National Aeronautics and Space Administration

Carbon Cycle in Small Ocean Worlds

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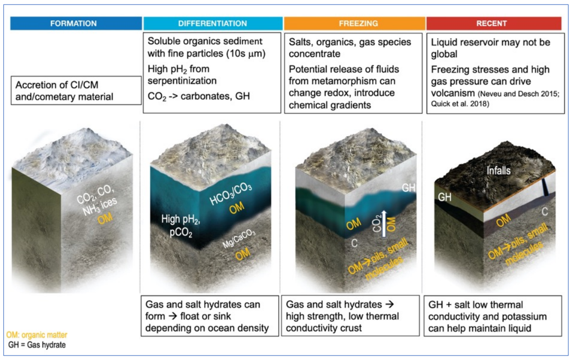
Program: FY22 R&TD Strategic Initiative
Strategic Focus Area: Fate of Organics in Ocean Worlds
Strategic Initiative Leader: Bryana L Henderson

Objectives:

The objective of this work was to develop a modeling framework capturing the exchanges of materials, especially carbon-rich compounds (e.g., CO, CO2, organic matter) inside ocean worlds, throughout their evolution. This work revealed processes that had received little attention in the literature. This new knowledge will help identify science investigations responsive to the Planetary Science and Astrobiology Decadal Survey, e.g., Ceres Sample Return, Uranus Orbiter and Probe, or Enceladus Orbilander.

Background:

Current understanding of early solar system dynamics emphasizes the role of pebbles rich in non-ice volatiles as a likely mechanism for explaining the rapid growth of outer solar system bodies, including icy moons, dwarf planets, and potentially also icy asteroids. At dwarf planet Ceres, the Dawn mission revealed many forms of carbon compounds, including carbonates and organic matter, sourced from various regions in Ceres' deep interior. Based on this information, it becomes possible to outline the geochemical cycle of carbon in Ceres, with application to other large (>500 km diameter) icy bodies.



FORMATION — Accretion of CI/CM and/cometary material

DIFFERENTIATION — Soluble organics sediment with fine particles (10s μm); High pH_2 from serpentinization; CO_2 -> carbonates, GH; Gas and salt hydrates can form → float or sink depending on ocean density

FREEZING — Salts, organics, gas species concentrate; Potential release of fluids from metamorphism can change redox, introduce chemical gradients; Gas and salt hydrates → high strength, low thermal conductivity crust

RECENT — Liquid reservoir may not be global; Freezing stresses and high gas pressure can drive volcanism (Neveu and Desch 2015; Quick et al. 2018); GH + salt low thermal conductivity and potassium can help maintain liquid

OM: organic matter
GH = Gas hydrate

Figure 1. This work investigated a variety of processes driving material physical and chemical evolution from the deep interior to the surface.

Approach and Results:

The method combines several thermodynamic codes: Geochemist's Workbench for aqueous chemistry modeling, FREZCHEM for simulating the freezing of a brine, and PERPLEx for tracking the evolution of hydrated rock as a consequence of thermal metamorphism. We report a single result here. The oceans of small, residual ocean worlds (Ceres, Uranus moons) should be very rich in carbon (organics, carbonates) and we quantified the flux of oxidants and reductants from the mantle to ocean as a consequence of thermal metamorphism [C]. We also showed – for the first time – that the accretion of cometary material can lead to much colder interiors than previously modeled with a carbonaceous chondrite (CC) composition [A]. This is because the large fraction of organics dilutes the rest of the material; as a result the relative abundances of radioisotopes are about half the CC abundances. The temperatures reached in the rocky mantle determine the relative fraction of CO_2 and CH_4 released as a consequence of the breakdown of organic compounds and carbonates. For example, in Titan, very little methane may be released with metamorphic fluids because the rocky mantle temperature never reaches sufficient temperatures (pressure-dependent) (see Figure 2). On the other hand a significant fraction of CO_2 may be released. The form taken by carbon in deep oceans is important because carbonates could make a significant contribution to ocean salinity and electrical conductivity (Figure 3) [E, F].

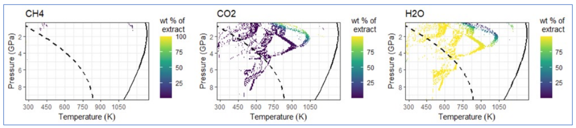


Figure 2. Pressure-temperature stability diagrams for water, methane, and carbon dioxide compared against the current (dashed line) temperature profiles of a model of Titan's rocky core with a starting composition dominated by cometary material (high organic fraction, relatively low radioisotope fractions).

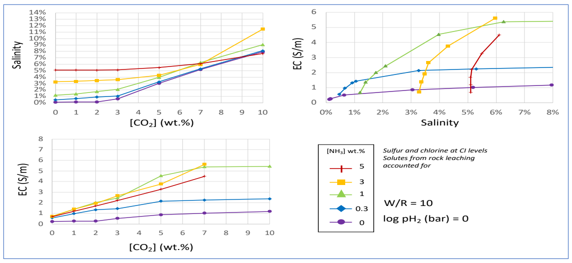


Figure 3. Relationships between the concentrations of accreted CO2 and NH3, the salinity of oceans formed from the melting of these compounds in liquid water, and the resulting electrical conductivity (EC). Small amounts of carbon dioxide can affect the salinity and EC if ammonia is also present in abundance >0.5 wt.%.

Significance/Benefits to JPL and NASA:

While the majority of the study processes are applicable to large icy moons, such as Europa and Titan, their investigation reveals the workings of "residual ocean worlds," a class of icy bodies that are not benefitting from tidal heating. These include dwarf planets (e.g., Ceres, Pluto) and most of the Uranian moons. Published models predicted that these bodies should not maintain a deep ocean until present. This task demonstrates that thermal metamorphism of the rocky mantle can lead to the release of a vast amount of water (equivalent to about ~20 km in a moon like Titania). The release of fluids from the mantle upon metamorphism can also deliver reductants and oxidants to this second generation ocean, the relative fraction of which depends on the specifics of the studied body (e.g., composition and size). Future missions can tailor their observational strategies to that class of bodies, for example to address their habitability potential.

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Publications:

[A] Julie Castillo-Rogez, et al. "Carbon Cycle in Ocean Worlds and Geophysical Implications," Submitted to Planetary Science Journal.
[B] Samuel Courville, "The Composition of Primordial Oceans in the Outer Solar System", Final internship report, available upon request.
[C] Mohit Melwani Daswani and Julie Castillo-Rogez, "Porosity-filling Metamorphic Brines Explain Ceres's Low Mantle Density. The Planetary Science Journal, 3(1), 21.
[D] Julie Castillo-Rogez, et al., " Role of nonwatery ice volatiles in Driving Ocean Salinity and Electrical Conductivity in Ocean Worlds," Geophysical Research Letters 49, e2021GL097256.
[E] Jack Diab, et al., " Bulk Composition and Thermal Evolution Constrain the Formation of Organics in Ceres' Subsurface Ocean." .
[F] Julie Castillo-Rogez, et al., "Compositions and Interior Structures of the Large Moons of Uranus and Implications for Future Spacecraft Observations ." J. Geophysical Research, accepted.

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