Lithospheric Extension on Icy Satellites

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1. Introduction

Terrestrial Rift Modes

Continental extension on Earth has been categorized into two general rift modes: narrow rifts and wide rifts. Narrow rifts (such as the East African Rift System, fig. 1) are regions of intense normal faulting on the order of 100 km wide. Narrow rifts are characterized by large lateral gradients in crustal thickness and topography (fig. 3). Wide rifts (such as the Basin and Range Province, fig. 2) have much more distributed regions of normal faulting, as large as 800 km wide. Wide rifts have much smaller crustal thickness and topography gradients (fig. 4). Rapid-Flow Narrow Rifts (identified as metamorphic core complexes by *Buck*, 1991) are a subcategory of narrow rifts, characterized by localized rifting, but lacking strong topographic or crustal thickness gradients.

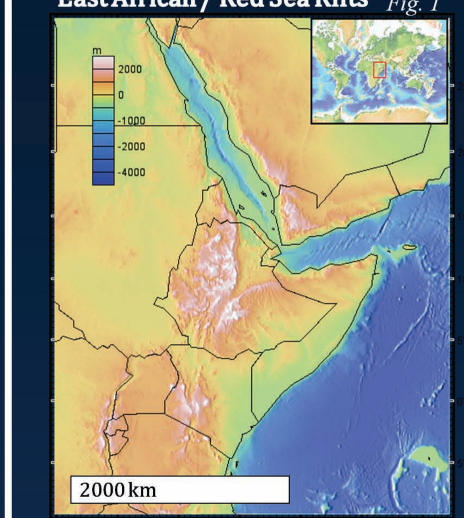

Fig. 1

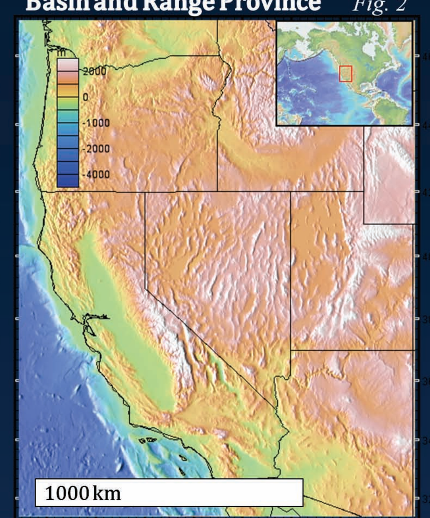

Fig. 2

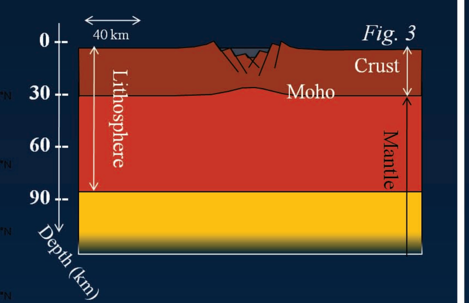

Fig. 3

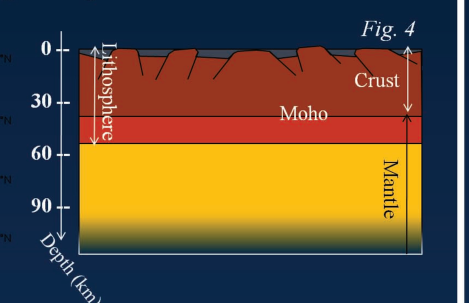

Fig. 4

Icy Satellite Rifts

"Icy satellites" are the collective moons of the outer solar system. They have low densities (1-3 g/cm³), and are primarily composed of ices and some silicates. Many are geologically active. Some of the satellites are postulated to have subterranean oceans, beneath their icy crusts.

Fig. 5

Ganymede (fig. 5(a)) is the largest of the Galilean satellites of Jupiter, and while it has an older surface then Europa (~4 Ga), it still possesses extensional features in the form of grooved terrain (fig. 6). Grooved terrain is characterized by relatively uniformly spaced parallel valleys and ridges. This terrain ranges from 10s to 100s of kilometers wide, and has been noted to resemble horst and graben systems found here on earth in wide rift systems.

Europa (fig. 5(b)) is the smallest of the Galilean satellites of Jupiter, but has a geologically young surface (~60 Ma). Linear bands (fig. 7), up to 30 km across, have been inferred to be analogous to terrestrial spreading centers (narrow rifts) due to overall bilateral symmetry of rifts and symmetric troughs.

Enceladus (fig 5(c)) is a small moon of Saturn that is currently geologically active (maximum surface age of 0.5 Ma). Tiger stripes (fig. 8) on its southern hemisphere are thought to represent localized narrow rifting (~2 km wide), and are generally associated with cryovolcanic plumes.

Ganymede: Grooved Terrain

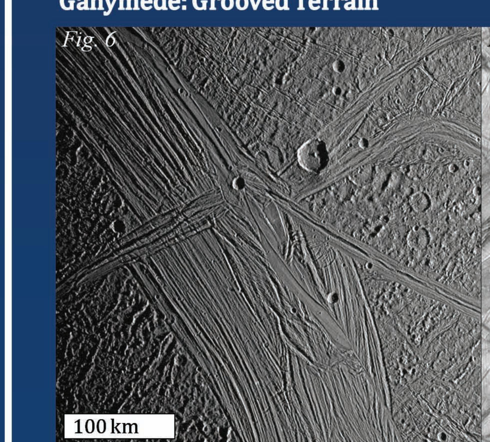

Fig. 6

Europa: Bands

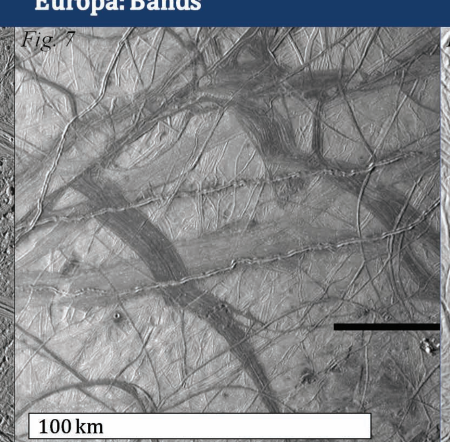

Fig. 7

Enceladus: Tiger Stripes

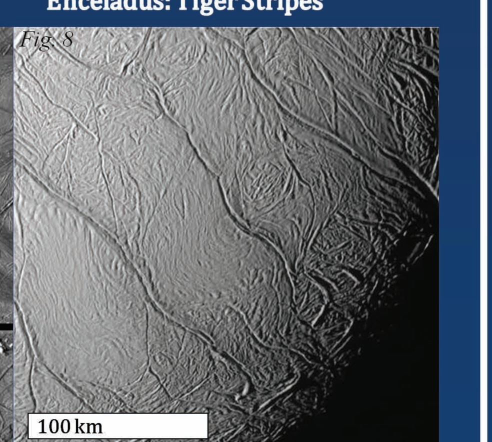

Fig. 8

My Project

I developed an original sequence of geodynamic rifting programs that are capable of modeling extension on the Earth and several icy satellites, including Europa, Ganymede and Enceladus. By modeling the thermal and crustal thickness evolution for a given lithosphere, and then calculating the resulting force changes, I can describe when wide rifts, narrow rifts, or high-flow narrow rifts form given various geophysical and rheological parameters. I repeated past work by *Buck* [1991] for terrestrial rifts and *Nimmo* [2004] for icy satellite rifts, and applied them for the first time to the tiger stripes of Enceladus, in order to determine if they can accurately describe the observed narrow rifting on this moon.

2. Geodynamics & Numerical Methods

Model Geometry

I modeled a laterally homogeneous and isotropic slab of lithosphere (fig. 9), with a crust overlying lithospheric mantle (with a thickness defined by an effective viscosity at the base of the lithosphere of 10^{21} Pa s). I applied a linear horizontal velocity to model pure shear stretching, and stretched the lithosphere till it reached a strain of 0.25.

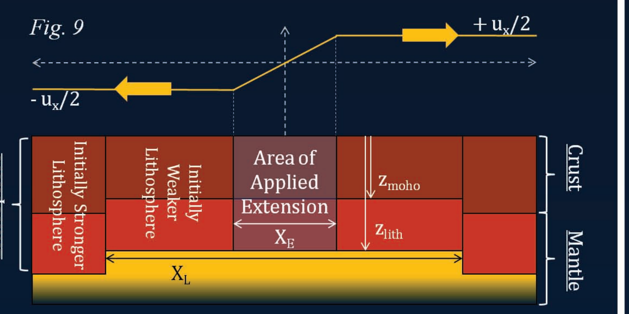

Fig. 9

Thermal Evolution

Starting with the initial, steady-state geotherm, I modeled the temperature evolution through the center of the rift as it rifted over time by numerically solving the one-dimensional heat transport equation (eq. 1). (See fig. 13 for an example of geotherm evolution over time.)

Eq. 1 – One-Dimensional Heat Transport:

$$\frac{dT}{dt} = \kappa\frac{\partial^2 T}{\partial z^2} - v\frac{\partial T}{\partial z} + H$$

Lower Crustal Flow

Lateral crustal thickness variants produce pressure differentials which can drive the viscous flow of the lower crust and affect the thickness of the crust at the center of the rift (eq. 2). The rate of lower crustal flow depends on the effective flow diffusivity, κ_f which in turn depends on the viscosity structure at the base of the crust, the lithology, temperature profile, and crustal thickness. Fig. 10, 11 show κ_f for terrestrial models, and fig. 12 for icy satellites.

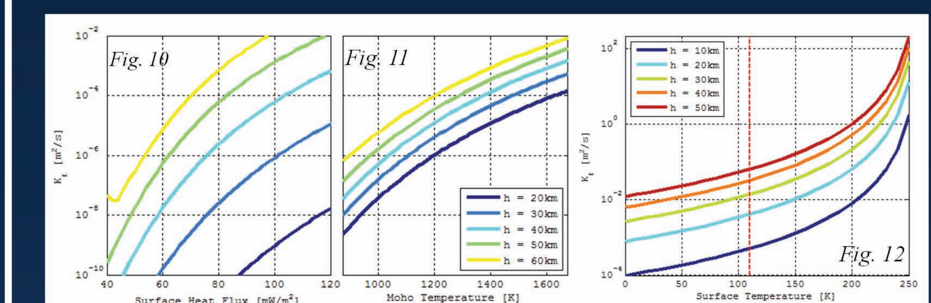
Fig. 10, Fig. 11, Fig. 12

Eq. 2 – Lower Crustal Flow:

$$\frac{dh}{dt} = \kappa_f\frac{\partial^2 h}{\partial x^2} - u\frac{\partial h}{\partial x} - h\frac{\partial u}{\partial x}$$

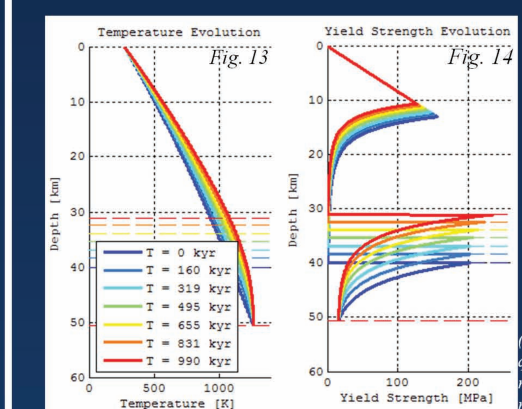

Fig. 13, Fig. 14

(For a 40 km thick terrestrial, quartzite crust, overlying olivine mantle, a surface heat flux of 80 mW/m², strain rate of 8 x 10⁻¹⁵ 1/s)

Yield Strength

The horizontal force required to cause extension of the lithosphere is found by integrating the yield stress over depth. The yield stress is taken to be the minimum of brittle stress or ductile stress (eq. 3).

Eq. 3 – Yielding Force:

$$F_{YS} = \int_0^{z_{lith}} \min\left[gBz,\ \left(\frac{\dot{\varepsilon}}{A}\right)^{\frac{1}{n}} \exp\left(\frac{E}{nRT}\right)\right] dz$$

Buoyancy Forces

Density anomalies in the lithosphere produce horizontal lithospheric stresses. Crustal buoyancy (eq. 4) results from the upwelling of denser mantle material (+Δρ) in the center of the rift due to thinning. Thermal buoyancy (eq. 5) results from the decrease in density (-Δρ) due to the warming and thermal expansion of material in the center of the rift due to the advection of heat. Thermal buoyancy and crustal buoyancy are of opposite sign.

Eq. 4 – Crustal Buoyancy Force:

$$F_{CB} = \int_0^{z_{lith}} g\ \delta\rho(z)\ z\ dz$$

Eq. 5 – Thermal Buoyancy Force:

$$F_{TB} = \int_0^{z_{lith}} g\ \rho_0(z)\alpha\ \delta T(z)\ z\ dz$$

Force Summation

By summing the yield strength (F_{YS}), thermal buoyancy (F_{TB}), and crustal buoyancy (F_{CB}) forces, I can calculate the total force required to create a rift. Rift modes can be inferred base on the total change of force, dF (eq. 6).

Eq. 6 – Total Change in Rifting Force:

$$dF = dF_{YS} + dF_{TB} + dF_{CB}$$

Wide Rifts occur when dF > 0: when dF is positive, the force required for extension is increasing with time, and thus rifting is not energetically favorable at that location. If possible, rifting will migrate elsewhere.

Narrow Rifts occur when dF < 0: when dF is negative, the force required for extension is decreasing with time, and thus rifting is energetically favorable at that location, and extension will remain localized.

Numerical Methods

First and second order finite central differences were used to solve the thermal and crustal thickness evolution over depth, while MATLAB's ODE15s was used to solve forward through time. My model was calibrated against [analytical] semi-infinite half-space cooling models, and steady state models to determine integration parameters that resulted in numerical errors far less than 1%.

3. Terrestrial Results

Comparison with Geologic Data

A large range of rift parameter space (e.g. crustal thickness, heat flow, rheology, etc.) was explored for terrestrial models. My results agreed with those of *Buck*, 1991. Notably, I am able to accurately predict the formation of narrow vs. wide rifts for nine different terrestrial rifts, based on previous estimates of crustal thickness, strain rate, and surface heat flow (fig. 15).

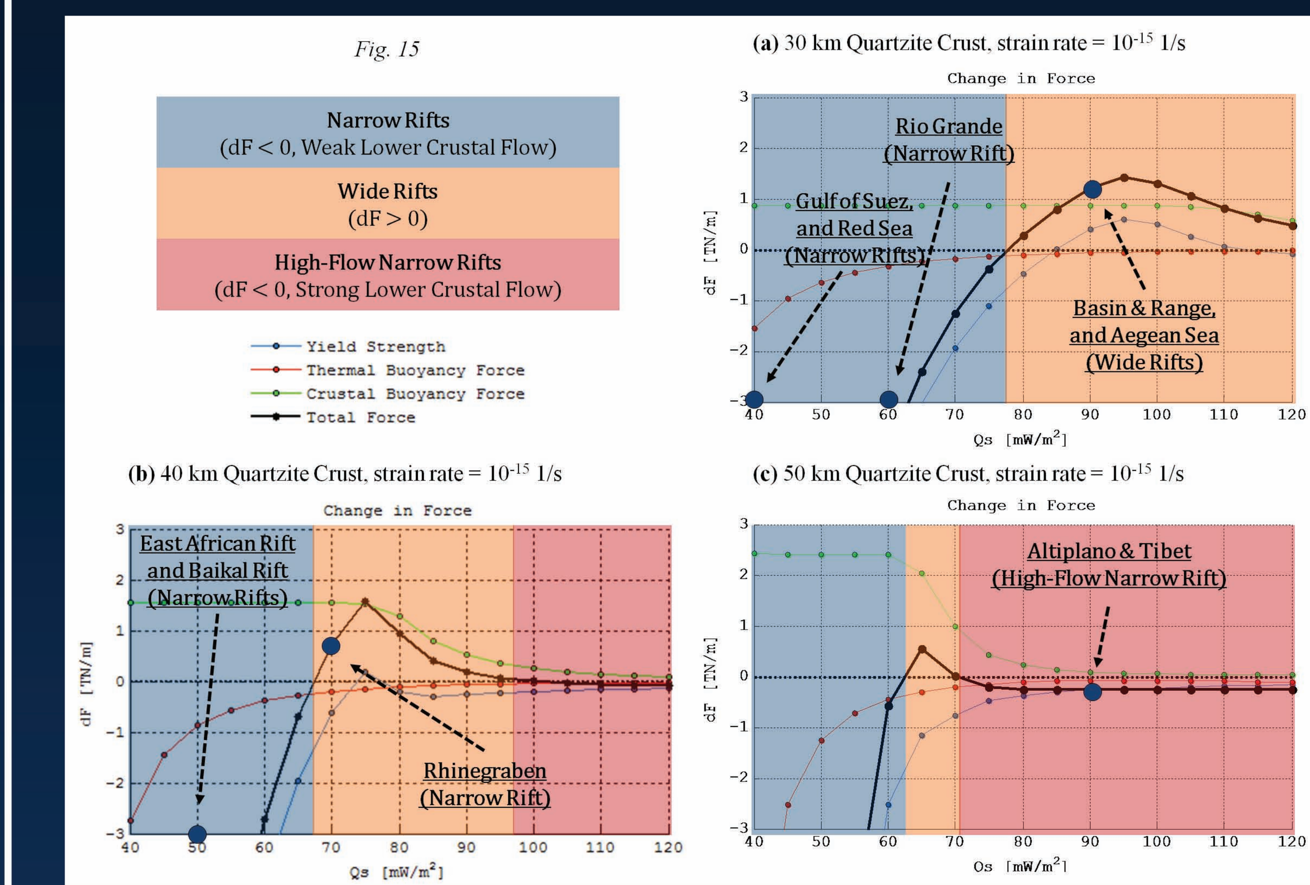

Fig. 15

Formation of High-Flow Narrow Rifts

One interesting result is the formation of high-flow narrow rifts (termed as metamorphic core complexes by *Buck*, 1991) as an alternate mode of narrow rift formation. High-flow narrow rifts form when lower crustal flow is rapid enough to significantly dampen or even prevent the thinning of the crust as rifting proceeds. Crustal buoyancy can be used as a proxy for rapid lower crustal flow and it's effect can be observed graphically by plotting crustal thickness as a function of time and horizontal distance (fig. 16).

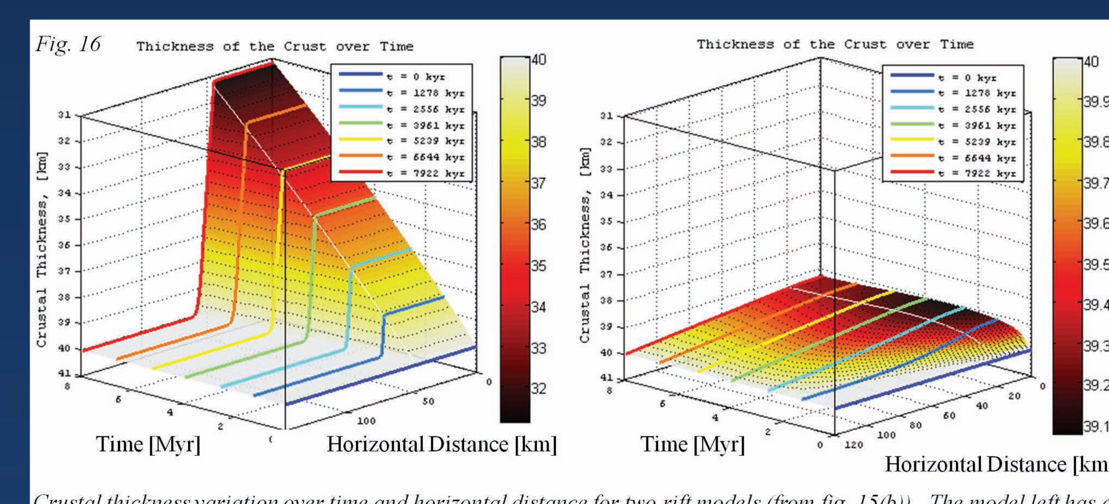

Fig. 16

Crustal thickness variation over time and horizontal distance for two rift models (from fig. 15(b)). The model left has a heat flow of 60 mW/m², while the model on right has a heat flow of 110 mW/m².

4. Icy Satellite Results

Rifting on icy satellites overwhelmingly tends to result in high-flow narrow rifts, for most parameter space. Unlike terrestrial rifts, there is no strong upper mantle to advect upwards and increase the strength of the rift; thus icy satellite rifts almost always become weaker (dF<0) as they evolve. Lower crustal flow is also more important due to the much lower strength of ice compared to terrestrial rocks. Below are plots of the effects of varying various parameters for a set of icy satellite rifting models with a range of crustal thicknesses between 2 and 40 km. Unless otherwise specified, the models are under an applied strain rate of 10^{-14} 1/s, with a "IceB" rheology (see below) with a grain size of 0.1 mm, and surface gravity of 1.4 m/s².

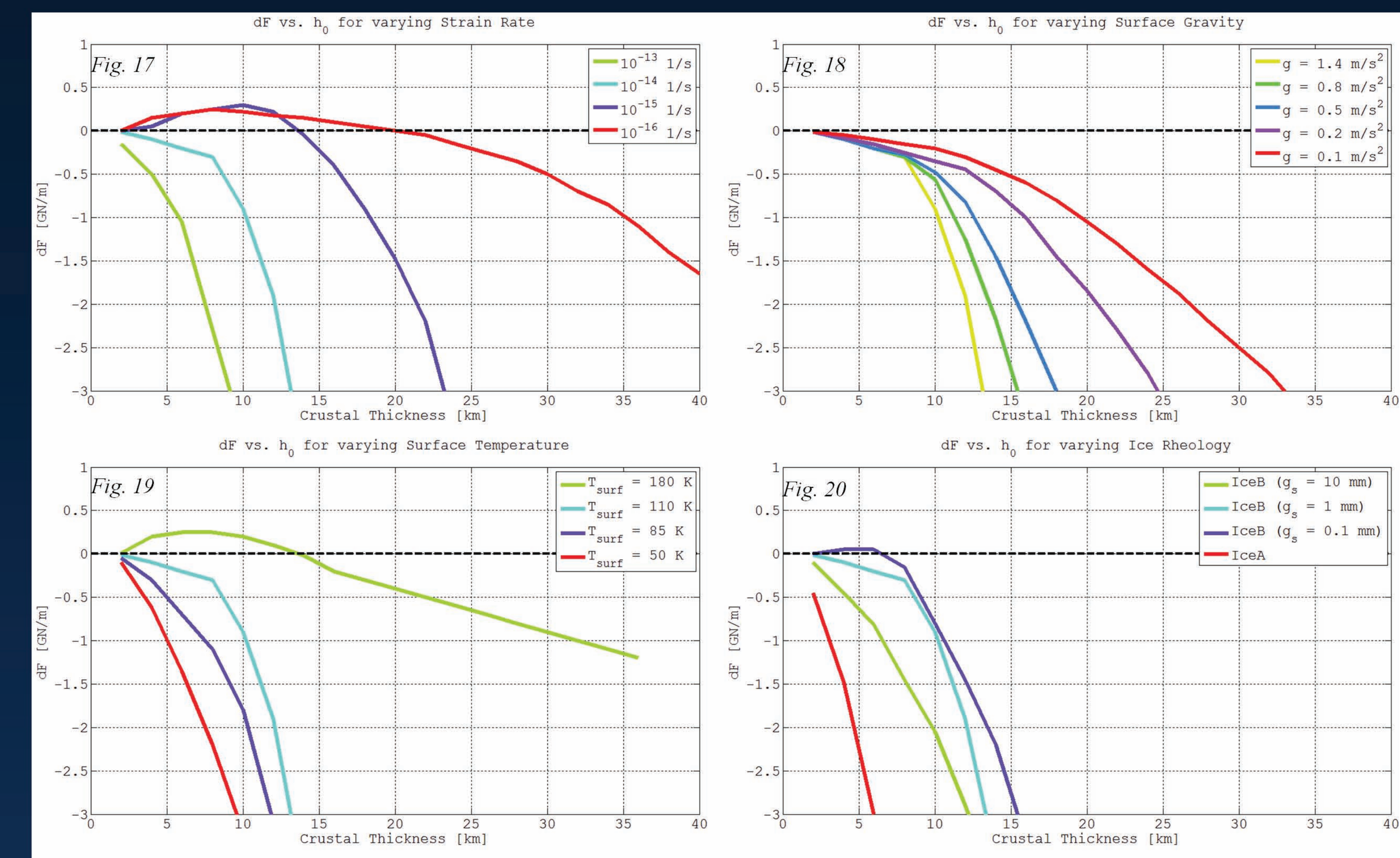

Fig. 17, Fig. 18, Fig. 19, Fig. 20

The single greatest factor controlling the formation of wide rifts is the strain rate (fig. 17). Strain rate most directly effects the yield strength of the lithosphere: increasing the strain rate increases the thickness of the brittle deformation regime, and thus creates larger negative values of dF_{YS}. This agrees with the work of *Nimmo*, 2004.

Surface gravity (fig. 18) has a weak effect on the development of different rift modes. Decreasing the surface gravity acts to dampen the change of forces.

Surface temperature (fig. 19) can be a significant determinant in the formation of different rift modes. For typical surface temperatures of the outer solar system (110 K for Ganymede or Europa, or ~75 K for most of Enceladus), narrow rifts form. However, for very high surface temperatures (such as 180 K at the tiger stripes of Enceladus), wide rifts can form for a range of crustal thicknesses.

The rheology (fig. 20) is the single largest uncertainty in any model of rifting of these icy crusts. At current, the exact properties are largely unknown. I modeled two different rheologies: "IceA" is a basal slip-accommodated grain boundary sliding rheology; "IceB" is a grain boundary sliding-accommodated basal slip (which is dependent on grain size). Varying rheology gives similar results, though a better understanding of ice rheology is necessary for future work.

The Case for Europa & Ganymede

Given the overall physical similarities between Ganymede and Europa (notably g and T_{surf}), the different rift modes observed on these two moons (narrow rifts for Europa and wide rifts for Ganymede) are likely due to either a) differing strain rates, or b) differing crustal thicknesses or a combination thereof.

The Case for Enceladus

For the full range of parameter space modeled, my model predicts wide rifts for Enceladus (fig. 21), which does not agree with the observations of narrow tiger stripes. In order to get narrow rifts, I would need to significantly lower the surface temperature, or dramatically reduce the strain rate. An alternate (and more probable) solution is to include the effects of magmatic dikes. Dikes can serve to significantly decrease the yielding strength of the crust, and thus in this case, could reverse dF and cause narrow rifting for Enceladus.

5. Conclusions

I have developed a robust geodynamic model for investigating the of different rift modes for both terrestrial and icy satellite systems. Through modeling a range of parameter-space, I have come to the following general conclusions about the controls of forming different rift modes:

- Stronger crusts (colder heat fluxes, stronger rheology, higher strain rates) have large, negative changes in the yield strength, which dominates the other forces, and are more likely to result in the formation of narrow rifts.
- Weaker crusts (hotter heat fluxes, weaker rheology, smaller strain rates) have smaller negative or positive changes in the yield strength. This leads to the formation of wide rifts, or high-flow narrow rifts.
- Lower crustal flow enables the formation of high-flow narrow rifts. Lower crustal flow becomes important when the effective flow diffusivity is large, which occurs when the viscosity at the base of the crust is lower, which occurs for warmer crusts and larger pressure gradients.

My model is able to accurately predict the rift modes for a number of terrestrial rifts (fig.15). For icy satellites, narrow rifts are the predominant mode of rifting for most parameter space. To form wide rifts on Ganymede (vs. narrow rifts on Enceladus), requires either lower strain rates or thinner crusts. The narrow tiger stripes on Enceladus cannot be explained by my force balance models. A possible solution is the implementation of cryomagmatic dikes into these icy satellite lithospheres.

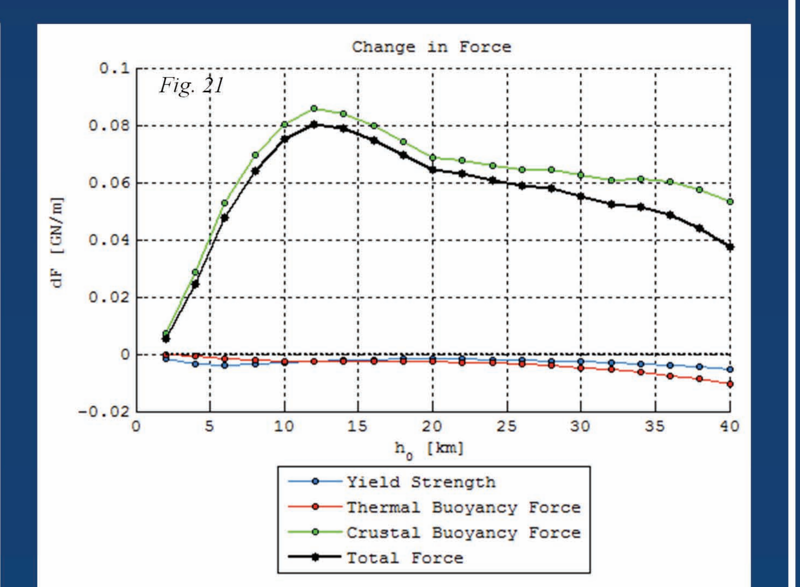

Fig. 21