**Introduction:** For several decades, the prospects that alien oceans could suffer entropic death was a concern for astrobiologists [1]. Recent studies have highlighted various processes for introducing chemical gradients into deep oceans (e.g., radiolysis, [2], exogenic material [3]). One potentially significant process in large icy bodies is the replenishment of redox-sensitive elements via fluids released to the hydrosphere during thermal metamorphism of rocky mantles. On Earth, elements that can occur in more than one valence state, such as Fe, C, N and S, are known to drive Earth’s chemical evolution as they cycle through various geochemical reservoirs [e.g., 4]. Similar cycling have likely been occurring in icy moons and dwarf planets and ultimately determine the redox budget of the ocean. We are developing a modeling framework that tracks the fluxes of major compounds in bodies that go through several major evolutionary events (e.g., differentiation, metamorphism, freezing and clathrate formation). Here, we focus on tracking the fate of carbon in these bodies because that element could represent a significant fraction of the make-up of cometary material, based on the results of the Rosetta mission at 67P (30% [5], which makes it equally abundant to oxygen and hydrogen). Hence, the state of carbon could play a major role in determining the chemical and physical properties of deep oceans.

**Source of Volatiles in Icy Worlds:** There are two main sources of volatiles and carbon-bearing materials representing feedstock for outer solar system bodies: cometary and carbonaceous chondrite (CC) parent bodies. They differ by their relative fractions of carbon (~25 wt.% in comets, <4 wt.% in CC). Carbon in these bodies can take several forms: volatiles (ices, clathrates) and organic matter (OM, soluble and insoluble). Depending on their formation location and the possible addition of planetesimals migrating from the far outer solar system, icy moons and dwarf planets could have accreted different fractions of carbon-bearing material.

In icy bodies large enough to go through a phase of global volatile melting (generally triggered by $^{26}$Al decay heat), carbon ices go in solution. If a small fraction of ammonia is also accreted, then CO$_2$ and CO ices are likely a source of carbonates [6]. Multiple types of carbonates and bicarbonate have been detected at Ceres and Enceladus, in association with ammonium likely derived from accreted ammonia (ices or hydrates) [7,8]. Ammonium-carbonate rich oceans are expected to be a dominant feature of icy bodies formed beyond Jupiter’s orbit and might also be relevant to Europa if the Galilean moon accreted cometary pebbles [9]. Hence, the ocean composition of these bodies may be traced to the origin of their building blocks.

**Modern Brines:** Thermal metamorphism is expected to represent a major stage in the evolution of the rocky mantles of large icy moons [10]. This process involves the dehydration of structural water in hydrated silicates and the breakdown of carbonates, sulfides, etc. The timing of thermal metamorphism depends on the mantle radius and its thermal conductivity (which itself depends on mineralogy). We are developing a code that tracks chemical and physical properties in a self-consistent manner. This code is intended to quantify the cycling of fluids and major elements, throughout the evolution of icy bodies up to Europa’s size. It is based on a combination of three pieces of geochemical modeling software: EQ3/6 (aqueous chemistry), PERPLEX (equilibrium assemblages) and Frezchem (freezing), tied together via a thermal evolution model (Figure 1).

![Figure 1](image.jpg)

*Figure 1. We are working toward the implementation of a code that will model the geochemical and physical evolution of icy bodies based on pieces of software in the public domain.*

Fluids released during thermal metamorphism are rich in CO$_2$, from the breakdown of carbonates and organics, and CH$_4$ that may form from CO$_2$ reacting with released H$_2$; sulfur in reduced (H$_2$S) or oxidized (SO$_2$) form, and minor carbon species from the breakdown of soluble organics. At this stage of development, the code does not treat the maturation of
insoluble OM due to lack of thermodynamical data. It
does account for some evolution of the insoluble OM
based on petroleum experimental literature in
conditions relevant to icy moons [11].

**Preliminary Results:** The original amount of water
trapped in rocky mantles following differentiation
depends on pressure, temperature, and redox conditions.
In Ceres, water was trapped primarily in clays (~19
wt.% water) and lizardite (~13wt.% water) [12]. In a
slightly larger body like Pluto, water is likely trapped in
the form of amphibole (~2wt.% water) [11]. In that case,
the amount of metamorphic fluids released from the
mantle to the hydrosphere may be limited. It also
depends on the size of the ocean at the time of
metamorphism. In the case of Ceres and Pluto, [11] and
[12] suggest that metamorphic fluids represent a large
fraction of the ocean, if not the bulk (a second
generation ocean), and they may drive the composition
of residual brines, which will be observed by future
missions. In the case of the Uranian moons, oceans at
present may be a mixture of residual fluids from an early
ocean and of metamorphic fluids [13]. On the other
hand, in the case of Europa or Titan, the relative
contribution of metamorphic fluids to the bulk ocean
composition of these moons is likely small.

The oxidizing or reducing nature of metamorphic
fluids is determined by the original composition of the
rock and the temperature reached in the rocky mantles.
Carbonates break down at about 650 K so that CO₂
is expected to be abundant in metamorphic fluids evolved
from CC or cometary material. Sulfides decompose at
about 500-650 K (at 100s MPa-1 GPa) and is predicted
to release H₂S in Ceres and Europa [10, 12]). In bodies
small enough with deep residual brines, CO₂: lead to a
large abundance of bicarbonate and carbonate ions in
solution and the potential oxidation of organic
compounds. hence, while a high concentration of salts
preserves liquid via decreasing the eutectic temperature,
the conditions predicted in these residual oceans are
likely unfavorable to life (e.g., too cold, ammonia
dominated).

**Future Brines:** We will present the spectrum of
possible metamorphic fluid abundance and composition
for a range of accreted materials and icy world thermal
evolution models. In the smaller ocean worlds (past or
present) such as Ceres or the Uranian moons,
metamorphic fluids could drive the physico-chemical
conditions in a residual brine layer. In larger ocean
worlds, metamorphic fluids may introduce chemical
gradient that help promote a habitable environment.
Future missions can test this model via compositional
measurements (salinity via conductivity, surface
mineralogy). For example, the Uranian moons are
expected to host residual (<50 km thick) brine layers
that are enriched in bi/carbonate, chlorides, ammonium,
and ammonia [13] (Figure 2). The payload
recommended for the Uranus Orbiter and Probe mission
prioritized by the Origins, Worlds, and Life Decadal
Survey [14] has the capability to find oceans and test
their habitability potential, adding to our knowledge of
deep ocean environments in our solar system.

![Figure 2](https://doi.org/10.17226/26522)

**Figure 2.** Concentrations of key compounds in residual
oceans in Uranus’ large moons. Besides NH₃, residual oceans
are dominated by sodium chloride and sodium bicarbonate.
After [13].

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