Exploring ocean worlds on Earth and beyond

The exploration of ocean worlds in the outer Solar System offers the opportunity to search for an independent origin of life, and also to advance our capabilities for exploring and understanding life in Earth's oceans.

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Earth — the blue planet — is not our Solar System's only ocean world. Over the past half-century, multiple planetary bodies that harbour large volumes of liquid water beneath ice-covered surfaces have been identified in the outer Solar System. These include three of Jupiter's four largest satellites — Europa, Ganymede and Callisto — and the Saturnian satellites Enceladus and Titan. Although yet to be confirmed, numerous other ocean worlds may populate the outer solar system, including Neptune's moon Triton, and possibly Uranus' moons Titania and Oberon. Together, all of these bodies are predicted to host more than twenty times the volume of liquid water found in Earth's oceans[1], and are prime targets in our search for evidence for an independent origin of life beyond Earth[2]. Whether or not these potentially habitable worlds are actually inhabited can only be determined through a bold robotic program to directly investigate the surfaces of these ocean worlds and the interiors of their oceans. The exploration of these distant oceans will be challenging and expensive, but it is technologically feasible to commence within the next few decades. Here, we argue that this investment should be leveraged to advance our understanding of Earth's oceans, too.

The oceans of the outer Solar System may be too distant from the Sun and too thickly covered by water ice for their oceans to host photosynthesis. But they may — like Earth — host ecosystems fuelled by energy generated in the moons' interiors. Europa and Enceladus are of particular interest because they are likely to have saltwater oceans that are in direct contact with an underlying rocky seafloor and thus potentially host chemosynthetic ecosystems driven by energy fluxes from the planetary interior[3]. There is growing support for the hypothesis that Enceladus and Europa could have hydrothermally active seafloors and chemically rich ice shells and that these may be capable of supporting life.

However, testing these hypotheses cannot be done through remote sensing alone. Orbiting spacecraft can reveal global- and regional-scale processes on ocean worlds, but landed robotic vehicles are important for directly sampling and analysing surface and subsurface compositions. The just-completed Cassini mission to the Saturn system[4] has paved the way for potential future robotic missions to Enceladus and Titan, and NASA's forthcoming Europa Clipper mission and the European Space Agency's JUICE (Jupiter icy moons explorer) mission could guide future landed explorations on Europa and Ganymede.

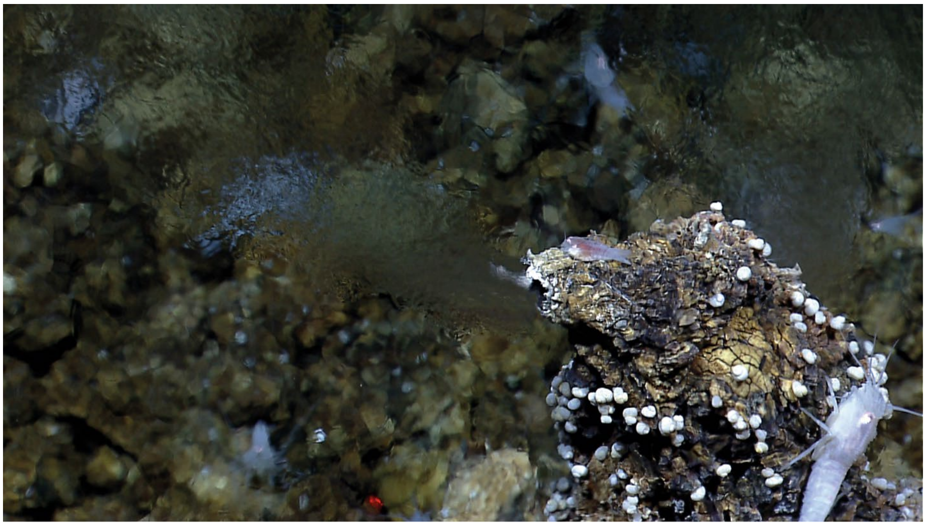

Fig. 1 | The Old Man Tree vent on the Mid-Cayman Rise, part of the ultramafic-influenced Von Damm seafloor hydrothermal field[9]. This site represents the closest known conditions on Earth to those invoked to explain putative hydrothermal signals on Enceladus[3,10]. Robotic exploration of both Earth and planetary oceans is needed to better understand these potentially habitable environments. Credit: NOAA Ocean Exploration program.

Challenges of the deep

It will be difficult to make sense of the data we gather from an extra-terrestrial ocean, however, without also understanding analogous environments on our own planet. Since the first discovery of high-temperature submarine vents in 1977, an ever-increasing range of seafloor fluid flow systems have been recognized[5] across Earth's ocean basins, in an ever-increasing range of geologic settings (Fig. 1). At least one chemosynthetic ecosystem has now been found in each of Earth's main ocean basins. Yet, the majority of Earth's deep oceans — in particular deep ocean trenches and fracture zones that cut the ocean floor — remain largely unexplored[6]. The good news is that efforts to explore planetary oceans can yield benefits in the exploration of Earth's oceans as well.

Space agencies have been forced to overcome technological challenges to make planetary exploration possible. For example, spacecraft engineers have long grappled with what is known as the rocket equation: a big spacecraft requires more propellant to launch, but the mass of that added propellant necessitates even more propellant. Innovation in space exploration is often measured in the reduction of the mass, power and volume of instruments needed to achieve the critical science. Small is beautiful, but smaller is even better.

The ship limitation

Historically, ocean scientists on Earth have not been similarly incentivized to innovate. Exploration of our oceans and cryosphere, using large ocean-going research vessels, has been able to take a brute force approach. Researchers have traditionally been able to put to sea for long campaigns aboard these

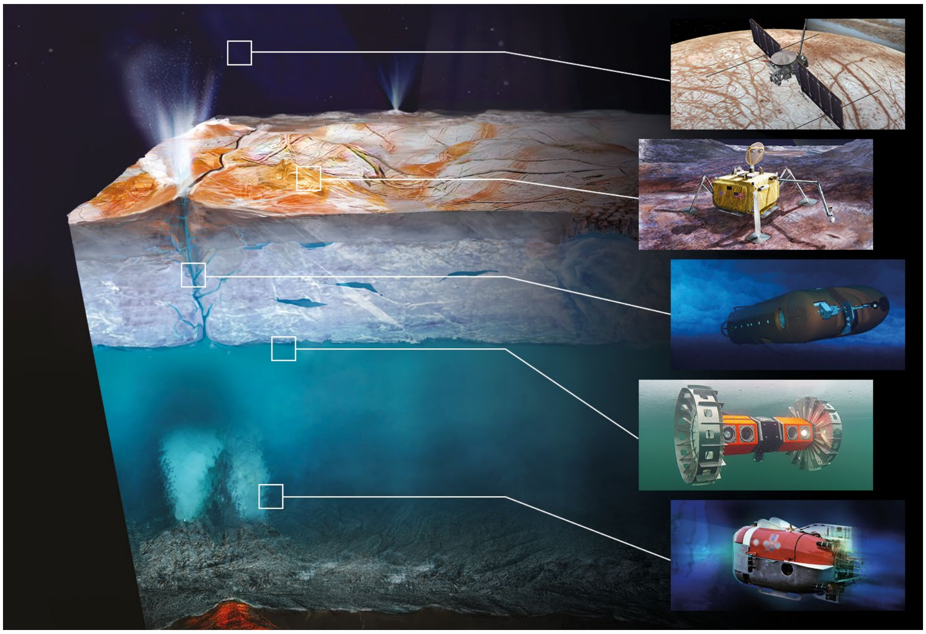

Fig. 2 | A vision for future exploration of ocean worlds. The initial stages of planetary ocean exploration involve orbiting spacecraft and landers. Investigations beneath the icy shells of ocean worlds, however, will require melt probes and autonomous underwater vehicles capable of collecting and analysing scientific data, and transmitting their results. The development and testing of robotic vehicles for future missions will enable a rigorous exploration program within Earth's ocean. Credit: K.P. Hand, NASA/JPL, Stone Aerospace and the Woods Hole Oceanographic Institution.

large research ships, carrying hundreds of tons of instruments that can be powered by the ships' generators. Those ships weigh two orders of magnitude more than any rocket put into space. Further, the research campaigns of such vessels have often followed an approach that focuses on simply identifying areas of interest on an initial mission and only pursuing targeted sample collection on a follow-up campaign. As exploration has moved out into Earth's most remote oceans, however, this approach has been found wanting — the delays between such stages of investigation have extended to a decade or more[7,8].

Furthermore, the most sophisticated mechanical, robotic and human-occupied vehicles currently used to investigate Earth's ocean interior are often focused on acquisition of samples that can be returned to the ship or shore laboratories for detailed analysis. The use of in situ sensors for more immediate analysis has been comparatively rare. With a growing community of oceanographers competing for the limited allocations of shiptime available, coupled with the slow transit speeds of the most sophisticated research platforms to reposition from one ocean location to another (15–25 $\mathrm{km\,h^{-1}}$), these limitations are becoming more acute and vast tracts of Earth's oceans still remain woefully unexplored.

The advent of a new generation of marine robotics, coupled with recent discoveries in the outer solar system, presents a particularly timely opportunity for deep-ocean- and ocean-world-research priorities to converge.

A joint investment in ocean science

With so much of Earth's oceans still to be explored, there are clear advantages to using longer endurance robotic platforms, especially packages that can be deployed from a wider variety of ships or from shore. But to take maximum scientific advantage of such platforms will also require a parallel and sustained investment in miniaturization and energy efficiency of sensors, instruments and their supporting engineering subsystems, as well as investments in autonomy and communications. Rigorous testing will also be required to ensure that such systems, once deployed, are reliable and robust. Fortunately a culture of sustained investment to ensure technical readiness prior to deployment already exists — for planetary exploration.

Long before rovers carved tracks on Mars, scientists and engineers tested similar rovers in a variety of deserts here on Earth. Similarly, before we send robotic explorers to distant worlds, we will have the opportunity to test the platforms and instruments in analogous environments here on Earth. Robotic vehicles and instruments for planetary ocean exploration will first be tested and utilized in Earth's ocean; and on, within and beneath Earth's cryosphere. Developing technologies for ocean exploration is a win–win for Earth science, planetary science and astrobiology (Fig. 2). Clearly, much of the investment for the exploration of planetary ocean worlds could be leveraged to improve exploration capabilities here on Earth.

NASA's missions — from the largest flagship class to the smallest CubeSats — have pushed in situ instrumentation to be lighter, smaller and more capable. Several such instruments — including mass spectrometers, Raman spectrometers and 'lab-on-a-chip' systems — have direct applications in the biogeochemical analysis of Earth's ocean environments, including the diverse forms of seafloor fluid flow systems.

Because they operate far from mission control and need to transmit valuable data back to Earth, NASA's spacecraft are optimized for power efficiency and data transmission. At increasing separation from Earth, they have also been designed programmatically to use autonomy to complement direct human operator control. Long duration vehicles in Earth's ocean that need to transmit acoustically or through satellite networks could undoubtedly benefit from adapting some of the same algorithms and design principles that NASA has developed for operations and efficiency.

Additionally, space navigation and landing systems — often referred to as entry, descent and landing technologies — could be adapted for use in our ocean to enable precise landings on desired targets. Currently, many deep ocean landers are passive systems that land wherever the drift takes them; consequently, scientific progress can remain at the mercy of deep ocean currents. Using some of the same software and concepts that were developed for the Mars Curiosity rover, and that are being further developed for the Mars 2020 mission and a possible future Europa lander, untethered deep ocean landers could actively target and land at specific sites on Earth's seafloor.

Finally, a key strength of NASA's robotic fleet is the systems engineering of each spacecraft. Clearly failures occur, but the success of so many complex engineering systems can be largely attributed to a high-fidelity systems engineering approach to spacecraft design. Although some of this has carried over to ocean exploration, a more common tendency has been to simply select components that are already commercially available and then adapt them in various combinations (with varying degrees of success) to best suit scientific needs.

Looking to the future, coordinated cross-agency and public–private initiatives that bring together scientists and engineers to work on these challenges jointly would be a productive step forward. Equally important to this process will be a sharing of information between space and oceanographic communities. NASA, for example, has a long history of investments in testing technologies that may provide breakthroughs, or that could prove to be a dead end. Other research agencies, by contrast, have often been more reluctant to fund such high-risk technology ideas. We should leverage the scientific and technological lessons learned from both Earth and planetary exploration. Moving forward, the opportunity to make great discoveries in our ocean and beyond will be advanced best by a shared vision for exploration. ❐

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