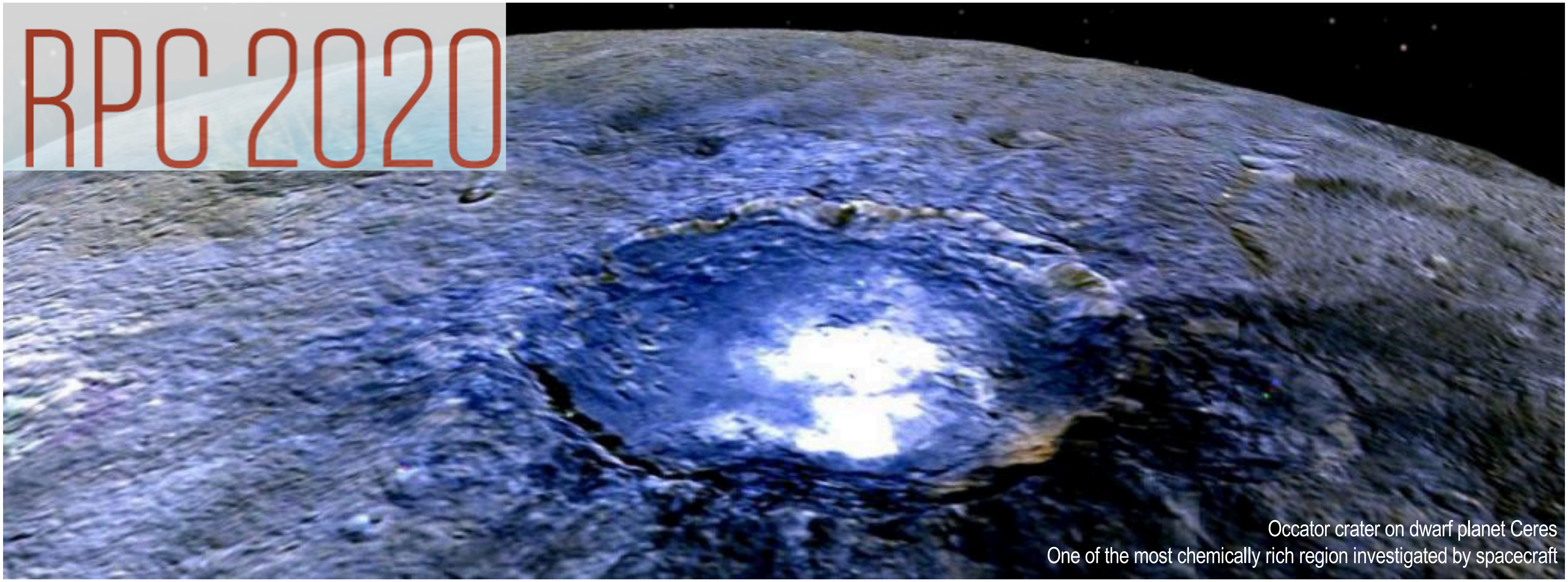

Virtual Research Presentation Conference

Carbon Cycle in Small Ocean Worlds

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Program: Strategic Initiative

Assigned Presentation RPC-084

Jet Propulsion Laboratory
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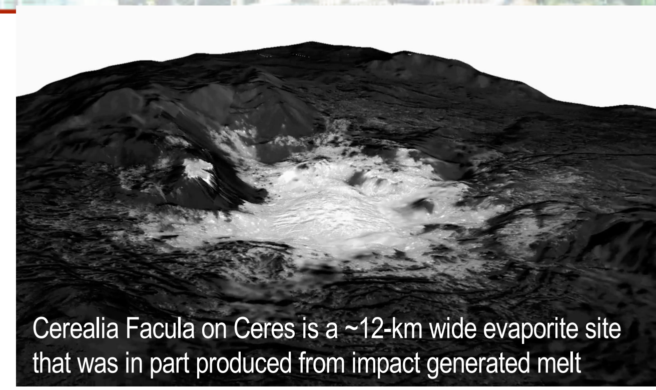
Tutorial Introduction

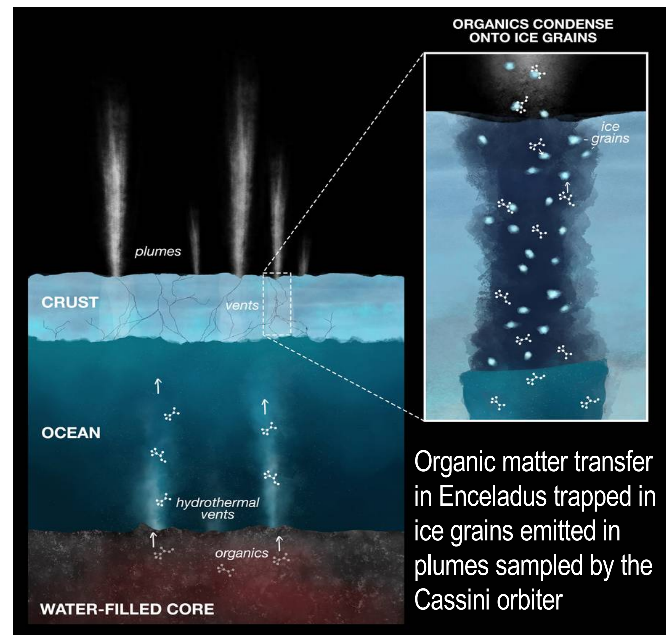
This strategic initiative addresses the fate of carbon in ocean worlds, e.g., icy bodies that contain deep liquid at present, like Jupiter's moon Europa or dwarf planet Ceres. In these bodies, carbon can take multiple forms: carbonates, organic compounds, and gas hydrates. This task simulates environments expected in these bodies in order to determine which form of carbon dominated as a function of space and time.

Environments of interest are (1) liquid reservoirs created by impact-produced heating under large craters, (2) porous, brine-rich rocky mantles in ocean worlds that are smaller than 1000 km in diameter, (3) evolved oceans. All three may be potentially habitable and are thus of interest for exploration by future missions.

The approach combines multiple geochemical modeling tools in order to cover the range of pressures and temperatures expected in these environments. Dwarf planet Ceres is taken as a reference application, because the Dawn mission found evidence for 20 wt.% of carbon in Ceres' shallow subsurface and the three forms of compounds mentioned above. Also, Dawn revealed the existence of the three environments of interest in Ceres with unprecedented observational constraints on their characteristics.



Cerealia Facula on Ceres is a ~12-km wide evaporite site that was in part produced from impact generated melt



Organic matter transfer in Enceladus trapped in ice grains emitted in plumes sampled by the Cassini orbiter

Problem Description

a) Context

In the past decade, organic compounds have been found on a variety of bodies: Enceladus, dwarf planets Pluto and Ceres, and main belt asteroids.

This task aims to understand the state of carbon and the role it may play in fostering habitability in these bodies throughout their history and at present.

For example, geological landforms sourced from Ceres' deep brine layer are dominated by carbonate when that layer is expected to be rich in organic matter. This suggests the organic matter may degrade over time.

b) Comparison or advancement over current state-of-the-art

The long-term chemical evolution of deep oceans and the sources and sinks of volatiles and major elements in icy bodies are just beginning to be studied.

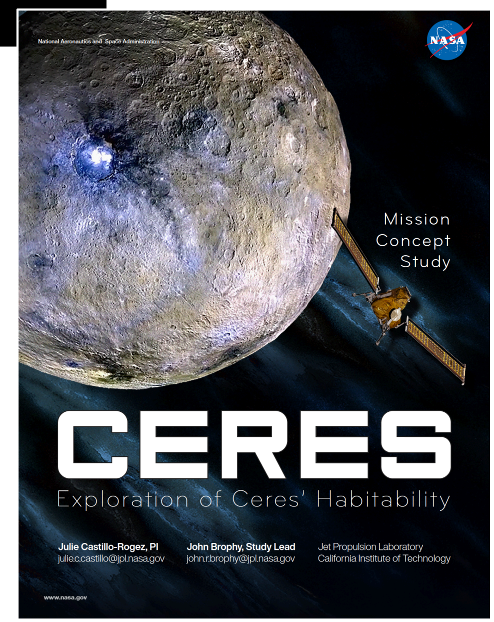
Impact-produced melt reservoirs and porous mantles are newly recognized environments of potential astrobiological interest.

c) Relevance to NASA and JPL

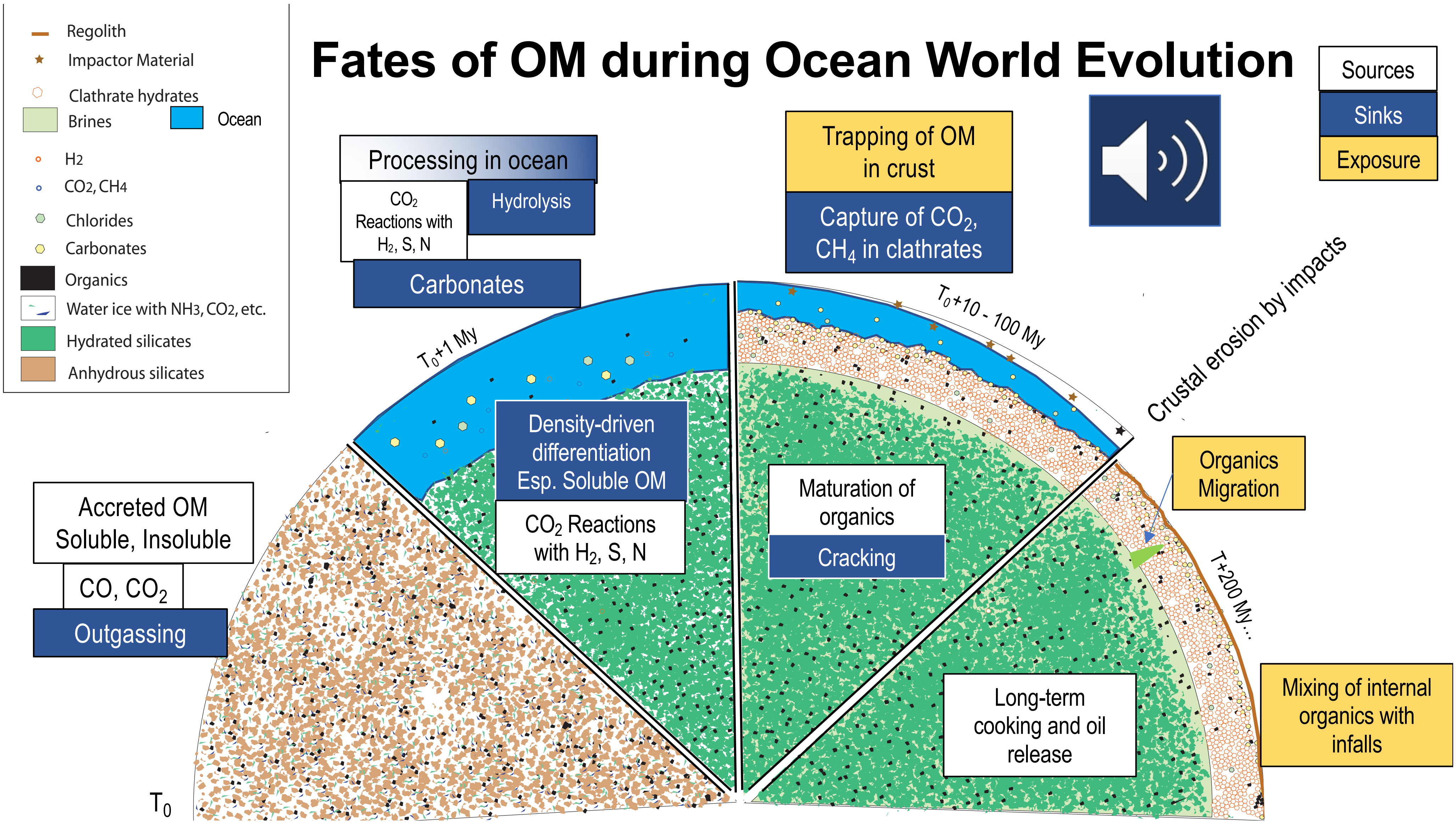
Understanding the state of carbon on the surface of high-priority targets is critical to future mission formulation and observation planning.

JPL is studying a mission to Neptune's moon Triton that may be an ocean world. Results from this task informed the chemistry of Triton's ocean the formulation of future investigations.

NASA recently sponsored mission concepts for Enceladus, Pluto and Ceres to inform the ongoing Planetary Science Decadal Survey. The Ceres concept led at JPL uses results from this task.



Fates of OM during Ocean World Evolution



Methodology

a) Formulation, theory or experiment description

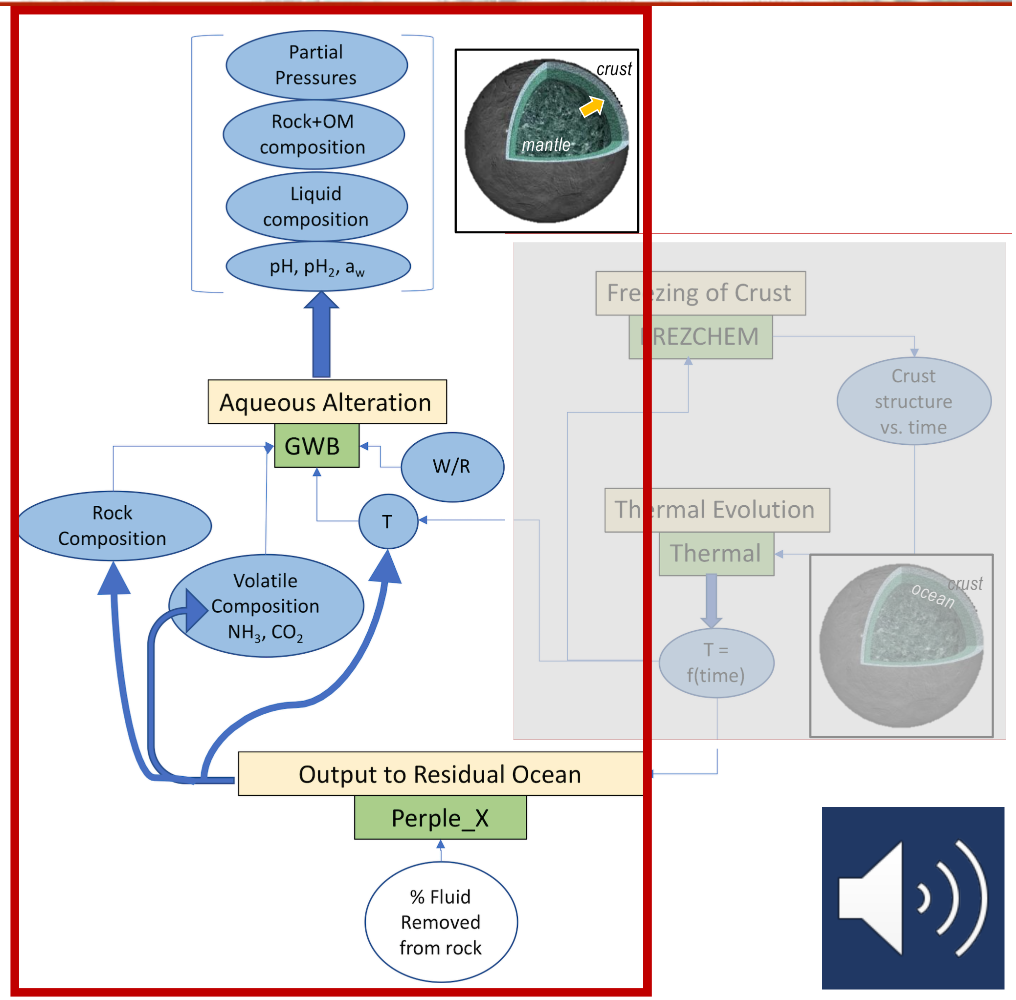
The method consists in combining pieces of geochemical/thermodynamical modeling:

- The *Geochemist's Workbench (GWB)* computes the products of aqueous alteration of accreted rock.
- *FREZCHEM* computes the freezing of the shell and the composition of the residual ocean.
- *Perple_X* tracks the petrological evolution of the rocky mantle as a consequence of heating and the release of fluids (gas and liquid) to the ocean.
- These codes are linked via thermal modeling of the interior.

b) Innovation, advancement

This work is the first attempt at combining thermodynamics models that can track the fate of major elements through space and time.

Besides carbon, other elements are tracked, such as nitrogen and sulfur, which are also of importance to Astrobiology.



Ceres' interior taken as reference

Results

a) Accomplishments versus goals

We modeled the three environments of interest; here we focus on volatile transfer from the rocky mantle of Ceres.

Fluids released from the rocky mantle shift the environmental conditions in long-lived lived ocean or even replenish a residual or dried up ocean.

These results show that the environments in evolved oceans could be oxidizing and drive the degradation of organic compounds into carbonates.

b) Significance

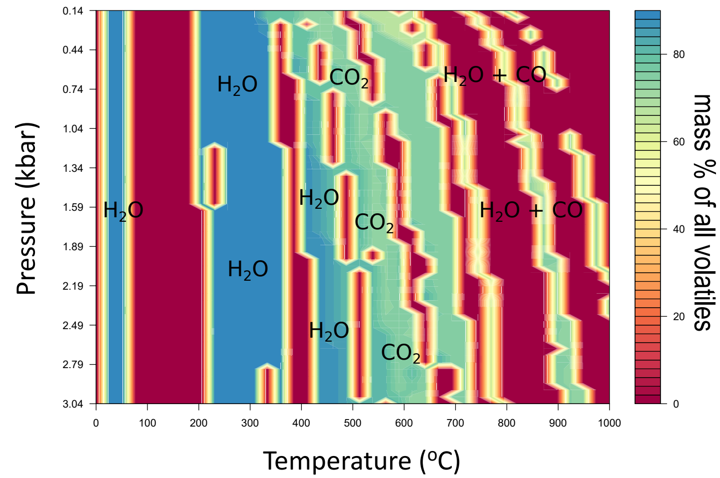
These results highlight the importance of carbonates in driving the salinity of ocean worlds, especially those formed in the far outer solar system.

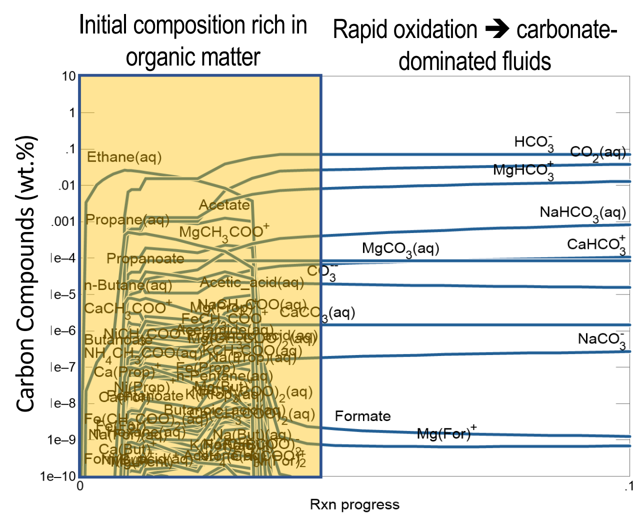
They also imply long-lived ocean may become inhabitable over time.

Organic compounds may be trapped in carbonates found on icy body surfaces.

c) Next steps

Next year, we will model the isotopic signatures of the various types of carbon compounds expected on ocean worlds and we will start devising strategies to find and characterize organic compounds with future missions.





Publications and References

[A] Melwani Daswani, M., Castillo-Rogez, J. C., et al. (TBD) Influence of fluid generation from thermal metamorphism on Ceres' rocky mantle density, in preparation for submission to *Journal of Planetary Science*.

[B] Castillo-Rogez, J. C., Melwani Daswani, M., et al. (TBD) Fate of organic compounds in the residual ocean of Ceres, in preparation for submission to *Journal of Planetary Science*.

[C] Castillo-Rogez, J. C., et al., Carbon cycle in ocean worlds, Invited paper to the Special Issue of *Minerals* on "Organic Matter and the Associated Mineralogy on Small Bodies of the Solar System"