FORMATION OF EUROPAN RIDGES BY INCREMENTAL ICE WEDGING

by

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ABSTRACT

Double ridges are one of the most ubiquitous surface features on Europa. Double ridges are pairs of linear topographic highs on the order of 100 m in topographic relief that are divided by a narrow trough. The double ridges are narrow, with widths less than 5 km. They span 100s of km, overlap with one another, and cover much of Europa's surface. The ubiquity of double ridges implies that the process forming them can occur globally rather than in a single region with unusual properties. Constraining the formation of ridges may provide constraints on possible shell thicknesses and thermomechanical states globally on Europa. However, the mechanism responsible for ridge formation is still uncertain. This thesis discusses tests of the viability of incremental ice wedging to create topography like that observed at Europa's ridges through finite element modeling. This work also narrows the range of depths at which a wedge could create a double ridge. The results indicate that shallow wedges less than 500 m from the surface can create deformation similar to observed double ridges.

CHAPTER 1. INTRODUCTION

This thesis presents my work on modeling the formation of double ridge features on Jupiter's moon Europa through incremental ice wedging. I used a finite element method (FEM) approach, and COMSOL Multiphysics was the primary FEM modeling software. Chapter 2 discusses the background of this project and previous modeling of similar ridge formation theories. Chapter 3 explains the setup of the elastic model used in this project, including a full description of the thermal modeling done in support of the primary models. Chapter 4 reports the results of the COMSOL Multiphysics models. Finally, Chapter 5 discusses and interprets the results and summarizes what conclusions can be drawn from the models.

CHAPTER 2. LITERATURE REVIEW

Europa is one of the four Galilean moons of Jupiter and is an icy world with a subsurface water ocean. Europa's surface is very young; cratering records place its age between 30 and 70 million years, implying recent geologic activity (Bierhaus et al., 2009). The existence of a subsurface ocean is supported by several lines of evidence, including the detection of an induced magnetic field by Galileo, the spacecraft that visited the Jupiter system in the 1990s and early 2000s (Kivelson et al., 2000). However, the thickness of the ice shell, the details of its internal structure, and the specifics of the geologic activity altering the surface are all unknown (Schubert et al., 2009). Estimates of shell thickness range from under 10 km to 40 km thick (Pappalardo et al., 1999). An ice shell 10 km or less implies heat transfer from the interior through pure conduction, but thicker shells would have two layers: a relatively cold, conducting layer and an underlying warmer, convecting layer (Barr and Showman, 2009). Without an ability to probe the subsurface directly, information about the shell's interior must be inferred from observations from the exterior. Understanding the connection between surface features and the shell interior is key to constraining the structure and thickness of the shell itself. If we can explain the formation and evolution of a certain surface feature we may be able to constrain the conditions and activity of the material beneath it.

The most prevalent type of landform on Europa are ridges, including single ridges, double ridges, and ridge complexes (Prockter and Patterson, 2009). The most common variety of ridges is double ridges (Prockter and Patterson, 2009). Double ridges are linear features consisting of a pair of topographic highs with a V-shaped trough in between them. Double ridges have widths from around 200 m to over 4 km (Prockter and Patterson, 2009). They are tens of kilometers to hundreds of kilometers long. Double ridge morphologies are mostly uniform over long distances, and the ridges can be notably straight over a majority of their length. Inner slopes of ridges are very straight, forming the V-shaped troughs along the middle of the double ridges (Pappalardo et al., 1999; Prockter and Patterson, 2009). The background terrain that surrounds a double ridge is sometimes visible along the outer slopes of ridges, possibly uplifted by ridge formation, but other times seems mantled by dark reddish material thought to be deposited by mass wasting. Marginal troughs a few tens of meters deep run along ridges, as do some subparallel flanking fractures

(Prockter and Patterson, 2009). Ridges have uniform heights ranging from tens of meters to ~350 meters above surrounding terrain (Prockter and Patterson, 2009).

Constraining the formation of ridges may provide limitations for possible shell conditions. If a formation theory requires a certain thermal structure or shell thickness to form double ridges, that constrains the hypotheses of shell structure compatible with the formation of double ridges. These constraints would apply globally on Europa because of the wide distribution of ridges across the surface. Also, as there are multiple generations of ridges overlapping, the conditions suitable for forming ridges must have lasted several times longer than the time required to form a new ridge (Pappalardo et al., 1999; Prockter and Patterson, 2009).

Multiple formation models have been proposed for double ridges, most relying on pre-existing cracks within Europa's shell. These pre-existing cracks are linked to tidal forces stressing the shell. Some formation theories rely on an extremely thin shell, only a few kilometers thick, which allows material from the ocean below to reach the surface as cryovolcanic debris or rise to the near-surface and stall as subsurface sills (Kadel et al., 1998; Dombard et al., 2013). A similar theory called tidal pumping posits that material rises into cracks and then is extruded over the course of a tidal cycle (Greenberg et al., 1998). Yet another theory suggests sill emplacement causes ridge deformation, as the liquid water sill slowly freezes (Johnston and Montési, 2014). Others assume that cracks on Europa's surface are shallow, not reaching the ocean, and that the double ridges are created from strike-slip motion and frictional heating (Han and Showman, 2008). Some suggest that ridges form through diapirism, as a warm layer of ice rises from underneath a colder overlying layer (Head et al., 1999). This thesis discusses the viability of incremental ice wedging as a theory of ridge formation. Incremental ice wedging is a cyclical process based on liquid water periodically filling cracks in Europa's shell and partially freezing. The water freezes onto the walls of the crack in layers, over time growing into an ice wedge intrusion that deforms the surface into a double ridge (Melosh and Turtle 2004; Han and Melosh, 2010).

These formation theories each have individual weaknesses. Cryovolcanism is unlikely to explain the uniformity of the ridges over long distances because it would require the deposition of cryovolcanic levees to accumulate uniformly over a ridges' entire length (Prockter and Patterson, 2009). The tidal pumping theory cannot move enough material to the surface due to the narrow openings involved in tidal forces pulling open the cracks (Gaidos and Nimmo, 2000). Water is expected to freeze within the cracks, which inhibits the motion of slush to the surface to form debris-built ridges (Prockter and Patterson, 2009). Diapirism struggles to explain why ridges with multiple sets of topographic highs sometimes form (Prockter and Patterson, 2009). Prockter and Patterson (2009) favor a shear heating theory of formation, primarily because it does not require the whole shell to be cracked. As we will discuss later in chapter 5, the incremental ice wedging theory could occur without water being sourced from the ocean and could occur in conjunction with shear heating.

In this project, we present modeling of the formation of ridges as the result of an incrementally growing ice wedge to test whether the resulting surface deformation matches the observed morphology of double ridges and whether this formation mechanism addresses some of the weaknesses described in the previous paragraph. I used finite element modeling (FEM) to test whether the resulting surface deformation matches the observed morphology of double ridges. Modeling different cases illuminates how the surface deformation is related to different physical parameters, like the depth of ice wedge. While previous modeling has investigated how the shape of an intrusion affects surface deformation (Johnston and Montési, 2014), I compare the topography caused by intrusions at different depths to observed topography. Specifically, I look at the widths of the deformation in our results and determine the probable depth of an ice wedge forming a ridge. The intrusion used by Johnston and Montési (2014) is different from an ice wedge as it is instead a sill that is emplaced and then freezes in place, rather than a slowly, cyclically building wedge, as I test here. The following section will provide background and support for our work based on previous work and publications.

2.1 Interior Structure of Europa and Ridge Formation

Europa's crustal structure is connected to the probability of different ridge formation theories, which means understanding the formation of ridges helps probe properties of Europa's shell. Schubert et al. (2009) provide a nuanced discussion of possible Europa interior structures. Based on the gravitational data and observations of Europa's shape from the spacecraft Galileo, Europa is thought to be composed of (in order from interior to surface) a metallic core, a rocky mantle, a liquid water ocean, and a solid water-ice shell. There are many outstanding questions regarding the nature of the two H_2O-rich layers, but the induced electric field detected by the Galileo magnetometer provides strong evidence that Europa has a global subsurface ocean (Kivelson et al., 2000). The total thickness of the liquid ocean and ice shell is thought to be around 100 km thick. The thickness of the ice shell is debated (Nimmo and Manga, 2009), but is estimated to be more than a few km (Turtle and Pierazzo, 2001) and less than or equal to 40 km (Pappalardo et al., 1999; Schubert et al., 2009).

Pappalardo et al. (1999) evaluated the observed indicators of the ocean from early analysis of Galileo imaging. They discussed nine types of geological evidence as they were understood at the time. The geological lines of evidence supporting the existence of a fluid subsurface include impact morphologies (McKinnon and Melosh, 1980), lenticulae (Reynolds and Cassen, 1979; McKinnon, 1999), cryovolcanic features (Pappalardo et al., 1999), ridges (Sullivan et al., 1997; Kadel et al., 1998; Head et al., 1999), topography, and global tectonics (Pappalardo et al., 1999). Even in 1999, Europa was recognized as having a young surface and being a possibly geologically active body. While this activity does not necessarily mandate that a global ocean exists, Pappalardo et al. (1999) suggest that an ocean would provide an explanation for a wide variety of geological features observed on Europa. They consider five formation models of ridges, some of which have deformation mechanisms in common with the ice wedging model. One of these models is an early form of the incremental ice wedging theory we tested.

The volcanic and tidal squeezing mechanisms rely on material from the ocean below reaching and building up on the surface, which requires material to rise farther than the ice wedging model. The farther liquid water has to travel through an ice shell the more pressurized a subsurface ocean would have to be in order to overcome the negative buoyancy of liquid water relative to solid ice. Liquid water is therefore more likely to rise into the shell without reaching the surface than to flow over the surface. The tidal squeezing model is very similar to the ice wedging model, except it assumes the water within the crack does not freeze within a tidal cycle and is instead extruded onto the surface when the tidal forces close the crack. At least some of the water that rises into the crack will be cooled enough by the surrounding ice to freeze, making a purely tidal squeezing mechanism of ridge formation unlikely.

The diapirism mechanism of ridge formation is similar to the ice wedging formation model in that it assumes the surface deformation is caused by a vertical planar intrusion in line with the ridge deformation. The source and type of intrusion separates the two theories and leads to different associated shell models. The planar diapirism requires a warmer, buoyant layer of ice to rise into the crack, but does not require a subsurface ocean. The compression model of ridge formation does rely on the tidal stresses acting on an existing crack (Pappalardo et al., 1999). The freezing wedge theory I test here would imply a liquid ocean and a thin shell of under 30 km.

The incremental ice wedging model as described in Pappalardo et al., 1999 does not specify the source of the water filling the crack other than linking it to possible tidal activity, but otherwise the theory matches the version tested here closely. Essentially the incremental ice wedging theory proposes water periodically gets into a crack in Europa's shell and freezes there, slowly forming an icy intrusion. Probable water sources are the subsurface ocean or regional melt. I assume for thermal modeling in this project that the water for the ice wedge is sourced from a subsurface ocean and that water rises into a crack and freezes each tidal cycle. The details of this model will be described in chapter 3, but it is important to note the water intruding on the crack is taken as a constant heat source. The other possible source of water is frictional melt from the motion caused during a tidal cycle falling into the crack and refreezing, which would cause the thermal environment around an ice wedge to differ from what is considered in this work. The meltwater source would create a colder formation case than the ocean water source. Possible water sources for ice wedging will be discussed further in later sections.

2.2 Ridge Morphology

The morphology of ridges and their evolution guides the creation of ridge formation theories. Prockter and Patterson (2009) provide a detailed discussion of ridge observations. There are a range of morphologies that are referred to as ridges. These include raised-flank troughs, double ridges, and complex ridges. Ridges and troughs can be thousands of kilometers long. Some are linear and others are curved cycloidal. Double ridges are the most common type of Europan ridges and are the type our model attempts to recreate. Figure 2.1 shows a section of ridge terrain as an example of double ridge morphology.

Double ridges have widths from around 200 m to over 4 km. They are tens of kilometers to hundreds of kilometers long. Double ridge morphologies are mostly uniform over long stretches of the ridges and the ridges can be notably straight over a majority of their length (Prockter and Patterson, 2009). Inner slopes of ridges are very straight and form V-shaped troughs along the middle of double ridges. Some interior slopes are striated perpendicular to the run of the ridge (Prockter and Patterson, 2009). These striations are thought to be caused by faulting and slumping followed by mass wasting. Some ridges have a shorter inner ridge or multiple inner ridges (Prockter and Patterson, 2009).

The surrounding background terrain is sometimes visible on the outer slopes of ridges, but other times seems mantled by dark reddish material thought to be deposited by mass wasting (Prockter and Patterson, 2009). Marginal troughs a few tens of meters deep run along ridges, as do some subparallel flanking fractures. These sections of ridge morphology may be caused by lithospheric loading or uplift (Prockter and Patterson, 2009).

Ridges have uniform heights ranging from tens of meters to ~350 meters above surrounding terrain. Inward facing slopes average 36.5 degrees and outward ones average 38 degrees (the angle of repose is 34 degrees) (Kadel et al., 1998; Prockter and Patterson, 2009). Some exterior slopes are locally steeper, up to 55 degrees. These sections may have partially consolidated material as cohesion would allow these steeper slopes to be maintained (Kadel et al., 1998; Prockter and Patterson, 2009).

Explaining the morphology of double ridges requires a formation mechanism that can maintain the background terrain as material is uplifted, which does not favor theories involving cryovolcanic flows or slush extrusion which would cover background terrain. The flanking fractures observed at some double ridges can also be a challenge for formation theories. Dombard et al. (2013) suggest these flanking fractures are the result of a freezing water sill and that formation theories that imply convergence at ridges are not able to recreate flanking fractures. However, it is important to note that some double ridges do appear to be convergent features (Culha et al., 2014), which suggests that convergent ridge formation is possible.

Johnston and Montési (2014) include more details of ridge morphology which may have relevance to formation theories. They note that there is a maximum ratio of height-width of ~0.5, reflecting that while a few ridges are ~4 km wide, those ridges are of lower relief than most. Even the tallest ridges do not exceed reliefs of 400 m, and the tallest sets of double ridges tend to be narrower than average (Coulter et al., 2009; Johnston and Montési, 2014).

2.3 Previous Modeling

The first quantitative modeling of the incremental ice wedging formation theory was described in two abstracts (Melosh and Turtle 2004, Han and Melosh 2010). The modeling was done in Tekton, a finite element modeling program designed for geophysical problems (Melosh and Raefsky, 1980). Both of these abstracts describe results with deformation similar to observed ridges. Han and Melosh (2010) note that the rate of the ice wedge's expansion may be relevant to the final shape of the surface deformation. Faster growing wedges may be capable of creating single ridges, according to their results.

Other than the work done in Tekton, Johnston and Montési (2014) is the closest previous work to the modeling we conduct in this project. Their focus is not on the freezing of water rising into the shell, but instead on the emplacement of water sills within the ice shell. They posit that single ridges form over horizontal sills and double ridges form over vertical dikes. The surface deformation is caused by the expansion of water as it freezes at the edge of the sill forming the intrusion, which the Johnston and Montési (2014) work expresses as an increase in pressure, with the intrusion growing vertically as well as horizontally. The paper points to disrupted surfaces on Europa having more frequent compositional heterogeneities as evidence of incorporation of ocean material into the shell. Johnston and Montési (2014) use the theory of crack formation from Manga and Wang (2007) with a slowly freezing Europa that creates a pressurized ocean.

The Johnston and Montési (2014) formation model has many similarities to the incremental ice wedging theory; what differentiates them is the rate and time at which the water is introduced. In their freezing sill model, cracks in the shell allow water to move into and through the shell. They consider purely elastic deformation caused by a freezing body of water within the shell. Johnston and Montési (2014) use a 20 km by 100 km quadrilateral mesh with higher element density near the model intrusion. They assume plane strain. They have rigid roller sides and a restoring force at the base of their shell. The freezing intrusion is centered along the width. They use a single elastic material with no variation of material properties to represent the ice shell around the sill. They model the intrusion as an ellipse. The cross-section of their intrusion is held constant but they vary the ratio of the principal axes and depth of the top of the intrusion.

The results of Johnston and Montési (2014) are reported in terms of stress fields and deformation profiles. If the intrusion is in the upper half of the domain, a topographic high forms above the intrusion. If the intrusion is in the lower half of the domain, a topographic low forms directly above the intrusion instead. The patterns of stress surrounding the intrusion determine the final surface deformation. The stress is concentrated in four lobes on the ends of the intrusion with the smallest radius of curvature. Stress is higher in a thinner ice layer above the intrusion. They find that the geometry of the freezing intrusion controls the morphology of the resulting topographic deformation. With a vertical intrusion (dike-like) the stress is concentrated near the surface and a double ridge forms at the surface. A horizontal intrusion (sill-like) forms a single ridge instead.

Johnston and Montési (2014) tested variations in central trough width based on the intrusion’s aspect ratio and found that as aspect ratio increases, the trough width also increases. The farther the intrusion is beneath surface the lower the topography maxima are and the wider the gap between the two highs. An intrusion in the lower half of the shell makes a broad depression on the surface.

Maximum heights in the models of Johnston and Montési (2014) are produced with the cases where the intrusions are closest to the surface. When intrusions were modeled as 500 m beneath the surface, the resulting double ridges reached heights of 105 m and single ridges reached heights of 800 m. The height of the ridges is linearly related to overpressure of the water body intrusion. The main models of this paper all consider the ice shell to be 20 km thick. Thinner ice shells would make taller ridges with steeper sides, while thicker shells would cause smaller ridges to form (Johnston and Montési, 2014).

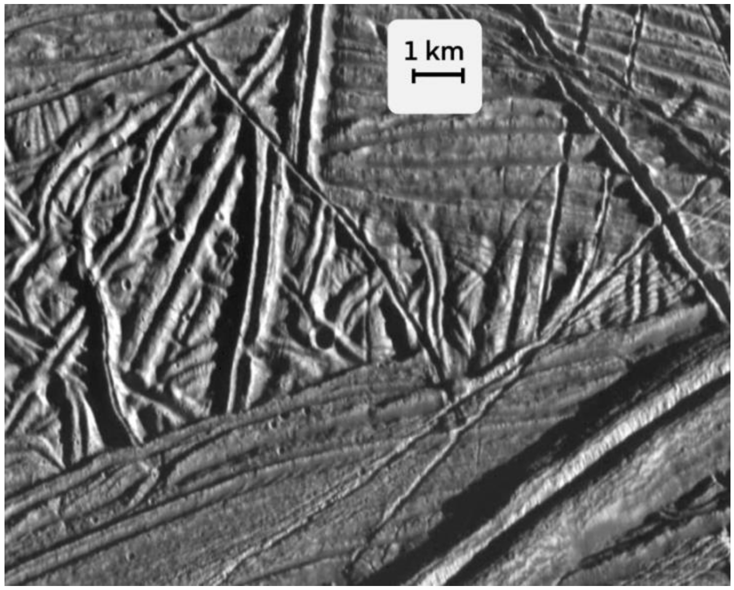

Figure 2.1 The image above displays a section of ridged terrain on Europa's surface. Multiple generations of narrow, linear ridges crisscross the terrain.

CHAPTER 3. METHODS

The model of ridge formation addressed in this thesis suggests that water in cracks pulled open by tides could create a water intrusion like a planar dike. A slowly freezing and growing intrusion, referred to here as an ice wedge, may be capable of creating a double ridge shaped deformation at the surface. The process forming the ice wedge is cyclical over the course of many tidal cycles as tidal stresses cause motion along pre-existing cracks, allowing water into the crack. That water freezes onto the walls of the crack in layers, over time growing into an ice wedge intrusion that deforms the surface into a double ridge (Melosh and Turtle 2004, Han and Melosh 2010). Figure 3.1 displays the proposed theory of formation tested here.

If the cracks do not reach the ocean and are shallow (Greenburg et al., 1998; Lee et al., 2005; Manga and Wang, 2007), another source of water would be required to fuel the growth of an ice wedge. An additional source of water that cyclically freezes may result from frictionally produced melt created under tidal stresses on the cracks. However, our thermal model and freezing rate calculations are based on the ocean water source case.

3.1 Purely Elastic Modeling

A majority of the modeling for this project was conducted in COMSOL Multiphysics, an FEM software with versatile applications. I modeled the elastic deformation of a 2D mesh of ice with dimensions of 8 km tall and 14 km wide. The Young's Modulus is assumed to be 10^9 Pa (Nimmo and Gaidos, 2002) and the Poisson's Ratio is taken as 0.25. The density of the ice is approximated at 1000 kg/m^3, which assumes that the ice shell contains some impurities. The height of the domain is likely smaller than the expected thickness of the ice shell, but is large enough to produce robust results. The ice within the model is assumed to be in a purely conducting thermal regime. The vertical extent of the block was chosen to be wide enough that the topographic highs of the ridge were 3 kilometers or more away from the edge but small enough that the mesh over the whole domain could be very fine while still limiting computation expense.

The modeling tested how the wedge's depth beneath the surface affected the resulting surface topography with different geometries placing the top of the wedge at depths ranging from 100 m to 1 km, in 100 m increments. The ice wedge expanded only horizontally and the vertical deformation of the surface was caused only by the Poisson effect. The rate of the wedge's expansion was determined by the results in thermal modeling done in MATLAB as described below.

The expansion rate at the center of the wedge is 4.554×10^{-10} m/s (described in the following section), and the rate decreases above and below center to reach 0 m/s at the top and bottom of the wedge. The change in the rate of expansion along the edges of the wedge are defined by a parabolic equation. The wedge itself is considered to be rigid in order to simplify the model. The top of the block is a free surface, while the left and right sides are held static in the x-direction and free in the y-direction. The base of the block is held in place. Gravity is neglected in this model because the material properties are not dependent on pressure in this purely elastic case.

3.2 Growth Rate from Thermal Modeling

The two-dimensional thermal model approximates the heating caused by water from the subsurface ocean repeatedly filling a crack in Europa's shell. A rectangle 30 km across and 10 km deep represents the ice shell. This would be a thin shell case and the shell was assumed to be entirely conductive to simplify the shell's background thermal profile. The thermal profile before the introduction of the water into the crack was taken as linear with depth with the surface held constant at 100 K and the base of the shell held constant at 273 K. The ocean and base of the ice shell may be cooler if the ocean is briny, but for the thermal modeling for this work pure water was assumed. Figure 3.2 shows the boundary conditions created to describe the ocean water source case.

The model is a Fourier expansion calculation of heat conduction through the rectangle representing the shell, with the maximum expansion coefficient of the Fourier series being the 30th. The error caused by neglected terms of the expansion is negligible for the purposes of estimating a grow rate of the wedge. The thermal diffusivity of the ice is taken as 1.335×10^{-6} m^2/s and the thermal conductivity is taken as 2.4 W/m K (Petrenko and Whitworth, 1999). One vertical edge of the rectangle is designated the crack which, because it has a renewing flow of water, is held at a temperature of 273 K, as figure 3.2 shows. The introduction of a heat source along that edge disrupts the background thermal profile by heating the ice surrounding the crack. The steady state produced by the Fourier law of heat conduction combined with the background temperature profile of the shell forms the thermal profiles shown in figure 3.2.

The y-coordinates begin at 0 at the bottom of the domain, which in this thermal model is treated as the base of the ice shell and held at a temperature of 273 K, and reach the surface of the ice shell at the 10 km coordinate. The version of the model shown in figure 3.2 assumes the water rises to 3 km beneath the surface, which does not match the finite element modeling done in COMSOL. This is due to the thermal model producing artifacts with sharp spikes in temperature when steep thermal gradients were caused by shallow depth wedges. This limited the thermal model and may cause the heat flow and freezing rate estimated here to be lower than it would be for a wedge at a shallower depth, surrounded by colder ice close to the surface.

The wedge and the crack below it on the edge are held at the same temperature, but only the top 900 m of that span is considered the wedge for the calculations below. A 900 m tall wedge is used in the growth rate calculations to mirror the wedge size in the COMSOL modeling described above.

To get the freezing rate of the wedge, *R*, assuming it has a constant source of water, I begin by calculating the heat flow, *Q*. *k* is the thermal conductivity of ice, ΔT is the change in temperature between two points, in this case the temperature where the ice wedge is freezing and the temperature a point a horizontal distance *z* from that point. Equation 1 shows this calculation.

$$Q = -k\frac{\Delta T}{z} \qquad (1)$$

From there, I multiply *Q* by the area the heat flow is going through, *A*, which is in m^2, and divide by the heat of fusion of water, *F* , with a value of 333.55 J/g.

This calculation results in the mass of water frozen per second along the wedge. Then the final steps are to use the density, ρ, to turn this mass freezing rate into a volume freezing rate, *V*. Equation 2 demonstrates how the volume freezing rate can be found from these inputs. Then dividing by the area to convert that to the horizontal expansion rate of the wedge, *R*, as equation 3 shows.

$$\frac{QA}{F\rho} = V \qquad (2)$$

$$\frac{V}{A} = R = \frac{Q}{F\rho} \qquad (3)$$

To get the growth rate used in the COMSOL modeling, the density of the ice is taken to be 997 kg/m^3, ΔT is -61.83 K, *z* is 1000 m, and *A* is 900 m^2. ΔT, the temperature diffence between the crack and a point *z* (1000 m) directly horizontal from the crack, is taken from a depth of 6.6 km. From these values the expansion rate R is 4.5540×10^{-10} m/s.

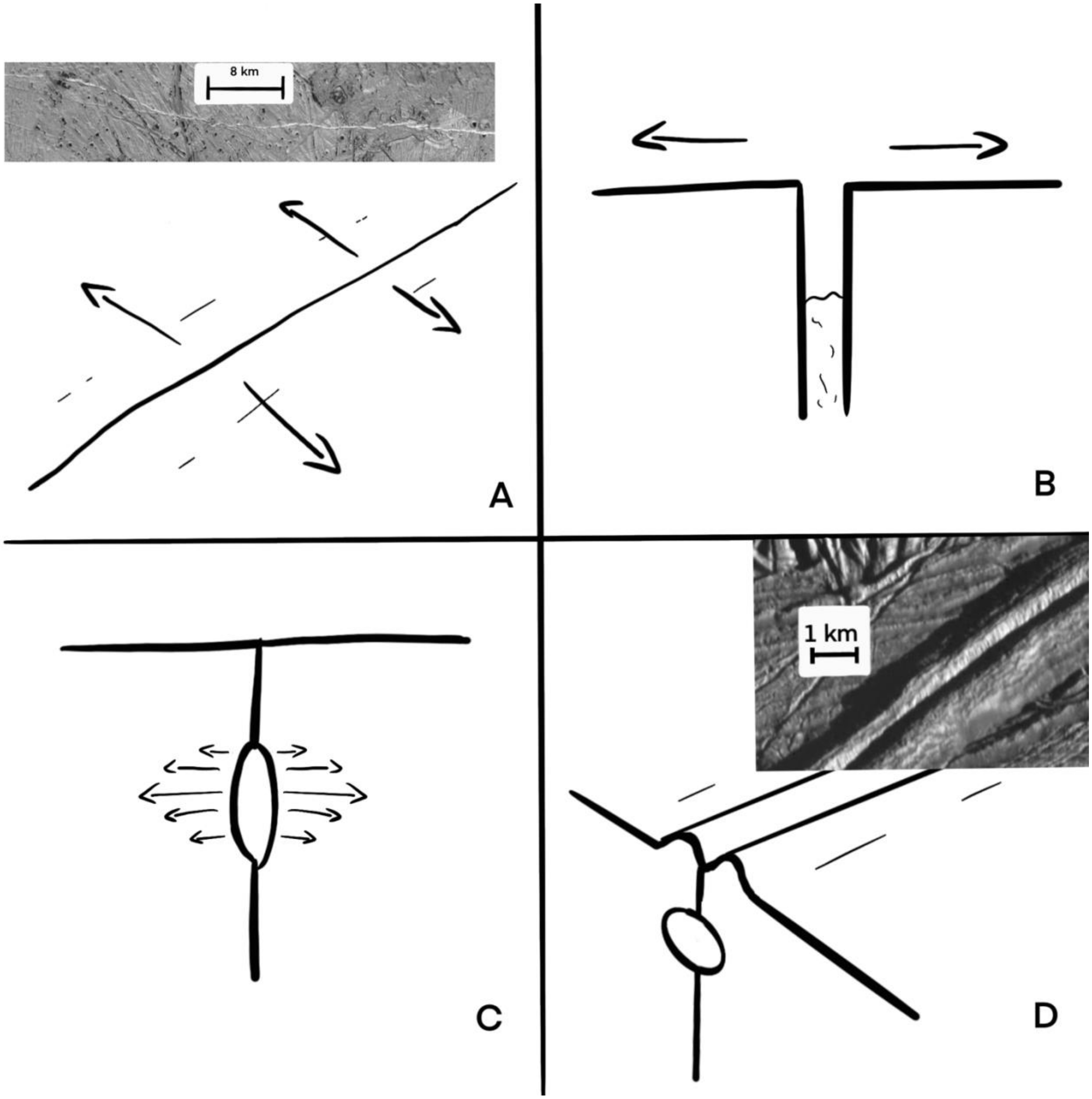

Figure 3.1 This figure displays the general theory of incremental ice wedging ridge formation. A) Tidal stresses on Europa form cracks and then cause motion at the cracks. B) The opening caused by tidal forces allows water into the crack. C) Each tidal cycle, water freezes and slowly builds an ice intrusion horizontally, deforming the surrounding shell. The arrows indicate the growth of the wedge. D) The ice wedge grows and creates surface deformation in the form of a double ridge.

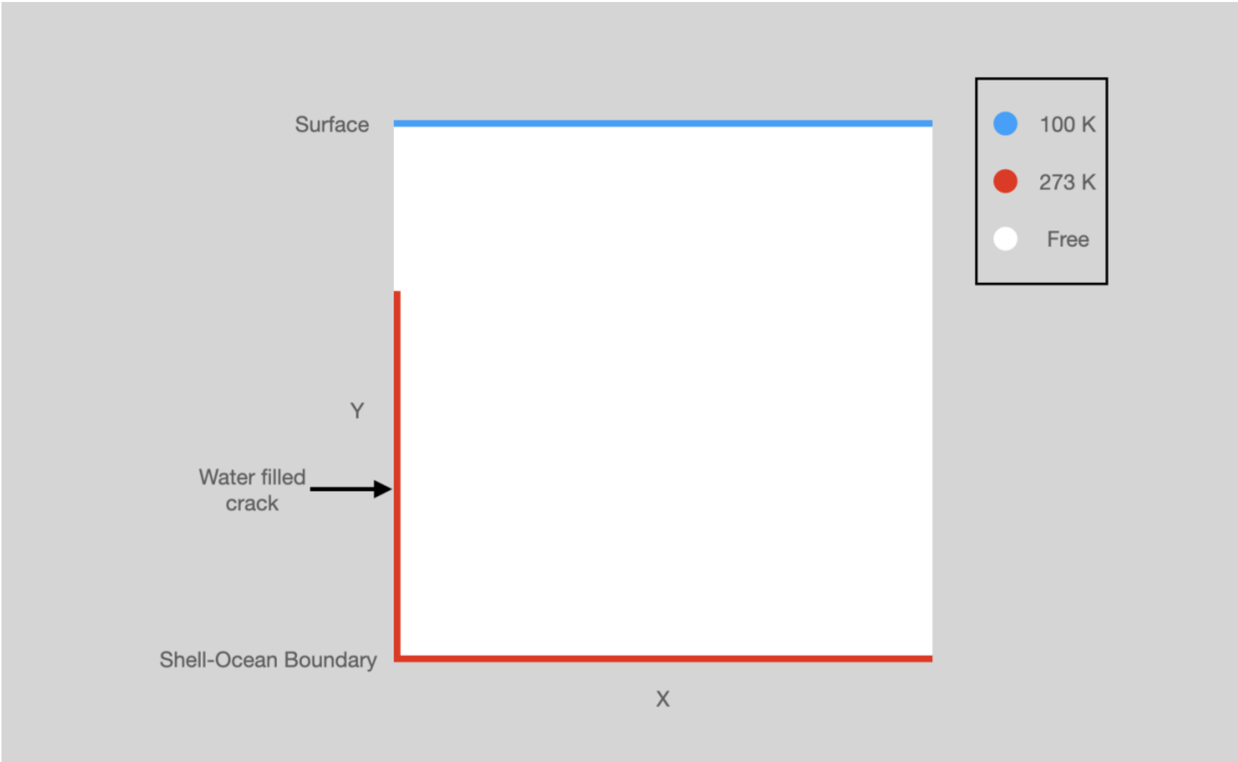

Figure 3.2 This image shows the boundary conditions defined for the thermal model.

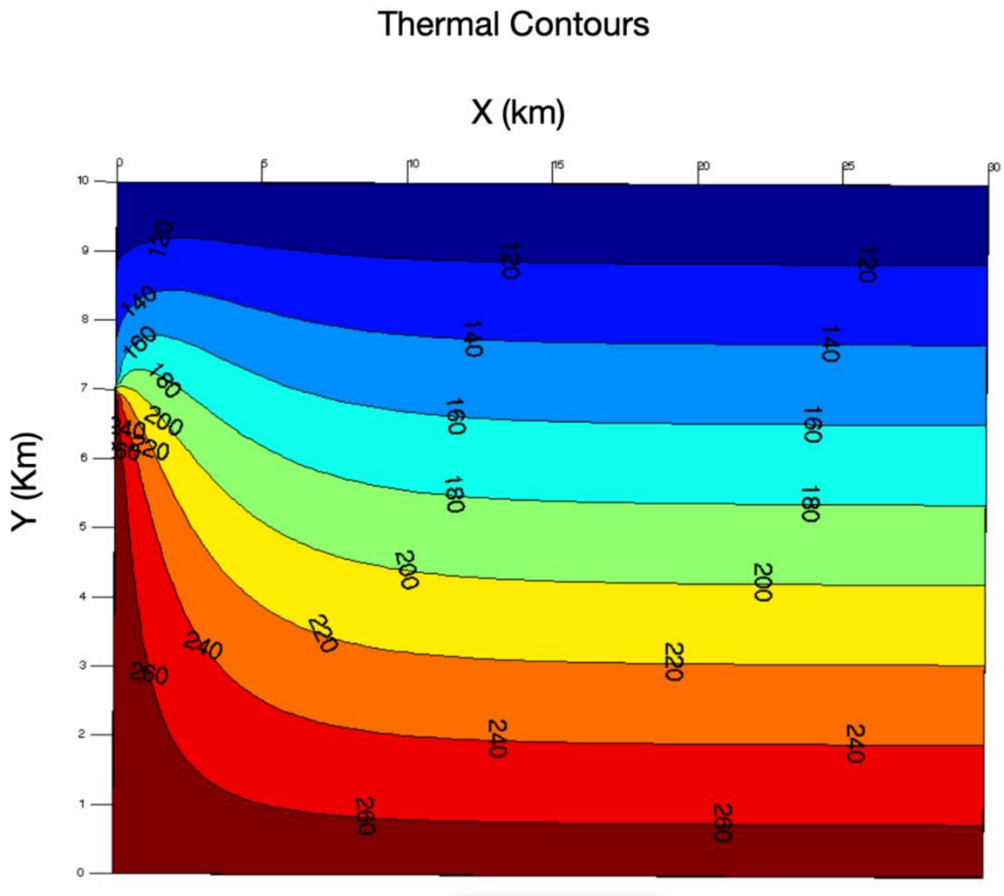

Figure 3.3 This plot shows the thermal profile's variation across the domain. Y designates the depth in the shell, where 0 is the base of the shell and 10 km is the surface, and the horizontal distance is represented by X, where 0 is the crack partially filled with water. The water reaches 7 km from the base of the shell. Temperatures are in Kelvin.

CHAPTER 4. RESULTS

4.1 Elastic Model Results

The opening wedge in the model results in surface deformation including a pair of topographic highs. The height of these topographic maxima is primarily determined by the size of the ice wedge at a given time and at what depth the ice wedge is opening. I allowed the ridges time to grow to the scale of double ridges observed on Europa, with the two maxima reaching ~100 m above their original position, in the 100 m depth case. The results of the deeper models ran for the same duration, 1.5×10^{12} seconds, not reaching the same maximum heights.

No matter the depth of the wedge, the opening wedge formed two topographic highs with a topographic low in between, centered above the wedge itself, as shown in figure 4.1. Depth affected the rate of growth of the topographic highs, and the width of the deformation at the surface. The wedges farther beneath the surface resulted in broader surface deformation and required longer times to create surface deformation at the scale of double ridges. The deformation created at the surface is a result of the Poisson effect, as the compressed section surrounding the wedge expands vertically, creating the raised double ridge.

Figure 4.2 shows representative example results from two cases, displaying the change in surface deformation caused by differing ice wedge depths. The deformation is narrower with the more shallow (100 m depth) wedge than it is with a deeper (500 m depth) wedge. The width of the deformation is defined here as the distance between where the free surface on returns to y = 0 on on the outside slopes of the topographic highs. The 100 m depth wedge is ~2 km across while the 500 m depth wedge exceeds 5 km in width. The 500 m depth wedge also forms a ridge at a far slower rate. Figure 4.2 shows that after the same duration, the 100 m depth ice wedge case has topographic highs exceeding 100 m while the 500 m depth ice wedge case reaches a maximum height of around 70 m. These trends in depth-deformation width and depth-deformation height continue for ice wedges placed at lower depths. The deepest ice wedges, placed at 1000 m below the surface, produce the widest and lowest relief surface deformation of all cases I tested, as table 4.1 and figure 4.3 show.

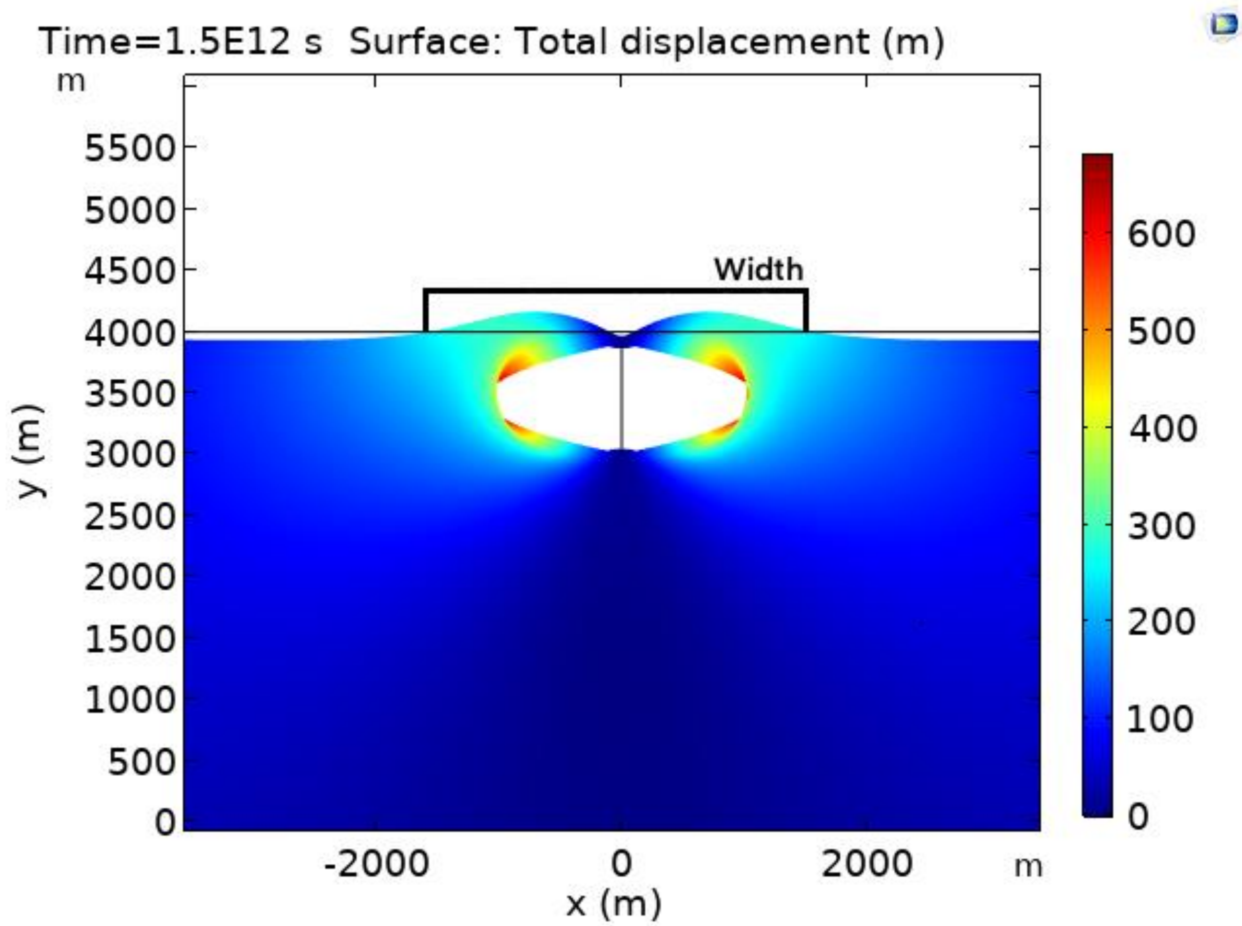

Figure 4.1 This figure shows the total final displacement of the model in the 100 m depth ice wedge case. The color map indicates the total distance each part of the mesh has moved. The shape of the ice wedge and resulting surface deformation are clearly displayed. The width discussed within the results is defined as shown in this image.

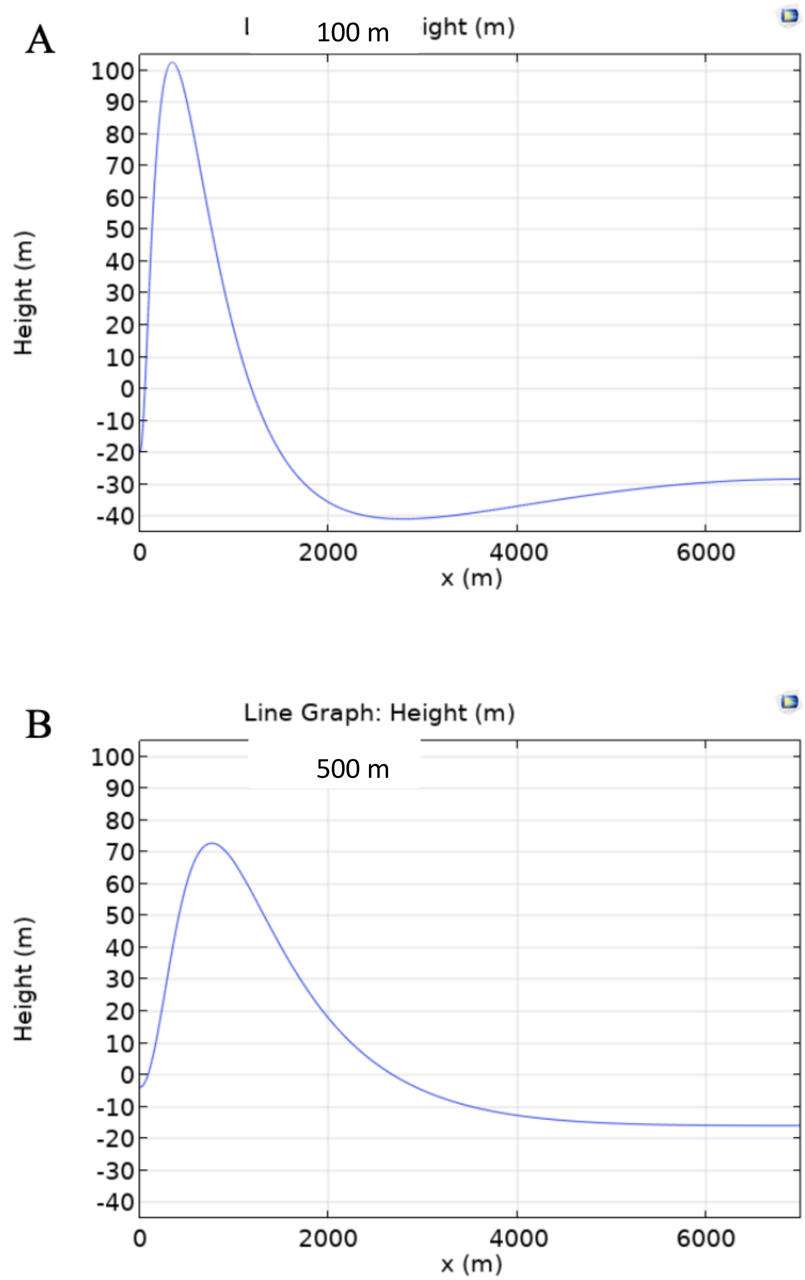

Figure 4.2 These images show the y-displacement of each point at the surface of the model and the resulting shape of the surface deformation from the growth of an ice wedge. A) Shows the y-displacement with a wedge positioned 100 m beneath the surface and B) shows the y-displacement with a wedge positioned 500 m beneath the surface.

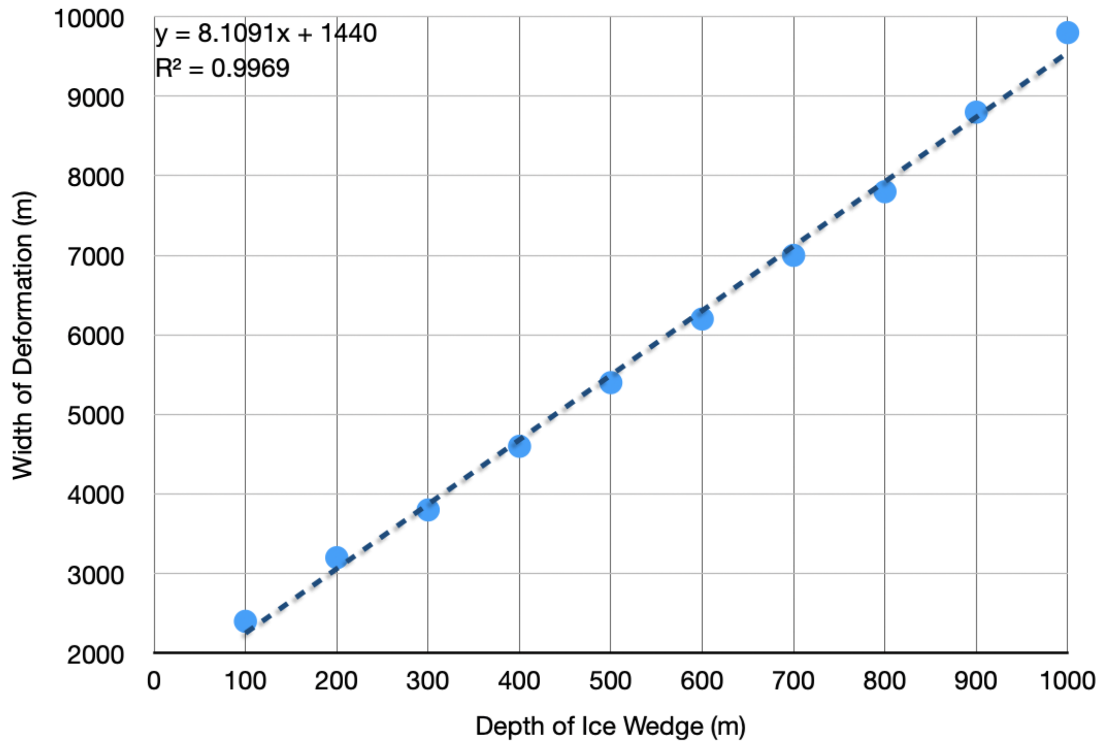

Figure 4.3 This plot shows the width of the final surface deformation from the FEM results versus the depth of the ice wedge along with the best-fit linear relation and associated R squared correlation coefficient in the relationship between the width and depth of the ice wedge.

Table 4.1 This table displays the variation of height and width of the double ridge-like deformation produced by ice wedges placed at differing depths.

Depth of Ice Wedge (m)	Height of Ridge (m)	Width of Positive Ridge Deformation (m)
100	105.4	2400
200	97.3	3200
300	88.7	3800
400	81.2	4600
500	74.8	5400
600	69.3	6200
700	64.7	7000
800	60.6	7800
900	57.1	8800
1000	54.0	9800

CHAPTER 5. DISCUSSION & CONCLUSION

I assess the morphological viability of the ice wedging model by comparing the induced deformation in the FEM results to the morphology of double ridges observed. The width of the deformation produced by the model matches the narrow (<5 km wide) topography of Europa's double ridges only if the ice wedge forms at shallow depths. Ice wedges placed deeper than 500 m elevate the surface to tens of meters above the original surface even at distances 2 km or more away from the center crack. With most observed double ridges having widths under 5 km, the results of our modeling imply an ice wedge must form within 500 m of the surface to create the observed double ridges.

This relationship between depth of intrusion and width and height of deformation is also seen in the results of Johnston and Montési (2014). Their shallowest intrusion shows the narrowest and highest double ridged shaped deformation, but it is important to note they did not test any intrusions at depths shallower than 500 m. Johnston and Montési (2014) had deformation that differs from our results in several ways. In the most shallow case of Johnston and Montési (2014), their 500 m depth intrusion created a double ridge 105 m high and a width of surface deformation that exceeds 5 km. All of the deeper cases have wider deformation, which is far wider than observed double ridges. The shallow results at depths less than 500 m described in this thesis match the widths of double ridges far more closely, with the surface deformation having widths less than 5 km.

Johnston and Montési (2014) produced both double and single ridges, and reported no negative surface displacement flanking their double ridges. My results do not produce single ridges in any case, as was expected since the deformation is caused by the Poisson effect from purely horizontal growth of a wedge, and have a negative y-displacement flanking the topographic highs of the ridge. These differences likely stem from how the intrusions are grown in the two scenarios. While ours grows horizontally as a rigid body of ice, Johnston and Montési (2014) had the intrusion represented by a pressurized body that did not grow in a purely horizontal direction. Their variation of aspect ratio of a pressurized intrusion makes the range of deformation in their results drastically different from the results of this work. Some marginal troughs are seen at the flanks of observed double ridges, but they are usually connected with flexure from the loading of the ridge. These marginal troughs are smaller in breadth than the negative displacement in my models. The model presented here would not have flexure caused by the loading of the ridge because there is no consideration of gravity, but Johnston and Montési (2014) did include gravity and reported no such flexure. These results could indicate such marginal troughs are connected to formation rather than flexure, but future modeling would be required to definitively determine that connection. The lower elevations flanking the ridges in my results are not caused by the size of the mesh, as tests with wider and taller meshes do not affect the lowering on either side of the ridges.

The shallowness of ice wedges that reproduce observed topography in my modeling can be linked to the possible water sources for the freezing ice wedge. The formation mechanism we are investigating is that a ridge is formed when water freezes within a preexisting crack. As tidal forces act on cracks, water from the ocean below may be able to rise into the shell. The water that forms a sill or ice wedge rises into the cracks in Europa's shell because of pressurization of the subsurface ocean. As Europa cools and freezes the shell thickens and, because water ice is less dense than liquid water, the change in volume likely leads to the pressurization of the ocean beneath the thickening shell (Manga and Wang, 2007). When existing cracks in the shell are opened by tidal forces the pressurization causes water to rise into these cracks, allowing the formation of an ice wedge. Alternatively, slip-strike motion along the cracks could cause local melt or debris to fall into the cracks (Han and Showman, 2008). Either way, as water intrudes into the crack and freezes as an intrusion at a certain depth, the surface deforms into a double ridge. Both water sources could create the observed surface deformation, but they create different thermal environments and involve different volumes of source water. The model results show that shallow ice wedges are more probable to make double ridges. This result suggests that the frictional melting source makes more sense for a shallow ice wedge case. The ocean water would have to travel a great distance to reach the position needed for a double ridge to form, while melt water could form an ice wedge at the correct depths by falling to the base of a crevasse a few 100s of meters deep.

If the frictional melt water case is taken as the basis for the model, the growth rate estimated in this thesis does not apply. The growth of the wedge will be dependent on the amount of water that melts along the crack over a tidal cycle rather than how fast the water can freeze within a crack filled with ocean water. Estimation of this meltwater growth rate was outside the scope of this work, but I would posit that the quantity of melt water would be the limiting factor of growth rate and result in a slower growing ice wedge. In either water source case, the growth of the wedge would not be continuous, which the ice wedge growth rate assumes within the model used here.

Material would only be added to the ice wedge during a fraction of a tidal cycle on Europa. This would make the growth of the ice wedge intermittent instead of constant as the model's wedge growth implies. The time it takes for a ridge to form within this modeling is therefore shorter than the time required for a real ridge to form through incremental ice wedging.

In our modeling, wedges deeper than ~500 m cause deformation wider than most double ridges observed on Europa, implying an ice wedge producing the observed topography would have to form at shallow depths. This either means that water from a pressurized ocean must rise to within a kilometer of the surface or that shallow cracks filling with melt water never reach depths farther than a kilometer. Moving water many kilometers upward through the ice shell from a subsurface ocean is only feasible if the cracks penetrate the entire shell and if the ocean is significantly pressurized to cause the water to rise to within in a few hundred meters of the surface. Unless the ice shell of Europa is extremely thin, the shallow cracks periodically filled with melt water is a more probable case of forming double ridges through ice wedging.

Future modeling should incorporate viscous flow into the final surface deformation to greatly improve the accuracy of the model. The results of preliminary creeping flow models show that neglecting the viscous properties of ice results in only a loose approximation for ridge formation, as the flow rates will cause noticeable change in deformation on the timescales of ridge formation. The flow rates in early modeling can reach magnitudes of ~10^{-4} m/s as topography rises, which over the course of 1.5×10^{12} seconds can cause extensive deformation even if flow rate is not constantly the maximum. The viscous behavior of the ice could cause the final surface deformation created by a growing ice wedge to be wider and a less extreme than the results reported here. The model can be further expanded and improved upon by considering plastic deformation and including a more complex rheology for the ice (Durham and Stern, 2001).

The results of this modeling indicate that incremental ice wedging can create observed double ridge-like deformation if the wedge forms at extremely shallow depths less than 500 m. This interpretation would imply either that the shell is thin enough for water from a pressurized ocean to reach the near surface through cracks or that shear heating creates enough consistent melt that an ice wedge can for within a shallow crack. Future modeling may be able to determine which of these water sources is more viable based on probable growth rates for the wedges of each case and possible morphological differences caused by the mechanisms creating the water sources.

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