Dalio Explore Fund

REMUS 6000 | Video Plankton Recorder

2019 ANNUAL REPORT

WOODS HOLE OCEANOGRAPHIC INSTITUTION

1930

Woods Hole Oceanographic INSTITUTION

2019 Annual Report

Ray Dalio

These investments in ocean science, engineering and operations have had great impacts

On the cover: A Nassau grouper greets the scientists arriving on the *Alucia* to study the Gardens of the Queen reefs in Cuba (credit: MacGillivray Freeman Films).

UNDERSTANDING THE OCEAN REQUIRES ACCESS. Ships and submersibles get us there and the tools of oceanography—sensors, samplers and cameras—allow us to make observations and collect data. WHOI operates two such tools on behalf of the Dalio Foundation, the REMUS 6000 autonomous underwater vehicle (AUV) and the video plankton recorder (VPR), and both made important contributions to our understanding of the ocean in 2019.

The REMUS 6000 was deployed on two major research cruises in the Western Pacific Ocean for the US Navy. The vehicle's high-resolution side scan sonar imaging and multibeam bathymetric sensors created detailed maps for the Navy's area of interest. The vehicle was able to fly steadily at a fixed height over an irregular sea floor for 35 missions down to the full 6000-meter depth rating of the vehicle. These very successful projects reinforce the brilliance of the REMUS 6000 business model, which is now entering its seventh year: Dalio Foundation ownership and support combined with WHOI's technical and operational prowess enable exploration and discoveries that advance our knowledge of the deep ocean. The model is also economically sustainable, with a portion of the income from REMUS 6000 projects paid back to the Foundation.

The VPR was deployed on missions to the Atlantic and Indian Oceans. The goal was to study plankton blooms found at oceanographic fronts and eddies associated with major currents—the Gulf Stream in the Atlantic Ocean and the Agulhas in the Indian Ocean off southeastern Africa. On both cruises the VPR proved once again to be an extraordinarily adaptive sampling tool, measuring and imaging "hot spots" and informing other sampling decisions by the science team. The Indian Ocean cruise was funded by the National Science Foundation and involved scientists from several countries. The science for the Atlantic "Hotspots" project was funded by the Dalio Explore Fund and conducted from the R/V *Neil Armstrong*, leveraging ship time funded by the National Science Foundation.

One new project was initiated under the Dalio Explore Fund in 2019. Led by principle investigator Dan Zitterbart, a new thermal imaging technology is being developed to automatically detect and help identify marine mammals from ships. The ultimate goal is to automate marine mammal observations, thereby reducing the risk of impact, increase the reliability of sightings and improve our understanding of behavior. The device will be installed aboard the research vessel *OceanXplorer1*, representing another milestone in the partnership between WHOI, the Dalio Foundation and its OceanX brand.

I am pleased to present the 2019 Annual Report for the Dalio Explore Fund, the REMUS 6000 and the Video Plankton Recorder. Since its inception in 2014, $10 million has been donated to the Dalio Explore Fund, which has funded 31 projects ranging in size from $17k to $870k. There is a balance in the Fund of $518k available to be awarded. The REMUS generated income for the Dalio Foundation of $820k against expenses and capital investments of $260k. The VPR generated new knowledge, with a cost to the Foundation of $113k for maintenance and $138k for capital improvements.

Over the years, The Dalio Explore Fund investments in ocean science, engineering and operations have had great impacts, including improving our understanding of western hemisphere hurricanes, developing high bandwidth through-water optical communications technology (now on *OceanXplorer1*'s submersibles), the first ever comprehensive study of Cuba's Gardens of the Queen coral reef, the exploration of the Northeast Canyons and Seamount Marine National Monument and many others. Taken as a whole, these projects are a testament to the goals of the Dalio Explore Fund and the efforts of the scientists and engineers to efficiently use the funds to advance our understanding of the ocean.

Ray, thank you for your continued support of WHOI. We look forward to an exciting and productive 2020 as we round out a decade of collaboration on the frontlines of ocean exploration and discovery.

Sincerely,

Rob Munier
Vice President for Marine Facilities and Operations

Ray, thank you for your continued support of WHOI. We look forward to an exciting and productive 2020 as we round out a decade of collaboration on the frontlines of ocean exploration and discovery.

U.S.- Cuban Collaborative Investigation of the Biodiversity of Protected Cuban Reefs

Amy Apprill, Marine Chemistry & Geochemistry

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OBJECTIVES

The goal of our project was to bring the first non-Cuban vessel into the highly protected reefs of Cuba and to utilize technological advancements to examine how coral reef biodiversity varies along a gradient of human impact and protection in the world famous Jardines de la Reina ("Gardens of the Queen").

In November of 2017, we sailed aboard the *Alucia* within Cuban waters with a team of U.S. and Cuban scientists. Our research was conducted over 240 kilometers of reef area, and our team worked together to collect data and samples to describe the biodiversity of the shallow reefs. We performed visual observations of reef biodiversity using SCUBA over 28 sites centered on 14 geographical areas. These surveys were focused on coral, invertebrate and fish diversity, abundance and health.

We also took samples to examine the "unseen" members of this reef ecosystem. Many of these samples and measurements leveraged new technological advancements in our WHOI and MIT laboratories. Reef chemicals were measured using an *in situ* reactive oxygen sensor and samples also were taken to examine the reef metabolome as well as coral nitrogen cycling. Water samples were collected to study the microorganisms driving the biogeochemistry of the reefs, and this analysis will be completed using genomics-based methods. Lastly, we deployed sound traps on select reefs to record the soundscape of the reef, including the noises of cryptic invertebrates and fish.

ACCOMPLISHMENTS TO DATE

Since the cruise, we have analyzed and published an unprecedented set of 11 different types of samples collected throughout the Jardines de la Reina coral reef ecosystem. We have 3 key papers to share from this past year:

Our group published an article in the journal *Environmental Microbiology* that described the key microbial and biogeochemistry factors that contribute to making Jardines de la Reina a healthy coral reef ecosystem. In December of 2019, WHOI issued a press release which highlighted our work comparing the Cuban reefs to those of the nearby and more

Co-chief scientist Amy Apprill underwater examining coral benthic cover on a Gardens of the Queen reef (credit: Laura Weber).

The team of U.S. and Cuban scientists gathers in the Alucia galley to plan their activities for the next day (credit: Barbara MacGillivary).

humanly-impacted Florida Keys. In addition, our team published an article in the journal *Frontiers in Marine Science* that shared our findings of how reef benthic biota showed more variation within a reef than throughout the Jardines de la Reina coral reef ecosystem. These results suggest that biological processes (e.g., recruitment and competition) are more important than hydrodynamics for driving the differences in reef community composition. Finally, our paper published in the journal *Environmental Science and Technology* detailed the first ever underwater measurements of the elusive coral-produced highly reactive type of oxygen, known as superoxide, which may play an integral role in the health of coral species. The paper described the design, development and validation of the DIver-operated Submersible Chemiluminescent SensOr (DISCO), the first underwater superoxide detector. Field deployment of the DISCO in the Jardines de la Reina showed that coral surfaces produce superoxide that varied distinctly with each coral species. In addition to the journal article, a press release was also issued about this new work.

The *Alucia's* dive master Steve Hudson (center) helped the group of US and Cuban organize their SCUBA missions and kept them safe while working underwater (credit: Amy Apprill)

OUTREACH

This project produced many outreach products and events. The Project Earth team of Fusion produced a 20-minute documentary about our project entitled, "Coral Reefs Last Stand: Cuba". This documentary was launched in April of 2018 on Fusion television, and is also freely available on the Project Earth website, where it has been viewed by thousands of individuals. Amy Apprill and MIT-WHOI Joint Program student

"We spent this year examining our unprecedented set of 11 different types of samples collected throughout the Jardines de la Reina coral reef ecosystem."

Laura Weber gave a standing room only public talk about this cruise to the Woods Hole and Falmouth local communities, hosted on the "big screen" at the Falmouth Cinema Pub, as part of the WHOI Ocean Science Café. We also have actively communicated our cruise experiences and preliminary insights to the media, including a National Public Radio live interview, and featured articles in *Yale 360*, *The Falmouth Enterprise*, and WHOI's *Oceanus* publications.

In October of 2018, the team traveled to Havana, Cuba to present at the MarCuba 2018 conference. We presented one poster and five oral presentations about the cruise, discussed project results with our colleagues, and enjoyed the unique culture of Havana.

A typical view from a day at the office for fish and shark survey scientists Leonardo Espinosa and Juan José Lake Barragán (credit: Leonardo Espinosa)

Biogeochemical Exploration of the Pescadero Basin Vents

Anna Michel, Applied Ocean Physics and Engineering

Science Team

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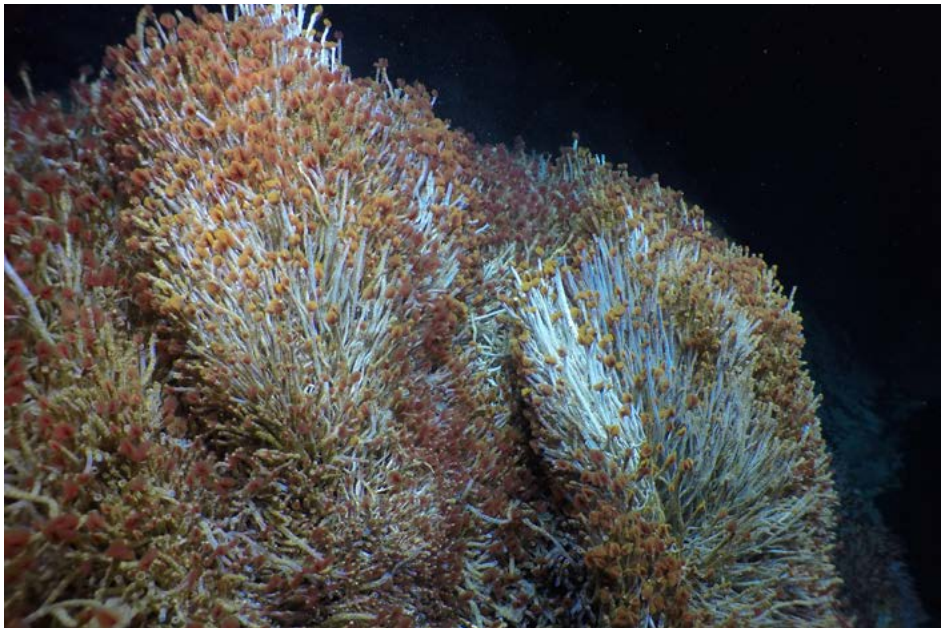
OBJECTIVES

In 2015, the deepest high-temperature hydrothermal vents in the Pacific Ocean (3,700 meters) were discovered in the Pescadero Basin (PB) in the Gulf of California. We were surprised to find biological communities thriving among carbonate chimney structures in a sediment covered basin along the Pescadero Transform Fault. As a result of their striking contrast to other hydrothermal systems, the high temperature, high carbon PB vents offered a unique opportunity to examine the influence of tectonics on the nature of seafloor vent sites, the fundamental geochemical controls on biological colonization in the deep ocean, and the role of fluid venting on global scale ocean chemistry and climate.

In November 2017, we set out aboard the E/V *Nautilus* to investigate this area of active venting. Using the Remotely Operated Vehicle (ROV) *Hercules*, our research was aimed at addressing multi-disciplinary questions: What large scale geologic processes are ultimately responsible for the formation of the PB carbonate chimneys and how does carbonate precipitation within these structures influence carbon flows to the ocean? What are the underlying sources of heat and carbon that drive the formation of these unique systems? How does the fluid chemistry influence meio-, macro-, and mega-faunal distribution and larval recruitment, as well as the distribution of sedimentary microbial activity and community composition? What is the relationship of these biological communities to neighboring sites of hydrothermal venting, such as the East Pacific Rise to the south and the Guaymas Basin to the north? What are the implications for the regional biogeography of deep-sea communities?



ACCOMPLISHMENTS TO DATE

Throughout the project, our efforts have focused on analyzing cruise data, including rock samples, biological and chemical samples, and processing *in situ* instrument data.

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Biology Summary:

- In 2019, two students were included in the team involved in analyzing the biological data.
- In March of 2019, Mary Toner, a graduate student at Tufts University, presented her research in a poster presentation at the Girls in Science Exposition.
- In July of 2019, Bethany Fleming, an undergraduate student at St. Andrews University in the United Kingdom submitted her undergraduate honors report based on data from this cruise. The report that she wrote was part of her requirements to earn her Master's degree. Fleming currently has a manuscript in preparation.

Geology Summary:

Detailed observations and samples of vent structures were collected to examine the diversity of hydrothermal systems in the Pescadero Vent field. Fluid temperatures at vents range from <50˚C to nearly 300˚C (122˚F to 572˚F). Variability in vent fluid temperatures with time was recorded by deployed temperature probes that showed diurnal to semi-diurnal

Much of the exploration of the Pescadero Basin vents was conducted through the use of two advanced underwater chemical sensors.

variations. A probe that recorded a longer time-series of vent fluid temperatures (6 months) showed larger and non-periodic variations in temperature. The analyses for determining whether variations are linked to tidal fluctuations in bottom pressure is still ongoing.

Samples collected during the cruise were examined for major mineralogy. Most samples were dominated by anhydrite ($CaSO_4$) and sulfide minerals (e.g., Pyrite Fe_2S), but barite ($BaSO_4$)-and calcite ($CaCO_3$)-dominated systems were also observed. Higher temperature anydrite-sulfide systems were located directly above a fault system that guides fluid flow. Lower temperature barite-dominated systems were located off the fault system, although they were likely situated over smaller faults in the sedimentary pile. Calcite-dominated systems were found at the highest temperatures. We are using the distribution of vent mineralogy as an indicator of long-term vent fluid compositions and temperatures that may provide controls for biological colonization and ecosystem dynamics. The geology research is still ongoing.

Chemical Summary:
Much of the exploration of the Pescadero Basin vents was conducted through the use of two advanced underwater chemical sensors. By pumping fluids past a thin membrane, the compositions of a wide variety of fluids across the ecosystem were measured either for chemical concentrations using an underwater mass spectrometer or for carbon isotopes using a laser spectrometer. Using these two instruments, the hydrothermally heated fluids emerging from the vent orifices at Pescadero were immediately identified as being heavily influenced by thermal alteration of buried organic matter. During this process, organic matter—whether originating from photosynthetic primary production at the sea surface, from terrestrial runoff or from chemosynthetic production at the seafloor—reacts with circulating super-heated, chemically-altered seawater. This results in the partial transformation of complex organic matter into a range of less complex molecules—including volatile alkanes such as methane, ethane, propane and butane—as well as the more basic components of organic matter, like carbon (in the form of carbon dioxide) and hydrogen. Indeed, the exceptionally high concentrations of all of these gases we encountered during our *in situ* measurements at PB immediately clarified the nature of this enigmatic system. In addition to these *in situ* analyses, discrete samples also were collected and continue to be studied for a wide suite of components. These analyses promise to provide valuable information regarding how this unique system was formed and has continued to evolve. We anticipate submitting a publication in 2020 on the results of our analyses.

OUTREACH

The team has continued to share the results of this cruise with both the public and the scientific community.

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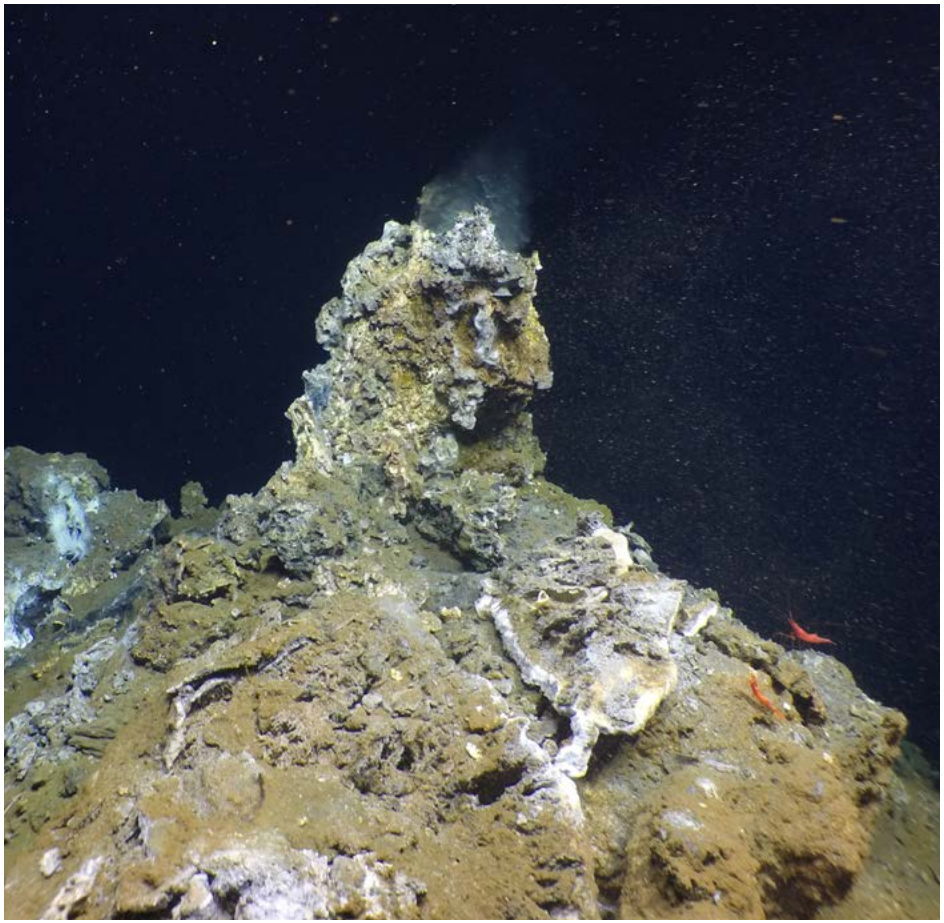
FUTURE WORK

The Principle Investigators expect to submit several papers for publication in 2020 and hope to return to the Pescadero Basin for further study.



Thar She Blows:
Remote Sensing of Whale Health Using Drone-enabled Imaging and Blow Capture

Michael Moore, Biology Department • Amy Apprill, Marine Chemistry and Geochemistry

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These results have provided a critical baseline of microbes in relation to lipids in the only resident Arctic whale, and may be used to assess animal health during the climate-driven habitat changes that are projected for the Arctic.

OBJECTIVES

The goal of this project was to use a small, unmanned multicopter drone to develop non-invasive indices of stress and health for baleen whales. We participated in a research cruise from February 16th to March 1st 2017 in the Gulf of Corcovado, Chile to study blue and humpback whales. Additionally, we have conducted cruises in 2017, 2018, and 2019 within Cape Cod Bay, Massachusetts to examine the endangered North Atlantic right whale.

During these expeditions, we acquired high resolution vertical images with an unmanned hexacopter (drone) to assess whale girth measurements, a technique previously shown to be effective as a quantitative measure of body condition. We also used the hexacopter to collect samples of respiratory blow to measure the diversity and composition of the whale's respiratory microbiome. Lastly, we sampled the surface seawater for associated microorganisms, to be used for comparison to the whale blow, as well as general characterization of the microorganisms in the Gulf.

ACCOMPLISHMENTS TO DATE

We have processed thousands of photogrammetry images and dozens of blow microbiome samples acquired during the cruises. In addition, we tested the validity of our collection method for the blow microbiome. Encouragingly, our control samples demonstrated that our methodology does indeed sample fluid from the lungs. Now that our method is successfully validated, we have been examining the whale respiratory blow microbiome data in more detail. Our preliminary analysis of the whale blow has shown that there is overlap in the composition of the microbiome between humpback whales, blue whales and North Atlantic right whales. This suggests that baleen whales share similar respiratory bacteria, which is likely driven by their anatomy and physiology.

Leveraging support from this project, we also conducted the first ever comprehensive study of the microorganisms found in the gastrointestinal tracts of large whales. We obtained gut contents from 38 bowhead whales that were taken by Native Alaskans during subsistence hunts in Utqiagvik, Alaska, which is part of a long-standing partnership between the Native Eskimo and scientific communities. We examined the microbiome and lipidome (lipids or fats) in samples from nine anatomical regions of the whales, from the stomach to the lower colon.

Our analyses showed that the microbiome varied in composition throughout the gastrointestinal tract. Similar to terrestrial mammals, the microbiome became much more diverse within the colon compared to the other upper regions of the gastrointestinal tract. We further examined these microbial communities in relation to the digestion of the prey lipids (from krill and copepods). We identified specific species of bacteria that may be responsible for lipid digestion in bowheads. Based on the evidence in other systems, this correlation suggests that lipids in the bowhead diet may influence the community structure of the microbiota, and in turn, the microbes may be involved in the digestion and absorption of the lipids. While we have not defined the intricacies of the coordination, the relationship between the lipids and microbes is most likely driven by diet, microbial composition

Drone-based photograph of a North Atlantic right whale and calf taken during the 2017 calving season off the coast of Florida.

WHOI microbiologist Amy Apprill swabs the petri dish which contains a sample from a drone flight above blue whale blow, which will be used to study the whale's microbiome and examine its relation to animal health. Photo by Dani Casado (DC Photo).

and function, and host physiology. These results have provided a critical baseline of microbes in relation to lipids in the only resident Arctic whale, and may be used to assess animal health during the climate-driven habitat changes that are projected for the Arctic.

OUTREACH

Portions of the Chilean research cruises and interviews from expedition scientists were featured in the award-winning documentary film, *Patagonia Azul*. This film was awarded the "Best Short Documentary" at the 2017 Woods Hole Film Festival, and was also featured at the Wildlife Conservation Film Festival in New York. Articles featuring our research have appeared in five Chilean magazines and newspapers, and the work was presented at the International Marine Protected Area Congress (IMPAC4) meeting in September 2017 in La Serena, Chile, and to public audiences at the Mystic Aquarium, in Mystic, Connecticut.

The whale digestive research was published in the *ISME Journal* in December 2019. The paper received recognition by this prestigious microbial ecology journal as a "20 Most Cited and Shared Articles of 2019". The findings of this research also were featured in a WHOI press release, which led to the article's coverage by numerous media agencies.

An article about our large whale health assessment research was authored by Amy Apprill for *The Conversation*, an online news journal, titled: "My team uses crossbows and drones to collect bacteria from whales—and the results are teaching us how to keep whales healthy".

FUTURE WORK

Our next goal is to examine the body condition (photogrammetry) and microbiome data together. This type of analysis will allow us to understand if more robust or fatter whales contain subtle differences in their blow microbiome compared to less robust or skinnier animals. Additionally, we will examine the data to determine if relationships exist between animal age or sex and the blow microbiome. Ultimately, this dataset will advance our understanding about the relationship between whale species, body condition and respiratory microbiome and the applicability of these tools to health monitoring.

Portions of this research cruise and interviews from expedition scientists were featured in the award winning documentary film, Patagonia Azul.

Life at the Edge: Adaptive Sampling Using the VPR, REMUS, and Other Methods

Dennis McGillicuddy, Applied Ocean Physics and Engineering

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Woods Hole Oceanographic Institution (WHOI)

Mike Purcell, WHOI

Rachel Stanley, Wellesley College

OBJECTIVES

Plankton are controlled by physical, chemical, and biological interactions operating across a broad range of scales. Traditional sampling of plankton with nets and bottles is limited in time and space and destroys their fragile forms. Since these organisms are the dominant components of oceanic communities, it is essential that we employ methods to study them that do not damage them. Nondestructive optical sampling using the high-speed Video Plankton Recorder (VPR) allows acquisition of plankton data while the ship is underway.

ACCOMPLISHMENTS TO DATE

The shelf-break front is where the colder, fresher water of the continental shelf meets the dense deeper waters of the western North Atlantic. We sampled hotspots in productivity at the shelf-break front south of New England, in the vicinity of the Ocean Observatories Initiative's Pioneer Array, a long-term ocean observatory that spans the edge of the continental shelf in this region. Measurements were made on two expeditions: voyage 1904 of the R/V *Ronald H. Brown* (RB1904) in May of 2019 and voyage 368 of the R/V *Thomas G. Thompson* (TN368) in July of 2019.

During the RB1904 cruise we observed a shelf-break eddy formation event, and our data revealed a new mechanism for eddy-induced upwelling at the shelf break. In particular, the association of high levels of nitrate within the cold and fresh eddy is an indication of the upwelling of subsurface shelf waters. As meanders develop due to instability processes along the front, shelf waters are transported southward. Surface waters are transported laterally, but deeper waters must rise as the shelf waters ride up and over the denser slope waters that lie below the front. As such, waters containing high levels of nitrate from the deeper part of the shelf are brought into the euphotic zone. This water mass becomes distinct from its source waters as the meander wraps around the water mass in formation of a shelf-break eddy. As the upwelled nitrate is consumed, levels of chlorophyll increase.

Nondestructive optical sampling using the high-speed Video Plankton Recorder (VPR) allows acquisition of plankton data while the ship is underway.

Opposite page: R/V *Neil Armstrong* crew recovers the Video Plankton Recorder after a survey of the *Phaeocystis* bloom.

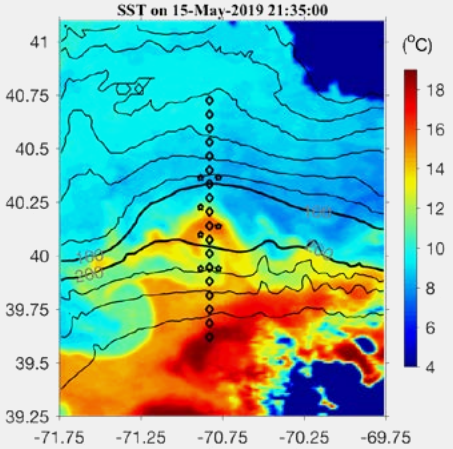


Figure 1. Satellite image of sea surface temperature on 15 May 2019. Diamonds indicate the cross-shelf line of stations on which the voyage was focused, and stars indicate the locations of the Pioneer Array moorings.

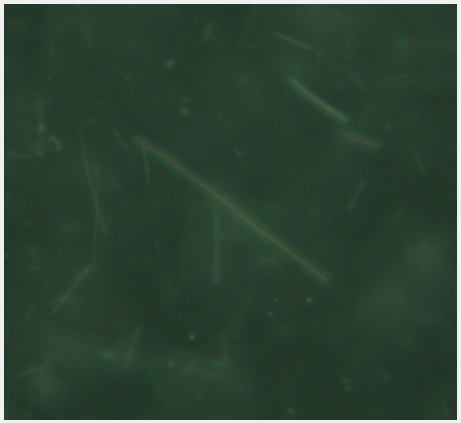
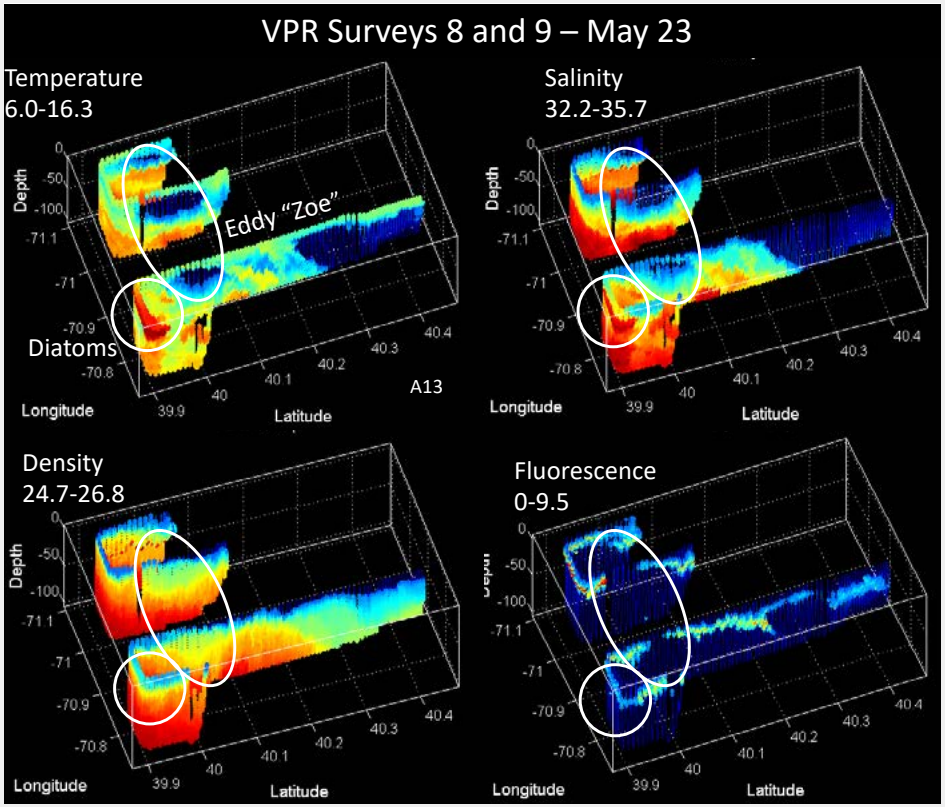


Figure 3. Example VPR image from the bloom of diatoms and colonial plankton.

Figure 2. VPR survey on May 23. Oval shaped area indicates the cold and fresh eddy, and the white circle indicates the area where rod-shaped diatom chains were present in high abundance (unrelated to the shelf-break eddy).



Future work to use AUVs to support science will include increasing autonomous behaviors to modify mission plans based on collected data, and extending vehicle endurance missions starting and ending nearshore.

During TN368 we encountered an extraordinary bloom of diatoms and colonial plankton resulting from interactions between the deep ocean and the shelf. A conceptual model has emerged which can explain our observations. First, high salinity waters are the niche for the blooms along the shelf edge. A large cyclonic eddy identified in satellite altimetry provides a means for their transport from a presumably Gulf Stream warm-core ring source. The jet in between the cyclone and the ring forming to its east impacts the edge of the continental shelf. Westward flow in the northwestern lobe of the cyclone would tend to deliver the source waters to our sampling area. Highest fluorescence occurs when the high salinity waters are illuminated via shoaling (increased wave height) of that water mass; this occurs in three regimes: the cyclone, along the shelf edge, and on the eastern side of the streamer. In addition to the VPR, a REMUS 600 AUV, fitted with a suite of sensors to measure nitrates, fluorescence, dissolved oxygen, conductivity, temperature and depth, was deployed to map the fine-scale structure of the bloom.

The VPR provided critical technology to adaptively sample the eddy formation event and the diatom bloom. Both processes could not be resolved by traditional methods of oceanographic sampling. This research is yielding new insights into what controls biological productivity of this important region, which has analogues throughout the world ocean.

The REMUS 600 AUV captured ocean physical and biological variability in a scale (~100 meters) that is much finer than conventional observational methods and revealed the patchiness of phytoplankton distributions below the surface. One mission targeted internal waves and captured Kelvin-Helmholtz billows, a small-scale (~10 meters) subsurface feature that is hard to measure *in situ* and confirmed that solitary internal waves on the shelf can induce these billows and strong vertical mixing.

OUTREACH

A short video describing our at-sea operation on TN368 is available online at https://www.youtube.com/watch?v=DDyz-1jRV5TQ. This is part two of a series begun on voyage 29 of the R/V *Neil Armstrong*.

FUTURE WORK

We will be classifying the images taken during the VPR survey and processing the collected data. REMUS surveys of the front reveal fine-scale patchiness of the physical, bio-optical, and biogeochemical properties. Variance increases from temperature to salinity to fluorescence to backscatter; oxygen and nitrate lie somewhere in between. Detailed analysis of the interrelationships among variables will hopefully yield insight into the mechanisms generating the observed patchiness.

The REMUS AUV work for this project is complete. The value of AUVs as measurement tools was evident in both the plankton and internal wave data. Future work to use AUVs to support science will include increasing autonomous behaviors to modify mission plans based on collected data, and extending vehicle endurance missions starting and ending nearshore.

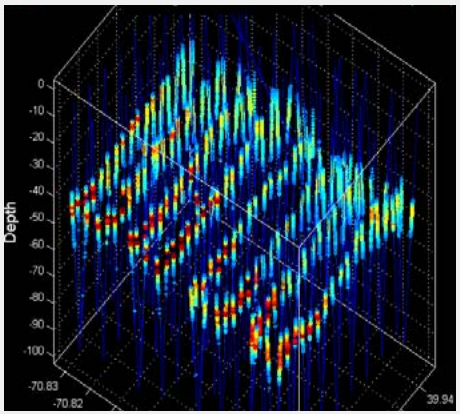
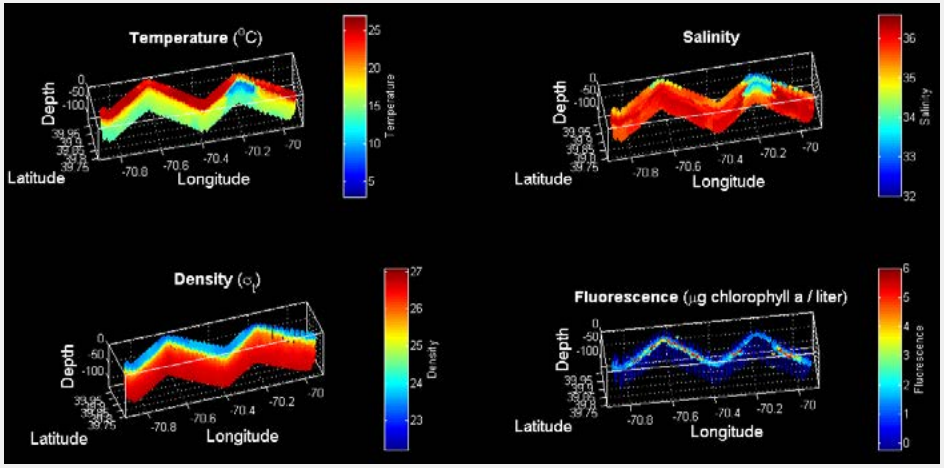


Figure 4. VPR5 July 12, starting from the line of stations shown in Figure 1 and surveying eastward.

Figure 5. REMUS survey of a diatom hotspot. Red (blue) areas are higher (lower) fluorescence, which is a proxy for phytoplankton abundance. Adjacent up/down cycles are less than 100m apart, providing unprecedented resolution of this feature.



Exploration of the U.S. Northeast Canyons and Seamounts National Monument

Timothy M. Shank, Biology

Science Team

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Casey Machado, WHOI

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Submarine canyons contain the most productive non-chemosynthetic habitats in the deep sea and may enhance local and regional species diversity, including those vulnerable to anthropogenic activities.

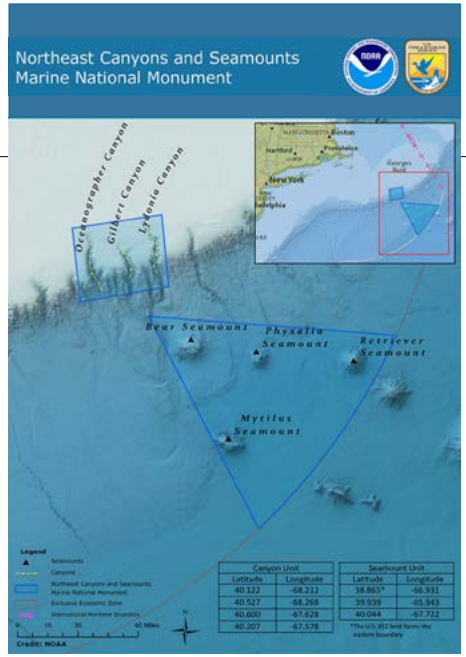
OBJECTIVES

1. Mission Background and Objectives: Submarine canyons contain the most productive non-chemosynthetic habitats in the deep sea and may enhance local and regional species diversity, including those vulnerable to anthropogenic activities. They also can be rich in natural resources (e.g., fisheries, oil and gas). Recently, there has been interest in exploring and extracting resources in Atlantic Ocean canyons, where more than 500 natural hydrocarbon seeps have been discovered. Our primary goal was to explore, characterize, and sample this area, focusing on the Northeast Canyons and Seamounts Marine National Monument (particularly the Lydonia, Gilbert and Oceanographer Canyons) to perform a comparative analysis of the ecosystems we encountered and their genetic diversity. In 2018, we conducted submersible dives to map and collect fauna representative of the canyons. Between these dives we field tested a new class of full-ocean-depth Autonomous Underwater Vehicle (AUV) called *Orpheus*.

1.1 Scientific Objectives: In 2019, we advanced these efforts by conducting a week of sea trials for *Orpheus* aboard the R/V *Armstrong*. Our key scientific objectives were: (1) to explore and characterize benthic habitats in Veatch Canyon to not only further our scientific understanding of connectivity and management; but also (2) to autonomously discover and characterize (through *in situ* chemical sensors and high-definition imaging systems) unknown areas and organisms inhabiting natural hydrocarbon seepages; and (3) to characterize the genetic biodiversity of canyon species through new barcoding approaches and third generation full genome sequencing and assembly.

1.2 Engineering Objectives: In 2019, we sought to: (1) complete the final construction of a second *Orpheus* class AUV. This was to be a full-ocean-depth, drone-like vehicle—a twin to *Orpheus*; (2) demonstrate baseline vehicle functions including mobility, power, high-definition imaging, and the creation of three-dimensional photo mosaics; (3) test autonomous behaviors, control loops, and mission planning; and (4) integrate *in situ* chemical sensors and seafloor imagery to obtain seafloor imaging transects to provide data for the development of terrain-relative navigation software algorithms.

1.3 Outreach Objectives: Our outreach objectives in 2019 were to build on the successes of OceanX that would feature our work and goals widely in digital and print media.



The Northeast Canyons and Seamounts National Monument covers approximately 4,913 square miles (12,724 square kilometers), is located about 130 miles east-southeast of Cape Cod, and includes two distinct areas: one that covers three canyons and one that covers four seamounts. (Map courtesy of NOAA)

A bubblegum coral (Paragorgia spp.) similar to, but distinct from, the new species identified in Lydonia Canyon. (Photo by Ivan Agerton, OceanX)

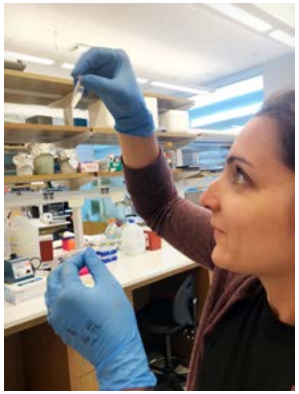
ACCOMPLISHMENTS TO DATE

2.1 Science accomplishments: In addition to identifying the species diversity of corals in Lydonia Canyon at three depth zones (shallow: 573-369 meters, mid-water: 650-608 meters, and deep-water: 903-862 meters) and creating a unique Global Information System (GIS) database for the Monument, populated with coral locations and cruise results, we successfully utilized *in situ* chemical sensors and high-definition seafloor imaging to locate and characterize a previously unknown hydrocarbon seep in Veatch Canyon at ~1,850 meters. The seep was in soft sediment and hosted dozens of seep-endemic bathymodiolin mussels.

In 2019, our efforts to reveal genomic diversity advanced greatly. Through genomic investigations, we have been revealing unexpected faunal species diversity, novel coral host and epifaunal relationships, and microbial communities in the canyons. Employing emerging sequencing technologies, we developed a shipboard genomic workflow that supports real-time species identification immediately after submersible collection. These methods will allow researchers on future expeditions to determine environmental diversity after each dive, before assigning subsequent collection sites, thereby facilitating faster and more efficient exploration of deep-sea areas. DNA barcoding analyses using both traditional and novel genetic markers and utilizing next generation technologies have revealed higher than expected coral diversity, with as much as 44% of the samples collected not genetically matching any known coral species. Therefore, these may represent previously unknown species. Through these efforts, we also have established workflows for studying microbial communities associated with canyon corals and have uncovered unexpected microbial species and diversity, including fungal communities that are typically associated with shallow corals and microbes connected with disease and species declines in other organisms, such as amphibians.

We also have employed third generation long-read sequencing technology to sequence and assemble the genome of one of the collected, unknown samples morphologically placed in the large, soft coral family Primnoidae. Representing the first genome sequence of a deep-sea coral, and the first genome sequence from any member of the Primnoidae, this genome will provide a powerful tool in our efforts to study deep-sea adaptations. Emerging sequencing technologies also have allowed for the assembly of complex, repeat rich genomes, such as that of the pelagic tunicates of the *Salpa* genus. Linking these genomic data with biometric and oceanographic data will support future research endeavors to understand how different species colonize unique, deep-sea environments and adapt in order to survive in these habitats. Leveraging the tools, workflows, and data enabled by the

Through genomic investigations, we have been revealing unexpected faunal species diversity, novel coral host and epifaunal relationships, and microbial communities in the canyons.



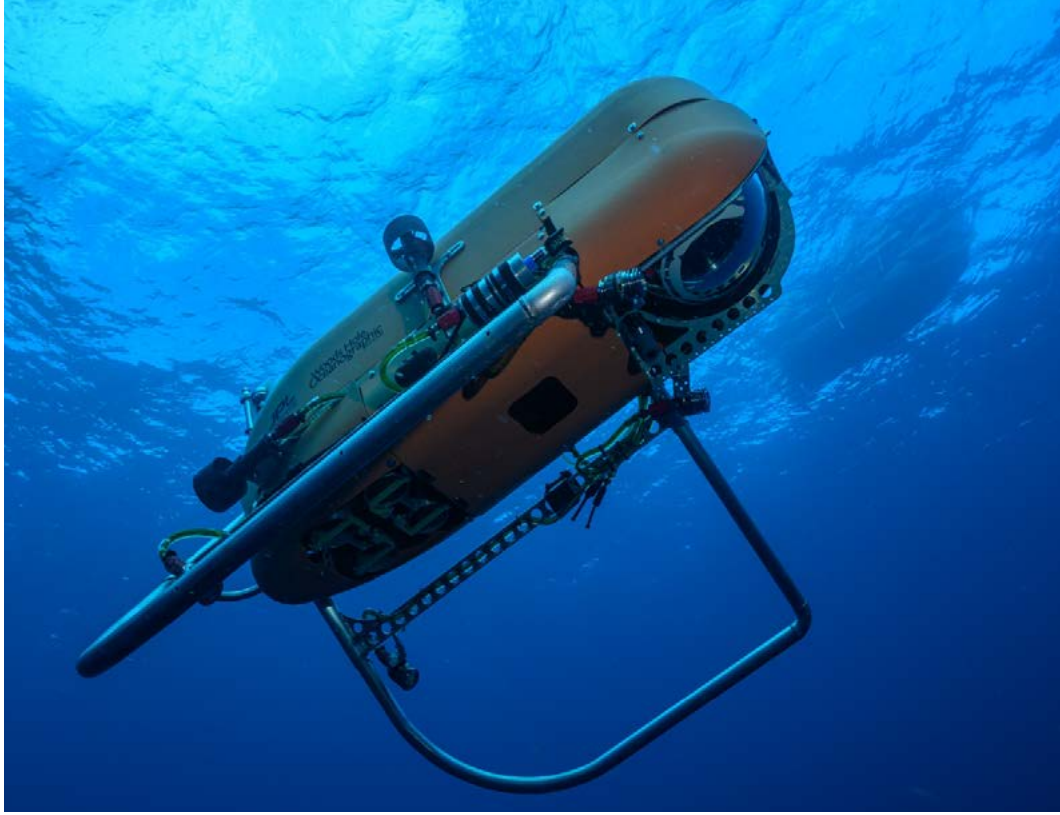
M/V *Alucia* expedition, we are establishing the Deep Ocean Genome Initiative, a ten year program that will: (1) enable the discovery of extreme ocean biodiversity; (2) uncover adaptations to extreme environments that will fuel novel technologies and applications in human, animal and environmental health, and; (3) synergize technological and biological advancements to explore the limits of life on Earth, as well as assist the discovery of life beyond Earth.

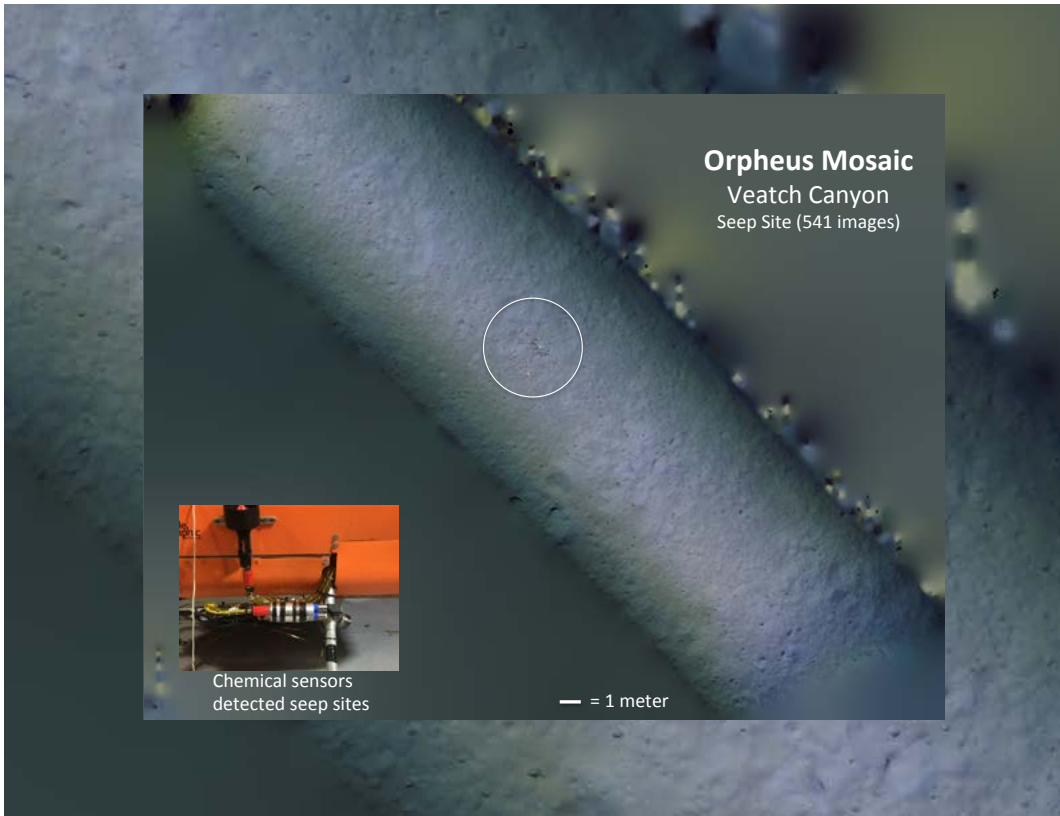
2.2 Engineering Accomplishments: We constructed a second full-ocean-depth vehicle, *Euridyce*, which we first tested at NASA's Jet Propulsion Laboratory and then field tested in tandem with *Orpheus* at greater depths, adding additional sensors and detectors. We deployed *Orpheus* twice in September 2019 to exercise core vehicle operations, and test and troubleshoot the functionality of sending and receiving commands and data remotely. We achieved strong correspondence between altitude ranges and depth-sensor estimates, as well as seafloor transit periods. In addition, we tested and exercised the limits of the battery systems and ascent procedures. Lastly, we integrated *in situ* chemical sensors, camera imaging systems and altimeter-sensor functionality that allows us to strongly advance to the next steps in successfully utilizing a new method for seafloor navigation—terrain relative navigation. The only other vehicle on Earth that utilizes this NASA-produced software is the Mars Helicopter, which is scheduled to be deployed in early 2021.

This year we extended our results to better inform policymakers and managers. These included feature articles in The Atlantic *magazine, the* New York Times, *digital media of* National Geographic

OUTREACH

This year we extended our results to better inform policymakers and managers. These included feature articles in *The Atlantic* magazine, the *New York Times*, digital media of *National Geographic*, and a video short featuring our discoveries in the canyons and our advancements in autonomous vehicle capabilities. T. Shank provided a congressional briefing, met with congressional members, and presented to the National Affairs and Legislative Committee, all focusing on the importance and value of the U.S. Northeast Canyons and Seamounts National Monument for accelerating scientific and societal advancements.





Large Whale Ecology and Conservation Through State-of -the-Art Thermal and Visual Imaging Technologies

Daniel Zitterbart, Applied Ocean Physics and Engineering

Science Team

Alessandro Bocconcelli, WHOI

Robert Petitt, WHOI

Daniel Gomez-Ibanez, WHOI

Fred Thwaites, WHOI

Alejandro Cammareri, Fundacion Marybio

Sebastian Richter, University of Erlangen-Nuremberg

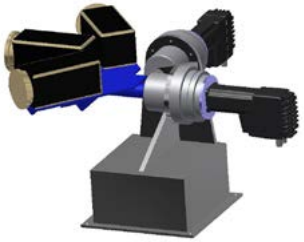
The goal of our project was to address the immediate concern that ship strikes may be bringing whale populations closer to extinction

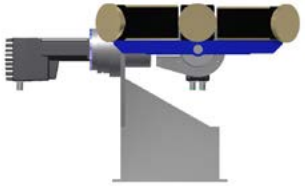
OBJECTIVES

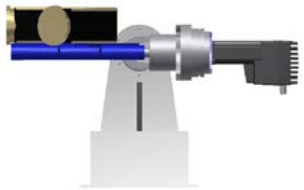
The goal of our project was to address the immediate concern that ship strikes may be bringing whale populations closer to extinction. This concern became clear in 2017, when 17 of the ~470 remaining North Atlantic right whales died, with at least six of these deaths believed to be due to vessel collisions. This high death rate was declared an unusual mortality event by the National Oceanic and Atmospheric Administration (NOAA, 2018), and illustrated the need for technologies that could help to mitigate ship strikes.

Currently, marine mammal detection is mainly achieved by human observers, which is not feasible for autonomous vessels. Furthermore, visual observations are only possible during daylight hours and require a large number of people to participate. Therefore, it is only implemented on seismic and naval vessels. However, autonomous vessels will soon become larger and more numerous, increasing the need for technologies that allow for the detection and avoidance of large whales. If successfully developed and deployed on these vessels, the whale detection system will simplify mitigation operations and allow for more effective whale conservation. The impact of this new technology will grow with time once it can be shown that ship strikes can be effectively reduced. Moreover, the potential will be greater for the detection system to become a standard tool, much like radar, which is currently installed on commercial and large pleasure crafts.

The goal of this project is to design, develop and install an automated whale detection system on the R/V *OceanXplorer1*. It will be the first vessel to operate such a system on a regular basis, both for conservation (vessel strike mitigation) as well as ecological studies (abundance estimation). The key part of such a system is the automatic detection algorithm for whale blows. The algorithm has been continuously developed since 2011 (Zitterbart et al., 2013, Zitterbart et al., 2020) and is tuned toward minimizing false positives while missing the fewest number of whale surfacings possible. The automatic detection algorithm relies on the spatial and temporal evolution of pixel intensity to detect thermal anomalies caused by whales, and therefore relies on a video stream stabilized for roll and pitch of the vessel to be able to calculate this metric pixel-to-pixel correspondence across individual frames. Furthermore, if the distance to the animal is to be assessed, then the horizon needs to be stable in the image. Stabilization of a video feed can be accomplished with two methods, either with a gyroscope-controlled active mechanical gimbal that stabilizes the camera mechanically against the vessel's motion, or with a pure algorithmic stabilization that uses information from an inertial measurement unit (IMU) to assess the ship's motion.







ACCOMPLISHMENTS TO DATE

In 2019, we achieved the following for the automated whale detection system:

- Finished the design for the electro-mechanical stabilization, which was co-funded by Canada's Department of Fisheries and Oceans (DFO).
- Placement of the whale detection system aboard *OceanXplorer1* was determined after discussions with the ship designers and shipyard managers.
- Thermal cameras, which are the central part of the whale detection system, were acquired and delivered to the team.

FUTURE WORK

Assembly and subsequent bench testing of the system were on schedule until the Covid 19 crisis shut down the WHOI campus. We will continue to work on the software integration parts that can be done from home, with final bench tests to be conducted as soon as the campus reopens. Initial offshore tests are now planned for the fall of 2020. This grant from the Dalio Explore Fund has allowed us to secure additional funding from DFO Canada so that we can keep pushing the limits of the technology—especially reducing size and weight—so that it may become a standard instrument on vessels in the future.

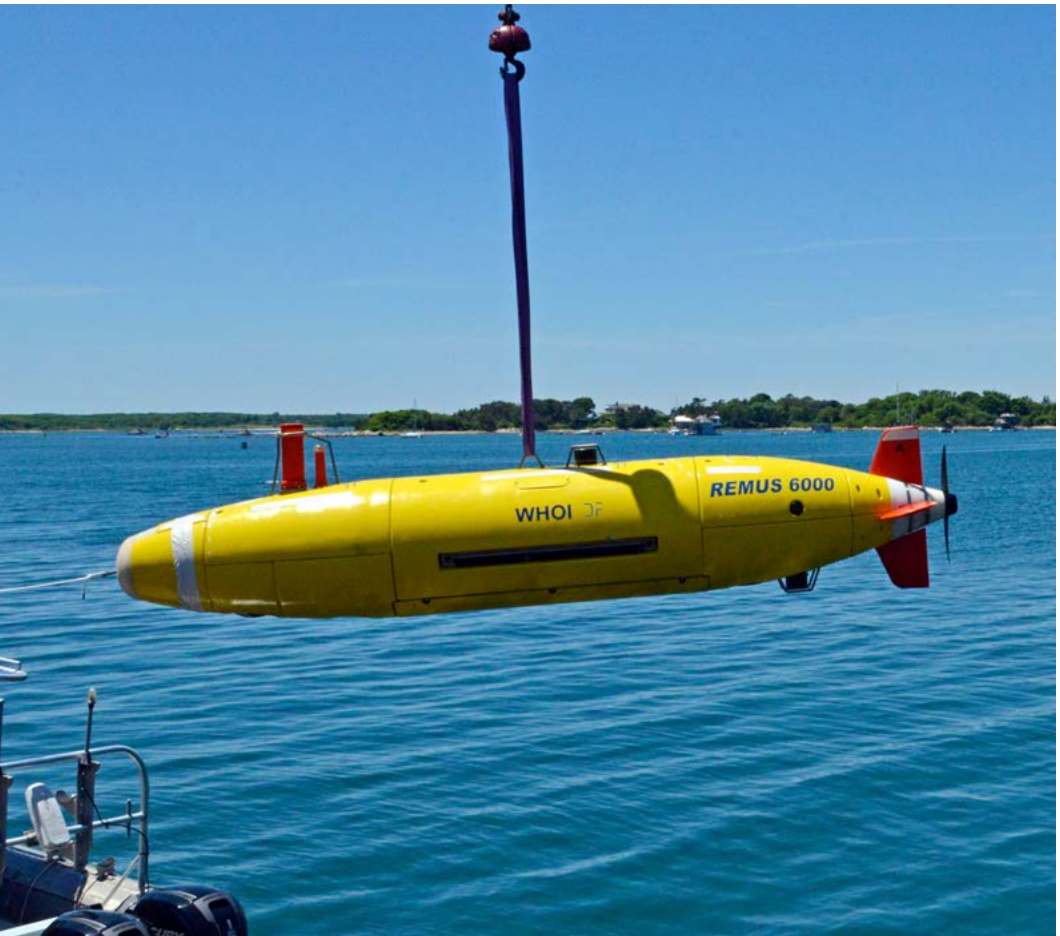
2019 REMUS 6000 Activities

Gregory Packard, Applied Ocean Physics and Engineering

The Dalio Foundation's REMUS 6000 Autonomous Underwater Vehicle (AUV) can perform high resolution ocean bottom surveys in the deep ocean environment. The AUV is capable of operations in water depths down to 6,000 meters. The vehicle is equipped with a variety of acoustic seafloor mapping sensors, high resolution cameras and water property measurement instrumentation. The REMUS 6000 is operated and managed under a cooperative agreement with Woods Hole Oceanographic Institution.

Two significant bottom survey and mapping cruises were completed during 2019. The primary focus of these cruises was to acquire near-bottom high resolution side scan and sub-bottom sonar data for the purpose of seabed characterization. During these cruises, the vehicle performed 35 long-duration missions down to full rated depth to support the mapping effort. The acquired data presented a comprehensive three-dimensional image of the seabed structure in the area that was being surveyed.

The REMUS 6000 will have system upgrades performed to its main processor units and sonar systems in 2020. Additional seabed survey cruises are planned for the summer months in the North Atlantic and late fall in the Eastern Pacific.



The Dalio Explore Fund Financial Report as of December 31, 2019

Established with a grant of $5,000,000 on February 28, 2013
Second grant of $2,500,000 on May 1, 2015
Third grant of $2,500,000 on March 21, 2017
From Ray Dalio and the Dalio Foundation, Inc.

ACTIVE PROJECTS

Researcher	Project	Award	Spent
Munier	*Discretionary Awards**	$28,993	$6,930
Zitterbart	*Large Whale Ecology Imaging*	$546,972	$124,026
	Subtotal	**$633,825**	**$130,956**

PROJECTS COMPLETED IN 2019

Researcher	Project	Award	Spent
Apprill	*US-Cuban Collaborative Invesitgation of the Biodiversity of Protected Cuban Reefs*	$328,912	$328,887
McGillicuddy	*Life at the Edge: Adaptive Sampling with the Video Plankton Recorder*	$437,095	$438,292
Michel	*Bigeochemical Exploration of the Pescadero Basin Vents*	$534,941	$534,808
Moore	*Thar She Blows: Remote Sensing of Whale Health using Drone-Enabled Imaging and Blow Capture*	$299,071	$299,071
Shank	*Explore Deep*	$268,985	$195,060
Shank	*Exploration of the US Northeast Canyons and Seamounts National Monument*	$267,999	$267,999
	Subtotal	**$2,237,114**	**$2,164,228**

PROJECTS COMPLETED PRIOR TO 2019

Researcher	Project	Award	Spent
Apprill	*Cuba*	$29,664	$29,664
Apprill	*Characterizing the Foundation of the Coral Foos Web in Cuba: The Last Frontier of the Caribbean*	$469,632	$469,632
Buesseler	*Quantifying the Sources and Fate of Radionuclides in the Ocean at th Marshall Islnds Using New Sampling Devices*	$660,026	$660,026
Cohen	*Finding and Protecting the World's Strongest Reefs*	$125,016	$125,016
Davis	*Video Plankton Recorder Sampling*	$210,816	$210,816
Davis	*VPR Cruise and Repair*	$159,560	$159,560
Davis	*Understanding Ocean Biology in a Changing Climate: High Speed Sampling of Plankton and Environmental Variables Across the Pacific Ocean Using the Video Plankton Recorder from the M/V Alucia*	$173,607	$173,593
Davis	*Refit of the Video Plankton Recorder*	$186,026	$186,020

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Donnelly	*Tropical Cyclone Risk*	$332,402	$332,402
Donnelly	*Reconstruct Hurricane Activity*	$870,542	$870,542
Donnelly	*Assessing Tropical Cyclone Risk in Northeastern US*	$500,005	$500,005
Farr	*Wireless Video Transfer from the Triton Submarine to the Surface: Development and Integration*	$547,145	$547,145
Gallagher	*Plankton of the Day. One Drop at a Time: High-Resolution Plankton Imagery from the M/V Alucia*	$183,780	$182,425
Hughen	*Investigation of Centennial Scale Climate Variability from Massive Corals in the Western Equatorial Pacific*	$89,210	$89,210
Jenouvrier	*The Danger Islands Expedition: A Multi-Scale Study of Remote Penguin Supercolonies*	$419,804	$415,393
Klein	*Exploring for Hydrothermal Activity at the St. Peter and St. Paul Archipelago, Mid-Atlantic Ridge*	$420,353	$420,353
Mullineaux	*Pescadero*	$110,111	$110,111
Pineda	*Identifying the Physical and Biological Processes Determining Ecological Hotspots via Exploration of a Shallow Seamount in the Eastern Pacific*	$452,795	$452,606
Shank	*Colombia Exploration with NHT*	$219,450	$219,450
Shank	*Colombia Exploration with Towcam*	$131,014	$131,014
Soule	*Exploration of the Submarine Volcanic Platform of the Galapagos Archipelago*	$438,316	$438,316
Thorrold	*Gulf of California Sharks*	$72,505	$72,505
	Subtotal	**$6,801,765**	**$6,795,804**

Total Grants	**$10,000,000**	
Total Awards	**$9,572,593**	
Fund Balance	**$427,407**	
Inception to Date Interest Earnings	**$87,776**	
Total Available Funding	**$515,183**	

DISCRETIONARY AWARDS*			
Researcher	**Project**	**Award**	**Spent**
Apprill	*Coral Reefs Cuba*	$6,930	$6,930
	Subtotal	**$6,930**	**$6,930**

Video Plankton Recorder Financials Report as of December 31, 2019

OPERATIONS AND MAINTENANCE		
Project	**Award**	**Spent**
VPR II Maintenance 2019	$113,293	$113,200
VPR CAPEX Servos 2019	$138,000	$29,119
Total	**$251,293**	**$142,319**

REMUS 6000 Financial Report as of December 31, 2019

OPERATIONS AND MAINTENANCE			
Contract Year	**Period**	**Award**	**Spent**
5	05/01/2018 - 04/30/2019	$159,000	$135,643
6	05/01/2019 - 04/30/2020	$159,000	$30,113
	Total	**$318,000**	**$165,756**

CAPEX			
Contract Year	**Period**	**Award**	**Spent**
5	5/1/2018 - 6/30/2019	$60,159	$55,375
6	5/1/2019 - 6/30/2020	$219,717	$38,782
	Total	**$279,876**	**$94,157**

FEES PAID TO THE DALIO FOUNDATION		
Project	**Sponsor**	**Fees**
US Navy Survey	Oceaneering	$320,000
US Navy Survey	Oceaneering	$270,000
	Total	**$590,000**

A black grouper feeding on a Gardens of the Queen reef (credit: Leonardo Espinosa).

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Woods Hole Oceanographic Institution