EPSC Abstracts
Vol. 13, EPSC-DPS2019-1199-1, 2019
EPSC-DPS Joint Meeting 2019


EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

# Europa-style plate tectonics: Extension, convection, and the fate of icy slabs

**Samuel Howell (1)**, Robert Pappalardo (1), Erin Leonard (1,2), Laurent Montesi (3)
(1) NASA Jet Propulsion Laboratory, California Institute of Technology, USA (2) University of California, Los Angeles, USA (3) University of Maryland, USA (samuel.m.howell@jpl.nasa.gov)

## Abstract

The origin and formation of tectonic terrains on icy satellites are tied to processes that link the ice shell and the ocean, such as spreading, rifting, subduction, and cryovolcanism. Some of the most prevalent tectonic terrains on Europa are inferred to occur from extension in the ice shell [1], commonly producing long, linear "bands." In contrast, Voyager and Galileo spacecraft images of Europa show little evidence of corresponding convergent tectonics [2]. Understanding if and where tectonic transport and recycling of surface material occurs has fundamental implications for Europa habitability because such processes may allow oxidants produced at the surface to reach a reducing seafloor [3]. We present the results of several recently published and ongoing studies into the tectonic deformation of Europa, using first principles analytical thought experiments and complex geodynamic numerical models. We find that extension plays a critical role in the surface exposure of deep material and affects ice shell thicknesses [4]. Additionally, we find that buoyancy forces are unlikely to contribute to resurfacing, requiring ice shell thickness changes and/or decoupling from the silicate interior to reproduce observed features [5]. We finally predict that the compositional structure may be key to unlocking the evolution of the ice shell and the source of its deformation.

## 1. Motivation and Setting

Observations that some tectonic deformation on Europa occurs within organized systems of plates involving extension, strike-slip, and convergence raises the possibility for a buoyantly-driven cycle of tectonic resurfacing and recycling that is similar to plate tectonics on Earth [6]. One of the most prevalent tectonic features, extensional band formation has been compared to mid-ocean ridge spreading on Earth [1]. We first present two-dimensional (2-D) numerical models of band formation with the outer ice shell of Europa, and track "fossil ocean" material frozen into the ice shell and deformed through geologic time [4]. We predict which band morphologies are most likely to expose fossil ocean material, and the conditions under which those bands form.

While corresponding convergent terrains are sparse, proposed "subsumption zones" may allow near-surface slabs to be reincorporated into the deeper ice shell and recycled [7]. Such a cycle could quickly deliver oxidants produced on Europa's surface to reductants produced on the seafloor of the interior ocean, fundamentally impacting potential habitability. Therefore, we next present 2-D semi-analytical models of slab evolution, and the potential for spacecraft detection of these subsumption zones [6].

One clue as to the tectonic evolution of the ice shell relates to the fact that on Europa, some tectonic features are associated with the exposure of more non-ice materials than their surroundings. The distribution

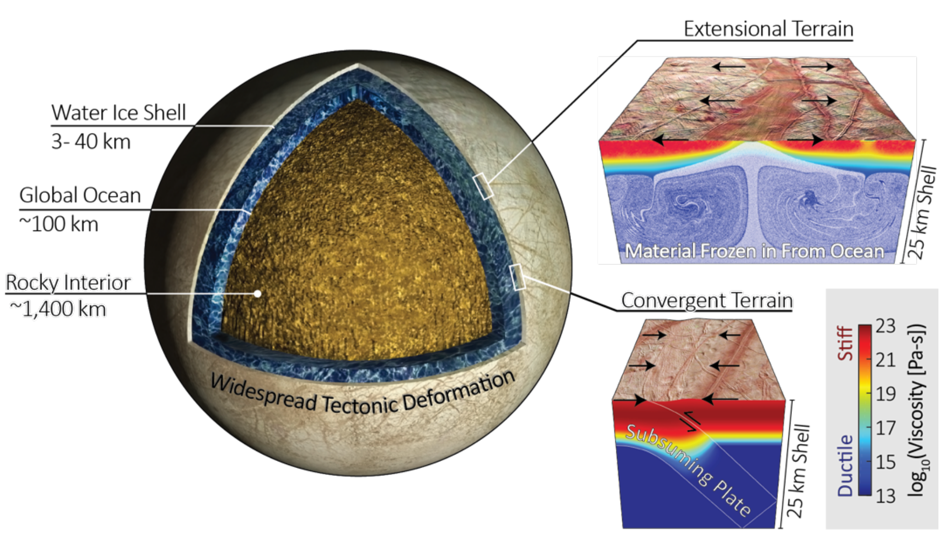


*Figure 1: Cutaway of Europa showing example 2-D numerical model of extension (top) and semi-analytical model of subsumption (bottom). Colors show viscosity and (top) white dots show fossil ocean material.*

of non-ice materials may reflect the evolution of the ice shell as new material froze in and later deformation that sampled compositional variations.

To understand what compositional variations may arise from a thickening ice shell and the associated surface exposure, we finally simulate the interaction between an outer ice shell and a mock interior ocean to create cross-sectional maps of historical freezing rate at the time of ice incorporation to the shell. Using freezing rate as an analogue for non-ice incorporation, we infer the distribution of non-ice impurities within the ice shell.

## 2. Methods

We use two approaches to characterizing the physics of ice shells in this presentation. To understand how the internal buoyancy forces provided by thermal and compositional variation promote resurfacing, we employ a pseudo two-dimensional, semi-analytical force balance [5,6]. We solve for the thermal and mechanical evolution of a slab intruded into a warm ice interior, accounting for composition and porosity, and calculate density anomalies with the surrounding interior ice. We then compare these buoyancy forces with the mechanical forces resisting resurfacing. Additionally, we expand upon these models to probe the physical nature of subsumed icy lithosphere intruding into a warm ice interior.

To track the deformation and freezing of Europa's ice shell, we extend the finite element code SiStER (Simple Stokes solver with Exotic Rheologies) [4] to simulate the visco-elasto-plastic behavior of ice I. In some simulations, we include partial melting and freezing that affects the density and mechanical behavior of particles within the finite difference mesh. For particles transitioning from the ocean to the ice shell, we record the maximum freezing rate ever experienced as an indicator of potential impurity incorporation. Models include internal tidal heat generation and basal silicate heat flux to the ocean.

## 3. Summary and Conclusions

Overall, we find that ocean material can be transported vertically into the ice shell through convection and advection, and fossil ocean may be exposed at smooth bands on Europa. However, the driving extensional forces remain poorly understood.

Addressing this issue, we investigate the potential for resurfacing through thermal or compositional convection akin to Earth-like plate tectonics. We find that in the outer ice-shells of icy satellites, the negative buoyancy associated with a downwelling slab is unlikely to contribute significantly to either the initiation or maintenance of subduction, and therefore unlikely to drive spreading.

To begin untangling the tectonic evolution of Europa and understanding the driving deformational forces, we infer spatial and temporal changes in Europa's ice shell composition from models of freezing rate of ocean water at the time of incorporation into Europa's ice shell. As tree rings provide an insight into the seasonal environment at the time of wood growth, we interpret these predictions of inferred global brine horizons to reflect the accretion history of incorporated ice. Non-ice distributions may record geologic history and interior heat flux, and might constrain whether the ice shell interior is convecting.

Future robotic exploration missions to ocean world ice shells, like NASA's planned Europa Clipper mission and ESA's planned JUICE mission, may test whether such thickening events are recorded by compositional variations within the ice shell.

## Acknowledgements

Portions of this work were performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Air and Space Administration. Government sponsorship acknowledged.

## References

1. L. M. Prockter *et al.*, Morphology of Europan bands at high resolution: A mid-ocean ridge-type rift mechanism. *Journal of Geophysical Research: Planets*. **107**, 4-1-4–26 (2002).
2. S. A. Kattenhorn, L. M. Prockter, Evidence for subduction in the ice shell of Europa. *Nature Geosci*. **7**, 762–767 (2014).
3. K. P. Hand, C. F. Chyba, J. C. Priscu, R. W. Carlson, K. H. Nealson, in *Europa*, R. T. Pappalardo, W. B. McKinnon, K. Khurana, Eds. (University of Arizona Press, Tucson, 2009), *The University of Arizona space science series*, p. 589.
4. S. M. Howell, R. T. Pappalardo, Band Formation and Ocean-Surface Interaction on Europa and Ganymede. *Geophysical Research Letters*. **45**, 4701–4709 (2018).
5. S. M. Howell, R. T. Pappalardo, Can Earth-like plate tectonics occur in ocean world ice shells? *Icarus* (2019), doi:10.1016/j.icarus.2019.01.011.
6. G. W. Patterson, J. W. Head, R. T. Pappalardo, Plate motion on Europa and nonrigid behavior of the Icy lithosphere: The Castalia Macula region. *Journal of Structural Geology*. **28**, 2237–2258 (2006).
7. B. C. Johnson, R. Y. Sheppard, A. C. Pascuzzo, E. A. Fisher, S. E. Wiggins, Porosity and Salt Content Determine if Subduction Can Occur in Europa's Ice Shell. *Journal of Geophysical Research: Planets* (2017), doi:10.1002/2017JE005370.