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Mechanical properties of Enceladus' icy plume deposit analogs

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Program: FY21 R&TD Topics **Strategic Focus Area: Habitable Worlds**

Objectives: Multiple mission concepts are in development within JPL and across NASA to access the surface (and subsurface) of these Ocean Worlds and study the habitability and potential for extinct/extant life there. Ice plume deposit regions would be prime landing target locations, however a critical lack of understanding of the mechanical properties of these terrains hinders the development of landing and sampling systems. Despite the importance of this research topic to JPL's and NASA's visions for the exploration of Ocean Worlds, only few efforts appear to be currently ongoing in this area based on publicly available literature. This research aims at 1) developing a fundamental understanding of the mechanical behavior of porous fine-grained ice as it sinters via a combination of experimental measurements and modeling, and 2) advancing our predictive capabilities of the mechanical properties of plume deposits as a function of emplacement age on Europa and Enceladus.

Background: The poor knowledge of the mechanical properties of plume deposit regions is a source of unknown risk to landed elements and sampling systems. Experiments on the cone penetration resistance of plume deposits as function of time and temperature (Choukroun et al., 2020; Choukroun et al., 2021 [Publication A]) provided new insights on the expected state of consolidation of plume deposits as function of location and age. However, cone penetration resistance alone does not inform on all aspects of mechanical properties that are needed to achieve a fundamental understanding of the mechanics of these materials and their microstructure under all applicable types of loading conditions (quasi-static and dynamic loading).

Approach and Result: The approach for this project is to conduct systematic measurements of mechanical properties and modeling of sintering ice samples.

1) Ice plume deposit analogs are prepared in the form of microspheres with mean radius close to Enceladus plume particles and sintered into bulk form at various temperatures.
2) At regular intervals in time, samples were to be tested for cone penetrometer resistance, uniaxial compressive strength (Figure 1, left), flexural strength and fracture toughness (Figure 1, right). Good progress on preparing for UCS testing in FY21, Installation of drop tower still underway for flexural strength and fracture toughness. Measurements will take place in FY22.
3) The evolution in grain size distribution, crystal shape, and relative neck size is studied by cryogenic optical microscopy at JPL (Figure 2). Developed methods and started analysis in FY21, will continue in FY22.
4) The microstructure, porosity, and packing arrangement are examined at Dartmouth College Ice Research Laboratory using micro-computed tomography (Figure 3). FY21 data showed evolution in packing over long sintering timescales, will continue analysis in FY22.
5) A Discrete Element Modeling effort integrates the various experimental results (Figure 4), and all new data will also help refine Co-I Molaro's sintering model. In FY21 we published DEM modeling related to cone penetration tests (Dhaouadi et al. 2021, publication B).

Significance/Benefits to JPL and NASA: This research has direct and immediate implications for ongoing (and possibly future) mission concepts in development, such as the Enceladus orbiter/lander Planetary Mission Concept study for the Planetary Science and Astrobiology Decadal Survey, and a JPL study for a New Frontiers Enceladus lander concept, as it seeks to better understand the mechanical properties of ice plume deposits under the surface conditions of Enceladus and Europa.

Publications:

A. Choukroun, M., Backes, P., Cable, M.L., Fayolle, E.C., Hodyss, R., Murdza, A., Schulson, E.M., Badescu, M., Malaska, M.J., Marteau, E. and Molaro, J.L., 2021. Sampling Plume Deposits on Enceladus' Surface to Explore Ocean Materials and Search for Traces of Life or Biosignatures. *The Planetary Science Journal*, 2(3), p.100.
B. Dhaouadi, W., Marteau, E., Kolvenbach, H., Choukroun, M., Molaro, J.L., Hodyss, R., Schulson, E.M. Discrete Element Modeling of Planetary Ice Analogs: Mechanical Behavior upon Sintering. *Granular Matter*, in press.

Figure 1. *Left:* Photograph of the cryogenic Instron press to be used for uniaxial compressive strength measurements. *Right:* Cryogenic Instron impact tower to be used for flexural strength and fracture toughness measurements.

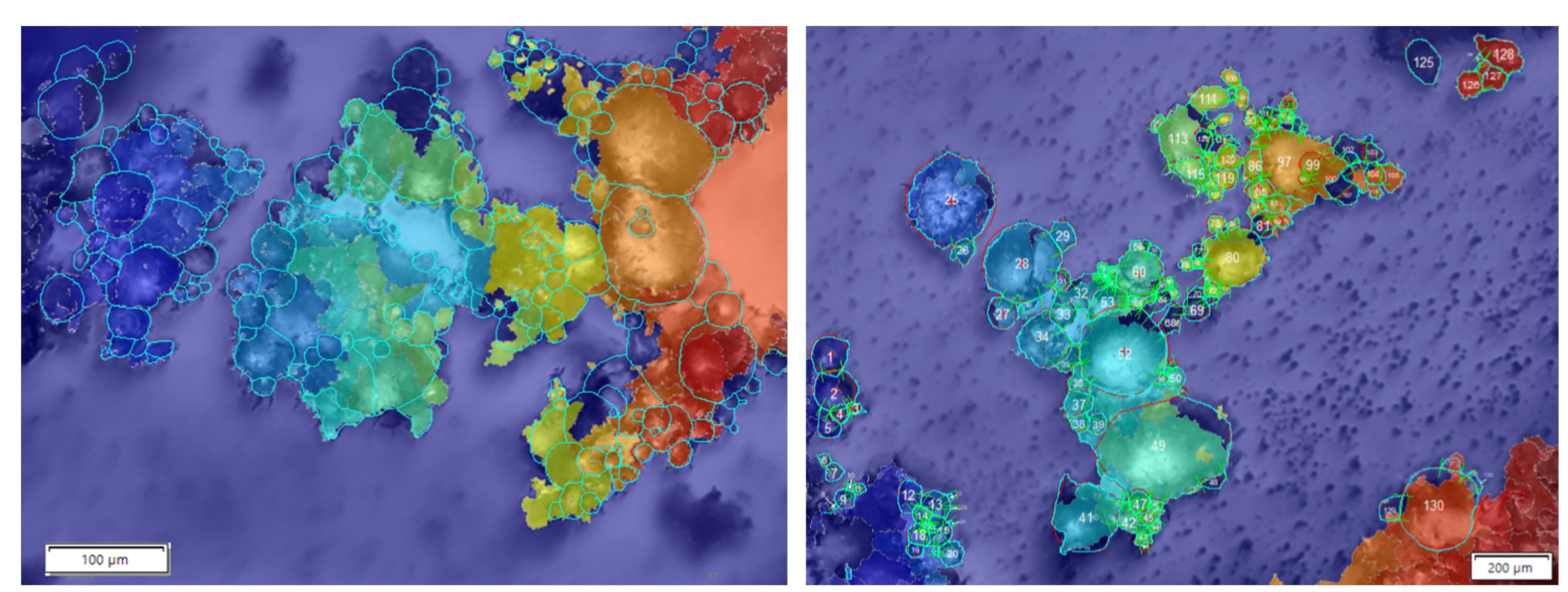

Figure 2. Microscope images processed for microstructure analysis of sintered ice. *Left:* Image after processing and automated detection of grain boundaries for analysis. *Right:* Image after manual processing for grain size and relative neck size.

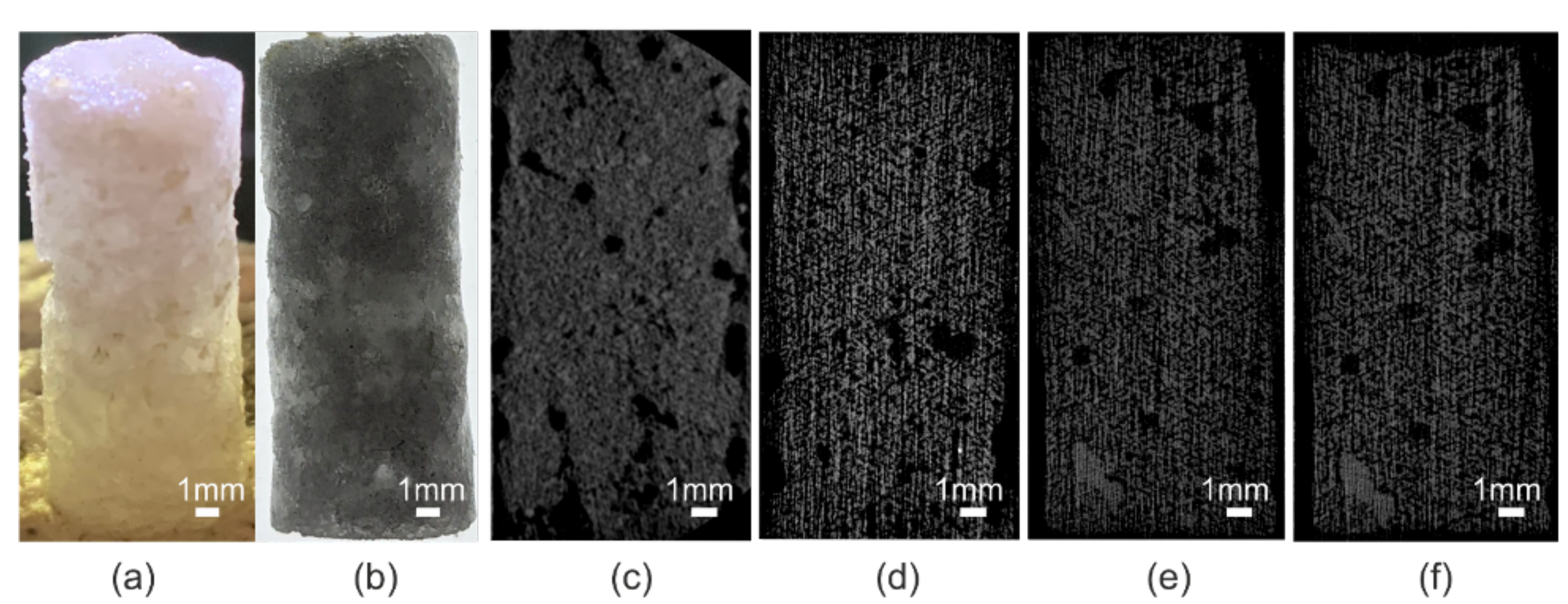

Figure 3. Optical photographs of a cylindrical sample of as-prepared sintered ice; the variations in contrast indicate cavities (a,b). Xray microtomographic images after sintering 1 month (c) and after 7 months (d) at -30 C. Xray microtomographic images of the same area after 7 months at -30 C before (e) and after (f) the ice was held in the Xray scanner at -14 C for 8 hours.

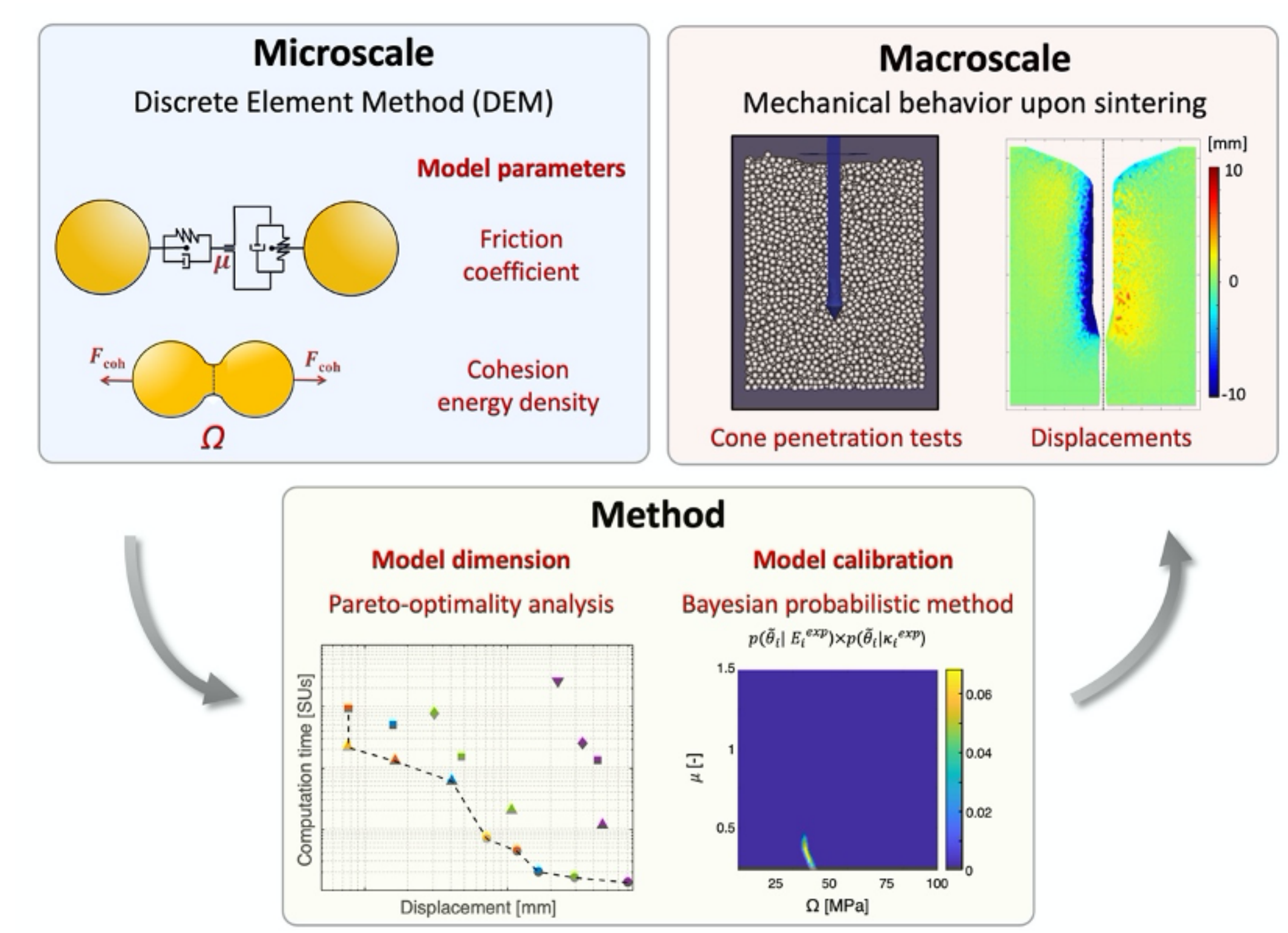

Figure 4. Discrete Element modeling of the mechanics of planetary ice analogs. After Dhaouadi et al. (2021, **[publication B]**).

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