PLUMBING AN ICY VOLCANO: CONSTRAINING THE SUBSURFACE BEHAVIOR OF ENCELADUS'S PLUME.

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Introduction: Enceladus is a satellite of Saturn, inferred to have a global subsurface water ocean, that is prioritized for the first in situ Ocean Worlds flagship by the 2023-2032 Planetary Science and Astrobiology Decadal Survey**,** as well as a key target in New Frontiers 5-7 [1]. Critically important are the South Polar Terrain (SPT) "Tiger Stripes." Jets of water vapor and icy grains are ejected from these long, linear fractures into the space environment to form a plume many times the diameter of the satellite. Depending on how well-linked the plume and the ocean are, as modulated by the icy and liquid transport processes, the plume may provide an accessible environment to directly study a planetary ocean. Thus, motivating the directed and competed astrobiology, geology, and geophysical goals related to the potential for life on Enceladus requires novel advancement of our qualitative and quantitative understanding of the link between Enceladus's ocean and surface.

While the plume of Enceladus likely sources to a global subsurface ocean [2], or deep reservoir fed by that ocean, we do not understand how water is transported from the subsurface liquid water reservoir to the surface. Two key pieces of missing information drive uncertainty in subsurface transport: (1) The highly-debated thickness of the ice shell beneath the SPT, with most estimates from geophysical, tectonic, and orbital remote sensing ranging from as low as 3-6 km [3, 4] to more than 30 km [5]; and (2) The geometry and nature of the plumbing system that connects the ocean to the surface. Currently, researchers consider that water in liquid, solid grain, and gas form flows in simplified geometries, commonly open pipes or vertical blade-like dikes of water, sometimes pinched into a nozzle in the near-surface, and almost always in direct connection with the ocean [6-8]. While these studies have considered the formation of near-surface nozzles and the escape of shallow ice and gases, which are constrained by Cassini data, our understanding of the mechanics of ocean-to-subsurface transport are more primitive, reflecting much poorer data constraints [8].

Because of limitations in our current understanding, there is an over-reliance on simplified plumbing constructs resulting from first-principles mass-energy balances [e.g., 6] that do not consider our understanding of realistic, complex multiphase (pure water in a solid, liquid, and gaseous state) transport within the solid interior of Earth and planets. While the plumes betray information about the near-surface environment, fluid transport from the ocean to the subsurface is likely to be affected by interactions between the background stress field and existing fractures and faults, mechanical stratification within the shell, ice shell rheology, compositional evolution of the fluids during transport, residence in fully and partially molten reservoirs, physical and thermal interactions between the magma and surrounding ice, surface topography, tectonic activity, and geologic history (high level summary in [9]). Additionally, liquid water is 10,000 to 100,000,000 times less viscous than rocky magmas, allowing water to more easily exploit complex fracture networks.

The goal of this work is to identify primary controls and potential configurations of a realistic plumbing system beneath Enceladus' south polar jets. We will consider how subsurface fractures and permeable structures (e.g. porous regions) might manifest on Enceladus, ranging from individual, vertical, curtain-like fractures extending to the ocean beneath the four Tiger Stripes, to fractures with various dips and curvatures, to pre-existing networks of fractures throughout the ice shell volume, to permeable porous layers.

Methodology: In order to begin to understand the subsurface plumbing on Enceladus, we must first map the surface fracture network, analyze the sensitivity to the changing tidal stress environment, and begin to project fracture networks into the subsurface. To accomplish our objectives, we will deploy advanced multiphysics models of varying complexity, informed by new and rigorous fracture mapping at the South Polar Terrain (SPT), to evaluate how complex plumbing systems alter deformation and material transport at the surface, at depth, and through time.

We will begin by characterizing the fracture environment through a comprehensive fracture map of the SPT using globally-controlled USGS mosaics [10] at a scale of 1:250,000, mapping all linear features > 250 m in scale (e.g., Fig. 1A). We will classify each potential fracture based on morphology, structural association, and predominant orientation. This initial fracture map will be used to create a two-dimensional (map view) discrete fracture network (Fig. 1B-E) using FracMan, a uniquely capable stochastic fracture network and flow analysis tool developed by WSP [11]. We will apply a time- and spatially-varying stress field to the SPT using existing FracMan capabilities that reflects the diurnal stresses generated through gravitational interaction with Saturn.

Then, we will extend the fracture network to fill an ice shell volume at the SPT with thickness ranging from

3-30 km. We will consider as the most basic case that vertical planar fractures extend beneath the Tiger Stripes to the ocean and then increase the complexity of the fracture network by considering additional cases where these curtain-like fractures dip at depth. Next, we will consider an added complexity where a second generation of fractures exists in the background, superimposed on the Tiger Stripes. We will generate separate realizations of fracture networks for different combinations of the spatial density of fractures, their diameter, their aperture, and their mean orientation.

In order to provide targets for these models to be tested against, we also will propagate error in the plume mass flux for both water vapor and icy grains. This will include data and uncertainties from Cassini's INMS, CDA-HRD, and CIRS instruments. We will use inverse techniques and Bayesian inference to understand the present-day uncertainties in erupted mass flux, and corresponding uncertainties in environmental controls.

Future Work: After we completed the fracture map and potential models of the 3-dimensional structure, we will work on incorporating fluid and gas flow using the multiphysics flow model PFLOTRAN incorporated into FracMan. From this, we aim to determine distributions in the following key constraints with depth, time, and lateral location: permeability, active conduit aperture, active conduit orientation, mass of mobile material, fraction of material in each phase (solid, liquid, gas), material velocity for each phase, and residence timescale of each phase.

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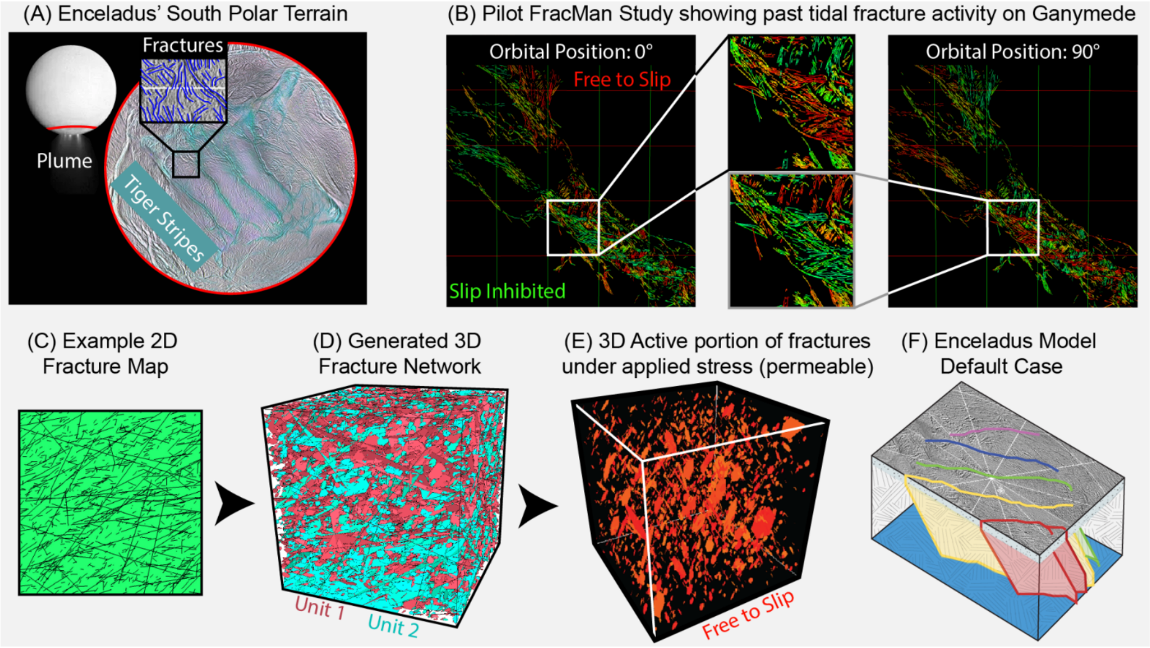

Figure 1: (A) Images of Enceladus' plume and enchased color image of the south polar terrain (red) highlighting the four Tiger Stripe fracture units, shown here in light blue. Smaller fractures are highlighted in the black callout. **(B)** Example FracMan results simulating past activity in Ganymede's Uruk Sulcus region (fracture set courtesy of L. Burkhardt, M. Cameron, G. Collins). Panels show changes in fracture activity with orbital position, and callouts show an inversion in active fracture orientation. **(C)** An example 2-D fracture map with two distinct geologic units is used to create **(D)** a FracMan DFN. **(E)** Under applied stress, only a subset of fractures with specific orientation are able to slip and dilate, guiding where water might actively flow. **(F)** The default model case considered, where the only fractures are sheet-like vertical extensions of the tiger stripes that extend with depth.