Ocean Worlds: A Roadmap for Science and Exploration
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 science goals 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

NASA's study of Ocean Worlds will be a critical component of solar system exploration in the next decade. With Galileo, Cassini, and the upcoming Europa Clipper and Dragonfly missions, NASA has taken the first steps in discovering and learning about Ocean Worlds. Ocean Worlds represent diverse opportunities to search for life in our solar system and to understand and characterize the formation and sustenance of oceans and the conditions required for life to take hold. This knowledge enables a better understanding of our own ocean and our own planet.

With the exception of Ceres, an end member ocean world, the Ocean World (OW) targets are in the outer solar system, resulting in naturally longer mission durations than inner solar system targets. As a result, careful advanced planning is required to execute an OW roadmap. *It is the responsibility of this Decadal Survey to define the plans for OW exploration in the coming decade, and to consider that a well-rounded OW program includes investigations of both known ocean worlds and of candidate ocean worlds.*

The Roadmaps to Ocean Worlds (ROW) team advocates for an Ocean Worlds program that utilizes different classes of missions (Flagships, New Frontiers, Discovery, and, as possible, smallsats to ride along with these missions) to address OW questions. These questions focus on 1) understanding where/why oceans are present, which allows for 2) characterizing ocean environments in these known ocean worlds. With known ocean environments it becomes important to 3) characterize their habitability and ultimately 4) search for extant life. (See the accompanying white paper by Hendrix et al., Ocean Worlds: Science Goals for the Next Decade.)

ROW Priorities: Summary

As outlined in this report, the known and candidate Ocean Worlds in the solar system are each wonderfully - and importantly - unique. Given their uniqueness, exploration of one or two ocean worlds in our solar system does not provide a complete picture. It is imperative to plan for a broad, well-rounded Ocean Worlds exploration initiative that includes determination of which bodies are in fact ocean worlds (and why or why not), whether the oceans are habitable, and whether the oceans host life.

The ROW team finds that the known ocean worlds, Enceladus, Titan and Europa, are the highest priority bodies to target in the near term to address OW goals. Of the candidate ocean worlds, Triton is the highest priority to target in the near term. As such, we encourage the Decadal Survey panels to prioritize these worlds for exploration with New Frontier or Flagship class mission opportunities. NASA has current plans to study the habitability of Europa with the Clipper mission and of Titan with the Dragonfly mission; these missions are key existing/ongoing foundations of NASA's OW program. Therefore, building on these foundations, ***in this Decadal Survey, missions to Enceladus and Triton should be rated as highest priority for Flagship or New Frontier class mission opportunities in order to build a well-rounded OW program in the next decade.***

The ROW team finds that Callisto and Ceres are the highest priority targets to address OW goals with the smaller, competed Discovery class missions. Since Discovery mission opportunities are open to all targets and not specifically prioritized by the Decadal Survey, ROW highlights their importance to the overall OW goals but does not set them as a priority for these larger mission classes.

1. Known Ocean Worlds

Europa, Titan and Enceladus are known ocean worlds and each is a compelling target in different ways. As known ocean worlds, the next step on the OW goals list for these bodies is to characterize the ocean and habitability (as needed) and then, when/if habitability is deemed adequate for life, to search for life. Ganymede and Callisto are also known ocean worlds, of lower priority in the Roadmap in terms of characterizing habitability or searching for life. However, they are high priority targets for OW goals to characterize the internal ocean of known ocean worlds.

Enceladus has a known ocean, material from which is delivered to the surface and to the near-Enceladus space in the active south polar plume. In July 2005, instruments on board the *Cassini* spacecraft detected endogenic heat and plume activity at Enceladus' south pole, which is associated with four prominent fractures (sulci) (Spencer et al., 2006; Hansen et al., 2006; Porco et al., 2006; Spahn, 2006). Triangulation of Imaging Science Subsystem (ISS) images shows that these sulci are also the sources of the observed plumes (Spitale and Porco, 2007).

The presence of subsurface liquid on Enceladus was strengthened by analysis of the chemical composition of the plume. Enceladus' plume is primarily composed of water vapor, with small amounts of carbon dioxide, methane, ammonia, methanol, molecular hydrogen and many heavier hydrocarbons and organic molecules (see Table 1 of Waite et al., 2009; Hansen et al. 2011; Waite et al., 2011, 2017). The detection of Na and K in the erupted ice particles (Postberg et al. 2011) is most readily explained by the presence of liquid water that at some point was in contact with silicates (Zolotov 2007). So is the detection of silica nanoparticles in the Saturn system, traced back to Enceladus (Hsu et al. 2015; Sekine et al. 2015). These compositional measurements constrain the pH of Enceladus' ocean to alkaline values of 8.5-9 or perhaps slightly higher (Glein & Waite 2020), i.e. similar to the 8.2 value of Earth's oceans. Careful analysis of Enceladus' orbital librations suggests that the extent of subsurface liquid is global, even though the ocean is likely thicker below the South Pole (Thomas et al., 2016). Finally, diverse and macromolecular organic compounds have been detected in plume particles; these are likely fragments of yet more complex compounds (Postberg et al., 2018; Khawaja et al., 2019). Together, these results suggest that Enceladus could harbor a biomass density (Cable et al. 2020) comparable to that detected in subglacial polar lakes on Earth (as summarized in Hand et al. 2017). **The presence and habitability of Enceladus' ocean has been established using Cassini measurements, and thus to address OW goals, a search-for-life mission should be sent as a next step.**

Evidence for a sub-surface ocean at Europa comes from a number of lines of indirect and direct image geology mapping evidence from the Galileo mission (Pappalardo et al., 1999). The most definitive evidence of a modern ocean comes from the measurement of an induced field at Europa, which matches the signature of an electrically conductive, sub-surface layer (Kivelson et al., 2000). The candidate plumes observed at Europa's south pole (Roth et al., 2013; Sparks et al., 2016) may be a part of a continuum of processes that also includes the extrusion of fluids onto the surface. Previous studies have suggested the presence of surface liquids on Europa, possibly emplaced as a result of cryovolcanic eruptions in association with subsumption in the ice shell (Kattenhorn and Prockter, 2014), or dome formation at the surface (Fagents, 2003; Pappalardo and Barr, 2004; Prockter and Schenk, 2005; Quick et al., 2017). Fluids may also be emplaced on the surface during the formation of chaotic terrain (Figueredo et al., 2002; Prockter and Schenk, 2005). Chemical disequilibrium in the ocean may be maintained on geological timescales by the supply of oxidants generated from the irradiation of surface water ice in Jupiter's magnetosphere (Hand et al., 2007) and transported downward through the ice shell (Kattenhorn & Prockter, 2014), and the supply of reductants from the reaction of water with reduced minerals at or below the rocky seafloor (Vance et al., 2016). Organic material has yet to be found but is expected to have been part of the materials accreted by Europa, continuously supplied by infall of meteorites and interplanetary dust particles, and synthesized as a product of water-rock interaction, placed together with the observed mineral deposits along the fractures. **The ROW team recommends that the Europa Clipper mission continue as planned because of its importance in characterizing the habitability of Europa. A landed Europa search-for-life mission is a logical next step after Clipper, especially if a science payload can be included that can yield important astrobiological information, even if biosignature results are ambiguous. Such a mission will advance the technologies needed to detect biosignatures at OW targets, especially from *in situ* measurements. A low-cost orbiter in the Discovery/New Frontiers class could provide invaluable data on deep geophysics and gravity while also carrying out a more intensive in-situ search for plume activity in Europa's atmosphere.**

Titan is unique among ocean worlds, with both a subsurface ocean and surface liquids. Titan is the only satellite with a substantial atmosphere, and the only world other than the Earth that possesses an active hydrologic system driven by solar energy, in addition to potential endogenic volcanism (Lopes et al, 2013). The outstanding science questions for Titan encompass inquiries that relate to both its subsurface ocean of liquid water and its surface reservoir of organic molecules. Titan is a world of two oceans, and environments of interest include settings where (1) organic molecules may have interacted with liquid water, (2) surface and atmospheric deposits of organic molecules may have undergone prebiotic chemical reactions, and more speculatively, (3) locations where hydrocarbon solvents support a form of life that does not depend on the presence of liquid water. The habitability of Titan's subsurface ocean and any interfaces between the ocean and surface, along with the surface lakes and seas of methane/ethane, has yet to be established. **Thus, a habitability/ocean characterization mission to Titan is a natural next step to advance OW goals at this body. The New Frontiers mission, Dragonfly, will help to characterize the habitability of regions of Titan, but additional missions are needed to further understand the nature of this unique and arguably most Earth-like of ocean worlds.**

Ceres is a newly recognized ocean world. Ceres is a unique case, a hydrous dwarf planet in the asteroid belt. Ceres is ~27wt.% H_2O and has a 40 km (average) thick shell dominated by volatiles, with a density of 1.25 g/cm^3. Ceres was a "candidate" OW at the time the Roadmap was developed (Hendrix et al., 2019); since that time, analysis of observations from the Dawn mission has provided new information on Ceres' OW status. High-resolution visible and infrared imaging revealed hydrated salts unstable on Ceres' surface, in one of the youngest regions (de Sanctis et al., 2020). These have to be continuously replenished to explain the Dawn observations. This observation complements other evidence for recent brine-driven activity on Ceres (Ruesch et al. 2019). Ceres' ocean is more evolved than those of large icy moons. From the composition of recently exposed evaporites, it is possible to constrain its temperature to >~245 K, which means only a few percent of its original ocean is left, so Ceres may provide an end-member scenario for medium-sized ocean worlds without tidal heating. Investigating the characteristics of that residual ocean (e.g., extent, composition) would set constraints on the chemical evolution of mid-sized ocean worlds and especially the evolution of their organic matter.

Ganymede and Callisto are planet-sized bodies with mean radii of 2631 km and 2410 km, respectively. Satellite densities of 1.94 g/cm^3 for the former and 1.84 g/cm^3 for the latter indicate bulk compositions of ~40% ice and ~60% rock (Anderson et al., 1996; Anderson et al., 2001). Measurements of moment of inertia suggest Ganymede is strongly differentiated with an iron core, a silicate mantle, and a 100s of km thick ice shell (Anderson et al. 1996). The presence of a current-day intrinsic magnetic field suggests that Ganymede's iron core is at least partially molten today (Kivelson et al. 1996; Anderson et al., 1996). Callisto, on the other hand, is likely only partially differentiated with a more rock and dense-ice-phase rich interior surrounded by a layer of less rock rich and more low-density-ice rich material (Anderson et al., 2001). Ganymede and Callisto (along with Titan) are the most massive water-rich solid bodies in the Solar System, and as such, they are end-member representatives of a possible population of potentially habitable "water world" exoplanets and exomoons in other planetary systems. The term "super-Ganymede" is sometimes used to describe theoretical massive water-rich exomoons (e.g. Heller and Pudritz, 2015; Vance et al., 2015) that may be directly observable in the near future. The relatively high gravity and non-negligible radiogenic heating on massive water worlds such as Ganymede and Callisto create pressure and temperature environments at the bottoms of their water layers that are potentially at the extreme end of what is observable in our Solar System. Thus, studying these bodies will provide valuable information for understanding ocean formation, maintenance, and exchange processes within potential "water world" habitats in other planetary systems.

2. Candidate Ocean Worlds.

Triton, Pluto, Ariel, Dione, and Miranda are among the possible ocean worlds in the solar system. Spacecraft data returned from these bodies suggest the possible presence of extant liquids in their interiors, but the size of any liquid reservoir is unknown. These bodies must be explored further to determine whether they have extant oceans and should be further studied as Ocean Worlds. The next missions to these bodies should establish the presence of oceans, perhaps using orbiting spacecraft (or multiple flybys) with magnetic, gravity field, libration, and/or topographic measurements of tidal flexing. Should extant oceans be found, future missions should characterize those oceans to establish their habitability and then potentially search for life. **Of the candidate ocean worlds in the solar system, Triton is deemed the highest priority target to address as part of an Ocean Worlds program in the next decade.**

Triton exhibits extraordinary hints of activity shown by the Voyager spacecraft such as: plume activity; smooth, walled plains units; and the cantaloupe terrain suggestive of ice shell convection. Given what is known about Enceladus (because of the results of the Cassini mission), it is not out of the question for ocean-driven activity to exist at Triton. While the source of energy for Triton's plume activity remains unclear, for all other bodies in the Solar System with plumes, this activity is driven by endogenic heat sources, and Triton's activity coupled with the young surface age makes investigation of an endogenic source important. Unlike other possible ocean worlds (such as Ariel or Dione) observations of geologically recent activity make investigating and understanding its source of activity a priority. Furthermore, many Triton mission architectures would simultaneously address Ice Giant goals on which high priority was placed in the Visions & Voyages Decadal Survey. Finally, as Triton likely represents a captured Kuiper Belt object (KBO), some types of comparative planetology with KBOs could also be addressed in a Triton mission. **The Decadal Survey should place high priority on Triton as a target in the Ocean Worlds program.**

Pluto is the first large object visited in the Kuiper belt and it displays young, potentially cryovolcanic, terrains indicating activity may have continued through much of its history. As for

Triton, the source of relatively *recent* internal heat on Pluto is not entirely constrained, but models suggest an ocean may persist into the present. Studying large KBOs opens up a new regime for exploring ocean worlds in the solar system, and by comparative planetology helps us understand what is possible for icy moons that are not currently tidally heated. A Pluto orbiter mission is necessary for understanding whether this distant target is an ocean world.

After the Voyager flyby of the outer solar system, similarities between Enceladus, Miranda, and Ariel were noted. Enceladus' extant geological activity and ocean were discovered only after Cassini's arrival. What potentially similar discoveries await us at Miranda and Ariel? Both show evidence for recent significant tectonism that could indicate subsurface oceans. Jankowski and Squyres (1988) suggest Voyager imaging captures thick surface flows (cryolavas) on Ariel and Miranda. A mission to the Uranian system should set as a top priority flybys of these moons to search for evidence of subsurface oceans.

3. Ocean Worlds Roadmap for the Next Decade

Based on the summary of targets above and the ROW recommendations, a broad outline of high-priority missions can be developed. Here we group targets by priority and list the mission goals that advance Ocean Worlds science goals.

As noted above, the key steps in an Ocean Worlds program are:
1. Identify/confirm ocean worlds
2. Characterize ocean
3. Characterize habitability of ocean
4. Search for life from/in the ocean

Given these key steps, the <u>next</u> phases/missions in a well-rounded OW program for the most important targets are:

Europa: Mission to characterize the habitability of the ocean– *Clipper in progress; Lander study in progress.*

Titan: (a) Mission(s) to characterize the habitability of possible surface-ocean interaction regions; (b) mission(s) to characterize ocean– *Dragonfly in progress (a); other mission types are possibilities for (b); e.g. Titan orbiter*

Enceladus: Search-for-life mission - *e.g. mission with multiple plume fly-throughs and/or Enceladus lander (PMCS report). Dive climbing bot to research mineral deposits/organics inside fractures in Enceladus south pole.*

Triton: Mission to characterize and confirm an Ocean – *Triton orbiter or Neptune orbiter with many Triton flybys*

Ceres: Mission to investigate the composition of evaporites and organic matter - *In situ hopper or sample return (PMCS report).*

Ganymede and Callisto: Mission to characterize their oceans – *JUICE in progress will characterize Ganymede's interior and confirm Galileo results at Callisto; Discovery class mission can accomplish OW goals for Callisto*

4. Recommendations for the Decadal Survey panels.

1. The Decadal Survey should rank highly an Enceladus mission (whatever the class: Enceladus PMCS Report, New Frontiers opportunities, etc.).

2. The Decadal Survey should place an especially high priority on a mission to study life/habitability at Enceladus and/or Titan. A mission that addresses both Enceladus and Titan should be considered (if possible).

3. If Europa Lander is under consideration by the Decadal Survey panels, the panels should also recognize the criticality of exploration of additional ocean worlds and thereby place high priority on missions to Titan, Enceladus and Triton as well. Technologies developed for Europa Lander should be leveraged for the in situ exploration of other ocean worlds.

4. Ice Giant missions under consideration by the Decadal Survey panels should prioritize ocean world science, particularly at Triton, Ariel and Miranda.

5. The Decadal Survey should recognize the importance of Ceres and Callisto to OW goals and should make sure that Discovery class mission conditions continue to allow exploration of these important targets with the smaller mission classes.

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