Ocean Worlds: Science Goals for the Next Decade

White paper submitted to the 2023-2032 Planetary Science and Astrobiology Decadal Survey

The Outer Planets Assessment Group (OPAG) formed the Roadmaps to Ocean Worlds (ROW) group to 1) assemble the scientific framework guiding the exploration of Ocean Worlds over the next several decades; 2) to design a roadmap(s) to explore these worlds to address science objectives, and 3) to recommend technology development to advance future OW mission capabilities. Many of the ROW results are summarized by Hendrix and Hurford et al. (2019). In this white paper we summarize the mission priorities for Ocean Worlds in the next ~decade. Because this is a **community document**, numerous authors have contributed including those listed below. Accompanying white papers review priorities and technologies.

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Hendrix and Hurford et al. (2019). The NASA Roadmap to Ocean Worlds. *Astrobiology*, Vol 19, Issue 1, 2019, pp.1-27

This white paper describes the scientific questions for investigations that are needed for the exploration of ocean worlds. Such investigations would be carried out by a robotic flight program that would measure needed quantities at ocean worlds, and by research efforts to characterize important physical processes potentially at work on ocean worlds. We outline the scientific questions to be addressed in, and overarching goal of, an ocean worlds exploration program. For the purposes of this document, and to bound the extent of a future Ocean Worlds program, we define an “ocean world” as a body with a current liquid ocean (not necessarily global). All bodies in our solar system that plausibly can have or are known to have an ocean will be considered as part of this document.

In considering ocean worlds, there are several bodies with confirmed oceans, several candidates that exhibit hints of possible oceans, and worlds in our Solar System that may theoretically harbor oceans but about which not enough is currently known to determine whether an ocean exists. As a philosophy, we deem it critical to consider all of these worlds in order to understand the origin and development of oceans and life in different worlds: does life originate and take hold in some ocean worlds and not others, and why? Thus, we support the creation of an exploration program that studies the full spectrum of ocean worlds.

The overarching goal for the exploration of ocean worlds is: **Identify ocean worlds, characterize their oceans, evaluate their habitability, and ultimately search for life in these worlds.** This overarching goal naturally can be subdivided into four underlying goals,:

Goal I: Determine which bodies have oceans and understand how to determine whether other bodies host current oceans.

I.A. Is there a sufficient energy source to support a persistent ocean?

Energy sources are perhaps the single most fundamental requirement for the maintenance of a present-day ocean on an otherwise frozen world. The identification of ocean worlds therefore requires identification of possible energy sources. Both radiogenic heating (e.g., for Europa, Ganymede, Callisto, and Titan) and tidal energy (e.g., for Europa, Enceladus) play a role in sustaining oceans (e.g. Hussmann et al., 2006). Available energy sources can be identified either through modeling or direct observation (or ideally a combination of the two). Theoretical modeling is valuable for predicting which bodies can sustain oceans. Some models anticipated oceans on icy moons (e.g. Europa) long before such oceans were ever actually detected (Lewis, 1971; Consolmagno and Lewis, 1978). For the largest satellites, remnant radiogenic heating may be sufficient to maintain an internal ocean, depending on the initial radiogenic content of the rock component, and the state of the overlying ice shell (Hussmann et al., 2006; Schubert et al., 2010). For smaller bodies (e.g., Enceladus) dissipation of tidal energy is critical (Schubert et al., 2010). This requires the presence of a parent planet or satellite with sufficient gravitational energy to deform the body and favorable orbit or rotational properties such as a high eccentricity (e.g. Europa, Sotin et al., 2009), libration (Wisdom, 2004), or obliquity (e.g., Triton, Nimmo and Spencer, 2015). Pluto and Charon lack all of these, so the energetics that permit a long-lived ocean within these bodies are still in question (Nimmo and Spencer, 2015). . In addition, the planet or satellite must be able to convert available tidal energy to heat (e.g., Tobie et al., 2005). This is demonstrated by the satellite Mimas, which despite its high eccentricity dissipates little tidal energy, likely because its interior has remained cold since shortly after its formation (McKinnon, 2010). The complex feedback between the orbital/rotational evolution of potential ocean worlds

and their internal structure requires careful theoretical modeling (e.g., Ojakangas and Stevenson, 1989; Showman et al., 1997; Hussmann and Spohn, 2004).

I.B. Are signatures of ongoing geologic activity (or current liquids) detected?

Over the past three decades, techniques have been developed for assessing whether subsurface oceans are present on icy worlds. In some cases, investigation of a satellite's surface is sufficient to infer the possible presence of an ocean below (Pappalardo et al., 1999). Recent or ongoing geologic activity, such as a young surface shaped by tectonics, hotspots, and plumes, is indicative of a warm interior that can potentially sustain an ocean. For example, the plume of Enceladus, along with the young, crater-free terrain and warm fractures from which it emanates, are strong indicators of an ocean, even in the absence of other geophysical data (Porco et al., 2006). Likewise, surface change could indicate ongoing geologic activity, again requiring a warm interior.

Surface composition can also suggest a subsurface ocean through the presence of chemical species originating in an ocean (e.g., Hand and Carlson, 2015). In the case of Ceres, the recent emplacement of salt-rich subsurface material in several places on the surface (e.g. Ahuna mons, Occator crater) is interpreted as evidence for briny liquids at depth (Ruesch et al. 2016; De Sanctis et al. 2016).

Not all ocean worlds reveal their present oceans in their surface characteristics. Ganymede and Callisto both have internal oceans, but to our knowledge, their surfaces are currently inactive (Pappalardo et al., 2004; Moore et al., 2004). For these worlds, and to confirm oceans on geologically active worlds, a number of geophysical measurements can be used to identify present-day oceans. In many cases, oceans can be revealed by the orbital and rotational state of a body, if it can be measured carefully enough. For example, the magnitude of Enceladus' physical libration requires the presence of a global ocean (Thomas et al., 2016). Titan's subsurface ocean is also revealed by differential rotation of its outer shell, which must be decoupled from its interior (Lorenz et al., 2008). For systems with a strong, inclined magnetic field (e.g., the Jupiter system), the electromagnetic response of the body, after correction for ionospheric background, provides a strong indication of an internal ocean, as demonstrated for Europa, Ganymede, and Callisto (Kivelson et al., 1999, 2000, 2002). With sufficient flybys, gravity data can also indicate the presence of an ocean (Iess et al., 2014; McKinnon, 2015), especially when coupled with detailed topography, as recently demonstrated for Dione (Hemingway et al., 2016).

Goal II: Characterize the oceans.

For confirmed oceans, the priority is to understand their physics and chemistry to assess their habitability. Such characterization permits identification of appropriate future life detection experiments, if warranted. In order to characterize the ocean, the following objectives and investigations must be addressed.

II. A. Characterize the physical properties of the ocean and outer ice shell

Properties of the external ice shell and its outer surface environment will not only influence ocean world habitability but will also determine the extent to which biosignatures may be expressed on the surface and impact the design of any future exploration (e.g. Chyba and Phillips, 2001; Figueredo et al., 2003; Hand et al., 2009). Ice on Earth is a rich habitat; should life arise on ocean worlds then their ice shells may be similarly inhabited, given proper conditions. Of specific interest are those properties that affect transport processes through the ice shell, both thermal and physical, as they play a crucial role in the evolution and dynamics of the world. Material transport

between the surface and subsurface mediates energy and nutrient flow, as well as ocean pH, oxidants, and other factors that govern habitability of the shell itself (potentially rife with brine zones, water pockets, and habitable ice grain boundaries) and that of the ocean below. The overall thickness of the ice shell, and any spatial variability, determines the propensity and timescales for ocean-surface interaction and what modes of transport are possible (e.g. McKinnon, 1999; Pappalardo and Barr, 2004; Gaidos and Nimmo, 2000; Katterhorn and Prockter, 2014; Howell & Pappalardo, 2018). In cold, brittle shells (or stagnant lids of thicker shells) fracture processes likely dominate as the viscosity of ice at low temperatures greatly hinders ductile deformation, and for any geothermal and tidal heat production regime there is a corresponding limit to when the shell transitions from conductive to convective heat transfer. Fractures in brittle conductive shells may provide a direct path for material exchange from the subsurface to the surface, however downward material motion is poorly understood and perhaps unlikely, as in the case of Enceladus' south polar terrain (e.g. Glein et al., 2015). For thicker, more temperate ice shells, large-scale convective motion of the ice and entrained or endogenic liquids can provide a geologically rapid transport mechanism between the underlying ocean and the upper portions of the shell (McKinnon, 1999; Pappalardo and Barr, 2004; Schmidt et al., 2011; Peddinti and McNamara, 2015). For an archetypical layered shell, like that of Europa, with a brittle stagnant lid overlying a convecting ice mantle, a combination of tectonic processes (such as subsumption/subduction (Katterhorn and Prockter, 2014)) and convective overturn could produce a continuous chemical cycling of oceanogenic reductants to the surface and oxidized materials from the surface back into the underlying ocean.

Basic characteristics of oceans (e.g. salinity, density) are critical for ultimately understanding habitability. Pressure increases with depth and will vary as a function of both the gravitational acceleration of the ocean world in question and the physical properties (e.g. compressibility) of the dominant liquid phase. At the top of the ocean, in any icy ocean world, we can imagine a near isothermal surface at the ice-water interface (Melosh et al., 2004). Densities of water masses will then vary primarily as a function of salinity. In an ocean world that has active ocean-atmosphere interactions, as on Earth, significant variations in salinity can be established through evaporation-precipitation cycles. On ice-covered ocean world systems, by contrast, introduction of any variations in salinity, like any thermal inputs, may only be able to occur through water-rock interactions – the same processes that are of interest in terms of habitability and the astrobiological search for life because of their potential to host and sustain chemosynthetic ecosystems.

II. B. Characterize the ocean interfaces

Interfaces are a critical component of habitability because they can present sharp gradients in the materials (e.g. CHNOPS) and energy sources (e.g. oxidants and reductants) required for life. On Earth, life is strongly associated with interfaces, prominent examples being the microbial mats that grow atop marine and aquatic sediments on the underside of sea ice and at and within young ocean crust. Association with these interfaces allows the cells comprising these communities to maintain an optimal position with respect to gradients of nutrients and energy in a turbulent environment. Because all life on Earth derives energy either from sunlight or from the reaction energy of chemical redox pairs (either present in the environment or produced by cells from energy in the environment), identification of a redox gradient is highly relevant to any search for life on ocean worlds. The fundamental nature of planetary material results in a partitioning of oxidants and reductants at the planetary surface and interior, respectively. As on Earth, interfaces

that constitute boundaries between the surface and interior may be ideal habitats. On an ocean world, liquid water can extend these boundaries by transporting oxidants and reductants, placing them in close enough proximity to fuel biological processes. Solid surfaces can also provide a location for the concentration of nutrients, an attachment point for cells, and a stable habitat for life, potentially, in a subsurface ocean.

The ice-ocean interface can be studied indirectly through measuring a combination of surface topography (whose physical support depends on the thickness and mechanical properties of the ice below), the tidal flexure of the ice shell (that depends upon its thickness), and magnetic signature (which places constraints on the total ice thickness and the conductivity of the ocean once the shell thickness is known). The ice-ocean interface can be directly observable by radar sounding for sufficiently thin shells. For Europa, this characterization could be the direct observation of the interface by the reflection of radar waves by the ice-ocean interface (radar waves are reflected by water), or through the damping of or loss of signal from warm, briny, or salty ice in an otherwise continuous ice shell.

From an astrobiological perspective, the nature of geologic processes that may be active at the seafloor and, specifically, what processes might drive the underlying heat flow are critical. For example, recent studies by Hsu et al. (2015) and Sekine et al. (2015) have suggested that hydrothermal venting on Enceladus may be relatively low temperature (50-200°C) and Glein et al. (2015) suggest that the ocean composition may be rather Na-rich like Earth, but significantly more alkaline. Such evidence suggests several candidate Earth analogs: ultramafic intermediate temperature hydrothermal systems such as the Lost City or Von Damm hydrothermal fields (Kelley et al., 2001; McDermott et al., 2015). In contrast, tidal modeling for Europa (Sotin et al., 2009) has provided evidence that dissipation of energy may occur predominantly in the liquid water ocean leading to flexing in the outer ice-shell but relatively little impact on the silicate interior (quite distinct from the abundant volcanism seen on its sister moon Io). If so, then the dominant thermal processes at the seafloor of Europa may be related less to active magmatism and volcanism and more to passive cooling (e.g., conductive) of radiogenic heating of the solid interior. In the latter case, progressive cooling might still be expected to lead to thermal contraction at the seafloor and cracking to allow fluid circulation to penetrate beneath the seafloor (Vance et al., 2007); the resulting generation of reduced hydrogen from serpentinization may equal or exceed potential fluxes from high-temperature hydrothermal activity (Vance et al., 2016). The style and vigor of any hydrothermal circulation might vary significantly depending upon the nature of the processes happening at and beneath the seafloor of any ocean world. In an isothermal ocean, even a weakly buoyant hydrothermal system might still penetrate all the way to the ocean surface but the interesting possibility arises that the most pertinent analog settings on Earth to inform our study of other ocean worlds might be in tectonic settings such as fracture zones or subduction zones that have been somewhat overlooked on our own planet. Indeed, even Earth's mid-ocean ridges remain 80% unexplored. Isolated volcanoes more reminiscent of what is seen elsewhere in our Solar System are also known to occur abundantly across Earth's ocean floor but also remain largely unexplored for seafloor fluid flow and habitability.

Key parameters to consider for the seafloors of other ocean worlds, therefore, would include a search for anomalies in both topography (the depth to the ocean floor) and heat flow (evidence for convection vs. thermal conduction) which could provide important evidence for geological processes operating on that ocean world (organized planetary-scale plate tectonics, isolated volcanism, and seafloor fracturing). Assuming slow rates of erosion and/or thermal relaxation of the planet's solid interior, the shape of the seafloor alone would provide important

evidence for past geologic activity, even if those processes are no longer active in the modern day. By adding heat flow or seismic investigations to such a study, however, one would also gain insights, immediately, into whether such processes might be ongoing.

Goal III: Characterize the habitability of the oceans.

III. A. What is the availability (type and magnitude/flux) of energy sources suitable for life, how does it vary throughout the ocean and time, and what processes control that distribution?

Life on Earth utilizes, as sources of energy, light in the visible to near-IR wavelength range and the chemical energy released in specific (mostly oxidation-reduction) chemical reactions; surface irradiation may alternatively be an effective source of oxidants at icy moons in giant planet magnetospheres (Cooper et al., 2001, 2009). The present understanding of biological energy metabolism indicates that chemical energy sources must satisfy discrete minimum requirements for both Gibbs energy change (ΔG) and power (flux of energy through time) in order to be useful. Light energy also must satisfy a discrete minimum requirement for flux (corresponding to light intensity; the requirement equivalent to ΔG is easily satisfied in any of the part of the wavelength range used by life). Additionally, the flux of energy constrains, in a direct relationship, both the maximum rate of new biomass synthesis (productivity) and the maximum quantity of standing biomass that can be sustained in steady state. That is, environments having greater energy flux can potentially support more abundant life, and might therefore be better targets for life detection. Importantly, at Europa, high oceanic fluxes of seafloor reductants from low- or high-temperature hydrothermal activity (Vance et al., 2016) may be complemented by oxidants generated by surface radiolysis (Hand et al., 2007), though it is as yet unclear how much oxygen reaches the ocean. The total redox flux to Europa's global ocean may exceed fluxes in other ocean worlds that have less active ice and less surface radiation, although too much abiotic oxygen could be detrimental to life, confirming calls for understanding the ice's geology, oxidation state, and corresponding rates of delivery of surface materials into the ocean.

III. B. What is the availability (chemical form and abundance) of the biogenic elements, how does it vary throughout the ocean and time, and what processes control that distribution?

The biochemistry of life on Earth is built around a core of elements – C, H, N, O, P, and S (CHNOPS) – that are required by all known organisms, as well as a variety of other elements (e.g., specific transition metals) that are required by specific subsets of life. Biominerals including silicon or calcium are also important to life. In earthly environments where life's requirements for water and energy are abundantly met – for example, the sunlit portions of Earth's aquatic environments – the distribution of these elements (notably N and P, together with the micronutrient Fe) can directly limit the abundance and productivity of life. In harsh surface irradiation environments, as on Europa's trailing hemisphere, where organic molecules are quickly destroyed when fully exposed, the residual elemental composition could still provide biosignatures. Each of these elements can be incorporated into a diversity of chemical forms, some of which may be less accessible or inaccessible to biology.

Goal IV: Understand what kind of life could be present in these oceans and how to search for it, and understand the biology.

IV. A. What are the potential biomarkers in each habitable niche? (determine what we're looking for)

Earth is the only planet yet where life is known to exist. Analogue studies of life in Earth's oceans and other habitable niches provide our only anchor for extrapolations to other ocean-bearing worlds. Examples of what can be learned from such studies include: (1) the range of physical (e.g. temperature, pressure, radiation levels) and chemical (e.g. pH, redox, salinity/water activity, major/trace elemental abundances) conditions that life tolerates; (2) whether known extremophiles exist at the temperatures, pressures, pH, radiation levels, etc. found on other ocean worlds; (3) whether there exist areas on Earth that do not support life (and why); (4) how long it takes ecosystems to colonize a given environment, or adapt/evolve to changing physicochemical conditions; (5) the metabolic diversity that might be expected in ocean world environments; and (6) the amount of potential biomass that could be sustained on a given ocean world.

Niches for extant life must provide a solvent, energy, and nutrients for a sufficient amount of time. By definition, ocean worlds provide a solvent, and the materials that planets form from can be expected to contain the necessary nutrients. Lacking sunlight, bioavailable energy requires the co-location, in chemical disequilibrium, of electron donors and acceptors. Determining which metabolic strategies are possible, which dominate, and what their spatial and temporal distribution is involves finding out which electron donors (EDs) and acceptors (EAs) are present, what their abundances are, whether there exist mechanisms to bring them together, and the quantification of sources, sinks, and their variation in space and time.

Ideal target indicators are specific to life (not found in abiotic systems), universal (not limited to life on Earth), and easy to detect. To date, we do not know of any single indicator that satisfies all three criteria. Darwinian evolution and reproduction may be the only specific and universal indicators, but we cannot measure them even for most of life on Earth, which we cannot culture. Growth (concurrent life stages) and activity (motility, feeding, biofilm formation) are specific, but may not be universal. Evidence for metabolism (isotopic fractionations from abiotic values, co-location of electron donors and acceptors) can be more easily detected, but its lack of specificity requires excellent contextual knowledge. Functional molecules (nucleic or amino acid polymers, pigments) are highly specific and easy to detect, but may not be universal. Potential biomolecule components (nucleic or amino acids, lipids, sugars), with structural preferences (non random chirality, carbon number, or trace element compositions) may be universal and easy to detect, but have low specificity.

IV. B How to search for and analyze data in different environments?

Although remote detection of extant life seems challenging, the presence of life might be expressed at the surfaces of ocean worlds. Currently, we do not know what kind of evidence might be seen, at what abundances, or how this evidence might be modified by radiation processing and oxidation. It would also be useful to determine to what extent remote spectroscopy techniques could measure co-located electron donors (e.g. $\text{H}_2 \pm \text{CH}_4$) and acceptors (e.g. O_2 , nitrate, Fe^{3+} , CO_2), and to what extent the geological context or other indicators might allow the inference of how long this co-location has persisted over time. On airless worlds, measuring remotely the surface distribution of elements and looking for any deviations from background bulk concentrations could represent another possible avenue, but relevant spatial scales have yet to be constrained. As a final example, remote spectroscopy techniques could detect pigments and/or other specific biomolecules.

Possible *in situ* investigations for life could seek to determine whether the inventory of detected organic molecules differs from those expected to be synthesized by abiotic chemistry. One could look for morphological signatures that indicate microenvironments containing chemical gradients; active, sharp physicochemical gradients of metabolic interest in ice or water columns (e.g., gradients in pH, Eh, temperature); evidence for enzymatic catalysis in the formation pathways of detected organic molecules (e.g. stable isotopic fractionations of CHNOPS that differ from those of abiotic systems over the full range of plausible habitat temperatures); or chemical cycling (organic or inorganic) or electrochemical / electrical activity not explained by abiotic processes that could be indicative of metabolic activity. Planned *in situ* investigations could benefit from lessons learned from previous life-detection experiments, such as the Viking suite. *In situ* investigations can also search for extant, dormant, or extinct life preserved in near-surface ice that results from upwelling through cracks; viable microorganisms have been found preserved in ancient ice on Earth.

Searches for extant life *in situ* should also include surveys with optical microscopy – under the temperatures and chemistry conditions of environments where extant life is likely to form (liquid water environments), the sizes of organisms will be constrained by the same effects as on Earth: chemical diffusion rates will set the upper limit, and the minimum amount of chemistry (information molecules and supporting chemistry) required for self-replication will set the lower limit. Fluorescent dyes that are specific to various classes of molecule without being single-molecule specific can be used to determine whether cell-like objects contain likely biotic chemistry, such as lipids, proteins, amino acids, and sugars. Various stimuli (chemical, photo, magneto, photo, thermo) can be applied to samples to induce changes in activity levels, such as growth, reproduction, or motility.

Key considerations for life detection include the choice of sampling location and sampled material (e.g. rocks, ice, water, soil, interface zones), limits of detection, contamination control, and meeting planetary protection requirements. Previous searches for life remotely, *in situ*, and in samples on Earth have taught us that such searches are highly path-dependent: decisions on which measurements to make depend on the results of previous measurements, and it is difficult to predict *a priori* which measurements will be needed. Identification of relevant sets of complementary observations and possible decision trees for observation types will be important. Also crucial is the ability to distinguish environments that are pre-biotic, host extant life, and post-biotic (harbored now extinct life), to understand the context of any null result. This requires reducing the possibility of false positives due to forward chemical and biological contamination (separately from planetary protection), by characterizing contamination signals and distinguishing them from indigenous signals. It also requires constraining the states in which we might find evidence for life (e.g. live, dead, stasis/frozen, fossilized, chemical residue/metabolic waste products). Relevant planetary protection issues include quantifying any exchange (or lack thereof) of biological material between Earth and ocean worlds, and identifying any synergies between scientific and planetary protection priorities.

The detailed Investigations associated with these Goals and Objectives are listed in Hendrix et al. (2019).