New Light on the Mantle below the Atlantic

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Executive Summary Three-dimensional (3-D) variations in Earth's material properties—temperature, composition, texture—cause seismic 'anomalies' due to elastic (and anelastic) seismic wave speed perturbations with respect to one-dimensional (1-D) reference Earth models [1, 2]. Seismic imaging remains the premier methodology to fully understand the structure and evolution of our planet [3], from the scale of mantle convection and the mechanisms of heat transfer from core to surface, the growth and decay of oceanic and continental crust, to the interaction between the deep Earth and surface processes such as plate motion and crustal deformation. Mismatches between observed and theoretical (numerical) predictions of seismograms, records of ground motion, are used to reconstruct the 3-D wave speed distribution in the regions sampled by seismic waves via a procedure known as seismic tomography [4, 5]. Unequal geographical data coverage fundamentally limits the quality of tomographic reconstructions of Earth's interior [6, 7]. All 3-D Earth models are marred by blank spots, and regions of substantial model discrepancy, where little or no reliable information can be obtained. Theory and modeling help—but new data *always* yield exciting new information [8]. Throughout the Atlantic Ocean, the situation is especially dire. Notwithstanding dense station coverage on land in North America and across Europe (Figure 1, *top left*), and a recent deployment [9] in the Azores-Canary Islands region, virtually no publicly available seismic data recorded over the Atlantic exist, despite an ongoing abundance of earthquakes worldwide (Figure 1, *top right*) suitable for deep-Earth imaging [10]. Floating hydrophones aboard Mobile Earthquake Recording in Marine Areas by Independent Divers (MERMAID) are the leading and most cost-effective solution for rapidly improving seismic coverage over the oceans [11–14]. Ocean-bottom seismometers (OBS) [15, 16], cabled hydrophone arrays [17, 18], distributed acoustic fiber sensing [19, 20], and SMART cables [21] have proven success or promise tremendous merit, yet none of these solutions can be swiftly scaled up due to issues of logistics (deployment, recovery) and the cost of ship time. An Atlantic-wide deployment of 33 MERMAIDs will shine thousands of 'light beams' into the mantle, with identifiable science outcomes in each of 4 years (Figure 1, *bottom*).

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Figure 1: (Top left) *Seismic stations with* any*, historical or current, freely available data.* (Top right) *Forty-five years of publicly cataloged earthquakes.* (Bottom) *Simulated trajectories and surfacing locations of 33 hydroacoustic autonomous* MERMAID *floats deployed across the mid-Atlantic in Year 1. Ocean currents taken from the oceanographic* ARGO *project [22]. Every surfacing yields multiple earthquake records [12]. Data acquired in near-real-time will yield regular science outcomes and avenues for peer-reviewed publication by the PI, Graduate Student, and Post-Doc.*

1 Introduction, Motivation, and Rationale

The Atlantic Ocean is a unique geodynamical setting with ample opportunity for seismic imaging but for the marked absence of oceanic recording stations. The Mid-Atlantic Ridge (green in Fig. 1) is a slow-spreading zone of passive upwelling and crust production characterized by steep flank topography. In contrast to the much more thoroughly studied Pacific Ocean, with its surrounding subduction zones that host deep and great earthquakes [23] and its fast-spreading, gently sloping ridges [24], the Atlantic is largely devoid of active zones with down-welling slab-like material. Putative (deep?) mantle sources of active hot spots [25] are associated with tracks of fossil volcanic islands [26, 27]. Do deep mantle plumes [28] feed magma to the Azores, Canary Islands, and Cape Verde [29]? Are Large Igneous Provinces at the surface structurally and dynamically related to the fringes of thermochemically buoyant Large Low Shear Velocity Provinces at the base of the mantle [30]? The jury is out—today's low-resolution global mantle models offer a multitude of interpretations, and remain mutually inconsistent even at intermediate length scales [31, 32]—see Figure 2.

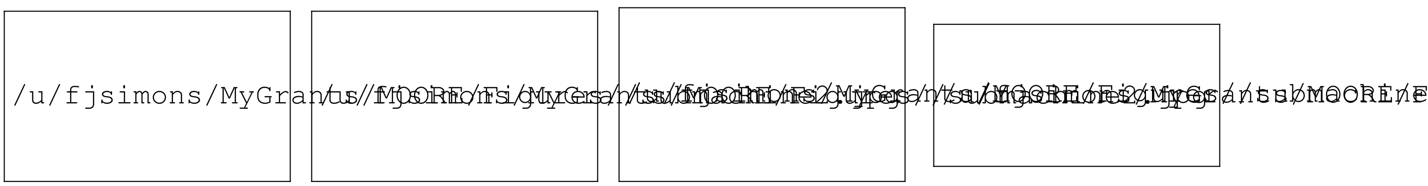

Figure 2: Coarse agreement, fine-scale tension between tomographic mantle models SEMUCB-WM1 [33], S40RTS [34], and TX2019slab-S [35], as exemplified by this cross-section through the Atlantic at 27.5° N. Red colors are *slow* (buoyant?) wave-speed anomalies, blue regions *fast*, in per cent from a 1-D background.

1.1 An Atlantic *Foundation Array* of Mobile Marine Sensors

The unique advantages of MERMAID sensors [36–38], autonomous hydrophones floating at ∼2000 m depth (see Figure 3) that report earthquake-triggered seismic waveforms in near-real-time (about once a week, depending on earthquake activity), are longevity (about 5 years), manufacturing cost, and ease of deployment from ships of opportunity. The technology is mature, and prior experiments in the Pacific and elsewhere [12, 14, 39–43] have demonstrated that the hypothetical outcome sketched in Figure 1 is achievable: a fleet of 33 MERMAIDs launched over the course of a one-year deployment period is capable of adding thousands of tomographically invertible seismic waveforms from distant earthquakes to our global archive.

In each project year, expected individual outcomes are: models of global and regional seismicity [12]; the identification of locally active earthquake fracture zones [40] and global earthquake phases including core phases [44]; the reporting of long-range hydroacoustic signals from underwater volcanoes or hydrothermal vents [45–47]; monitoring of the ocean gravity-wave-heave induced infrasonic noise field [13]; modeling of mesoscale oceanic water-temperature variations [48] (passive seismic ocean thermometry [49] in addition to direct temperature measurements and oceanic current mapping). The ultimate end goal is the production of a new regional seismic model for Atlantic mantle structure and its geodynamic interpretation.

Budgeting for a fraction of the MERMAID floats to be equipped with deep (4–6,000 m) conductivity-temperature-depth (CTD) sensors, fields beyond deep-Earth seismology and hydroacoustic sensing that will be profoundly impacted include sea-floor geodesy [50] and oceanic hydrography, vital to constraining global circulation models of oceanic heat content [51]. In this project we will *not* include high-frequency acoustic sensors (useful for whale research [52] and ocean soundscape monitoring [53]), nor bathymetric sounders, but the progress made with "traditional" MERMAID sensors should facilitate those developments later.

The Atlantic MERMAID *Foundation Array* will be the indispensable foundation and scientific backbone for larger-scale and possibly more permanent instrumentation efforts, such as have been called for by a European group of scientists led by Ana Ferreira at University College London. They have been circulating ideas for a proposal to form what they call an *AtlanticArray* of cabled and ocean-bottom seismic sensors.

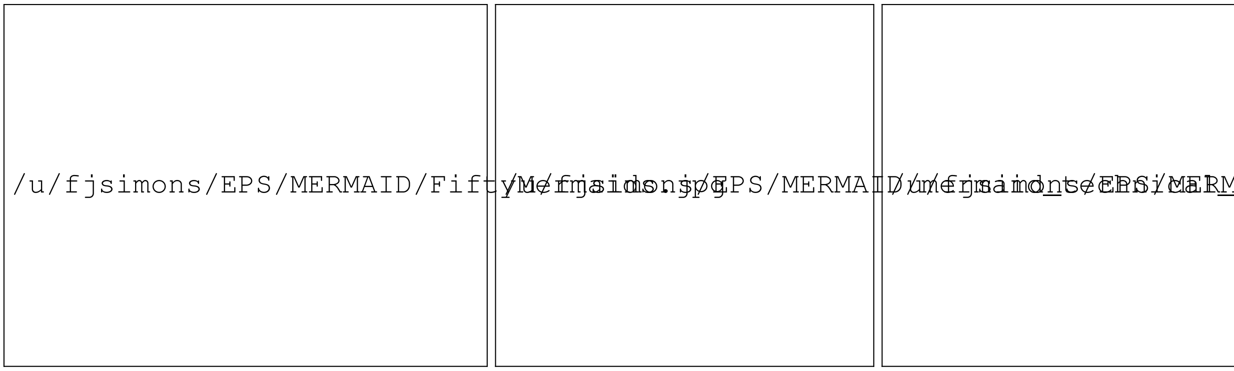

Figure 3: The current incarnation of the MERMAID instrument, built by OSEAN SAS in Le Pradet, France.

1.2 The EarthScope-Oceans Consortium

EarthScope-Oceans (ESO) is an international multidisciplinary group of geoscientists who coordinate efforts to create a global network monitoring the solid Earth system from within the oceanic environment, founded at Princeton in 2016, by academics from the US, Japan, France, South Korea, New Zealand, China, and the UK. Then-IRIS (Incorporated Research Institutions for Seismology) granted us the use of the servicemark *EarthScope*, also the name of a 2003–2018 NSF program, but EarthScope-Oceans is not affiliated with either the NSF or The EarthScope Consortium (IRIS' new name). EarthScope-Oceans *operations* are currently not supported by any NSF funds. NSF support for *research* by the PI does stipulate that all MERMAID data collected are deposited with EarthScope's Data Management Center as part of SAGE/GAGE operations. For this proposal, a similar arrangement will continue with the next operator of the National Geophysical Facility, whoever that will be. Hence, data collected by the proposed Atlantic MERMAID *Foundation Array* will be made available publicly on a rolling basis within 2 years of collecting.

EarthScope-Oceans is an all-volunteer organization run by a *Steering Committee* headed by the PI, with members from France (Guust Nolet [Géoazur], Karin Sigloch [Géoazur], Alessia Maggi [Strasbourg], Mathieu Belbéoch [OceanOps]), Japan (Masayuki Obayashi [JAMSTEC]), Brazil (Marcelo de Bianchi [São Paulo]), South Korea (Geunyoung Kim [KIGAM]), and China (Yongshun John Chen [SUSTECH]). The *Technical Committee* is composed of Yann Hello (Head [Seisocean Consulting]), Olivier Philippe [OSEAN SAS], Sébastien Bonnieux [Géoazur], Dorian Cazau [ENSTA Bretagne], Ken Gledhill [GNS Science, emeritus], Hajime Shiobara [Tokyo], and Bud Vincent [DBV Technology], who together represent a range of nations, technical expertise, and a mix of academic, governmental, and small business interests. The *Data Committee* is responsible for developing standards and setting data sharing policy. Headed by Tim Ahern [IRIS, emeritus], it is composed of Joel Simon [Princeton], Christoph Waldmann [MARUM], and Yong Yu [Chinese Earthquake Administration]. Finally the *Science Committee* is composed of Alessia Maggi [Strasbourg], Ying Zhou [Virginia Tech], Hiroko Sugioka [Kobe], Jessica Irving [Bristol], Ebru Bozdağ [Colorado School of Mines], and Lucia Gualtieri [Euro-Mediterranean Center on Climate Change]. Website and app development is in the hands of a rotating cast of Princeton undergraduate student interns working hourly.

EarthScope-Oceans is member of the International Federation of Digital Seismograph Networks (FDSN), where Joel Simon is serving as an Executive Committee Member and elected Chair of Working Group V, charged with helping guide this international organization with members from 78 nations maintain free and open data access. In the last two years, Joel has led the development, acceptance, and implementation of a new data standard (`GeoCSV`) for "rapidly changing metadata"—such as those of our mobile marine sensors.

Support from the Moore Foundation will enable EarthScope-Oceans to join The EarthScope Consortium, and also the International Seismological Centre, as a Voting Member. This will cement our status as a provider of openly accessible data to the global community, and provide helpful synergies with their staff.

2 Acquisition of Instrumentation Years 1–2

We will purchase 25 third-generation MERMAID floats from French engineering company OSEAN, based in Le Pradet, France. These are the "classic", tried and true, robust, long-lived, earthquake-detecting and reporting floats, equipped with a hydrophone, GPS, and two-way IRIDIUM communication, designed for a parking depth of 2,000 m. *These units will be available within 6 months per batch of 10, so that deployments and data return can start in Year 1 of the project.*

We will purchase 3 fourth-generation MERMAID floats from OSEAN with 4,000 m diving capability and which will be equipped with a SeaBird SBE61 conductivity-temperature-depth (CTD) sounder. While parked at 2,000 m in earthquake detection mode, prior to every surfacing for data reporting, they will take a 4,000 m CTD profile and report that as well. *Their availability is within 7 months, and their deployment will be integrated with the others as part of Years 1–2.*

We will purchase 3 "deep" MERMAID floats that have full-ocean-depth 6,000 m diving capability, also with a SeaBird SBE61 conductivity-temperature-depth sensor. They are currently under development by OSEAN at no cost to this proposal. *It is predicted that an order can be placed with 6 months, which will secure their deployment as part of our Year 2 effort.*

We will purchase 2 MERMAID floats of the novel *Bouncing Ocean-Bottom Seismometer* (BOBS) type with 6,000 m depth capability—a fusion between an ocean-bottom *seismometer* and a *hydro-acoustic* profiling float, merging the strengths of both technologies. Capable of autonomous data return, BOBS is a transformative solution to global-scale sea*floor* instrumentation, minimizing the need for dedicated shiptime, providing longer autonomy in the open ocean, and much more cost-effective than traditional ocean-bottom seismometers, which rely on scarce, cost-intensive and polluting infrastructure (which to date has meant that no existing ocean-bottom seismometry has been able to scale into a dense network of global coverage). These are currently under development by OSEAN with our partner Géoazur at no cost to this proposal. *An order will be placed in Year 2 a for a planned deployment in Year 2 or 3.*

Figure 4: *The* Bouncing Ocean-Bottom Seismometer*, fusion of seafloor seismometer and a robotic hydrophone float.* (Left) *After deployment by a ship of opportunity, BOBS dives, lands on the seafloor, and records three-component seismograms. Upon detection of earthquake activity, BOBS surfaces, transmits data, and recharges batteries via solar panels, then dives down again.* (Middle) *The by now "traditional" operation of the "classic"* MERMAID *hydrophone, which autonomously descends to mid-column depth, transmits data upon positive earthquake detections, and resumes its journey.* (Right) *The expensive paradigm of Ocean-Bottom Seismometry, whose data collection requires recovery of the entire instrument package via research vessel, a costly and often risky (in terms of data return) procedure.*

3 Deployment of Instrumentation Years 1–3

Over the last twenty-odd years (since 2003, to be precise), MERMAID instruments, including its prototypes and predecessors, have been deployed by a variety of ships of opportunity, small and large, commercial and academic. The PI has sailed on research vessels like the *Sproul* and the *Saikhon* in California [39], the *Alis* in Polynesia [12], the *Fukae Maru* in Japan [54], the *Endeavor* in the Atlantic, the *Atlantic Explorer* in Bermuda, and the *Blue Manta* in Puerto Rico. His students, post-docs, and collaborators have journeyed on the *Atalante*, the *Sikuliaq*, the *Mirai* and the *Shinsei-maru* in the Pacific, *Shyan II* and *Shyan VI* in the South China Sea, *Sagitta III* in the Mediterranean, and the commercial vessel *Ypapanti* in Santorini, Greece.

Beyond modest travel and shipping costs, we are not budgeting for any shiptime to deploy the new MERMAID fleet in the Atlantic over the course of project years 1–2. Counting on ships of opportunity and volunteer collaborators in the densely trafficked Atlantic realm, we will ultimately follow the operational model of ARGO [22], though we may forge specific new alliances (e.g., with German, British, or Portuguese research institutions), or reach out to other foundations (e.g., Schmidt, OceanX). The ability to deploy MERMAID from just about any platform, and the near-real time availability of earthquake data almost immediately after immersion, are among the core benefits of using autonomous mid-column instrumentation for global seismology, in order to close the coverage gap for seismic tomography of the deep Earth interior.

4 The EarthScope-Oceans Data Collection Center

In the words of the NSF (solicitation 23-594), the geosciences are "experiencing an explosion of data acquisition capacity," along with modeling and analysis improvements. Resources are required to harness these technological advancements, to maximize our capabilities for addressing priority Earth science questions, such as those identified by *Earth in Time* (2020). Among the questions for which data and data products from mobile marine seismological devices are crucial: Q3 *How are critical elements distributed and cycled in the Earth?*; Q4 *What is an earthquake?*; Q5 *What drives volcanism?*; Q6 *What are the causes of topographic change?*; and Q12 *How can Earth science research reduce the risk and toll of geohazards?*

The EarthScope-Oceans (ESO) Data Collection Center (DCC) prepares and deposits curated hydroacoustic waveform (meta)data into the National Geophysical Facility (NGF) data centers. Additionally, ESO DCC **collects data** (e.g., acoustic buffer requests and continuous time series, hydrographic CTD profiles) that otherwise are not being supported by any other source. Our team will continue its history of innovation by making **software tools**, data products, and providing responsive **services**, in collaboration with a global user base of oceanic solid-Earth researchers, and with the future operators of the NGF, as per their mandate.

Software examples are tools to interface with floats for data recovery and mission control (`automaid`); to conduct outreach activities (*Adopt-A-Float*), to query ocean-temperature and salinity fields aiding in the determination of background acoustic velocity fields; to access the oceanic drivers of the ambient seismic noise field via [55]; to run waveform simulations via `TauP` [56], `Instaseis` [57] and `SPECFEM-2D` [58, 59] and FK-`SPECFEM-3D` [60]; and to analyze bathymetry [61]. **Data products** include earthquake *associations*, frequency-dependent *arrival*-time measurements and *travel*-time anomalies in one-dimensional reference models [12], *synthetic* waveforms that honor bathymetry and the "oceanic last mile" of teleseismic wave propagation [14], and custom *buffer requests* from interested communities [44], e.g., to study the oceanic mesoscale temperature field and its temporal evolution ("seismic ocean thermometry") [49], both indirectly (from the MERMAID-III acoustic floats, Figure 5) and directly (from the CTD units inboard the MERMAID-IV floats). Many of the recent **service needs** arose from interactions with oceanographic and climate communities outside the solid-earth tomography community, and involve data for which MERMAID was not originally designed (its sole original mission was to collect *P*-wave arrival times), but which have proven to be supremely useful. *Letters of Collaboration* are included from users of those data.

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Figure 5: *Current (June 11, 2025) location of the* MERMAID *fleet managed by EarthScope-Oceans. Display software written by third-year undergraduate Jonah N. Rubin and fourth-year Stefan Kildal-Brandt. A smartphone iOS version was developed for use in our* Adopt-a-Float *outreach project by third-year undergraduate Peter Mwesigwa.*

The day-to-day routine **technical operations** required to maintain our fleet of MERMAIDs, which resurface on average every 6.25 days, involve checking data and log files and state-of-health messages on the receiving server, a virtual machine that is managed in-house, backed up, under `git` version control, behind the University firewall. The open-source software pipeline to keep the graphical display live (*and* online for the public, *and* accessible to our iOS app *Adopt-a-Float*) has been robust but requires upkeep and maintenance along with the fleet's ups and downs. While freely floating MERMAID is not actively being "piloted" in the strict sense of the word, it does require trajectory monitoring, and periodic intervention. In order to avoid areas with shallow bathymetry, cruising depth adjustment decisions are made. When a MERMAID drifts into very active earthquake zones, or in rare cases of electronic glitches, reporting-sensitivity adjustments are made to prioritize the capturing of *teleseismic* phases, with an eye towards maintaining the collective longevity of the instruments. Other aspects of active mission control involve sending MERMAID down, or keeping it at the surface, in order to influence its trajectory (somewhat). While MERMAID is not designed to be recovered (its very essence is to close the oceanic coverage gap for seismology while *halving* ship time), we have been able to recapture some, on occasion. Such was the case with instrument P0023, which yielded an unprecedented one-year-long buffered time series of *everything* it had recorded before we redeployed it. In June 2025, float P0006 was recovered in Fiji after an extraordinary seven years of active service. The MERMAIDs currently deployed in the Mediterranean will need active trajectory monitoring in order for ships of opportunity to be able to recover and service them before they enter the Atlantic.

The day-to-day **scientific operations** include scheduling data requests for specific time intervals of interest (e.g., to access late-arriving phases, volcanic signals, aftershock sequences), and mining and managing the resulting data. Such requests are currently being honored from a multitude of institutions. Ongoing scientific work requires "associating" seismic waveforms to global earthquake catalogs to determine multiscale travel-time anomalies, uncertainties, and signal-to-noise ratios, for mantle seismic tomography [12, 44, 62], and for sharing with the International Seismological Centre, to whom these records have proven vital to improve earthquake location accuracy [63]. Novel scientific tasks include designing and conducting experiments that explore altering the cruising depth, as a means of collecting ocean thermometry inversion data, and integrating the new MERMAID-IV floats with a CTD sensor and diving capacity to 4,000 m and 6,000 m.

The ESO DCC is committed to **outreach, teaching, and training**. Our website (all source code available from `GitHub`) and social media accounts (*LinkedIn* and 𝕏) are actively communicating. Our team will continue training research staff at collaborating institutions. Most recently, departing post-doc Joel D. Simon has trained Dr. Yong Yu (SUSTech), Dr. Dalija Namjesnik and Dr. HyeJeong Kim (Géoazur & ISC), and Ms. Yuko Kondo (Kobe University) on his event-association and travel-time anomaly determination software (on `GitHub` at `joelsimon/omnia`). The *Steering Committee* has and will continue to organize AGU Townhalls and Press Conferences, and Special Interest Groups (at IRIS/EarthScope/SAGE/GAGE).

5 Engaging a Technical Contractor — Description and Need Years 1–4

At Princeton, EarthScope-Oceans (ESO) is currently run by the PI, one graduate student (Sirawich Pipatprathanporn, graduating and moving on September 2025) and one post-doc (Joel Simon, whose contract ends June 2025), supplemented by occasional undergraduate research interns, casual hourlies, and volunteer labor. To rebuild the core team (in the complete absence of National Science Foundation opportunities after the shutdown of its *Instrumentation & Facilities* program in May 2025, and the forced withdrawal, in June 2025, of all grants submitted to the Program after January 20th), we will recruit one Graduate Student in Year 1, and hire one Post-Doctoral researcher in Years 2–4 of the project. To anchor these appointments, to provide continuity with the ongoing operations of EarthScope-Oceans, and to build the Atlantic MERMAID *Foundation Array*, we will begin by hiring an advanced professional, in Year 1, for all four years of the project. In the now dead language of the National Science Foundation, such a hire would have been called a "Cyberinfrastructure Professional" or a "Technical Position"—not a post-doc. We map this role onto that of one or more "Consultants" or "Contractors" in the Moore Foundation vocabulary, budgeting accordingly.

The Contractor(s) will bring the expertise, flexibility, and stability required to keep up with data collection and analysis of the current aging MERMAID fleet and its expansion to the Atlantic by 33 units, and to continue engaging with a growing group of domestic and international partners. The Contractor(s) are available to assist in field operations related to prototype testing and new instrument launches, and to conduct (rare) instrument recovery and redeployment using ships of opportunity. With PI, Graduate Student, and Post-Doc, the Contractor(s) will shepherd the Atlantic MERMAID *Foundation Array* into the international forum. Together they will coordinate decision-making on instrument deployment, data management, dissemination, archiving, education, and outreach efforts—and *finish* them within the 4 years of the project.

MERMAID is a freely drifting robotic mid-column oceanic float that records low-frequency hydroacoustic and hydrographic data at depth, surfacing to send data and receive communications via satellite. EarthScope-Oceans is the only organization covering the space between land-based (continental and island) and ocean-bottom (seafloor) instrumentation. The Contractor manages the pipeline from raw data acquisition in the oceans to their curated deposition in data management centers for open-access user requests by the seismological (and oceanographic) community. No other funded entity is currently charged with or capable of doing this. This proposal ensures the delivery of unique geophysical data and products for dissemination and long-term archiving into the data centers operated by the National Geophysical Facility.

From its first generation in 2004, MERMAID captured distant earthquakes [36, 39]. Other identifiable signals and noise sources are from whales, waves, weather, underwater volcanic eruptions, icebergs and ships. Approximately twenty second-generation MERMAID instruments operated for several years each in

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Figure 6: MERMAID-*III (*left*, 106 produced) and* MERMAID-*IV (*right*, including CTD profiler, yellow sensor to the right, 13 produced) deployed in the Pacific today (79 total). With* Moore Foundation *funding, 25+3+3 new units are purchased for deployment in the Atlantic. To plan and conduct their deployment and to handle the expected rich data return, the Contractor(s) are experts on seismic data and networks, earthquake seismology, marine instruments, developers of innovative software solutions upon community requests.*

the Mediterranean, the Indian Ocean, and in the Pacific, generating a wealth of data [39, 64], primarily for tomographic mantle modelling [41], though, in addition to teleseismic waves, MERMAID records local earthquakes. A swarm in the Indian Ocean produced 235 detections unreported by any other station, whether on land or anywhere else [40]. We expect a similarly rich data return from our Atlantic MERMAID array.

Thirty third-generation MERMAID instruments (Figure 6, *left*) are still floating at about 2 km depth in the Pacific and the South China Sea, using IRIDIUM satellites for near-real-time *triggered* and *requested* data transfer, surfacing approximately weekly to report hydrophone records, using GPS for location and timing. The 25 newly purchased units will replace the dwindling fleet, with a dedicated new focus on the Atlantic. The Contractor keeps an eye on the fleet, matches seismic phase data to known earthquakes, remotely troubleshoots and periodically resets units, and conducts day-to-day tasks as spelled out in Section 4. They develop products and software solutions for the benefit of, and as requested by, an interdisciplinary global user community, in order to supply and curate the ongoing data stream that is being collected from all active units deployed globally. Fourth-generation MERMAID (Figure 6, *right*) branched out into different directions. The *Stanford* model (seven launched in the Mediterranean in 2021) has a lower frequency-response hydrophone system and reports acoustic *power-spectral densities* in order to fuel the burgeoning field of environmental seismology [65–67]. The Contractor develops data formats and software products for this new kind of seismology, in collaboration with domain experts. The *Princeton/JAMSTEC* model (three deployed in the Pacific in 2023) carries a conductivity-temperature-depth (CTD) sensor in addition to its seismic package, and performs dives down to 4,000 m. Three of these will be newly purchased and deployed. Three more will have diving capability down to 6,000 m. The *Brazilian/Observatório Nacional* suite (six units to be launched in 2025) was redesigned in order to be able to rest on the ocean floor to enable the detection of regional seismicity. *Géoazur* is developing "landing" MERMAID models that incorporate seismometers, not just hydrophones (BOBS, see Figure 4, two of which will be purchased). The Contractor works with OSEAN to support products, tools and services for these nascent instruments, and new data types, in close coordination with the research groups involved, and ensures, through a federated system of data sharing agreements, that their data become part of the public archives hosted by the National Geophysical Facility.

It is within the mandate of the National Geophysical Facility (NGF), to archive and distribute geophysical (meta)data, using distributed cloud storage and state-of-the-art identity management, and to provide detailed reports on data use. The Contractor will interface with the operator of the NGF, in order to continue and strengthen the pathway for MERMAID hydroacoustic waveform data and metadata into their data centers. Examples of metadata are instrument responses and detailed geographical information of the perennially shifting network information. Examples of data formats are the custom-made `GeoCSV` format that we developed and which is to be merged with StationXML and adopted by the International Federation of Digital Seismograph Networks (FDSN). Examples of data products that require sustained development are "value-added", such as earthquake associations and catalogs, arrival-time picks, travel-time anomalies, synthetic time series, noise measurements, and identified volcano eruptions. The Contractor performs planning and monitoring services for deploying MERMAID instrumentation, develops new tools, and readies their data streams to feed into the NGF, where they are stored and made available to the world.

Triggered waveforms [12], will continue to be submitted periodically (well within two years of collection) to the NGF data management centers for permanent storage in the cloud. Per its mandate, NGF will report on their access statistics. *Buffer* requests [44] from various research groups, most lately from Virginia Tech, Caltech, WHOI, UC Santa Barbara, Penn State, JAMSTEC, UW, IPGP, and MBARI, will continue being honored, see *Letters of Collaboration*. *Continuous* data (from unexpectedly recovered instruments) are future windfalls that require dedicated processing (specifically for GPS clock corrections) that have led to unprecedented opportunities for scientific discovery [13]. The cumulative near-real-time data (product) stream (triggered waveforms, power-spectral densities, buffer requests, deep hydrographic CTD profiles, earthquake associations, travel-time measurements, arrival-time anomalies, waveform synthetics, float trajectories, and instrumental metadata) that the Contractor(s) will handle comprises the shared records from all our member institutions, signatories to the EarthScope-Oceans *Charter*, which maintains clear labor divisions for meeting the purely scientific objectives of, e.g., global earthquake sound monitoring, mantle tomography, and oceanic hydrography, but with common data management goals, needs and wants.

The Contractor is entrusted with ongoing innovation in terms of data management (curation, archiving), open-source software solutions and data product development. Other *academic institutions* will join our collaboration, some contributing new floats and capabilities. The Contractor will further ongoing communications with research groups in Louisiana, Puerto Rico, Norway, South Korea, and Saudi Arabia, whose scientific objectives are geared towards shallow environments, the detection of regional and local seismicity, submarine landslides, tsunami, ambient noise spectra, and under-ice exploration. EarthScope-Oceans will work with new member institutions (most lately, Brazil's Observatório Nacional, which is conducting an Atlantic experiment) to get their instruments deployed, their floats monitored on a day-to-day basis, and their data quality-controlled and packaged within the customary two-year moratorium for depositing into the NGF data centers for open-access use by US investigators and scientists worldwide. Other *Letters of Collaboration* are from those with whom we have or will exchange data before they become public. These reference the "EarthScope-Oceans Data Collection Center", see Section 4.

EarthScope-Oceans is partnered with the *Joint IOC-World Meteorological Organization Technical Commission for Oceanography and Marine Meteorology* and abides by the *Law of the Sea* and UNESCO agreements on global ocean observation systems, which spell out end-of-life provisions for MERMAID. In 2021 UNESCO endorsed ESO as a *Decade Action*, and the Contractor will help liaise with that community.

6 Mentoring of a Graduate Student — Years 1–4

The new fleet of Atlantic MERMAIDs will detect, identify, and report hydroacoustic waveforms for seismic tomography. Over the course of the project, they will collect a steadily growing database of high signal-to-noise 20 Hz waveforms in 250 s segments. As described in Section 5, the Contractor(s) will match the steadily incoming data stream with phase predictions based on global earthquake catalogs, and determine recording location and time so that accurate travel-time residuals can be determined following [12, 62]. These are among the "core" (meta)data and products that result from this proposal, see Section 8.

MERMAID seismograms are already used for travel-time tomography with picked arrival times [41]. The next frontier, Full-Waveform Inversion (FWI) of hydroacoustic seismograms [68, 69], requires simulating *seismic* wave propagation in a 3-D globe with an ocean in which *acoustic* waves propagate. This is far too computationally expensive at the frequencies 0.1–10 Hz, where MERMAID's instrument response is flat and the signal-to-noise high. One solution [14] is to first model the response of the solid Earth from the teleseismic earthquake to the ocean bottom, and then the wave propagation within the ocean layer.

Starting in Year 1, a Graduate Student will further these innovative wave-propagation approaches and analyze all waveforms in our data base as it continues to acquire new event-MERMAID pairs in the under-explored Atlantic realm. As is common practice, a beginning graduate student will receive a component of formal classroom education while commencing research right away, with a peer-reviewed publication expected at the end of Year 2. A successful Ph.D. typically contains at least three published manuscripts.

The PI has a proven track record in mentoring a small number of closely supervised graduate students, and a history of embedding them in a larger group of like-minded fellow students and colleagues. Named academic collaborators, who themselves are training one or two graduate students each, will continue to be Jeroen Tromp (at Princeton University), former Princeton colleague Jessica Irving (now at Bristol University), former post-doc Ebru Bozdağ (now at the Colorado School of Mines), and former graduate student Karin Sigloch (now at Géoazur). Irving, Bozdağ, and Sigloch serve on the EarthScope-Oceans *Science Committee*. They are all qualified to act as outside committee members for graduate students at Princeton University, and likewise, the PI has served on their students' committees as an external examiner.

6.1 Two-Dimensional Waveform Forward Modeling Years 1–2

We precompute elastic Green's functions using `Instaseis` [57] to obtain 2 Hz displacement seismograms within a 1-D reference earth model. We use `SPECFEM-2D` [58, 59] to solve the coupled elastic and acoustic wave equations, taking into account bathymetry and pressure-wave propagation within the water column. The simulations return time series of vertical *displacement* at the ocean bottom due to incoming plane waves, and acoustic *pressure* at the MERMAID depth. We de-convolve them to obtain a catalog of response functions between the displacement at the conversion point of plane waves from distant earthquake sources and the sound pressure, for a variety of environments and ray parameters. For any earthquake-receiver pair, we convolve the vertical displacement from `Instaseis` with the appropriate response function to model hydroacoustic pressure waveforms observed by MERMAID. In this way we can successfully model MERMAID records within the first few seconds following the *P*-wave arrival, in a high-SNR frequency band.

The correlation between synthetics and observations in our test data set (2,538 seismograms, 673 earthquakes) is high (max 0.98, median 0.72), and very coherent across the array (see Figure 7). Allowing for the determination of cross-correlation travel times will finally open up MERMAID seismograms to conduct full-waveform tomography of Earth's mantle. Synthetic waveforms and measurements are an innovative data product resulting from this proposal. We will work with the NGF data centers to host such non-primary data, a small but not unprecedented (see, e.g., *ShakeMovie*) departure from their usual holdings.

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Figure 7: *Waveform modeling of* MERMAID *records of CMT earthquake C201808171535A, magnitude 6.5, depth 529 km. Adaptive frequency selection effectively and optimally splits the record in a noise and a signal segment with high signal-to-noise ratio. Observations are in blue, synthetics modeled via our procedure [14] in red, aligned via cross-correlation. Note the extremely coherent waveform fits.* MERMAID *name and number are indicated, as are frequency band, cross correlation* `argmax` *and value, and relative travel-time anomaly.*

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Figure 8: *Bandwidth selection for a magnitude 6.50 event at distance 70° recorded by* MERMAID *P0009. Adaptive frequency selection splits the record in a noise segment and a signal segment, and determines the optimal temporal split and the signal-to-noise ratio. (a) Spectrogram, highpass filtered at 0.40 Hz.—(b) High-passed spectral density over the same time interval as in (a), calculated via overlapping segment analysis. (c) Time-domain zooms. (d) The passband-to-bandstop SNR ratios of the seismograms filtered on a grid of pairs of corner frequencies.*

Compared to travel-time “onset picking” [43], waveform-based modeling and correlation-based travel-time anomaly determination are inherently finite- and multi-frequency operations, and the Graduate Student will proceed carefully with determining the optimal modelable bandwidth for every record. Each measurement furthermore requires its own sensitivity kernel that we will explicitly determine [70, 71] in order to feed it to linearized inversion schemes—or implicitly incorporate under adjoint-based full-waveform inversion approaches [72]. Our working hypothesis is that for every MERMAID record a pair of corner frequencies can be found that maximizes the signal-to-noise ratio (SNR) in the frequency band above the microseismic noise, but bounded above by the 2 Hz maximum frequency readily modeled by INSTASEIS. Figure 8 shows that simply maximizing SNR is not actually *sufficient*—we may need to simultaneously *minimize* the SNR in the complementary “rejection” band. Graduate Student and Post-Doc will judiciously conduct experiments.

6.2 Three-Dimensional Waveform Forward Modeling — Years 2–4

The Graduate Student will extend the approach outlined above [14] to a fully three-dimensional approach whereby the global teleseismic wavefield generated by distant earthquakes will be modeled via FK-SEM wavefield injection [60]. Under that approach the “oceanic last mile” now will be handled by `SPECFEM-3D`, such that full oceanic bathymetry [61] and out-of plane scattering can be accounted for. Figure 9 shows a cartoon and a snapshot of the teleseismic wavefield. After conducting benchmarking tests with a flat seabed underlain by a homogeneous halfspace, the full modeling will include actual seafloor topography underneath the recording MERMAID sensor, and incorporate more detailed crustal models [73]. Those are known to generate important reverberation effects that are a clearly observable nuisance in ocean-bottom records [74].

Beyond endeavoring to model the waveforms as exactly as possible in order to use them for finite-frequency cross-correlation-based measurements suitable for Full-Waveform Inversion tomography centered on the Atlantic realm, an important part of the analysis will center on *understanding* the shape and structure of the received waveforms. To this end the Graduate Student will perform a suite of modeling experiments in random media, generated via prior analysis of seafloor topography. Substantially extending the pioneering work of [75–78], the PI and collaborators have developed an efficient maximum-likelihood-based method to invert for the parameters in the Matérn hyperclass of stochastic models [79] that is robust to discretization effects, irregular boundaries, and incomplete structured and random sampling (i.e., covering real-world bathymetric sounding scenarios). These will be further developed to include anisotropic structure and multivariate fields such that both surface and subsurface topography can be adequately captured [80].

Figure 9: *Incorporating 3-D bathymetry and crustal structure in waveform modeling of* MERMAID *records. Building on our earlier work [14], which combined 1-D spherical global models with 2-D Cartesian spectral-element approaches that include the full effect of acoustic wave propagation in the ocean, we will next combine global wave propagation using frequency-wavenumber (FK) simulations coupled to `SPECFEM-3D`, following the method of [60].*

7 Nurturing Post-Doctoral Talent Years 2–4

The Princeton group has pioneered adjoint-based full-waveform tomographic inversion at the scale of the globe [8, 81–87], culminating in a joint compressional and shear-wave speed tomographic earth model with uncertainty quantification [88]. However, as most recently shown by [7], the contribution of ocean(-floor) data to these models has been minimal. The forward modeling work of the Graduate Student, described in Section 6, will allow incorporating MERMAID seismic waveforms into new Atlantic-centered global models.

In Year 2 we will engage a Post-Doctoral researcher to lead the seismic inverse modeling and tomography efforts. The Post-Doc will be an expert in geophysical inversion, uncertainty quantification, and advanced seismic imaging techniques using global broadband seismic data, capable of uniting exascale computing on big, heterogeneous data sets—an integration not yet fully realized in seismology [5]. Data collected in the water column by the Atlantic MERMAID *Foundation Array* will be assimilated to complement globally available catalog data, and data newly available from the UPFLOW project [9]. If and when the anticipated *AtlanticArray* (see Section 8.1) enjoys a healthy data return, and if successful measurements are made by the funded *Continent, Azores and Madeira* (CAM) Science Monitoring And Reliable Telecommunications (SMART) cable system [21, 89–91], these will be integrated into our modeling workflow.

The PI has a track record of mentoring post-doctoral researchers, who have gone on to a variety of academic (T. Lee at U. Hawaii, P. Moulik at Columbia, M. Wamba at Uni Bern, Q. Liu and Z. Zhang at IGCAS Beijing, L. Gualtieri at the Euro-Mediterranean Center on Climate Change, D. Borisov at Kansas U., U. bin Waheed at King Fahd U., C. Harig at U. Arizona, E. Kite at U. Chicago, A. Plattner at U. Alabama, K. Lewis at Johns Hopkins, R. Kopp at Rutgers), and industry positions (Y. Yuan, G. Sterenborg, Z. Liu).

Princeton's Geosciences has a vibrant postdoctoral community. Together with the other Geophysics postdocs working with Jeroen Tromp, Allan Rubin, and those in Geology and Mineral Physics, our postdocs form a cordial, collaborative and productively interacting group. We see postdoctoral advising very much as a shared activity. Joint oversight happens in the form of regular (weekly) group and scheduled committee meetings. This, historically, has allowed our small group of postdocs to thrive and continue on to rewarding research and teaching careers. To date, none of our former group members are working outside the fields in which they received advice, professional development, and career mentoring.

7.1 Tomographic Inverse Modeling of Earthquake Waveforms Years 3–4

The Post-Doc will, for the first time ever, integrate MERMAID waveforms into Full-Waveform Inversion, focused on the Atlantic, informed by regional and teleseismic events. They will run sensitivity and resolution tests, and develop methods to quantify the uncertainty in the images obtained. In consultation with Princeton colleague Jeroen Tromp and former Princeton post-doc Ebru Bozdağ, they will harness high-performance computing to conduct the calculations. Former Princeton colleague Jessica Irving and former Princeton graduate student Karin Sigloch will help advise on analysis and model interpretation as "unfunded collaborators" under the collegial model described in Section 6.

7.2 Harnessing of Seismic Ambient Noise Years 2–4

MERMAID is designed to capture distant earthquakes suitable for mantle imaging. Even in the absence of continuous data segments (which can be remotely requested and are completely available upon rare instrument recovery), short triggered segments contain information about noise conditions, see Figure 8. Before the accumulating new earthquake data can add their weight to full-scale tomographic inversions, the Post-Doc will make study of the acoustic noisescape in the ocean. As shown by [14], and see Section 8, what MERMAID records at depth can be predictively related to wind-generated wave-heave, which is the focus of oceanographic models and hindcasting, and of great environmental [92] and societal [53] concern.

7.3 Modeling of Underwater Eruptions Years 2–4

MERMAID has recorded numerous hydroacoustic events that cannot be related to teleseismic earthquakes and hence are presumed to be caused by volcanic activity. In the specific case of the 15 January 2022 Hunga Tonga-Hunga Ha'apai (HTHH) eruption [47, 93–99], targeted buffer requests have yielded an unprecedented data set related to this unique event [100]. Data from the Atlantic MERMAID *Foundation Array* will be mined for signals of underwater volcanic eruptions, which will be studied to reveal their source signatures, and to investigate the interaction of the laterally propagating hydroacoustic wavefield with seafloor bathymetric structure. Our work to date on HTHH [100] has substantiated the hypothesis that the seafloor environment along the propagation path is the main driver of mutual decorrelation and individual signal attenuation when received by MERMAID hydrophones across the ocean basin. Forward and inverse modeling of these records will be conducted in comparison with observations from the International Monitoring System (IMS) and other stations, where available. Both the Graduate Student and the Post-Doc will be involved in this effort.

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Figure 10: *Time-frequency behavior of the hydroacoustics signal of HTHH, recorded by* MERMAID *float P0045. The spectrogram reveals strong and sustained HTHH signal at frequencies up to the 10 Hz Nyquist. Comparing signals recorded by different* MERMAID*s reveals substantial influence from seabed structure.*

7.4 Modeling of Seafloor Structure and Interactions Years 1–3

Records both from teleseismic earthquakes (*P* waves arriving from the deep Earth with steep incidence angles) and from underwater volcanic activity (*T* waves travelling laterally through the ocean layer over long distances) are substantially influenced by the bathymetric structure of the seabed, see Sections 6.2 and 7.3. We will be conducting statistical analyses of seafloor topography under the hypothesis that it contains a random component adequately captured by a Matérn covariance structure [101], and a deterministic one composed of seamounts and fracture zones. Inversions for generalized descriptions of seafloor *roughness*, either at the conversion point from elastic *P* waves into pressure waves underneath the receiving MERMAID, or all along the oceanic travel path in the case of purely hydroacoustic *T* waves, are complicated by the fact that so little of the seafloor has been directly mapped, e.g., using ship-based multibeam sonar [102]. Maximum-likelihood estimation methods that we developed to handle highly irregular sampling scenarios [79] will be adapted to handle directionally anisotropic structure parameters, and the presence of both surface and subsurface topography, mediated by flexural and isostatic compensation processes [80]. Graduate Student and Post-Doc will be involved in this effort, which is not dependent on collecting any new data.

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Figure 11: *Oceanic bathymetry along a portion of the Mid-Atlantic Ridge. Only 34% (*left*) has been directly mapped from shipboard observation, the other 66% is derived from satellite observations (*middle*) to make the composite image (*right*), which confounds statistical analysis.*

8 Science Products and Data Deliverables Years 1–4

Seismic imaging of Earth's mantle constrains present-day dynamics and the secular thermal evolution of our planet. *Smooth* (e.g., tomographically derived from transmitted waves) and *sharp* (e.g., from reflections and phase conversions) wave-speed heterogeneity mapping helps delineate the presence and morphology of subduction zones and mantle plumes [4, 5]. Plumes display variability in size and shape in the mid- to deep-mantle, where high-resolution imaging remains elusive due to a dearth of ocean seismic data. Narrow, seismically slow, conduits from the base of the mantle to the surface are not consistently observed. Plume widths in global tomographic models [7] have been criticized as unrealistically wide. Subduction zones in global models show a range of behaviors, interacting with Earth's layered rheology in a variety of ways, from stagnating and stalling to sinking straight to the bottom of the mantle [103–107]. Impedance contrast maps and wavespeed models suggest reduced mass and heat transfer near 1000 km mantle depths [8]. Despite the use of full wavefields, three-dimensional sensitivity kernels, and data-adaptive parameterizations, high-resolution imaging of this depth range is hampered by the lack of data from the oceans. Radically remedying the situation by deploying floating hydrophones, MERMAIDs, worldwide [11, 39], is the overarching goal of EarthScope-Oceans, and of this proposal. The 50 MERMAIDs deployed in the Pacific [62] introduced "mobile marine seismology" to tomographic mantle imaging beneath Galápagos [41] and Tahiti [12], known to be underlain by a low-velocity feature that may rise through the lower mantle to the transition zone. The Polynesian MERMAIDs are on their last legs. Data collection is winding down, and analysis will soon culminate in the publication of a new tomographic mantle model and its geodynamical interpretation.

With the support of the Moore Foundation, the acquisition and deployment of 33 new MERMAIDs in the Atlantic will open up tremendous opportunity for mantle tomography in this region. Unlike the Pacific, which is surrounded by subduction zones that host deep and large earthquakes [23], and hosts fast-spreading gentle ridges [24], the Atlantic Ocean is largely devoid of active zones with downwelling cold slabs, and the prominent mid-Atlantic ridge is a slow-spreading zone of passive upwelling and crustal production with steep flank topography on either side [108]. The suspected mantle sources of active hot spots [25] and their associated tracks of fossil volcanic islands [26, 27] in this unique geodynamical setting present ample opportunities for seismic imaging—but for the absence of oceanic recording stations.

8.1 Connection to Ideas Circulating About an *AtlanticArray*

A European consortium of scientists has been generating ideas for an ambitious multi-national proposal to form a geophysical *AtlanticArray*. A White Paper has called for an Atlantic-wide *ocean-bottom* seismo-acoustic array complemented by other (e.g., electromagnetic) sensors and new technologies (e.g., cabled sensors [109], cables as sensors [20], and SMART cables [21]). In the ecosystem of geophysical observation from within the oceanic domain, traditional ocean-bottom "stations", whether cabled or not, are *point* sensors; fiber-optic measurement systems are *distributed* acoustic sensors; and SMART cables occupy a niche in-between. What none of those proven or promising technologies do, however, is *move around*, as time goes by, continuously illuminating new corridors sampled by seismic waves propagating from various earthquake zones to new "station" locations (which are no longer "stationary", hence the name "mobile marine sensors" for MERMAID-like devices, and the need for innovative software and data products).

Despite all enthusiasm and momentum, *AtlanticArray* is a few years from becoming a reality. Hence the importance and timeliness of this proposal: the mobile Atlantic MERMAID *Foundation Array* will form an indispensable foundation and scientific backbone for any future endeavors that are planning to involve ocean-bottom stations. Before any of those future installations will have returned any data, our 33 new instruments will collect and report thousands of paths from many hundreds of earthquakes. Purchasing and deploying the two BOBS units supported by this proposal will aid with data intercomparison between mid-column floating hydrophones and ground-coupled seismometers when they become available.

8.2 Data Collection and Quality Analysis

Central to MERMAID's fleet management is `automaid` (find it on `GitHub` at `earthscopeoceans`), a suite of `Python` tools that interfaces with satellite communications, parses `log` and `bin` (systems messages) and `vit` (state-of-health indicators) files, and extracts compressed `mer` files (wavelet-transform coefficients that reorder the time series in a lossless time-scale multiresolution representation) containing the **acoustic** (time series, spectral densities) and **hydrographic** (CTD profiles) **data**. Our team will work with OSEAN and partner institutions to continually update the development version and merge and integrate it with the public track. In particular, we will affirm that data acquisition locations are properly computed [43], and that the software reports `mseed` files that are fully compliant with the international FDSN standards.

Accurate sensor *location* and precise *timing* are vital for seismic tomography, which relies on measuring seismic wave *speeds* and their model deviations to address the distribution and cycling of critical elements in the Earth, and discovering the deep mantle drivers of surface volcanism. Hence, `automaid` performs location interpolations such that seismic waveforms can be assigned to the right acquisition positions [110]. It handles clock drift corrections using GPS time stamps (and packages them into FDSN-compliant `mseed` files, which requires sustained development). This is an active space for further innovation. MERMAID location errors arising from non-constant bathyal drift velocity and path curvature effects [42] map differently into timing inaccuracies depending on whether the ascent immediately follows the triggering event ($\sim$0.028 s) or not ($\sim$0.042–0.214 s). For global tomography, location errors have no significant impact on the accuracy of picked arrival times from teleseismic earthquakes (steeply dipping phases, extended source domains). Further study is required, both from an oceanographic (marine current distributions, mesoscale temperature fluctuations) and seismological (regional events) perspective, as we have reported [43].

Our team will support the continual **software hardening and improvement** of all important systems operations for the incoming data stream, making further enhancements especially with respect to time-correction management and the location-interpolation scheme in the dynamic ocean environment.

8.3 Trajectories and Other Metadata, and State-Of-Health Messages

MERMAID is a floating array: no two seismograms are acquired in the same place. We accommodate this novel data type in a new format (`GeoCSV`) that can be efficiently queried by the seismological community. FDSN will adopt it as a standard on par with `miniSEED` and `StationXML`. The primary metadata, bathyal trajectories, are of great utility for physical oceanographers also. MERMAID tracks ocean currents at its cruising depth (above 2,000 m for MERMAID-III, 4,000 m for MERMAID-IV, and 6,000 m for the latest models), see Figure 12. Float trajectories and other **metadata** are openly accessible via the ESO website, containing GPS time, position and precision, battery and voltage levels, internal and external pressure,

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Figure 12: *Three years of the trajectory of* MERMAID *P0016, with the interpolated locations of earthquake arrival detections (crosses), overlain on a model of oceanic bathymetry. The third and fourth-generation* MERMAID *models are only aware of their parking* depth. *Future floats with EarthScope-Oceans may have the added capability of actively measuring* ocean *depth, i.e., bathymetry.*

commands received, files queued, and uploaded. These are displayed by the *Adopt-a-Float* iOS app for education and outreach [111]. We support the day-to-day monitoring of these files for navigational indicators and to flag any instrument problems that require intervention. Mission-parameter updates can be passed on at every available surfacing. Recent requests from WHOI and Caltech necessitated adjusting MERMAID's diving depth to maximize the recovery of ocean-temperature-sensitive hydroacoustic *T* phases. Requests by JAMSTEC, Géoazur, and UCSB, have targeted underwater eruptions. Metadata `GeoCSV` files containing *all* GPS time and location fixes are a new data product that lists all timing corrections applied. The packaging of these files and their delivery to NGF data centers will enable the community to check our location interpolations, or perform their own, for whichever seismological or oceanographic purpose they see fit.

8.4 Short Triggered and Requested Waveforms, and Their Metadata

Third- and fourth-generation MERMAIDs perform continuous onboard processing to prioritize the recovery of *teleseismic* waveform data suitable for global seismic tomography (see Figure 13). The primary data are seismic waveforms. Probabilistic scoring [64] of every detection allows "false triggers" to be identified, with surfacings designed to transmit highly promising arrivals, including runners-up. While domain-specific scientific analysis happens downstream by science teams at the partner institutions, including by the Graduate Student and the Post-Doc, the Contractor will ensure that every automatically retrieved waveform (based on `mer` files of the so-called `det` type) will be delivered to the NGF data centers for public access. The baseload task is data conversion to the FDSN `miniSEED` data standard, replete with instrument response information. Outside researchers will then be able to request these files from the NGF data centers. Every `mseed` file will be paired with an additional metadata file listing instrument parameters necessary for seismological data analysis—not all such parameters fit into the `miniSEED` standard. It is the very special nature of the movable MERMAID array that every seismogram requires its own "response" file, if only because the station *location* is an ever-evolving *position* (which is desirable for seismic tomography). Metadata include trigger settings, quality scores, frequency information, etc. After ironing out formatting issues, the team will implement the workflow and provide **continuous review** of all incoming and outgoing data.

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Figure 13: *Waveforms transmitted by all 16 Princeton members of the MERMAID array, many of which still report from the South Pacific after more than 5 years. Traces from nearby island stations are in gray. Travel-time predictions made in the `ak135` reference model.*

Accommodating **user requests** is an important objective. MERMAIDs have a one-year rolling buffer available for query. Data segments require handling and packaging for delivery to the NGF data centers. We will work with a Caltech and WHOI group to recover tertiary, or *T* phases, which hold the key to determining mesoscale ocean temperature variations (in-between ARGO profiles) [48]. Researchers from JAMSTEC are now targeting the sounds of the 2023 Ioto eruption. Studying volcanic eruptions, e.g., 2022 Hunga Tonga, which 24 MERMAIDs recorded in great detail [100, 112], has become a unique activity for mobile marine seismology, in line with *Earth in Time* (2020) questions on geohazard risk and toll reduction. Among the questions that increased azimuthal coverage helps resolve are the directionality of energy input, bathymetric influence, the detailed pulsed sequence of volcanic events [113–115], and the location of unidentified sources.

8.5 Long Time Series, Recovered Records, and Buffer Requests

MERMAID enables near-real-time (days) data acquisition over a (proven) five-year period without costly recovery cruises, except under exceptional circumstances. These include possible end-of-life recovery (a "dead" float is buoyant, its GPS broadcasting while the Lithium batteries last). In 2019 we accomplished the recovery and redeployment of Princeton float P0023, aided by a team of undergraduate interns who developed prediction algorithms to target the recovery from a ship of opportunity. In June 2025 a float was picked up by a fisherman in Fiji—after its batteries were nearly depleted, it went into low-power recovery mode and continued emitting surface locations, enabling its recovery. Future opportunities will be seized.

The exceptional recovery of P0023 [13] provided insight into what MERMAID *hears* beyond what it automatically *reports*. Figure 14 shows a spectrogram of a global earthquake. The details of the *P* wave arrival are not visible at this scale, but later-arriving phases, including *S* conversions, surface-wave wavetrains, and *T* phases, are visible in the frequency bands below 0.1 Hz and above 1 Hz, respectively. Such longer waveform records show significant promise for seismological analysis beyond traditional tomography. Complexities from source-side structure, source-time-functions, and propagation effects will be a treasure trove for community analysis. Researchers who operate ocean-bottom seismometer (OBS) arrays cross-check their records with ours, and we will respond to their requests (see *Letters of Collaboration*). We will deposit long waveforms with the NGF data centers, and endeavor to acquire more such records, as our earliest-deployed Pacific floats become inactive and might be captured and repurposed for the Atlantic.

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Figure 14: *Spectrogram of the* MERMAID *record of the M7.5 Peru-Ecuador 2019 earthquake. Seismic* P, S *and* T *waves are visible against a background of microseismic noise whose temporal fluctuations are of independent scientific utility, matching wave-based oceanographic retrodictions [13]. These will continue to be actively studied for the Atlantic data set acquired with Foundation support.*

8.6 Signal and Noise Spectral Densities from Serendipitously Recovered Floats

Fig. 14 reveals the acoustic frequency band in-between 0.1 and 1 Hz to be rather noisy. The retrieval of the one-year P0023 buffer allowed us to understand its nature in detail. Fig. 15 shows two of the twelve available months of noise power-spectral densities [13], after removal of all reported events, unreported events matched in post-processing, suspected intervals containing ship noise, and various other transients that are not part of the "normal" oceanic environment. By design, MERMAID's sensitivity is cut off beyond 10 Hz, and the instrument transfer function rolls off below about 0.05 Hz [12]. After removing all earthquakes and volcanic transients [46], the ocean-wave-generated infrasound noise can become the signal of interest, as shown in Figure 15. We will explore analyzing noise segments even on triggered records from the Atlantic.

Nature provides us with natural experiments: the oceans drive these intervals of acoustic spectral power and their temporal variations [116]. High correlation ($\leq$0.845 [13]) is observed between ocean-wave forcing derived from the [55] ocean model at 0.21–0.23 Hz, and acoustic noise recorded by MERMAID between 0.36–0.38 Hz. The well-known double-frequency mechanism of microseismic noise generation [65–67, 117] is observed by MERMAID *in situ*, making it, effectively, an *environmental* sensor.

When MERMAID floats are recovered in the future, we will work with relevant authorities to repatriate it and recover the memory card data. Our team will analyze and make available their full buffer.

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Figure 15: *Oceanic "noise" spectra recorded by exceptionally* recovered MERMAID *P0023. Red curves show median behavior. White curves demarcate the* 5^{th} *and* 95^{th} *percentiles. Earthquakes are clearly seen between 0.05–0.10 Hz. T phases are observed between 2–10 Hz. "Signal" is the percentage of the buffer that contained signal* removed *prior to spectral density computation.*

8.7 Direct Spectral Recovery

Figures 14–15 shows unanticipated "bycatch" of MERMAID (designed for short segments of *P* waves, as in Figure 13). [13] showed the rich information obtainable from spectral-density data products from our records. Their analysis will benefit our understanding of earthquake detection thresholds, and has potential for revealing atmosphere-ocean-surface-water-column-solid-earth interactions [118–125]. Ambient noise is of interest in the community, both for what it tells us about the meteorological environment [126] and for its potential in Earth imaging in the absence of impulsive (earthquake) sources [127, 128], where an understanding of source homogeneity, directionality, and seasonality is of substantial importance.

The *seven* MERMAIDs (deployed 2021) whose data stream we monitor and manage as part of ongoing operations (with Lucia Gualtieri, see *Letter of Collaboration*) were a new model type (see Section 5), equipped with lower-frequency sensitive hydrophones (compared to the original MERMAID-III which optimized teleseismic earthquake recovery), and re-engineered to report spectral densities directly, at regular intervals, to enable just this kind of study. Our team will review, quality-control, package, and guide these data into the NGF data centers, and publish our analyses in the peer-reviewed scientific literature.

8.8 Earthquake Association: *Value-Added* Metadata

A MERMAID waveform is a time series of acoustic pressure. Georeferenced and accurately timed by our team—but initially without awareness of what *seismic* event triggered instrument ascent. To render triggered sections *seismologically* useful, they need to be matched to an earthquake—hence the important task of catalog matching. The method published by [62] accomplishes this procedure. To date, nearly 4,000 earthquakes have been matched to some 40,000 waveforms transmitted by over 70 MERMAIDs, see Figure 16. Work on the Polynesian floats will soon be completed, in time for the new data stream from the newly purchased and deployed Atlantic MERMAID *Foundation Array* over the course of the next four years.

Every triggered waveform already comes tagged with statistical information about exactly what flagged it, and a probabilistic score of the likelihood that the record indeed contains a *teleseismic* earthquake phase, derived from wavelet analysis [64, 129]. Value-added metadata result from running our probabilistic multiscale onset determination software (available on `GitHub` at `joelsimon/omnia`), which delivers seismic measurements of delay times and their uncertainties, resulting in MERMAID catalog entries [62]. Figure 17 shows waveform onsets [12], used to obtain travel-time residuals and uncertainty estimates referenced to water-layer-adjusted `ak135` models, and with the red vertical line our "pick"—see [43] for more analysis.

Earthquake catalog matching constitutes the data wrangling that critically precedes the geophysical analysis carried out by us and our partner institutions for domain-specific analysis (mantle travel-time tomography, first and foremost). We are collaborating with the International Seismological Centre (ISC), see *Letter of Collaboration*, for it to become the final hosting body for our catalogs of earthquake associations and phase matches (see Section 8.9) that accompany our waveform records already hosted within SAGE/GAGE,

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Figure 16: *The current catalog of* associated *events. Princeton and Géoazur waveforms are now available from the EarthScope Data Management Center. All Chinese, Japanese data are to follow by the end of Spring 2025. Brazilian data (also from the Atlantic) will be added as they become available. Ray-theoretical travel-time residuals are computed for tomographic imaging, a cumulative data product for the Atlantic experiment of this proposal.*

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Figure 17: *Travel-time residuals of first-arriving compressive P waves. Seismograms (filtered to 1–5 Hz) show detail in a 30 s window aligned on the theoretical first-arriving phase in* `ak135` *models adjusted for bathymetry and* MERMAID *cruising depth [12], with uncertainties estimated via the AIC-based method developed in-house [62].*

later the NGF. These data have formed and will form the basis of research projects by interested groups worldwide. Our team will help evaluate the contribution of MERMAID data to ISC's location results.

8.9 Phase Matching and *Validation* Through Terrestrial Network Analysis

The geographical extent spanned by the Pacific MERMAIDs comprised all of 6.5% of Earth's surface. International data centers list just 19 island seismometers with data at time of deployment, of which five are Raspberry Shakes [130–132]. Six short-period seismometers in the Réseau Sismique Polynésien do not report to any data center [133–136]. The situation in the Atlantic is comparatively even more striking, as virtually no data suitable for mantle tomography are available in the public domain.

The distribution of MERMAID *P*-wave residuals in Figure 18b agrees well with that from traditional seismometers in Figure 18a, and to a lesser extent with Raspberry Shake stations in Figure 18c. All are positively biased: on average, the *P* wave was *late* compared to the `ak135` prediction. The standard deviation of MERMAID residuals is smaller than for the other two instrument classes, demonstrating that MERMAID data are indeed useful for seismic tomography [12]. Our team will sustain (and innovate, see Section 6) the **seismological analysis** and validation of the incoming data from the Atlantic. Inasmuch as they are not already available, we deposit any data used for comparative analysis with the NGF data centers also.

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Figure 18: *P-wave travel-time residuals from traditional (green),* MERMAID *(blue), and Raspberry Shakes (red).* MERMAID *data match land stations, uncertainties and SNR are comparable to Shakes.*

9 Timeline, Milestones, and Risk Assessment

Approximate timings have been integrated throughout this document. The big-ticket items in Years 1–2 are the ordering, manufacturing, and delivery of MERMAID instruments (see Section 2). Information obtained from the manufacturer indicates that we should be able to take delivery of a first batch well within Year 1, which means that planning their deployment from ships of opportunity (see Section 3) will commence as soon as funding is received. In that first year, the PI and the Contractor(s) will spin up the *EarthScope-Oceans Data Collection (and Quality Assurance) Center*. Currently operational for floats worldwide, they will handle the tail end of the Pacific and Mediterranean deployments, while working with our Brazilian partners to get their already ordered and delivered floats deployed and tracked in the Atlantic. The Graduate Student will familiarize themselves with the intricacies of waveform simulations, first in 2-D (Section 6.1), and from Year 2, in 3-D (Section 6.2). In case of a delay with hardware, there will be no shortage in digital scientific deliverables related to existing instruments and the planned Brazilian launch. By Year 2, all but the BOBS-type MERMAID floats should have been delivered, and most of them deployed, while the two BOBS are expected to be ordered and deployed shortly thereafter, at the latest in Year 3. During all of these project years, the Contractor(s) will be designing, building, and maintaining software tools to handle diverse data types, and engaging with community and consortium partners, including possible and hoped-for new additions to EarthScope-Oceans (Section 1.2). In-between and concurrently with new instrument deployments, the Post-Doc, starting in Year 2, together with the Graduate Student, will engage in the projects outlined in Sections 7.1–7.4. Throughout Years 1–4, team members will divide their time in supporting the science and data deliverables outlined in Section 8. Significant structural models for the Atlantic are to be expected by Year 4, ultimately depending on array configuration and earthquake availability. We expect at least one peer-reviewed publication in each project year to acknowledge support from the Moore Foundation.

10 Key Personnel

Frederik J. Simons is a Professor of Geophysicsat Princeton University. Simons is interested in the seismic, mechanical, thermal, and magnetic properties of the Earth's lithosphere and of the terrestrial planets and moons. He designs theoretical and computational inverse methods, tomographic, and statistical techniques to analyze complex, large, and heterogeneous geophysical data sets for seismology, space-based, and terrestrial geodesy. He has furthered the design of mid-column floating hydrophones to open up the sparsely instrumented oceanic domains for global tomography and environmental sensing, and of deep-ocean instrumentation to conduct long-term seafloor geodesy. He received the Vladimir Keilis-Borok Medal for Mathematical Geophysics from the IUGG, served as a Distinguished Lecturer for the Seismological Society of America and the IRIS Consortium, received a National Science Foundation CAREER Award, and the quadrennial Charles Lagrange Prize from the Royal Belgian Academy. Simons received an M.Sc. in geology from KU Leuven, Belgium and a Ph.D. in geophysics from the Massachusetts Institute of Technology.

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References

[1] P. Moulik, G. Ekström, Radial structure of the earth: (I) Model concepts and data, Phys. Earth Planet. Inter. (2025) 107319, doi: 10.1016/j.pepi.2025.107319.

[2] P. Moulik, G. Ekström, Radial structure of the earth: (II) model features and interpretations, Phys. Earth Planet. Inter. (2025) 107320, doi: 10.1016/j.pepi.2025.107320.

[3] B. Romanowicz, Global seismic tomography using time domain waveform inversion, in: A. Ismail-Zadeh, F. Castelli, D. Jones, S. Sanchez (Eds.), Applications of Data Assimilation and Inverse Problems in the Earth Sciences, Special Publications of the International Union of Geodesy and Geophysics, Cambridge Univ. Press, Cambridge, UK, 2023, pp. 220—238, doi: 10.1017/9781009180412.015.

[4] J. Tromp, Seismic wavefield imaging of Earth's interior across scales, Nat. Rev. Earth Env. 1 (2020) 40–53, doi: 10.1038/s43017–019–0003–8.

[5] A. Fichtner, B. L. N. Kennett, V. C. Tsai, C. H. Thurber, A. J. Rodgers, C. Tape, N. Rawlinson, R. D. Borcherdt, S. Lebedev, K. Priestley, C. Morency, E. Bozdağ, J. Tromp, J. Ritsema, B. Romanowicz, Q. Liu, E. Golos, F.-C. Lin, Seismic tomography 2024, B. Seismol. Soc. Am. 114 (3) (2024) 1185–1213, doi: 10.1785/0120230229.

[6] B. Romanowicz, D. Giardini, The future of permanent seismic networks, Science 293 (5537) (2001) 2000–2001, doi: 10.1126/science.1061771.

[7] M. D. Wamba, F. J. Simons, J. C. E. Irving, Data-space cross-validation of global tomographic models to assess mantle structure underneath the Pacific Ocean, Geophys. J. Int. 241 (2025) 241–259, doi: 10.1093/gji/ggaf044.

[8] Z. Zhang, J. C. E. Irving, F. J. Simons, T. Alkhalifah, Seismic evidence for a 1000 km mantle discontinuity under the Pacific, Nat. Commun. 14 (2023) 1714, doi: 10.1038/s41467–023–37067–x.

[9] R. Cabieces, K. Harris, A. M. G. Ferreira, M. Tsekhmistrenko, S. P. Hicks, F. Krüger, W. H. Geissler, K. Hannemann, M. C. Schmidt-Aursch, Clock drift corrections for large aperture ocean bottom seismometer arrays: application to the UPFLOW array in the mid-Atlantic Ocean, Geophys. J. Int. 239 (3) (2024) 1709–1728, doi: 10.1093/gji/ggae354.

[10] G. Ekström, M. Nettles, A. M. Dziewonski, The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes, Phys. Earth Planet. Inter. 200–201 (2012) 1–9, doi: 10.1016/j.pepi.2012.04.002.

[11] F. J. Simons, J. D. Simon, S. Pipatprathanporn, Twenty-thousand leagues under the sea: Recording earthquakes with autonomous floats, Acoustics Today 17 (2) (2021) 42–51, doi: 10.1121/AT.2021.17.2.42.

[12] J. D. Simon, F. J. Simons, J. C. E. Irving, Recording earthquakes for tomographic imaging of the mantle beneath the South Pacific by autonomous MERMAID floats, Geophys. J. Int. 228 (1) (2022) 147–170, doi: 10.1093/gji/ggab271.

[13] S. Pipatprathanporn, F. J. Simons, One year of sound recorded by a MERMAID float in the Pacific: hydroacoustic earthquake signals and infrasonic ambient noise, Geophys. J. Int. 228 (1) (2022) 193–212, doi: 10.1093/gji/ggab296.

[14] S. Pipatprathanporn, F. J. Simons, Waveform modeling of hydroacoustic teleseismic earthquake records from autonomous MERMAID floats, Geophys. J. Int. 239 (1) (2024) 136–154, doi: 10.1093/gji/ggae238.

[15] J. A. Collins, F. L. Vernon, J. A. Orcutt, R. A. Stephen, K. R. Peal, F. B. Wooding, F. N. Spiess, J. A. Hildebrand, Broadband seismology in the oceans: Lessons from the Ocean Seismic Network Pilot Experiment, Geophys. Res. Lett. 28 (1) (2001) 49–52, doi: 10.1029/2000GL011638.

[16] H. Kawakatsu, G. Ekström, R. Evans, D. Forsyth, J. Gaherty, B. Kennett, J.-P. Montagner, , H. Utada, Pacific Array (Transportable Broadband Ocean Floor Array), Geophys. Res. Abstr. 18 (2016) EGU2016–2514.

[17] D. R. Bohnenstiehl, M. Tolstoy, R. P. Dziak, C. G. Fox, D. K. Smith, Aftershock sequences in the mid-ocean ridge environment: an analysis using hydroacoustic data, Tectonophysics 354 (2002) 49–70, doi: 10.1016/S0040–1951(02)00289–5.

[18] R. P. Dziak, D. R. Bohnenstiehl, H. Matsumoto, C. G. Fox, D. K. Smith, M. Tolstoy, T.-K. Lau, J. H. Haxel, M. J. Fowler, *P*- and *T*-wave detection thresholds, *Pn* velocity estimate, and detection of lower mantle and core *P*-waves on ocean sound-channel hydrophones at the Mid-Atlantic Ridge, B. Seismol. Soc. Am. 94 (2) (2004) 665–677, doi: 10.1785/0120030156.

[19] A. Sladen, D. Rivet, J. P. Ampuero, L. D. Barros, Y. Hello, G. Calbris, P. Lamare, Distributed sensing of earthquakes and ocean-solid Earth interactions on seafloor telecom cables, Nat. Commun. 10 (2019) 5777, doi: 10.1038/s41467–019–13793–z.

[20] E. F. Williams, M. R. Fernández-Ruiz, R. Magalhaes, R. Vanthillo, Z. Zhan, M. González-Herráez, H. F. Martins, Distributed sensing of microseisms and teleseisms with submarine dark fibers, Nat. Commun. 10 (2019) 5778, doi: 10.1038/s41467–019–13262–7.

[21] B. M. Howe, M. Angove, J. Aucan, C. R. Barnes, J. S. Barros, N. Bayliff, N. C. Becker, F. Carrilho, M. J. Fouch, B. Fry, A. Jamelot, H. Janiszewski, L. S. L. Kong, S. Lentz, D. S. Luther, G. Marinaro, L. M. Matias, C. A. Rowe, A. E. Sakya, A. Salaree, T. Thiele, F. J. Tilmann, C. von Hillebrandt-Andrade, L. Wallace, S. Weinstein, W. Wilcock, SMART subsea cables for observing the earth and ocean, mitigating environmental hazards, and supporting the blue economy, Front. Earth Sci. 9 (2022) 775544, doi: 10.3389/feart.2021.775544.

[22] A. P. S. Wong, S. E. Wijffels, S. C. Riser, S. Pouliquen, S. Hosoda, D. Roemmich, J. Gilson, G. C. Johnson, K. Martini, D. J. Murphy, et al., Argo data 1999–2019: Two million temperature-salinity profiles and subsurface velocity observations from a global array of profiling floats, Front. Mar. Sci. (2020) 700, doi: 10.3389/fmars.2020.00700.

[23] B. D. Rinard Hinga, Ring of Fire: An Encyclopedia of the Pacific Rim's earthquakes, tsunamis, and volcanoes, ABC-CLIO, Santa Barbara, Calif., 2015.
[24] D. W. Forsyth, the MELT Seismic Team, Imaging the deep seismic structure beneath a mid-ocean ridge: The MELT experiment, Science 280 (5367) (1998) 1215–1218, doi: 10.1126/science.280.5367.1215.
[25] R. Montelli, G. Nolet, F. A. Dahlen, G. Masters, E. R. Engdahl, S.-H. Hung, Finite-frequency tomography reveals a variety of plumes in the mantle, Science 303 (5656) (2004) 338–343, doi: 10.1126/science.1092485.
[26] A. Burky, J. C. E. Irving, F. J. Simons, Mantle transition zone receiver functions for Bermuda: Automation, quality control, and interpretation, J. Geophys. Res. 126 (3) (2021) e2020JB020177, doi: 10.1029/2020JB020177.
[27] A. Burky, J. C. E. Irving, F. J. Simons, The mantle transition zone beneath eastern North America: Receiver functions and tomographic velocity models, Phys. Earth Planet. Inter. 340 (2023) 107035, doi: 10.1016/j.pepi.2023.107035.
[28] W. J. Morgan, Convection plumes in the lower mantle, Nature 230 (5288) (1971) 42–43, doi: 10.1038/230042a0.
[29] R. Montelli, G. Nolet, F. A. Dahlen, G. Masters, A catalogue of deep mantle plumes: New results from finite-frequency tomography, Geochem. Geophys. Geosys. 7 (11) (2006) Q11007, doi: 10.1029/2006GC001248.
[30] J. Austermann, B. T. Kaye, J. X. Mitrovica, A statistical analysis of the correlation between large igneous provinces and lower mantle seismic structure, Geophys. J. Int. 197 (1) (2014) 1–9, doi: 10.1093/gji/ggt500.
[31] V. Lekić, S. Cottaar, A. Dziewonski, B. Romanowicz, Cluster analysis of global lower mantle tomography: A new class of structure and implications for chemical heterogeneity, Earth Planet. Sci. Lett. 357–358 (2012) 68–77, doi:10.1016/j.epsl.2012.09.014.
[32] K. Hosseini, K. J. Matthews, K. Sigloch, G. E. Shephard, M. Domeier, M. Tsekhmistrenko, SubMachine: Web-based tools for exploring seismic tomography and other models of Earth's deep interior, Geochem. Geophys. Geosys. 19 (5) (2018) 1464–1483, doi: 10.1029/2018GC007431.
[33] S. W. French, B. Romanowicz, Broad plumes rooted at the base of the Earth's mantle beneath major hotspots, Nature 525 (2015) 95–99, doi: 10.1038/nature14876.
[34] J. Ritsema, A. A. Deuss, H. J. van Heijst, J. H. Woodhouse, S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime and normal-mode splitting function measurements, Geophys. J. Int. 184 (2011) 1223–1236, doi: 10.1111/j.1365–246X.2010.04884.x.
[35] C. Lu, S. P. Grand, H. Lai, E. J. Garnero, TX2019slab: A new *P* and *S* tomography model incorporating subducting slabs, J. Geophys. Res. 124 (11) (2019) 11549–11567, doi: 10.1029/2019JB017448.
[36] F. J. Simons, G. Nolet, J. M. Babcock, R. E. Davis, J. A. Orcutt, A future for drifting seismic networks, Eos Trans. AGU 87 (31) (2006) 305 & 307, doi: 10.1029/2006EO310002.
[37] Y. Hello, A. Ogé, A. Sukhovich, G. Nolet, Modern mermaids: New floats image the deep Earth, Eos Trans. AGU 92 (40) (2011) 337–338, doi: 10.1029/2011EO400001.
[38] Y. Hello, G. Nolet, Floating seismographs (MERMAIDS), in: H. K. Gupta (Ed.), Encyclopedia of Solid Earth Geophysics, Encyclopedia of Earth Sciences, Springer, New York, 2020, pp. 1–6, doi: 10.1007/978–3–030–10475–7_248–1.
[39] F. J. Simons, G. Nolet, P. Georgief, J. M. Babcock, L. A. Regier, R. E. Davis, On the potential of recording earthquakes for global seismic tomography by low-cost autonomous instruments in the oceans, J. Geophys. Res. 114 (2009) B05307, doi: 10.1029/2008JB006088.
[40] A. Sukhovich, S. Bonnieux, Y. Hello, J.-O. Irisson, F. J. Simons, G. Nolet, Seismic monitoring in the oceans by autonomous floats, Nat. Commun. 6 (2015) 8027, doi: 10.1038/ncomms9027.
[41] G. Nolet, Y. Hello, S. van der Lee, S. Bonnieux, M. C. Ruiz, N. A. Pazmino, A. Deschamps, M. M. Regnier, Y. Font, Y. J. Chen, F. J. Simons, Imaging the Galápagos mantle plume with an unconventional application of floating seismometers, Sci. Rep. 9 (2019) 1326, doi: 10.1038/s41598–018–36835–w.
[42] G. Nolet, J. D. Simon, S. Bonnieux, How accurately are MERMAID seismograms located?, Seismol. Res. Lett. 95 (4) (2024) 2368–2374, doi: 10.1785/0220230377.
[43] G. Nolet, B.-H. Nguyen, S. Bonnieux, Y. Kondo, F. Kong, M. Obayashi, S. Pipatprathanporn, K. Sigloch, J. D.Simon, F. J. Simons, H. Sugioka, J. Yoshimitsu, Q. Zhang, Picking first arrivals in hydroacoustic seismograms from MERMAID floats, Seismica 4 (1) (2025) doi: 10.26443/seismica.v4i1.1505.
[44] J. D. Simon, F. J. Simons, J. C. E. Irving, A MERMAID miscellany: Seismoacoustic signals beyond the *P* wave, Seismol. Res. Lett. 92 (6) (2021) 3657–3667, doi: 10.1785/0220210052.
[45] G. Tepp, W. W. Chadwick Jr., M. M. Haney, J. J. Lyons, R. P. Dziak, S. G. Merle, D. A. Butterfield, C. W. Young III, Hydroacoustic, seismic, and bathymetric observations of the 2014 submarine eruption at Ahyi seamount, Mariana Arc, Geochem. Geophys. Geosys. 20 (2019) 3608–3627, doi: 10.1029/2019GC008311.
[46] G. Tepp, R. P. Dziak, The seismo-acoustics of submarine volcanic eruptions, J. Geophys. Res. 126 (4) (2021) e20912, doi: 10.1029/2020JB020912.
[47] R. S. Matoza, D. Fee, J. D. Assink, A. M. Iezzi, D. N. Green, K. Kim, L. Toney, T. Lecocq, S. Krishnamoorthy, J.-M. Lalande, K. Nishida, K. L. Gee, M. M. Haney, H. D. Ortiz, Q. Brissaud, L. Martire, L. Rolland, P. Vergados, A. Nippress, J. Park, S. Shani-Kadmiel, A. Witsil, S. Arrowsmith, C. Caudron, S. Watada, A. B. Perttu, B. Taisne, P. Mialle, A. L. Pichon, J. V. adn Patrick Hupe, P. S. Blom, R. Waxler, S. D. Angelis, J. B. Snively, A. T. Ringler, R. E. Anthony, A. D. Jolly, G. Kilgour, G. Averbuch, M. Ripepe, M. Ichihara, A. Arciniega-Ceballos, E. Astafyeva, L. Ceranna, S. Cevuard, I.-Y. C.

R. D. Negri, C. W. Ebeling, L. G. Evers, L. E. Franco-Marin, T. B. Gabrielson, K. Hafner, R. G. Harrison, A. Komjathy, G. Lacanna, J. Lyons, K. A. Macpherson, E. Marchetti, K. F. McKee, R. J. Mellors, G. Mendo-Pérez, T. D. Mikesell, E. Munaibari, M. Oyola-Merced, I. Park, C. Pilger, C. Ramos, M. C. Ruiz, R. Sabatini, H. F. Schwaiger, D. Tailpied, C. Talmadge, J. Vidot, J. Webster, D. C. Wilson, Atmospheric waves and global seismoacoustic observations of the January 2022 Hunga eruption, Tonga, Science 377 (6601) (2022) 95–100, doi: 10.1126/science.abo7063.

[48] H. L. L. Ervik, J. D. Simon, F. J. Simons, W. Wu, J. Callies, Harnessing earthquake-generated sound waves for ocean thermometry with autonomous floats, Presented at 2024 Ocean Sciences Meeting Session OT001, New Orleans, LA, Feb. .

[49] W. Wu, Z. Zhan, S. Peng, S. Ni, J. Callies, Seismic ocean thermometry, Science 369 (6510) (2020) 1510–1515, doi: 10.1126/science.abb9519.

[50] R. Bürgmann, D. Chadwell, Seafloor geodesy, Annu. Rev. Earth Pl. Sc. 42 (2014) 509–534, doi: 10.1146/annurev–earth–060313–054953.

[51] N. V. Zilberman, V. Thierry, B. King, M. Alford, X. André, K. Balem, N. Briggs, Z. Chen, C. Cabanes, L. Coppola, G. Dall'Olmo, D. Desbruyères, D. Fernandez, A. Foppert, wilford Gardner, F. Gasparin, B. Hally, S. Hosoda, G. C. Johnson, T. Kobayashi, A. Le Boyer, W. Llovel, P. Oke, S. Purkey, E. Remy, D. Roemmich, M. Scanderbeg, P. Sutton, K. Walicka, L. Wallaced, E. M. van Wijk, Observing the full ocean volume using Deep Argo floats, Front. Mar. Sci. 10 (2023) 1287867, doi: 10.3389/fmars.2023.1287867.

[52] S. Bonnieux, D. Cazau, S. Mosser, M. Blay-Fornarino, Y. Hello, G. Nolet, MeLa: A programming language for a new multidisciplinary oceanographic float, Sensors 20 (21) (2020) 6081, doi: 10.3390/s20216081.

[53] P. Tyack, T. Akamatsu, O. Boebel, L. Chapuis, D. Elisabeth, C. de Jong, C. Erbe, K. Evans, J. Gedamke, T. Gridley, G. Haralabus, R. Jenkins, J. Miksis-Olds, H. Sagen, T. Frank, K. Thomisch, E. Urban, Ocean sound essential ocean variable implementation plan, Tech. rep., Partnership for Observation of the Global Ocean (POGO) (2023).

[54] E. Stokstad, These ocean floats can hear earthquakes, revealing mysterious structures deep inside earth, Science 364 (6437) (2019) 218–219, doi: 10.1126/science.aax7339.

[55] WAVEWATCH III, User manual and system documentation of WAVEWATCH III(R) version 6.07, Tech. Rep. 333, Environmental Modeling Center, Marine Modeling and Analysis Branch (2019).

[56] H. P. Crotwell, T. J. Owens, J. Ritsema, The TauP Toolkit: Flexible seismic travel-time and ray-path utilities, Seismol. Res. Lett. 70 (2) (1999) 154–160, doi: 10.1785/gssrl.70.2.154.

[57] M. van Driel, L. Krischer, S. C. Stähler, K. Hosseini, T. Nissen-Meyer, Instaseis: instant gloabl seismograms based on a broadband waveform database, Solid Earth 6 (2) (2015) 701–717, doi: 10.5194/se–6–701–2015.

[58] D. Komatitsch, J. P. Vilotte, The spectral element method: An efficient tool to simulate the seismic response of 2D and 3D geological structures, B. Seismol. Soc. Am. 88 (2) (1998) 368–392, doi: 10.1785/BSSA0880020368.

[59] D. Komatitsch, C. Barnes, J. Tromp, Wave propagation near a fluid-solid interface: A spectral-element approach, Geophysics 65 (2) (2000) 623–631, doi: 10.1190/1.1444758.

[60] P. Tong, C. Chen, D. Komatitsch, P. Basini, Q. Liu, High-resolution seismic array imaging based on an SEM-FK hybrid method, Geophys. J. Int. 197 (1) (2014) 369–395, doi: 10.1093/gji/ggt508.

[61] GEBCO Bathymetric Compilation Group, The GEBCO_2019 grid—A continuous terrain model of the global oceans and land, Tech. rep., British Oceanographic Data Centre, National Oceanography Centre, NERC (2019).

[62] J. D. Simon, F. J. Simons, G. Nolet, Multiscale estimation of event arrival times and their uncertainties in hydroacoustic records from autonomous oceanic floats, B. Seismol. Soc. Am. 110 (3) (2020) 970–997, doi: 10.1785/0120190173.

[63] D. Namjesnik, K. Sigloch, S. Bonnieux, Y. Hello, D. Storchak, F. J. Simons, J. D. Simon, J. Harris, T. Garth, Locating earthquakes recorded by mermaids, independent divers floating in the ocean, Presented at the EPOS SP / ORFEUS Adria Array Worksop in Dubrovnik, Croatia, 3–5 April .

[64] A. Sukhovich, J.-O. Irisson, F. J. Simons, A. Ogé, Y. M. Hello, A. Deschamps, G. Nolet, Automatic discrimination of underwater acoustic signals generated by teleseismic *P*-waves: A probabilistic approach, Geophys. Res. Lett. 38 (18) (2011) L18605, doi: 10.1029/2011GL048474.

[65] L. Gualtieri, E. Stutzmann, Y. Capdeville, F. Ardhuin, M. Schimmel, A. Mangeney, A. Morelli, Modelling secondary microseismic noise by normal mode summation, Geophys. J. Int. 193 (3) (2013) 1732–1745, doi: 10.1093/gji/ggt090.

[66] L. Gualtieri, E. Stutzmann, V. Farra, Y. Capdeville, M. Schimmel, F. Ardhuin, A. Morelli, Modelling the ocean site effect on seismic noise body waves, Geophys. J. Int. 197 (2) (2014) 1096–1106, doi: 10.1093/gji/ggu042.

[67] L. Gualtieri, E. Bachmann, F. J. Simons, J. Tromp, The origin of secondary microseism Love waves, Proc. Natl. Acad. Sc. 117 (47) (2020) 29504–29511, doi: 10.1073/pnas.2013806117.

[68] J. Lecoulant, C. Guennou, L. Guillon, J.-Y. Royer, Three-dimensional modeling of earthquake generated acoustic waves in the ocean in simplified configurations, J. Acoust. Soc. Am. 146 (3) (2019) 2113–2123, doi: 10.1121/1.5126009.

[69] B. Fernando, K. Leng, T. Nissen-Meyer, Oceanic high-frequency global seismic wave propagation with realistic bathymetry, Geophys. J. Int. 222 (2) (2020) 1178–1194, doi: 10.1093/gji/ggaa248.

[70] Y. Tian, S.-H. Hung, G. Nolet, R. Montelli, F. A. Dahlen, Dynamic ray tracing and traveltime corrections for global seismic tomography, J. Comput. Phys. 226 (2007) 672–687, doi: 10.1016/j.jcp.2007.04.025.

[71] Y. Tian, R. Montelli, G. Nolet, F. A. Dahlen, Computing traveltime and amplitude sensitivity kernels in finite-frequency tomography, J. Comput. Phys. 226 (2007) 2271–2288, doi: 10.1016/j.jcp.2007.07.004.

[72] J. Tromp, D. Komatitsch, Q. Liu, Spectral-element and adjoint methods in seismology, Comm. Comput. Phys. 3 (1) (2008) 1–32.
[73] C. Bassin, G. Laske, G. Masters, The current limits of resolution for surface wave tomography in North America, Eos Trans. AGU 81 (2000) F897.
[74] H. Kim, H. Kawakatsu, T. Akuhara, N. Takeuchi, T. Isse, H. Shiobara, H. Sugioka, H. Utada, Y. Kim, S.-M. Lee, Application of the reverberation waveform inversion for the high-resolution sediment layer structure in the pacific, Geophys. J. Int. 240 (2) (2025) 1331–1344, doi: 10.1093/gji/ggae444.
[75] J. A. Goff, T. H. Jordan, Stochastic modeling of seafloor morphology: Inversion of Sea Beam data for second-order statistics, J. Geophys. Res. 93 (B11) (1988) 13589–13608, doi: 10.1029/JB093iB11p13589.
[76] J. A. Goff, T. H. Jordan, Stochastic modeling of seafloor morphology: Resolution of topographic parameters by Sea Beam data, IEEE J. Ocean. Eng. 14 (4) (1989) 326–337, doi: 10.1109/48.35983.
[77] J. A. Goff, T. H. Jordan, Stochastic modeling of seafloor morphology: A parameterized Gaussian model, Geophys. Res. Lett. 16 (1) (1989) 45–48, doi: 10.1029/GL016i001p00045.
[78] J. A. Goff, B. K. Arbic, Global prediction of abyssal hill roughness statistics for use in ocean models from digital maps of paleo-spreading rate, paleo-ridge orientation, and sediment thickness, Ocean Modelling 32 (1–2) (2010) 36–43, doi: 10.1016/j.ocemod.2009.10.001.
[79] A. P. Guillaumin, A. M. Sykulski, S. C. Olhede, F. J. Simons, The debiased spatial Whittle likelihood, J. R. Stat. Soc., Ser. B 84 (4) (2022) 1526–1557, doi: 10.1111/rssb.12539.
[80] F. J. Simons, S. C. Olhede, Maximum-likelihood estimation of lithospheric flexural rigidity, initial-loading fraction and load correlation, under isotropy, Geophys. J. Int. 193 (3) (2013) 1300–1342, doi: 10.1093/gji/ggt056.
[81] E. Bozdağ, D. Peter, M. Lefebvre, D. Komatitsch, J. Tromp, J. Hill, N. Podhorszki, D. Pugmire, Global adjoint tomography: first-generation model, Geophys. J. Int. 207 (3) (2016) 1739–1766, doi: 10.1093/gji/ggw356.
[82] W. Lei, Y. Ruan, E. Bozdağ, D. Peter, M. Lefebvre, D. Komatitsch, J. Tromp, J. Hill, N. Podhorszki, D. Pugmire, Global adjoint tomography—model GLAD-M25, Geophys. J. Int. 223 (1) (2020) 1–21, doi: 10.1093/gji/ggaa253.
[83] Q. Liu, U. bin Waheed, D. Borisov, F. J. Simons, F. Gao, P. Williamson, Full-waveform centroid moment tensor inversion of passive seismic data acquired at the hydrocarbon exploration scale, Geophys. J. Int. 230 (3) (2022) 1725–1750, doi: 10.1093/gji/ggac137.
[84] Z. Liu, J. Hoffmann, F. J. Simons, J. Tromp, 3-D acoustic-elastic full-waveform inversion and migration of marine VSP data from Norway, in: SEG Tech. Prog. Expanded Abstracts, Soc. Explor. Geophys., Denver, Col., 2022, pp. 797–801, doi: 10.1190/image2022–3750936.1.
[85] Q. Liu, S. Beller, W. Lei, D. Peter, J. Tromp, Pre-conditioned BFGS-based uncertainty quantification in elastic full-waveform inversion, Geophys. J. Int. 228 (2) (2022) 796–815, doi: 10.1093/gji/ggab375.
[86] C. Cui, E. Bachmann, D. B. Peter, Z. Liu, J. Tromp, Source-encoded waveform inversion in the Northern Hemisphere, Geophys. J. Int. 235 (2023) 2305–2322, doi: 10.1093/gji/ggad363.
[87] Z. Liu, J. Hoffmann, E. Bachmann, C. Cui, F. J. Simons, J. Tromp, Laplace-domain crosstalk-free source-encoded elastic Full Waveform Inversion using time-domain solvers, Geophysics 89 (4) (2024) R355–R375, doi: 10.1190/GEO2023–0351.1.
[88] C. Cui, W. Lei, Q. Liu, D. Peter, E. Bozdağ, J. Tromp, J. Hill, N. Podhorszki, D. Pugmire, GLAD-M35: a joint P and S global tomographic model with uncertainty quantification, Geophys. J. Int. 239 (1) (2024) 478–502, doi: 10.1093/gji/ggae270.
[89] Y. You, Harnessing telecoms cables for science, Nature 466 (7307) (2010) 690–691, doi: 10.1038/466690a.
[90] B. M. Howe, B. K. Arbic, J. Aucan, C. R. Barnes, N. Bayliff, N. Becker, R. Butler, L. Doyle, S. Elipot, G. C. Johnson, F. Landerer, S. Lentz, D. S. Luther, M. Müller, J. Mariano, K. Panayotou, C. Rowe, H. Ota, T. Song, M. Thomas, P. N. Thomas, P. Thompson, F. Tilmann, T. Weber, S. Weinstein, SMART cables for observing the global ocean: science and implementation, Front. Mar. Sci. 6 (2019) 424, doi: 10.3389/fmars.2019.00424.
[91] P. Voosen, 'smart' fiber-optic cables on the sea floor will detect earthquakes, tsunamis, and global warming, Science (2024) doi: 10.1126/science.zqoh993.
[92] R. C. Aster, A. T. Ringler, R. E. Anthony, T. A. Lee, Increasing ocean wave energy observed in Earth's seismic wavefield since the late 20th century, Nat. Commun. 14 (1).
[93] A. T. Ringler, R. E. Anthony, R. C. Aster, T. Taira, B. R. Shiro, D. C. Wilson, S. De Angelis, C. Ebeling, M. Haney, R. S. Matoza, H. D. Ortiz, The Global Seismographic Network reveals atmospherically coupled normal modes excited by the 2022 Hunga Tonga eruption, Geophys. J. Int. 232 (3) (2022) 2160–2174, doi: 10.1093/gji/ggac284.
[94] J. P. Terry, J. Goff, N. Winspear, V. P. Bongolan, S. Fisher, Tonga volcanic eruption and tsunami, January 2022: globally the most significant opportunity to observe an explosive and tsunamigenic submarine eruption since AD 1883 Krakatau, Geosci. Lett. 9 (24) (2022) 1–11, doi: 10.1186/s40562-022-00232-z.
[95] C. J. Wright, N. P. Hindley, M. J. Alexander, M. Barlow, L. Hoffmann, C. N. Mitchell, F. Prata, M. Bouillon, J. Carstens, C. Clerbaux, S. M. Osprey, N. Powell, C. E. Randall, J. Yue, Surface-to-space atmospheric waves from Hunga Tonga–Hunga Ha'apai eruption, Nature 609 (7928) (2022) 741–746, doi: 10.1038/s41586–022–05012–5.
[96] D. A. Yuen, M. A. Scruggs, F. J. Spera, Y. Zheng, H. Hu, S. R. McNutt, G. Thompson, K. Mandli, B. R. Keller, S. S. Wei, Z. Peng, Z. Zhou, F. Mulargia, Y. Tanioka, Under the surface: Pressure-induced planetary-scale waves, volcanic lightning, and gaseous clouds caused by the submarine eruption of Hunga Tonga-Hunga Ha'apai volcano, Earthquake Res. Adv. 2 (3)

(2022) 100134, doi: 10.1016/j.eqrea.2022.100134.
[97] R. J. Le Bras, M. Zampolli, D. Metz, G. Haralabus, P. Bittner, M. Villarroel, H. Matsumoto, G. Graham, N. M. Özel, The Hunga Tonga–Hunga Ha'apai eruption of 15 January 2022: Observations on the International Monitoring System (IMS) hydroacoustic stations and synergy with seismic and infrasound sensors, Seismol. Res. Lett. 94 (2A) (2023) 578–588, doi: 10.1785/0220220240.
[98] S. J. Purkis, S. N. Ward, N. M. Fitzpatrick, J. B. Garvin, D. Slayback, S. J. Cronin, M. Palaseanu-Lovejoy, A. Dempsey, The 2022 Hunga-Tonga megatsunami: Near-field simulation of a once-in-a-century event, Sci. Adv. 9 (15) (2023) eadf5493, doi: 10.1126/sciadv.adf5493.
[99] J. Thurin, C. Tape, Comparison of force and moment tensor estimations of subevents during the 2022 Hunga–Tonga submarine volcanic eruption, Geophys. J. Int. 235 (2) (2023) 1959–1981, doi: 10.1093/gji/ggad323.
[100] J. D. Simon, F. J. Simons, J. C. E. Irving, W. Wu, M. Obayashi, Y. Yu, Y. J. Chen, H. Sugioka, Y. M. Hello, Hydroacoustic observations of the 15 January 2022 Hunga Tonga-Hunga Ha'apai eruption: The role of bathymetry along the path, J. Geophys. Res. (2025) submitted.
[101] T. Gneiting, W. Kleiber, M. Schlather, Matérn cross-covariance functions for multivariate random fields, J. Am. Stat. Assoc. 105 (491) (2010) 1–11, doi: 10.1198/jasa.2010.tm09420.
[102] The Nippon Foundation, GEBCO & Seabed 2030, Roadmap for Future Ocean Floor Mapping, 11th Edition, The Nippon Foundation, 2020.
[103] R. D. van der Hilst, S. Widiyantoro, E. R. Engdahl, Evidence for deep mantle circulation from global tomography, Nature 386 (1997) 578–584, doi: 10.1038/386578a0.
[104] R. D. van der Hilst, H. Kárason, Compositional heterogeneity in the bottom 1000 kilometers of Earth's mantle: Toward a hybrid convection model, Science 283 (5409) (1999) 1885–1888.
[105] Y. Fukao, S. Widiyantoro, M. Obayashi, Stagnant slabs in the upper and lower mantle transition region, Rev. Geophys. 39 (3) (2001) 291–323, doi: 10.1029/1999RG000068.
[106] D. Zhao, Global tomographic images of mantle plumes and subducting slabs: insight into deep Earth dynamics, Phys. Earth Planet. Inter. 146 (1–2) (2004) 3–34, doi: 10.1016/j.pepi.2003.07.032.
[107] W. P. Schellart, V. Strak, Geodynamic models of short-lived, long-lived and periodic flat slab subduction, Geophys. J. Int. 226 (3) (2021) 1517–1541, doi: 10.1093/gji/ggab126.
[108] G. M. Purdy, R. S. Detrick, Crustal structure of the Mid-Atlantic ridge at 23°N from seismic refraction studies, J. Geophys. Res. 91 (B3) (1986) 3739–3762, doi: 10.1029/JB091iB03p03739.
[109] R. A. Petitt, D. W. Harris, B. Wooding, J. Bailey, J. Jolly, E. Hobart, A. D. Chave, F. Duennebier, R. Butler, A. Bowen, D. Yoerger, The Hawaii-2 Observatory, IEEE J. Ocean. Eng. 27 (2) (2002) 245–253, doi: 10.1109/JOE.2002.1002479.
[110] C. Joubert, G. Nolet, S. Bonnieux, A. Deschamps, J.-X. Dessa, Y. Hello, *P*-delays from floating seismometers (MERMAID), Part I: Data processing, Seismol. Res. Lett. 87 (1) (2016) 73–80, doi: 10.1785/0220150111.
[111] F. Bigot-Cormier, J.-L. Berenguer, How students can experience science and become researchers: Tracking MERMAID floats in the ocean, Seismol. Res. Lett. 88 (2A) (2017) 416–420, doi: 10.1785/0220160121.
[112] J. D. Simon, Y. Yu, M. Obayashi, H. Sugioka, F. Simons, J. C. E. Irving, The Earthscope-Oceans Consortium, The 15 January 2022 Hunga Tonga-Hunga Ha'apai eruption as recorded by MERMAIDs adrift in the Pacific: Investigating the effect of bathymetric occlusion on hydroacoustic signature, Abstract S23A-07 presented at 2023 Fall Meeting, AGU, San Francisco, Calif., 14–18 Dec .
[113] J. Thurin, C. Tape, R. Modrak, Multi-event explosive seismic source for the 2022 $M_{\rm w}$ 6.3 Hunga Tonga submarine volcanic eruption, The Seismic. Rec. 2 (4) (2022) 217–226, doi: 10.1785/0320220027.
[114] J. Thurin, C. Tape, R. Modrak, *Erratum to* Multi-event explosive seismic source for the 2022 $M_{\rm w}$ 6.3 Hunga Tonga submarine volcanic eruption, The Seismic. Rec. 3 (2) (2023) 168–170, doi: 10.1785/0320230014.
[115] Y. Zheng, H. Hu, F. J. Spera, M. Scruggs, G. Thompson, Y. Jin, T. Lapen, S. R. McNutt, K. Mandli, Z. Peng, D. A. Yuen, Episodic magma hammers for the 15 January 2022 cataclysmic eruption of Hunga Tonga-Hunga Ha'apai, Geophys. Res. Lett. 50 (8) (2023) e2023GL102763, doi: 10.1029/2023GL102763.
[116] N. Nakata, L. Gualtieri, A. Fichtner, Seismic Ambient Noise, Cambridge Univ. Press, Cambridge, UK, 2019.
[117] M. S. Longuet-Higgins, A theory of the origin of microseisms, Phil. Trans. R. Soc. London, Ser. A 243 (857) (1950) 1–35, doi: 10.1098/rsta.1950.0012.
[118] H. Bradner, L. G. de Jerphanion, R. Langlois, Ocean microseism measurements with a neutral buoyancy free-floating midwater seismometer, B. Seismol. Soc. Am. 60 (1970) 1139–1150.
[119] A. C. Kibblewhite, C. Y. Wu, The generation of infrasonic ambient noise in the ocean by nonlinear interactions of ocean surface waves, J. Acoust. Soc. Am. 85 (5) (1989) 1935–1945, doi: 10.1121/1.397847.
[120] A. C. Kibblewhite, C. Y. Wu, A reexamination of the role of wave–wave interactions in ocean noise generation, J. Acoust. Soc. Am. 85 (5) (1989) 1946–1957, doi: 10.1121/1.397848.
[121] J. M. Babcock, B. A. Kirkendall, J. A. Orcutt, Relationships between ocean bottom noise and the environment, B. Seismol. Soc. Am. 84 (6) (1994) 1991–2007.
[122] S. C. Webb, Broadband seismology and noise under the ocean, Rev. Geophys. 36 (1) (1998) 105–142, doi: 10.1029/97RG02287.

[123] T. Tanimoto, The oceanic excitation hypothesis for the continuous oscillations of the Earth, Geophys. J. Int. 160 (1) (2005) 276–288, doi: j.1365–246X.2004.02484.x.

[124] D. Brown, L. Ceranna, M. Prior, P. Mialle, R. J. Le Bras, The IDC seismic, hydroacoustic and infrasound global low and high noise models, Pure Appl. Geophys. 171 (3) (2014) 361–375, doi: 10.1007/s00024–012–0573–6.

[125] J. Rhie, B. Romanowicz, Excitation of Earth's continuous free oscillations by atmosphere-ocean-seafloor coupling, Nature 431 (2004) 552–556, doi: 10.1038/nature02942.

[126] L. Gualtieri, S. J. Camargo, S. Pascale, F. M. E. Pons, G. Ekström, The persistent signature of tropical cyclones in ambient seismic noise, Earth Planet. Sci. Lett. 484 (2018) 287–294, doi: 10.1016/j.epsl.2017.12.026.

[127] N. M. Shapiro, M. Campillo, L. Stehly, M. H. Ritzwoller, High-resolution surface-wave tomography from ambient seismic noise, Science 307 (5715) (2005) 1615–1618.

[128] G. D. Bensen, M. H. Ritzwoller, M. P. Barmin, A. L. Levshin, F. Lin, M. P. Moschetti, N. M. Shapiro, Y. Yang, Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, Geophys. J. Int. 169 (3) (2007) 1239–1260, doi: 10.1111/j.1365–246X.2007.03374.x.

[129] A. Sukhovich, J.-O. Irisson, J. Perrot, G. Nolet, Automatic recognition of T and teleseismic P waves by statistical analysis of their spectra: An application to continuous records of moored hydrophones, J. Geophys. Res. 119 (8) (2014) 6469–6485, doi: 10.1002/2013JB010936.

[130] A. L. Bent, J. Cassidy, C. Prépetit, M. Lamontagne, S. Ulysse, Real-time seismic monitoring in Haiti and some applications, Seismol. Res. Lett. 89 (2A) (2018) 407–415, doi: 10.1785/0220170176.

[131] R. E. Anthony, A. T. Ringler, D. C. Wilson, E. Wolin, Do low-cost seismographs perform well enough for your network? An overview of laboratory tests and field observations of the OSOP Raspberry Shake 4D, Seismol. Res. Lett. 90 (1) (2019) 219–228, doi: 10.1785/0220180251.

[132] E. Calais, D. Boisson, S. Symithe, R. Momplaisir, C. Prépetit, S. Ulysse, G. P. Etienne, F. Courboulex, A. Deschamps, T. Monfret, J.-P. Ampuero, B. M. de Lépinay, V. Clouard, R. Bossu, L. Fallou, E. Bertrand, Monitoring Haiti's quakes with Raspberry Shake, Eos Trans. AGU 100 (11) (2019) 17–21.

[133] D. Reymond, O. Hyvernaud, J. Talandier, E. A. Okal, T-wave detection of two underwater explosions off Hawaii on 13 april 2000, B. Seismol. Soc. Am. 93 (2) (2003) 804–816, doi: 10.1785/0120010296.

[134] J. Talandier, O. Hyvernaud, E. A. Okal, P.-F. Piserchia, Long-range detection of hydroacoustic signals from large icebergs in the Ross Sea, Antarctica, Earth Planet. Sci. Lett. 203 (1) (2002) 519–534, doi: 10.1016/S0012–821X(02)00867–1.

[135] I. C. Wright, W. W. C. Jr, C. E. J. de Ronde, D. Reymond, O. Hyvernaud, H.-H. Gennerich, P. Stoffers, K. Mackay, M. A. Dunkin, S. C. Bannister, Collapse and reconstruction of Monowai submarine volcano, Kermadec arc, 1998–2004, J. Geophys. Res. 113 (B8) (2008) B08S03, doi: 10.1029/2007JB005138.

[136] J. Talandier, O. Hyvernaud, R. C. Maury, Unusual seismic activity in 2011 and 2013 at the submarine volcano Rocard, Society hot spot (French Polynesia), Geophys. Res. Lett. 43 (9) (2016) 4247–4254, doi: 10.1002/2016GL068342.

Appendices

1. Budget

2. Budget Justification

3. Equipment Quote

4. Letters of Support

On January 23rd 2025, the PI submitted a proposal to the U.S. National Science Foundation under the title *"Technician Support: The EarthScope-Oceans Data Collection and Quality Analysis Center"*. On May 29th 2025, Dr. Luciana Astiz, a Director of the *Earth Sciences–Instrumentation & Facilities* Program informed the PI over the telephone that the entire program was being shut down. In light of recent Presidential Executive Orders, all proposals submitted on or after January 20th were considered to be "not aligned with Agency priorities". None of the proposals had been sent out to review, and all PIs were being asked to withdraw their submissions. On June 4th, 2024, Princeton University withdrew National Science Foundation Proposal Number 2520563. No further news is available. The withdrawn proposal was accompanied by **fifty-four *Letters of Collaboration*** from stakeholders, past and future users of MERMAID data, who wrote in support of our efforts to deliver observations from mobile marine hydroacoustic sensors to the global community. These are enclosed here, alphabetically by last name.