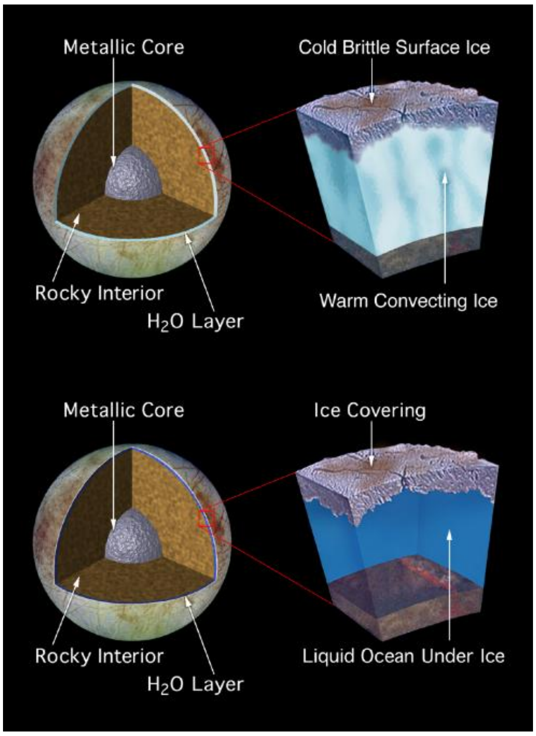

Figure 12: Two models have been proposed for the inner structure of Europa. Top model: A warm, convecting ice layer lies several kilometers below a brittle ice crust. Bottom model: A thick layer of liquid water lies below a thin ice covering (NASA/JPL, 1999).

Ojakangas and Stevenson (1989) found that if the total thickness of the water layer exceeds 25 km it is unlikely to be completely frozen. The thickness of the outermost ice shell is the subject of a great debate between scientists. Two main models have been proposed: A thick shell consisting of a cold brittle surface layer overlaying a warm convecting layer and on the other hand a thin ice shell directly above a thick liquid layer (Fig. 12). Billings and Kattenhorn (2005) published a list of estimates for the thickness of the ice shell found by various methods. They found that the thickness ranges from <1 km to >30 km depending on the method used. The range results from the difference in methods, some apply to the total thickness of the ice shell including a ductile[2] lower layer while other methods give only the thickness of the elastic[3] layer. Billings and Kattenhorn (2005) also used flexure analysis, where they modeled the elastic ice layer as flexing under a line load, to assess the thickness of the elastic layer. For three linear ridges examined they found the thickness to be 500-2200 m in two sites and 200-1000 m in the third. This is in accordance with the general conclusion that the thickness of the elastic layer is ≤ 2 km (Pappalardo et al., 1999). Ojakangas and Stevenson (1989) used thermal equilibrium to estimate the global thickness and found an average thickness of 13-25 km depending on the type of rheology (Maxwell rheology or generalized flow law). Hoppa et al. (1999c) explained the formation of cycloidal features on Europa with a model that requires the shell thickness to be only a few kilometers and directly overlying a liquid ocean. By inspecting impact craters Schenk (2002) infers a total ice thickness of at least 19 km. For a fluid layer that is heated from below or within and cooled from above gravitational unstability should arise from the density difference of the light warm fluid and the cool dense fluid (Turcotte and Schubert, 2002). Scientists suggest that if the layer reaches a certain thickness convection would take place in the ductile layer.

3.1 Convection and diapirism

Pappalardo et al. (1998) calculated the required thickness of a warm sublayer for the onset of solid-state convection. From the definition of the critical Rayleigh number

$$Ra_{cr} = \frac{\rho g h^3 \alpha \Delta T}{\kappa \eta} \tag{1}$$

where the density is assumed $\rho = 923\, kgm^{-3}$, the thermal expansivity $\alpha = 1.4 \cdot 10^{-4}\, K^{-4}$, the thermal diffusivity $\kappa = 1.4 \cdot 10^{-6}\, m^2 s^{-1}$, $\Delta T = 76\, K$, $g = 1.31\, ms^{-2}$ and the effective viscosity $\eta_{eff} \cong 10^8 - 10^9 MPa\, s$ Pappalardo et al. found, for $Ra_{cr} = 2000 \pm 1500$, the thickness of the sublayer to be $h = 2 - 8\, km$ at the start of convection. They suggest that diapirism, the buoyant upwelling of relatively warm and light ice, generates roughly circular surface features collectively called pits, domes and spots (Fig. 13). The formation of salt domes on Earth are another example of diapirism. Greenberg (2005), an advocate of the thin ice model, criticizes the definition of pits, spots and domes and claims they are simply locations of chaotic terrain which he explains as places of melt through of the thin ice. Pappalardo and Barr (2004) later revised their model to a double-diffusive convection model, where the required buoyancy is achieved by a difference in composition of the warm diapir and the surrounding ice. Nimmo and Giese (2005) examined both the

[2]Ductile or plastic deformation is a continuous, irreversible deformation without fracture.

[3]Elastic materials deform when a force is applied and return to their original shape when the force is removed. Earth's crust is divided in a similar manner.

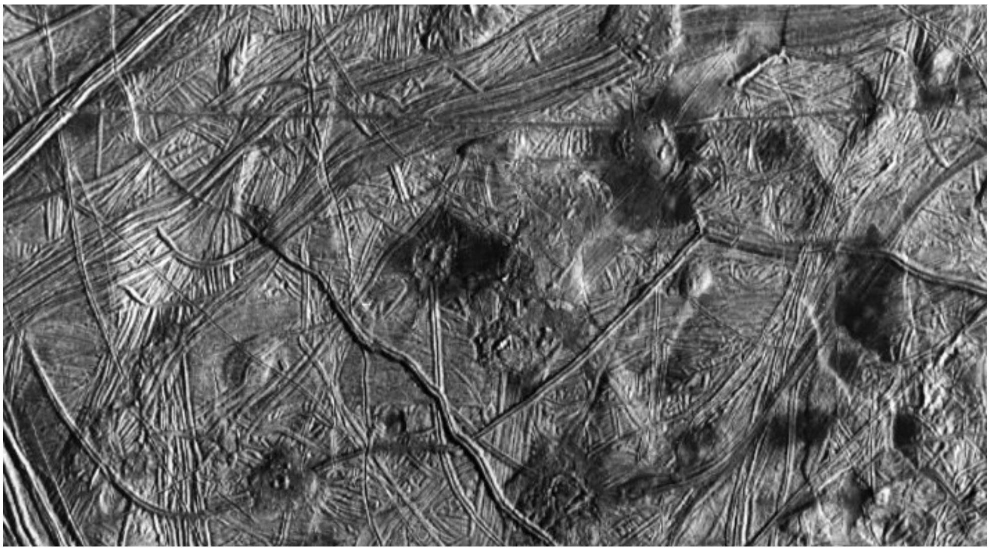

Figure 13: Scientists suggest that the semicircular uplifted features seen in this image are surface manifestations of diapirs rising through the outermost icy shell (NASA/JPL-Caltech, 1997).

melt through model and the diapirism model in relation to chaos formation and found that neither could satisfactorily explain the development of chaotic terrain. In another article Nimmo, in association with Michael Manga, used the diameter of dome-shaped features to infer the thickness of a conductive stagnant lid overlying a convective layer (Nimmo and Manga, 2002). They also used the mean observed dome diameter to infer the thickness of a lower thermal boundary layer. In the following section Nimmo and Manga's estimations of the thickness of the stagnant lid are re-calculated.

3.2 Estimation of the thickness of the stagnant lid

The surface temperature of Europa is around 100 K (Greenberg, 2005) and the ice near the surface behaves in a rigid fashion. This is the conductive stagnant lid. The top portion of the stagnant lid ($\leq$2 km; Pappalardo et al. (1999)) behaves elastically and may reduce the deformation caused by convection. Nimma and Manga assume that the thickness of the stagnant lid, δ_0, and the thickness of the elastic layer, t_e, are simply related because both are dependent on temperature. They give $t_0 = \phi\delta_0$ where $\phi = 0.4$ by comparison of the elastic thickness with the oceanic lithosphere on Earth. The maximum stress induced on the elastic layer by a rising spherical diapir of radius r can be found by applying Archimedes' principle to a cube of diameter $2r$. The stress is given by $S = \frac{F}{A}$ where $F = \Delta\rho V g = \Delta\rho(2r)^3 g$ is the buoyancy force and $A = (2r)^2$ is the area of the top face of the cube. Thus, the maximum stress is $S = \Delta\rho 2rg$. Following Watts (2001) the height, h, of the surface deformation by an ascending spherical diapir of initial radius r

is given by

$$h = \frac{2r\Delta\rho}{\rho} \frac{1}{1 + \frac{16D\pi^4}{\lambda^4 \rho g}}, \; D = \frac{Et_e^3}{12(1-\sigma^2)}. \tag{2}$$

E is the Young's modulus, λ is the effective wavelength of the diapir, σ is the Poisson's ratio and ρ the density of the ice. $\Delta\rho$ is the density difference between the diapir and the surrounding ice and g is the gravitational acceleration.

The change in volume, and therefore the change in density, $\Delta\rho$, can be calculated from the definition of thermal expansivity (Turcotte and Schubert, 2002):

$$\alpha = \frac{\Delta V_0}{V} \Delta T. \tag{3}$$

For the given value of $\alpha = 1.4 \cdot 10^{-4}\, K^{-1}$, the temperature difference $\Delta T = 40\, K$ and the ice density $\rho = 917\, kgm^{-3}$ we get $\Delta\rho = 5.1\, kgm^{-3}$. The authors assume that the effective wavelength appropriate for a spherical diapir is $\lambda = 4r$ and for an elongated diapir $\lambda = 8r$. The elongated diapirs account for the lateral spreading of the diapir as the stagnant lid is approached. The effect of spreading is the reduction of the surface deformation by a factor of four (Koch and Manga, 1996, as cited by Nimmo and Manga). From equation (2) we can now calculate the topography for a given radius of a diapir and thickness of the stagnant lid.

Fig. 14 shows the results of the calculations. Assuming the lowest detectable height of domes to be $10\, m$ we can see that the minimum radius of a spherical diapir capable of deforming the surface to a detectable degree is 1 - 2 times δ_0. Spreading diapirs show the same results. The smallest dome-shaped features detected on Europa (also called lenticulae) have a radius of $2\, km$, implying that the value of δ_0 unlikely exceeds $2 - 4\, km$. Taking uncertainties into consideration, Nimmo and Manga find the lid thickness to range from 1 - 5 km. The uncertainties lie mainly in determining ϕ and the properties of the ice, which are poorly known. The debate of the thickness of Europa's ice shell will likely not be resolved until new data emerge from future exploration missions.

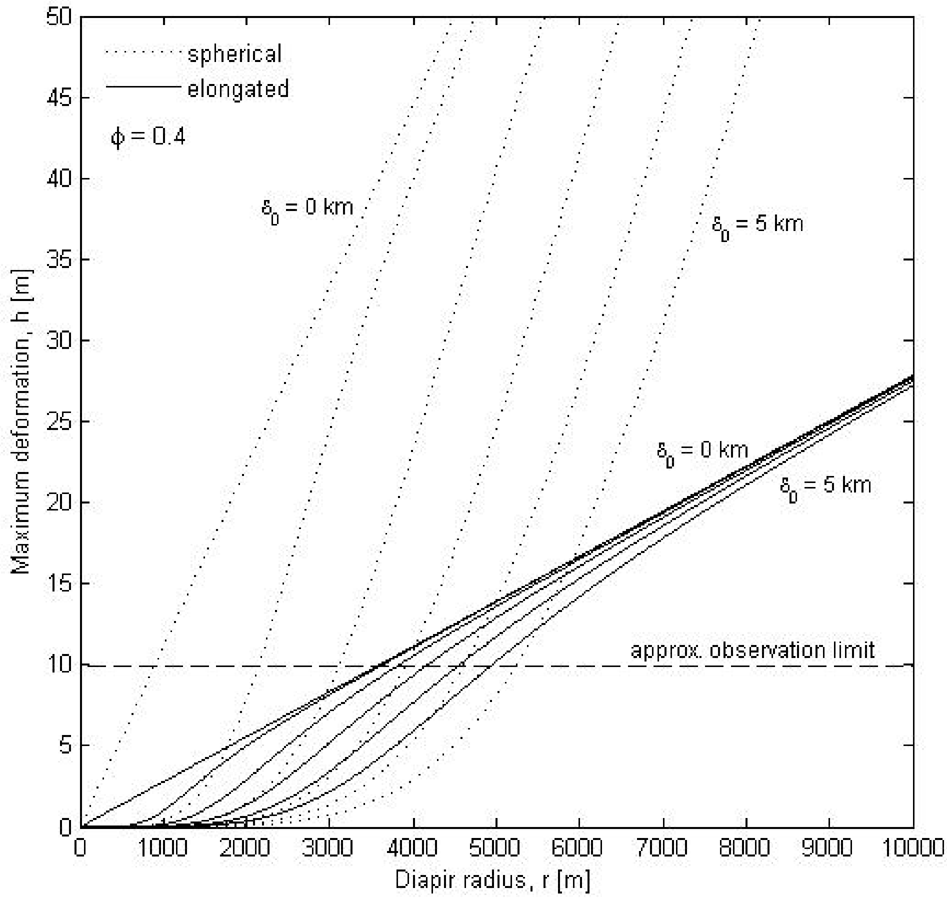

Figure 14: Surface deformation, h, as a function of initial diapir radius, r, and conductive lid thickness, δ_0. Dotted lines show results for spherical diapirs and solid lines for elongated diapirs.

4 Magnetic field measurements

As mentioned in Chapter 1 the strongest evidence for a current subsurface ocean on Europa comes from measurements of Jupiter's magnetic field in the vicinity of the satellite. Jupiter's magnetic field is slightly tilted and as Europa orbits the rotating planet, the moon experiences a time-varying magnetic field. This time-varying magnetic field drives inductive currents through the electrically conducting layer of liquid water believed to lie near the surface. The inductive currents generate a secondary field, whose source can be represented as a time-varying magnetic dipole moment lying in Europa's equatorial plane with an orientation approximately anti-parallel to the instantaneous orientation of the primary field (Kivelson et al., 2000). Scientists have found evidence of this secondary field in magnetic measurements from Galileo. First results were inconclusive because the possibility of a permanent dipole moment tilted toward the y-axis[4] could not be excluded as the source of the observed magnetic perturbations (Kivelson et al., 2000). The reason was that the data used came from the close Europa passes on Galileo's fourth and fourteenth orbit (E4 and E14) and both passes occurred in Jupiter's northern magnetic hemisphere. An induced equatorial dipole moment changes orientation and amplitude over a synodic period in a predictable manner. To confirm the existence of the inductive field a flyby in the southern magnetospheric hemisphere was designed. Kivelson et al. found that the signature observed on the close Europa pass of the 26^{th} orbit around Jupiter (E26), which occurred in the southern hemisphere, was consistent with a reorientation of the equatorial dipole moment confirming that Europa has an induced magnetic field.

In addition to the induced magnetic field there are magnetic field perturbations owing to the interaction of Europa's atmosphere with the jovian magnetospheric plasma (Schilling et al., 2007; Kivelson et al., 2000). Europa's tenuous atmosphere consists mostly of oxygen, with a vertical O_2 column density of $2.4 - 14 \cdot 10^{18}\, m^{-2}$ (Hall et al., 1998). The magnetospheric plasma which Europa travels in rotates with Jupiter at approximately the same speed. The azimuthal speed of the plasma is faster than the orbital velocity of the Europa, so the plasma overtakes the satellites (Kivelson et al., 2004). This is true for the other Galilean satellites as well. The interaction of the plasma with the atmosphere generates currents which leads to a secondary induction effect, creating discrepancies in the modeled signature and the data (Kivelson et al., 2000). The time-varying field generated in the interior of the moon also has an effect (Schilling et al., 2007). Schilling et al. combine in their model the electromagnetic induction taking place in the interior of Europa and perturbations from the plasma interactions. Their results show an improved fit to observation data. Fig. 15 and 16 show the observed and modeled magnetic field for the E4 flyby in the EPhiO coordinate system. The E4 pass of Europa occurred in Jupiter's northern magnetic hemisphere (Kivelson et al., 2000). The red curve shows the magnetic field measured by the Galileo spacecraft (Kivelson et al.,

[4] The coordinate system used in Kivelson et al. is Europa-centric with x along the co-rotating plasma flow, y radially in toward Jupiter, and z parallel to Jupiter's spin axis. This coordinate system is referred to as EPhiO (Kivelson et al., 2000).

1997; as cited by Schilling et al. 2007). The dashed black curve represents results for a pure plasma interaction without induction in the interior. The other lines show the predicted field including induction for a range of ocean conductivities. In fig. 15 the assumed thickness of the crust is 25 km and the assumed thickness of the ocean is 100 km. In fig. 16 the assumed value of the thickness of the crust is the same as in fig. 15 but the ocean assumed to be 25 km thick. By considering results from two additional flybys (E14 and E26) the authors conclude that an ocean conductivity of 500 mS/m or larger combined with ocean thicknesses of 100 km and smaller fit the magnetic field data best. This leads to the following relation: electrical conductivity $\times$ ocean thickness $\geq$ 50 S/m km. Because the induced field is almost saturated for ocean conductivities $>$ 500 mS/m the authors are not able to set an upper limit for the conductivity. The results of Schilling et al. (2007) agree with the findings of Zimmer et al. (2000). They conclude that Europa possesses a conductive layer with conductivity of at least 60 mS/m at maximum depth of 200 km.

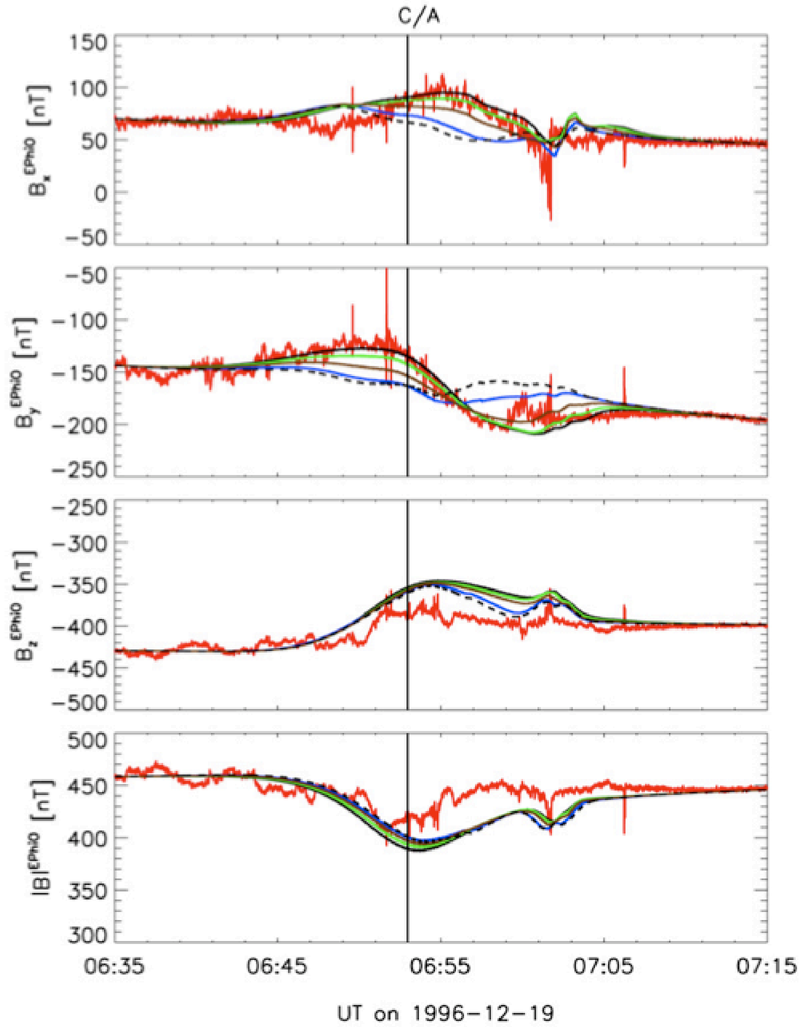

Figure 15: Observed and modeled magnetic field from Schilling et al., 2007. Data from the E4 flyby was used and the coordinate system is EPhiO. The red curve shows the measured field (Kivelson et al., 1997). The dashed black curve shows the predicted field when no induction is included in our model. The predicted field by including induction is shown for the ocean conductivities σ_{oc}: 100mS/m (blue), 250 mS/m (brown), 500 mS/m (green), and 5 S/m (black). The assumed thickness of the crust is 25 km and the assumed thickness of the ocean is 100 km (Schilling et al., 2007).

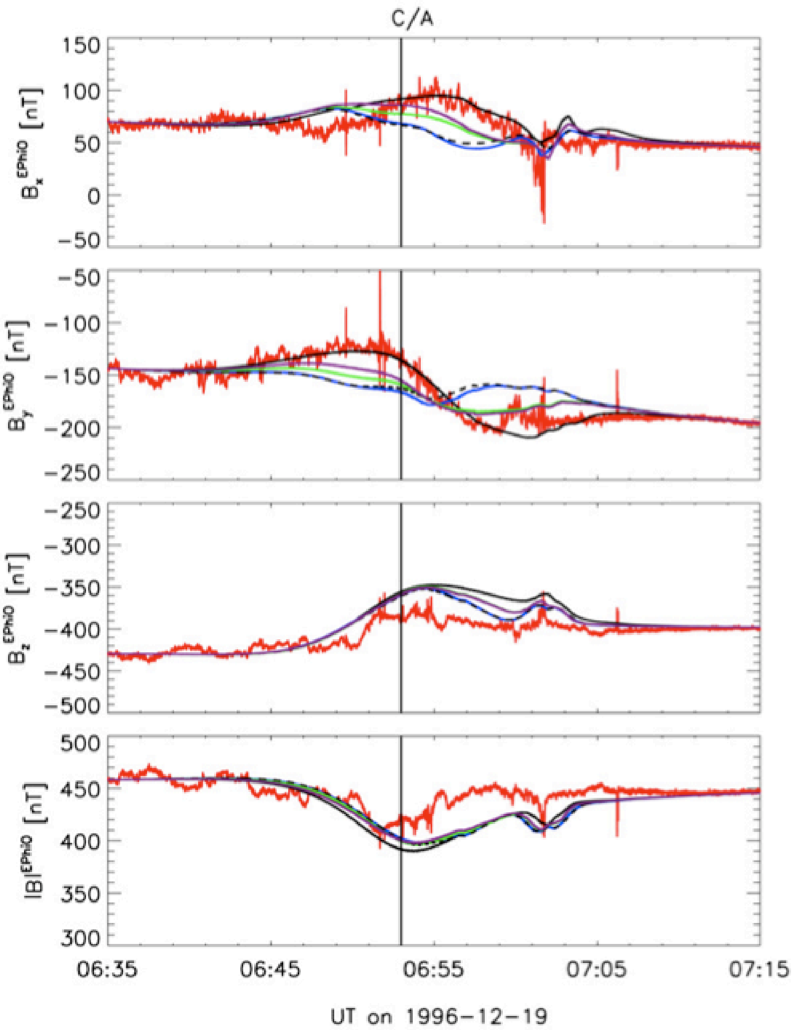

Figure 16: Same as figure 11 for an ocean thickness of 25 km. The predicted field by including induction is shown for the ocean conductivities σ_{oc}: 100 mS/m (blue), 500 mS/m (green), 1 S/m (purple), and 5 S/m (black) (Schilling et al., 2007).

5 Search for life on Europa

The great allure of Europa lies in the possibility of a vast subsurface ocean encircling the satellite beneath an icy crust, as indicated by magnetic field measurements (Kivelson et al., 2000). Water is one of the fundamental conditions for the evolvement of life as we know it (Chyba, 2000). This makes Europa one of the likeliest places in our solar system to harbor extraterrestrial life. Two other places in our solar system have been proposed as suitable for life, either in the past or present: our neighbour Mars and Saturn's largest moon Titan (Lunine, 2005). Other requirements of life as we know it include the presence of organic material, notably including carbon, and a useful source of free energy (Chyba, 2000). All these factors help scientists to detect signs of life. The near-infrared mapping spectrometer on Galileo (NIMS) found no evidence of organic molecules on the surface (Lunine, 2005). This does not exclude the potential for organic molecules existing below the icy crust, but indicates that when the molecules reach the surface the carbon-hydrogen bonds are broken apart by particle radiation and the hydrogen escapes into space. NIMS has however found evidence of hydrated minerals, such as evaporite salts and clays, on the surface of Europa, suggesting that water is extruded to the surface. Greenberg (2005) points out that life could exist in these cracks and slivers of sunlight might reach these organisms enabling photosynthesis. Others have suggested the thermal diapirs as habitable environments (Ruiz et al., 2007). Other sources of free energy have also been proposed. Organisms might feed directly off the thermal energy radiating from the ocean base, similar to creatures around so called black smokers on the ocean floor of the Earth. Tidal currents might provide kinetic energy and even the magnetic fields in the ocean have been considered as possible sources of free energy (Lunine, 2005). The future exploration of Europa centers on one hand on confirming the existence of liquid water beneath the icy crust, e.g. by radar measurements of the thickness of the outermost layer and the behaviour of the ice shell as it is pulled and squeezed by tidal forces, and on the other hand on finding signs of life. The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have joined together in the Europa Jupiter System Mission (EJSM) in the exploration of Jupiter, Europa and Ganymede with the goal of answering the question whether the Jupiter system harbors habitable worlds (NASA/ESA, 2009). It consists of two flight systems, the Jupiter Europa Orbiter (JEO) from NASA and the Jupiter Ganymede Orbiter (JGO) from ESA, planned for two separate launches in 2020 arriving at the Jupiter system in 2025.

6 Conclusion

Strong evidence have been found of a global layer of liquid water underlying the frozen crust of the icy moon Europa. Results from magnetic measurements require a layer of liquid water with dissolved salts underlying the ice shell at relatively shallow depths. A liquid layer is necessery to enable the crust to deform sufficiently to account for the stress needed to overcome the strength of the ice, leading to the formation of ridges, cycloids and other linear features on the surface. Non-synchronous rotation and polar wander suggest that the crust is decoupled from the mantle by a liquid layer enabling the ice shell to slip as a whole relative to the spin axis.

Although the science community generally agrees on the existence of a subsurface ocean the thickness of the ice shell covering the satellite is one of the most strongly debated issues concerning Europa with estimates ranging from <1 km to >30km. Unfortunately, existing data is unsufficient to resolve this matter and scientists will have to wait for new data to be collected, hopefully within the next 20 years. Another question burning on scientists, and the public as well, is whether Europa, or other moons in the Jupiter system, harbor conditions suitable for the existence of life. The presence of water certainly makes Europa a primary target for astrobiologists and hunters for extraterrestrial life but we should not expect intelligent life forms. If there is life on Europa it is more likely in the form of microbes and tiny creatures able to survive the harsh conditions of the icy world. All we can hope for is that our curiosity and thirst for knowledge that drives our exploration of the solar system will one day bring us the answers of all these unanswered questions, whether it will be in the time of our generation or the next.

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