FY24 Strategic Initiatives Research and Technology Development (SRTD)

# Determining the Scientific Impact of a Geodesy Network at Enceladus

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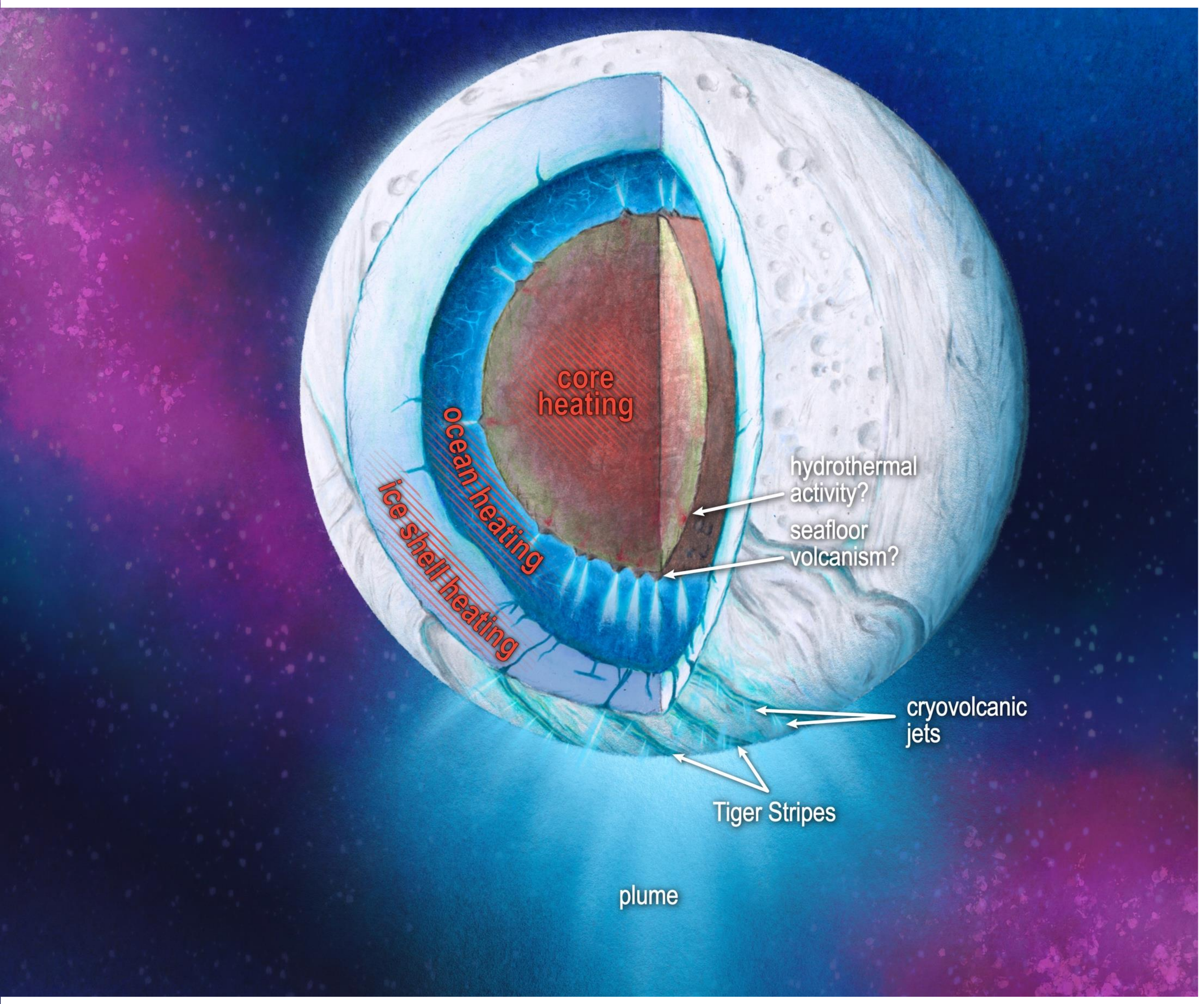
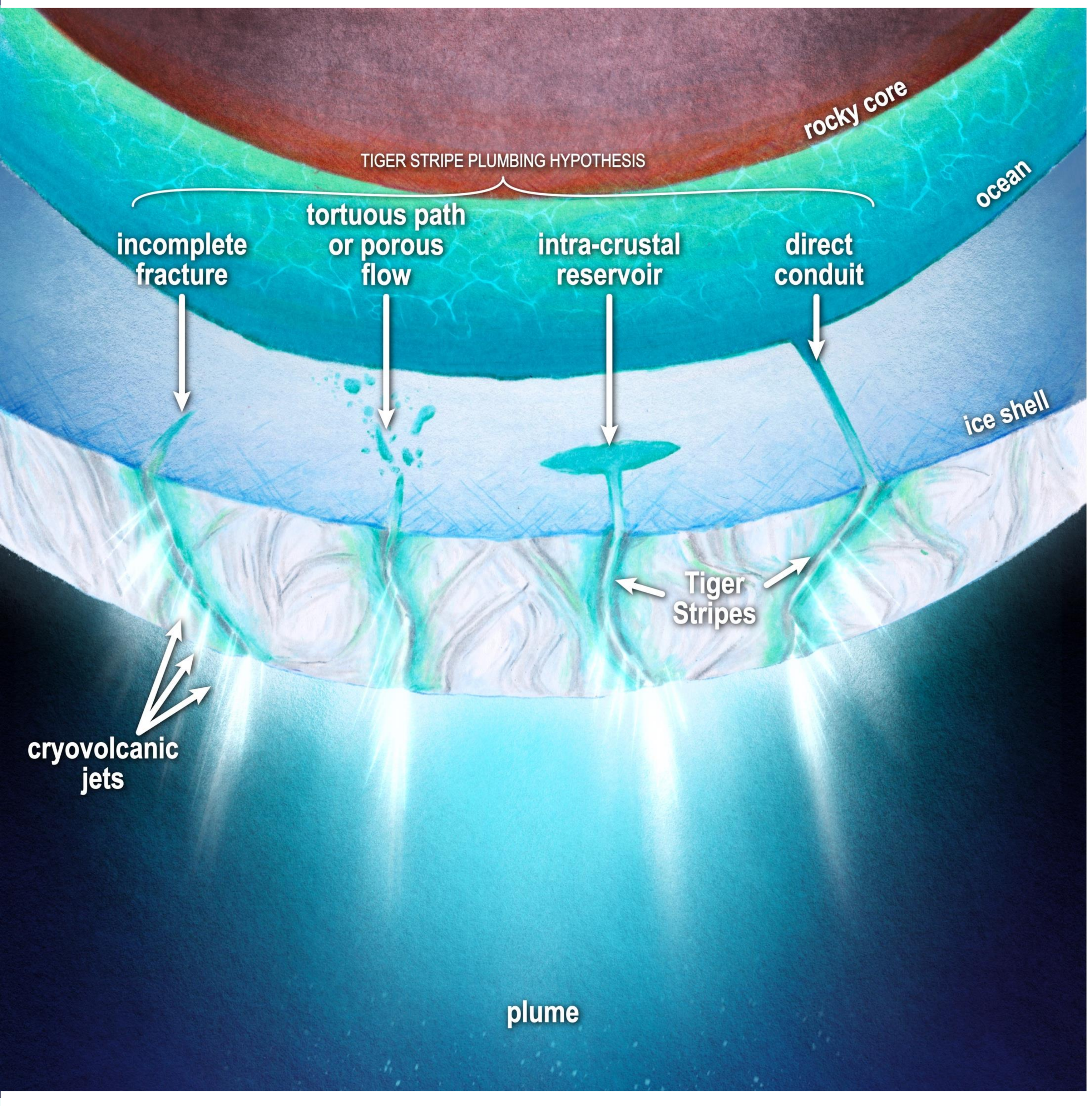
**Strategic Focus Area:** Next-Generation Ocean World Geodesy: Enceladus — **Strategic Initiative Leader:** Steve Vance




**The central goal of this R&TD is to develop the requisite scientific tools that motivate and enable transformative ocean world science using geodesy at Enceladus.** At present, there are critical gaps in available geophysical models of Enceladus, inhibiting the community's ability to create quantitative, testable hypotheses and ultimately answer outstanding science questions. Most state-of-the-art geophysical models of Enceladus are built on questionable simplifying assumptions (e.g., fault geometry, rheology, crustal structure). Enceladus's faults are the conduits by which ocean material is ejected into space, yet we do not understand how they form or evolve, nor their role in Enceladus's past/present habitability. In this SRTD, we developed a new geophysical model of Enceladus, **SatDef**, that is capable of simulating crustal deformation, viscoelastic rheology, shell thickness variations, faulting, and other relevant processes at high spatial and temporal scale. SatDef is built upon a finite element toolkit, PyLith, which is commonly used for terrestrial applications. Through this SRTD, we have not only developed this new tool (and shared it with the public), but applied it to several outstanding science problems for Enceladus. We expect this tool and the work it enables will feed forward to future investigations at Enceladus and beyond.

**Objective 1: Develop a new global geophysical model of Enceladus.** As detailed above, most geophysical models of Enceladus are built on questionable simplifying assumptions (e.g., presence/absence of faults, rheology, global symmetry). Our new viscoelasto-plastic finite element model, "SatDef", allows us to both test outstanding science questions and define new, quantitative testable hypotheses for future investigations. We have benchmarked this code against analytical models (e.g., SatStressGUI) and other finite element models (e.g., Běhounková et al. 2017). We have now published several papers about this model (Berne et al. 2023a, 2023b, 2024) and released the code to the public.

**Objective 2: Answer key questions about Enceladus's interior structure and habitability.** With the development of a new Enceladus finite element model complete, we were able to apply it to three very specific science problems:

**(A)** What is the magnitude of deformation on Enceladus's tiger stripes, and how does this deformation manifest in geophysical observables? Previous work (Běhounková et al. 2017) make predictions for deformation at Enceladus's tiger stripes, but do not consider realistic fault geometries and frictional characteristics. We have applied SatDef to this problem and found some notable differences (Berne et al. 2023a, 2023b). We have developed new predictions for key geophysical parameters including Love numbers and how they vary as a function of crustal structure (Berne et al. 2023a).

**(B)** What causes the offset in predicted peak tectonic stress and plume output? The peak output from Enceladus's plumes do not correlate with predicted peak tectonic stress (e.g., Hedman et al. 2013, Ingersoll et al. 2020). Applying SatDef to this problem we found that peak plume output actually correlates with peak of strike-slip motion predicted along the faults (Berne et al. 2024).

**(C)** How do other faults on Enceladus contribute to its deformation? Enceladus's tiger stripes are predicted to affect local and global deformation patterns (Běhounková et al. 2017), but the role of Enceladus's other faults around/beyond the south pole are unknown (e.g., Crow-Willard & Pappalardo 2015, Yin & Pappalardo 2015, Leonard et al. 2021). Our models include these other faults, and have shown that they can play a major role in accommodating tidal stress (Berne et al. 2023a).

**By understanding the details of Enceladus ice shell, it lets us start to probe the deeper interior structure of Enceladus, including the properties of the ocean and rocky core.** This interface is important to understand the extent of hydrothermal activity that might support life. We developed a framework for cross referencing gravity with other measurements in order to infer the ocean density and the viscosities of the ice shell and solid core (Vance et al. 2024). A manuscript about using Monte Carlo methods to explore the science return for different measurement constraints is in preparation.

**This SRTD has already had some exciting spin-off results for other planetary bodies.** For example, we recently utilized this model to examine tidal deformation of Earth's moon and probe its interior structure in new ways. A publication about this is currently in review (Park et al., in review).

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## Publications:

A. Berne, M. Simons, J. T. Keane, E. J. Leonard, and R. S. Park (2024). Jet activity on Enceladus linked to tidally driven strike-slip motion along tiger stripes. Nature Geoscience, 17: 385-391. https://doi.org/10.1038/s41561-024-01418-0.

R. S. Park, N. Mastrodemos, R. A. Jacobson, A. Berne, A. T. Vaughan, D. J. Hemingway, E. J. Leonard, J. C. Castillo-Rogez, C. S. Cockell, J. T. Keane, A. S. Konopliv, F. Nimmo, J. E. Riedel, M. Simons, and S. Vance (2024). The Global Shape, Gravity Field, and Libration of Enceladus. Journal of Geophysical Research (Planets), 129: e2023JE008054. https://doi.org/10.1029/2023JE008054.

C. S. Cockell, M. Simons, J. Castillo-Rogez, P. M. Higgins, L. Kaltenegger, J. T. Keane, E. J. Leonard, K. L. Mitchell, R. S. Park, S. M. Perl, and S. D. Vance (2023). Sustained and comparative habitability beyond Earth. Nature Astronomy. https://doi.org/10.1038/s41550-023-02158-8.

A. Berne, M. Simons, J. T. Keane, and R. S. Park (2023). Using Tidally-Driven Elastic Strains to Infer Regional Variations in Crustal Thickness at Enceladus. Geophysical Research Letters, 50: e2023GL106656. https://doi.org/10.1029/2023GL10665610.22541/essoar.168677232.29718733/v1.

A. Berne, M. Simons, J. T. Keane, and R. S. Park (2023). Inferring the Mean Thickness of the Outer Ice Shell of Enceladus From Diurnal Crustal Deformation. Journal of Geophysical Research (Planets), 128: e2022JE007712. https://doi.org/10.1029/2022JE007712.

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