1 Results from Prior Funding

PI: **Frederik J. Simons**. Co-PI: **Jessica C.E. Irving**. Grant Number: OCE-1917058. Amount: $550,406. Period of support: 07/15/2019–09/30/2022. Title: *Through the Ocean to the Mantle: Seismic study of the Pacific mantle with long-lived autonomous floating seismic sensors*.

Broader Impacts include [1] developing of and [2] documenting and releasing of computer software, [3] mentoring (under)graduates and postdocs to deliver "reproducible research" using FAIR (Findability, Accessibility, Interoperability, and Reusability) principles, and [4] engagement with public elementary and middle-school science teachers in the NJ-PA area. Undergraduates Peter Mwesigwa and postdoc Mathurin Wamba are Black role models. Three EarthScope-Oceans (ESO) *Steering Committee* members (Maggi, Sigloch, Zhou) are mid-career women. All *Science Committee* members (Maggi, Sugioka, Irving, Gualtieri and Bozdağ) are female. The EarthScope-Oceans *Data Management Policy* was modeled on that of the Incorporated Research Institutions for Seismology (IRIS) organization, from whom we license the service-mark *EarthScope*, and is in line with the NSF OCE public-access standards. MERMAID was granted the International Federation of Digital Seismograph Networks (FDSN) seismic network code MH. With six international institutions (Géoazur, Princeton, SUSTECH, JAMSTEC, Kobe University, Stanford University) contributing instrumentation, and sharing oceanic deployment infrastructure, EarthScope-Oceans promotes the further development of its network as an ongoing community experiment modeled on the ARGO program.

Intellectual Merit of OCE-1917058 proved the *tomographic utility* of MERMAID data. Seismic imaging of Earth's mantle provides constraints on present-day mantle dynamics, and on the thermal evolution of our planet. Images of 3-D seismic wavespeed heterogeneity delineate the shape and position of mantle plumes, which constrains their temperature, density, chemistry, and rheology. Plumes imaged by global tomographic models display variability in size and shape in the mid- to deep mantle, where high-resolution imaging remains elusive due to lack of oceanic seismic data. OCE-1917058 finished and published a tomographic model of the Galápagos plume based on nine second-generation MERMAID instruments, and prepared data for the construction of robust, high-resolution tomographic images of the South Pacific plumes. We conducted the very first analyses of an unprecedented acoustic waveform data set acquired in near real-time by eighteen autonomous MERMAIDs launched in the Pacific in Aug–Sept 2018, with a further twenty-four launched in Aug 2019, the longest-lived now 5 years old. We continue to measure the ever-growing set of *first-arrival travel-time anomalies* recorded by our evolving (now $\sim$75 units), large-aperture array of mid-column hydrophones, integrating their analysis with three-component records from nearby islands.

Science Takeaways In *Imaging the Galápagos mantle plume with an unconventional application of floating seismometers* (Nolet et al., 2019) we showed how nine MERMAIDs (of the short-lived *second generation*) detected 580 arrival times for different ray paths, yielding a significant increase in tomographic imaging quality for the oceanic upper mantle, improving the resolution where otherwise virtually no seismic information is available. In *Seismic evidence for a 1000 km mantle discontinuity under the Pacific* (Zhang et al., 2023) we introduced a wave-equation-based imaging method, Reverse-Time Migration (RTM) Full-Waveform Inversion (FWI) of precursors to surface-reflected seismic body waves, to uncover both mantle transition zone and mid-mantle discontinuities, and interpreted their physical nature. We imaged a thinned mantle transition zone southeast of Hawaii, and a prominent mid-mantle reflector below the central Pacific.

Publications of OCE-1917058 include Nolet et al. (2019), Simon et al. (2020), Burky et al. (2021), Simon et al. (2021), Simons et al. (2021), Pipatprathanporn & Simons (2022), Simon et al. (2022), Zhang et al. (2023). All contain extensive *Online Supplements* with (meta-)data (products) (e.g., travel-time anomalies).

Products of OCE-1917058 include the continued pipeline of waveform data and their metadata delivery to the EarthScope IRIS DMC. Other products are an FDSN-adoptable format (`GeoCSV`) for mobile seismic data; tools for the incoming data server; for the downstream data processing and seismological "packaging"; software for the iOS *Adopt-A-Float* app; for the Web server; for the measurement of travel-time anomalies. All of these are version-controlled and shared on `GitHub`, a central piece of our *Data Management Plan*.

2 MERMAID: From Prototype to Fourth Generation

The continents, and a small number of oceanic islands, are covered with geophysical (geodetic and seismic) instrumentation. Their data management needs are currently being met by the EarthScope Consortium (formed from the 2023 merger of IRIS and UNAVCO) through the Seismological and Geodetic Facilities for the Advancement of Geoscience (SAGE/GAGE), which includes the operation of a portion of the Global Seismographic Network (GSN). The solid Earth does not stop at the water's edge, nor are the physical properties (e.g., its acoustic wavespeed) of the ocean itself (which furthermore acts as an ambient global noise source) without interest to solid-Earth researchers. For data to be collected in the oceans, the traditional approaches involve measurements made, or devices deployed, from ships. Data, products and tools for ocean-floor seismic instrumentation are in the hands of the Ocean Bottom Seismic Instrument Center (OBSIC), and support for seafloor geodetic instrumentation has been earmarked as part of NSF's future National Geophysical Facility (NGF). Yet the deep ocean environment is extremely difficult to reach. Challenges with instrument recovery rarely allow for 100% of data returned from the equipment deployed. The costs of operating research vessels is substantial, and commercial shipping routes avoid areas of scientific interest.

The global seismological community has begun embracing alternative solutions to close the oceanic data coverage gap. Inspired by NOAA's ARGO project (which is *hydrographic* and does not collect any acoustic observations nor any data relevant to seismology), in 2002–2004 we designed a **first-generation** freely drifting hydrophone, MERMAID, *Mobile Earthquake Recording in Marine Areas by Independent Divers* (Hello et al., 2011; Simons et al., 2006a,b, 2009; Sukhovich et al., 2011). MERMAID floats autonomously at $\sim$1500 m depth while capturing *acoustic* signals triggered by distant earthquakes (in addition to identifiable noise sources from marine mammals, ships, icebergs, and storms), and surfaces for satellite data reporting in near-real-time. It needs no recovery. Our very first tests returned positive earthquake identifications.

Approximately twenty **second-generation** MERMAID instruments operated for several years each in the Mediterranean, the Indian Ocean, and in the Pacific, generating a wealth of data (Simons et al., 2009; Sukhovich et al., 2011) and producing a unique new tomographic model of the Galápagos mantle plume (Nolet et al., 2019). A comprehensive account of MERMAID data worldwide was published by Sukhovich et al. (2015). In addition to the *teleseismic* waves detected, MERMAID recorded a *local* earthquake swarm in the Indian Ocean that produced 235 detections not reported by any other station, land-based or otherwise.

The **third-generation** MERMAID (Figure 1) is an unrecovered freely drifting diver that combines a hydrophone recording earthquakes while floating at up to 2 km depth, GPS for location and timing, a digitizing and processing unit that uses STA/LTA (Allen, 1978), probabilistic wavelet-based detection and discrimination algorithms (Sukhovich et al., 2011), and IRIDIUM for near real-time (both *triggered* and *requested*) data transfer. The 55 kg instrument is manufactured by OSEAN, and has a proven lifetime of 5+ years. Additional configurable sensors available today include SeaBird 41/61 CTD, and, in the future, a suite of other instruments with utility in bioacoustics, environmental monitoring, meteorology, bathymetric determination, and chemical and physical oceanography. This proposal supports developing products and software solutions for the benefit of, and as requested by, an interdisciplinary global user community, to supply and curate the ongoing data stream that is being collected from all currently active units deployed globally.

With its **fourth-generation**, MERMAID (Figure 1) 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 (Gualtieri et al., 2013, 2014, 2020). The latest *Princeton/JAMSTEC* model carries a conductivity-temperature-depth (CTD) sensor in addition to its seismic package, and performs dives down to 4,000 m. The *Brazilian/Observatório Nacional* suite has been redesigned in order to be able to rest on the ocean-floor to enable the detection of regional seismicity. This proposal supports the development of products, tools and services for these new data types, in close coordination with the groups involved, and to ensure that their data become part of the publicly available archives already hosted by the EarthScope (IRIS) Consortium.

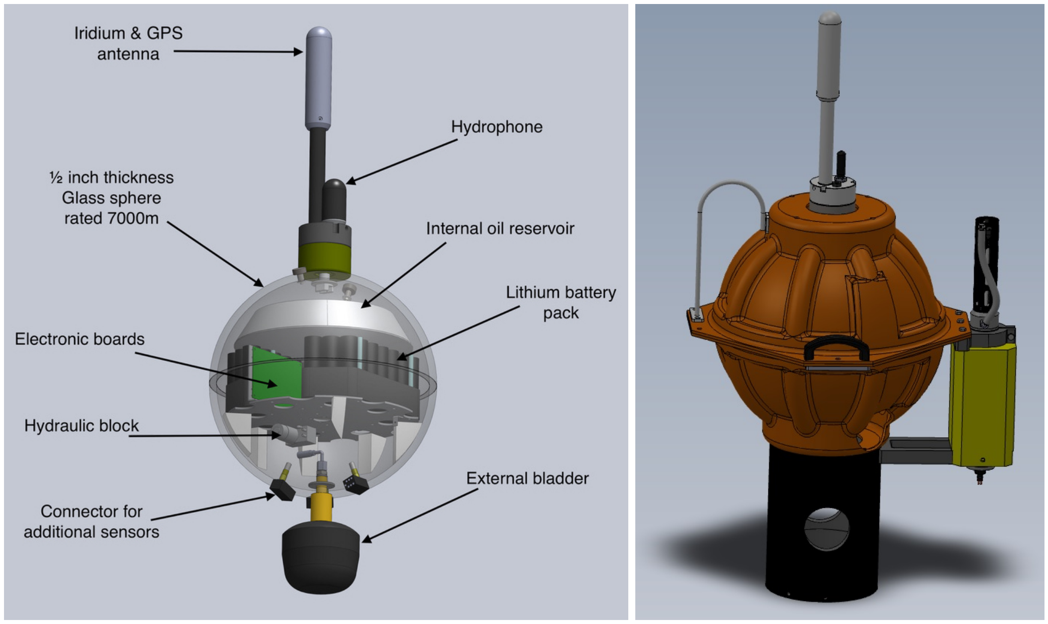

Figure 1: Technical drawing of MERMAID-III and design rendering of MERMAID-IV (including CTD profiler).

3 EarthScope-Oceans (ESO): An International Community

Global seismic models of the interior of the Earth are marred by blind spots. The *EarthScope-Oceans* consortium was founded in 2016, with academic members from the US, Japan, France, South Korea, New Zealand, China, and the UK, and with the French small business, engineering company OSEAN SAS, as an industrial partner. *Incorporated Research Institutions for Seismology* (IRIS), another global consortium of academic institutions, granted us the use of the servicemark *EarthScope* (also a 2003–2018 NSF Program).

Since 2016, *EarthScope-Oceans* (ESO) has been known and continues to operate under its present name. In 2023 IRIS merged with UNAVCO to form the *EarthScope* Consortium. It is important to know that the activities of *EarthScope-Oceans*, hence of this proposal, relate to, but are independent of, the activities of the *EarthScope* Consortium. EarthScope-Oceans is currently *not* supported by *any* NSF funds. The mission and mandate of the EarthScope Consortium do *not* include marine seismology, let alone of the mobile variety. However, prior, expired NSF support for the PI included a *Data Management Plan* whereby all MERMAID data collected by EarthScope-Oceans were deposited with the EarthScope Consortium, which continues to this day (to query our data in the IRIS Data Management Center, use FDSN seismic network code MH).

It has been and will be within scope for the EarthScope Consortium (see *Letter of Collaboration*) to archive and distribute our MERMAID hydroacoustic waveform data and metadata (instrument responses and detailed geographical information of the perennially shifting network information using the custom-made `GeoCSV` format that we jointly developed and which will be adopted by the International Federation of Digital Seismograph Networks FDSN). No "value-added" data, i.e., no data *products*, no earthquake associations or catalogs, no arrival-time picks, no travel-time anomalies, no synthetic time series, no noise measurements, are planned to be available from the EarthScope (IRIS) DMC. No services are being performed, no new tools are being developed by EarthScope—the raw data are simply stored and made available as part of our joint, continued commitment to open geophysical data sharing, and to honor prior data management policies. This proposal seeks funding for the US lead and institutional founder of the **EarthScope-Oceans** (ESO) Consortium in order to firmly establish its **Data Collection** (and Quality Analysis) **Center** (DCC) as an innovative cyberinfrastructure resource. We will hire a *Cyberinfrastructure Professional* for these tasks.

ESO represents a multidisciplinary group of geoscientists who have pledged to coordinate efforts to create a **global network of autonomous floating acoustic sensors** to monitor the Earth system from within the oceanic environment. ESO shepherds PI-led projects into the international forum where globally relevant, applicable, and mutually agreed-upon decisions can be made on technological aspects of instrument development, science objectives and priorities on different time scales, data management, dissemination, archiving, education and outreach efforts. Our activities have become increasingly interdisciplinary. After twenty years of instrument design, development and deployment success with MERMAID primarily in the realm of *hydroacoustics* (earthquakes, volcanoes, infrasonic noise), EarthScope-Oceans has begun the transition to integrating with *hydrography* (conductivity-temperature-depth) and *bioacoustics* (cetacean census). After launching ∼75 MERMAID-III instruments (acoustics only, diving to 2,000 m depth) in three oceans, in 2023 three newly developed co-designed MERMAID-IV floats were deployed with conductivity-temperature-depth (CTD) profiling capability and an operational range down to 4,000 m. New models developed by Géoazur and OSEAN for our Brazilian partners will have ocean-floor "landing" capability in order to prioritize capturing regional earthquake events. Future models will add a high-frequency acoustics package to enable bioacoustic monitoring. We have begun planning to add active bathymetric sounding to later models.

Organization. A *Steering Committee* led by the PI meets yearly. Standing Committees jointly promote *Technology*, *Science*, *Data Management*, and *Education & Outreach*. 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*.

Data Management and Access. *Triggered* waveforms are continually being submitted to the EarthScope (IRIS) Data Management Center for public availability (Simon et al., 2022), which reports on their access independently. *Buffer* requests from various research groups are being honored, most lately from Virginia Tech, Caltech, and WHOI (Simon et al., 2021). *Continuous* data (from unexpectedly recovered instruments) are future windfalls that require dedicated processing (specifically for GPS clock corrections) yet have led to unprecedented opportunities for scientific discovery (Pipatprathanporn & Simons, 2022). The cumulative near-real-time data (product) stream (for now: 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 we will handle as part of this proposal comprises the shared records from all those institutions, signatories to the EarthScope-Oceans *Charter*, which maintains clear labor divisions for meeting the purely scientific objectives of, e.g., global monitoring, mantle tomography, and oceanic hydrography, but with common data management goals.

Ongoing innovation in terms of data management (curation, archiving), open-source software solutions and data product development is a vital component of ESO's mission. Other **academic institutions** will join our consortium, contributing new floats and capabilities. We are communicating with 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, and ambient noise spectra. As with recent additions to our consortium (most lately, Brazil), ESO will, through this proposal, work with them to get their instruments into the water, their floats followed on a day-to-day basis, and their data quality-controlled and packaged after the customary two-year moratorium, for depositing into the EarthScope (IRIS) DMC for open-access use by US investigators and scientists worldwide. After OSEAN (CEO Olivier Philippe), we are likely to sign on other **industrial partners** as well. Chief among them are the California-based small business *Seatrec* (CEO Yi Chao), and the Rhode Island-based small business *DBV Technology* (CEO Bud Vincent), with whom we have collaborated informally for several years. *Seatrec* manufactures energy harvesting systems that are being adapted for use in oceanic seismic observing systems, which could in principle give MERMAID an indefinite lifetime. *DBV* manufactures hydrophones and develops underwater positioning technology. Both companies are open to exploring future avenues of collaborative research, and will share their preliminary data. See their *Letters of Collaboration*.

4 Intellectual Merit: The ESO Data Collection Center (DCC)

To quote the 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 sciences questions, such as those identified by *Earth in Time* (2020). Among the questions (as numbered) 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?*

MERMAID is a robotic profiling float that records and processes low-frequency hydroacoustic (and hydrographic) data autonomously, sending and receiving communications via IRIDIUM. 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, needs support. We preemptively rebut the objection "Isn't EarthScope (formerly IRIS) already doing this?". As first explained in Section 3: No!

While depositing curated waveform (meta)data into the EarthScope DMC is an objective supported by this proposal, EarthScope-*Oceans* (ESO) **collects data** (e.g., acoustic buffer requests and continuous time series, hydrographic CTD profiles) that EarthScope is *not* mandated to support. Under this proposal, EarthScope-*Oceans* furthermore innovates by making **software tools**, data products, and providing responsive **services** for which EarthScope has neither the appetite nor the funded bandwidth. Examples of software are `automaid`, interfacing with all floats for data recovery and mission control; *Adopt-A-Float*, helping conduct outreach activities; tools 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 WAVEWATCH III (2019); to run waveform simulations via `TauP` (Crotwell et al., 1999), `Instaseis` (van Driel et al., 2015) and `SPECFEM-2D` (Komatitsch & Vilotte, 1998; Komatitsch et al., 2000); and to analyze and incorporate bathymetry (GEBCO Bathymetric Compilation Group, 2019). **Data products** include earthquake *associations*, frequency-dependent *arrival*-time measurements and *travel*-time anomalies in one-dimensional reference models (Simon et al., 2022), *synthetic* waveforms that honor bathymetry and the "oceanic last mile" of teleseismic wave propagation (Pipatprathanporn & Simons, 2023), and custom *buffer requests* from interested communities (Simon et al., 2021), e.g., to study the oceanic mesoscale temperature field and its temporal evolution ("seismic ocean thermometry", Wu et al., 2020), both indirectly (from the $\sim$75 MERMAID-III acoustic floats, Figure 2) and directly (from the 3 MERMAID-IV CTD-equipped units). Many of the recent **service** needs arose from interactions with oceanographic and climate communities outside the solid-earth tomography crowd, and involve data for which MERMAID was not designed (its sole original mission was to collect first-arriving *P* wave arrival-times), but has turned out to be supremely useful.

Figure 2: *Current (December 5, 2023) 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 EarthScope-Oceans (ESO) Data Collection (and Quality Analysis) Center (DCC) is a nimble, innovative cyberinfrastructure resource. Almost the full extent of the proposed ESO DCC is budgeted for in this proposal, and the balance is expected to derive from other support (e.g., as part of the *Data Management Plan* of focused science submissions to the NSF, e.g., the PI submitted proposal 2341811 to *Geophysics*).

The day-to-day routine **technical operations** required to maintain our fleet of ∼75 MERMAIDs, which resurface on average every 6.25 days, involve checking `log` and `bin` files and state-of-health messages in `vit` files that accumulate on the receiving server `mermaid.princeton.edu`, 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 growth of the fleet.

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** may 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 Princeton instrument P0023, which yielded an unprecedented one-year-long buffered time series of *everything* it had recorded before we redeployed it. The MERMAIDs managed for Stanford, deployed in the Mediterranean, will need active trajectory monitoring in order for ships of opportunity to be able to recover and redeploy (with our partner institution Géoazur) before they enter the Atlantic. These instruments report *power-spectral densities* rather than triggered teleseismic waveforms: a new instrumental capability that falls upon the ESO DCC to fold into its day-to-day workflow, as far as automatically reported waveforms and spectra are concerned (so-called `mer` files of the `det` variety).

The day-to-day **scientific operations** include scheduling and submitting data requests for specific time intervals of interest (e.g., to access late-arriving phases, or aftershock sequences), and to mine and manage the resulting `mer` files (of the so-called `req` variety). Such requests are currently being honored from WHOI, Caltech, and Virginia Tech (see *Letters of Collaboration*). Other scientific tasks are to design and conduct experiments that change cruising depth, as part of what will be required to optimize inversions for ocean thermometry, and to integrate the three new MERMAID-IV floats that have a CTD sensor and double the diving capacity, to 4,000 m. There is the ongoing matching of seismic waveforms to global earthquake catalogs (earthquake "association") to determine multiscale travel-time anomalies, uncertainties, and signal-to-noise ratios, for mantle seismic tomography, following the algorithms and procedures published by Simon et al. (2020, 2021, 2022). Our latest innovation is the capability to produce synthetic waveforms according to the workflow designed by Pipatprathanporn & Simons (2023). At the outset, MERMAID was designed only to recover first-arriving teleseismic *P* phase *picks*. The quantitative matching of the recorded noise field (Pipatprathanporn & Simons, 2022) and computational modeling of the reverberating *waveforms* are opening up avenues of research beyond what was originally envisaged. Making new products and tools available to the widest possible community is among the transformative objectives supported by this proposal.

The ESO DCC commits to ongoing **outreach, teaching and training** tasks. ESO's website (all source materials, scripts, and back-end code available from `GitHub` at `fjsimons/earthscopeoceans`) and social media accounts (*LinkedIn* and 𝕏, formerly *Twitter*) are actively communicating. The *Cyberinfrastructure Professional* will continue the work of training research staff at our collaborating institutions. Most recently, Joel D. Simon has trained Dr. Yong Yu (SUSTech), Dr. Dalija Namjesnik (Géoazur & ISC), and Ms. Yuko Kondo (Kobe University) on the use of his event-association and travel-time anomaly determination software (on `GitHub` at `joelsimon/omnia`). The *Steering Committee* has organized AGU Townhalls and Press Conferences, and Special Interest Groups (at IRIS/EarthScope), and will do so again.

5 Intellectual Merit: Data, Tools, and Products for Community Use

5.1 Data Collection and Quality Analysis Software

Central to MERMAID's fleet management is `automaid` (find it on `GitHub` at `earthscopeoceans`), a suite of `Python` tools that interface with satellite communications, parses `log` and `bin` (systems messages) and `vit` (state-of-health indicators) files, 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. The manufacturer's clone of `automaid` has diverged from the official release by EarthScope-Oceans; this proposal will help the *Cyberinfrastructure Professional* work with OSEAN to get the development version back on the public track.

Accurate sensor *location* and precise *timing* are vital for seismic tomography, which relies on measuring seismic wave *speeds* and their model deviations to answer *Earth in Time* priority questions: it is among the principal means to address the distribution and cycling of critical elements in the Earth (Q3), and to find the deep mantle drivers of surface volcanism (Q5). Hence, `automaid` performs **location interpolations** such that seismic waveforms can be assigned to the right acquisition positions (Joubert et al., 2016). 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. Nolet et al. (2023) show that MERMAID location errors arising from non-constant bathyal drift velocity and path curvature effects map differently into timing inaccuracies depending on whether the ascent immediately follows the triggering event (∼0.028 s) or not (∼0.042–0.214 s). For global seismic tomography, location errors have no significant impact on the accuracy of picked arrival times from teleseismic earthquakes (steeply dipping phases, extended source domains), but they require further study, both from an oceanographic (marine current distributions, mesoscale temperature fluctuations) and seismological (regional events) perspective.

This proposal will support the continual **software hardening and improvement** of all of those 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.

5.2 Trajectories and other Metadata, including State-Of-Health (SOH)

MERMAID is a floating array, thus no two seismograms are acquired in the same place. We have successfully worked with EarthScope (IRIS) to accommodate this novel data type in a new format (`GeoCSV`) that can be efficiently queried and rendered usable for the community at large. FDSN will adopt it as a standard on par with `miniSEED` and `StationXML`. The primary metadata, **bathyal trajectories**, are of great utility also for physical oceanographers. MERMAID tracks ocean currents at its cruising depth (above 2,000 m for MERMAID-III, 4,000 m for MERMAID-IV). Figure 3 illustrates this crucial aspect for Princeton float P008.

Float trajectories and other **metadata** are openly accessible via the ESO website, as text files containing GPS time, position and precision, battery and voltage levels, internal and external pressure, and the numbers of commands received, files queued for upload, and uploaded. The *Adopt-A-Float* iOS app accesses those, and displays them for education and outreach (Bigot-Cormier & Berenguer, 2017). This proposal supports the day-to-day monitoring of these files for navigational indicators and to flag potential instrument problems requiring intervention. Mission-parameter updates can be passed on at every available surfacing. Recent requests from WHOI and Caltech have necessitated adjusting MERMAID's diving depth in order to maximize the recovery of ocean-temperature-sensitive *T* phases, depending on their mode number and frequency.

Complete `GeoCSV` metadata files containing *all* GPS time and location acquisitions are a **new data product** enabled by this proposal, which will also list all timing corrections applied. The packaging of these files and their delivery to the EarthScope DMC will enable community researchers to check our location interpolations, or perform their own, for whichever seismological or oceanographic purpose they see fit.

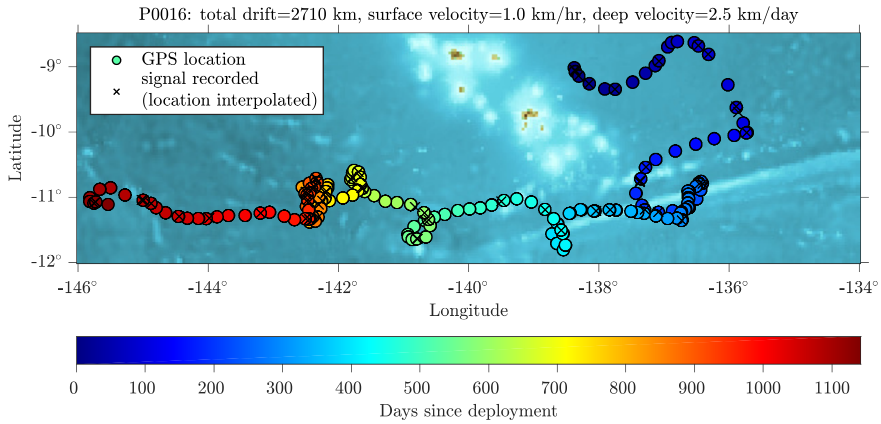

Figure 3: *Three years of the trajectory of* MERMAID *P016, with the interpolated locations of earthquake arrival detections (crosses), overlain on a model of oceanic bathymetry. The third and fourth-generation* MERMAID *models are only aware of their parking* depth. *Future floats with EarthScope-Oceans will have the added capability of actively measuring* ocean *depth, i.e., bathymetry.*

5.3 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 4). The primary data are **seismic waveforms**. There are "false" triggers: every detection is probabilistically scored (Sukhovich et al., 2011), and surfacings are designed to transmit highly promising arrivals, but they also include runners-up.

While domain-specific scientific analysis happens downstream by the individual science teams at the partner institutions, this proposal will ensure that *every* automatically retrieved waveform (based on `mer` files of the so-called `det` type) will be delivered to the EarthScope DMC for public (measured) access.

The baseload task is **data conversion** to the FDSN `miniSEED` data standard, replete with *instrument response* information. Outside researchers will be able to request these files from the EarthScope DMC. Every `mseed` file will be paired, as part of this proposal, with an additional metadata file listing instrument parameters necessary for seismological data analysis—simply because 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 a (desirably for seismic tomography) ever-evolving *position*. Metadata further include trigger settings, quality scores, wavelet basis information, etc. We have previously worked with EarthScope and FDSN to iron out major formatting issues, and this proposal will continue the work and provide **continuous review** of all incoming and outgoing data.

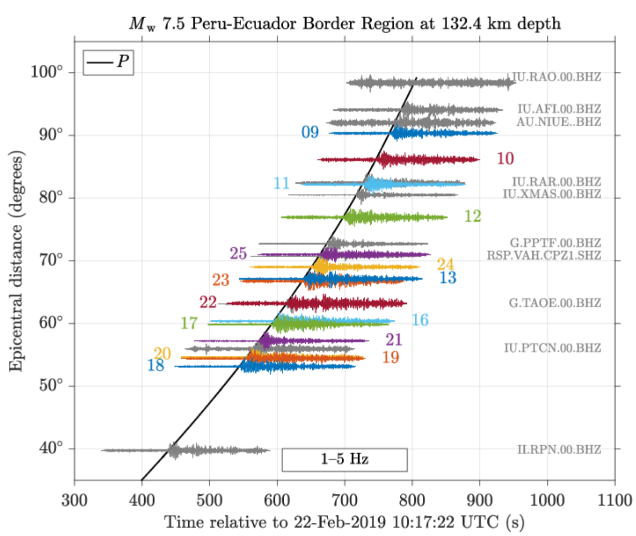

Figure 4: *Waveforms transmitted by all 16 Princeton members of the* MERMAID *array, all of which are still reporting from the South Pacific after more than 5 years. Traces from nearby island stations are in gray. Travel-time predictions made in the* `ak135` *reference model.*

Accommodating **user requests** is supported by this proposal. MERMAIDs have a one-year rolling buffer available for query. Data segments require handling and packaging for delivery to the EarthScope DMC. We will work with a Caltech group to recover tertiary, or T phases, which hold the key to determining mesoscale ocean temperature variations (in-between ARGO profiles). 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 exquisite detail (Simon et al., 2023a,b) has become a unique activity for mobile marine seismology, in line with *Earth in Time* questions, e.g., Q12 on geohazard risk and toll reduction. Among the questions that increased azimuthal coverage helps resolve is the directionality of energy input, bathymetric influence, and the details of the pulsed sequence of volcanic events (Thurin et al., 2022; Zheng et al., 2023).

5.4 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 P023, aided by a team of undergraduate interns who developed prediction algorithms to target the recovery from a ship of opportunity. Future opportunities will be seized.

This exceptional recovery (Pipatprathanporn & Simons, 2022) provided insight into what MERMAID *hears* beyond what it automatically *reports*. Figure 5 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 wave-trains, 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 will want to cross-check their records with ours, and we will respond to their requests whenever possible. This proposal will deposit long waveforms with the EarthScope DMC. We will endeavor to acquire more such records, as our earliest-deployed floats become inactive and might be captured and repurposed.

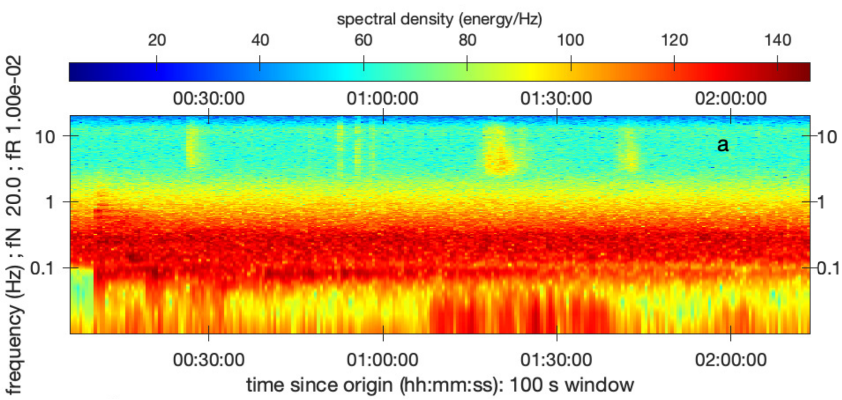

Figure 5: *Spectrogram of the* MERMAID *record of the M7.5 Peru-Ecuador 2019 earthquake. Seismic* P, S *and* T *waves are visible against a background of microseismic noise whose temporal fluctuations are of independent scientific utility, matching wave-based oceanographic retrodictions (Pipatprathanporn & Simons, 2022).*

5.5 Signal and Noise Spectral Densities from Serendipitously Recovered Floats

Figure 5 reveals the acoustic frequency band in-between 0.1 and 1 Hz to be rather noisy. The retrieval of the one-year P023 buffer allowed us to understand its nature in detail. Figure 6 shows two of the twelve available months of **noise power-spectral densities** (Pipatprathanporn & Simons, 2022), after removal of all reported events, all unreported events matched in post-processing, all suspected intervals containing ship operations, and various other transients that are not part of the *normal* oceanic noise environment. By design, MERMAID's sensitivity is cut off beyond 10 Hz, and the instrument transfer function rolls off below about 0.05 Hz (Simon et al., 2022). After removing all earthquakes and volcanic transients (Tepp & Dziak, 2021), the ocean-wave-generated infrasound noise can become the signal of interest, as shown in Figure 6.

Nature provides us with *natural* experiments: the oceans drive these intervals of acoustic spectral power and their temporal variations (Nakata et al., 2019). Pipatprathanporn & Simons (2022) showed that the

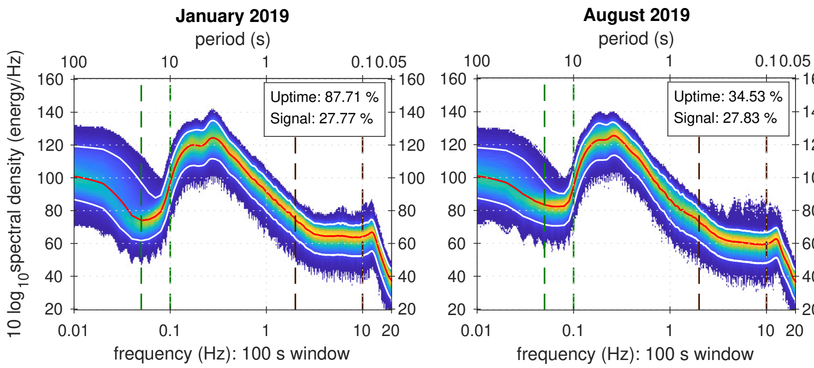

Figure 6: *Oceanic "noise" spectra recorded by exceptionally* recovered MERMAID *P023. Red curves show median behavior. White curves demarcate the 5*th *and 95*th *percentiles. Earthquakes are clearly seen between 0.05–0.10 Hz. T phases are observed between 2–10 Hz. "Signal" is the percentage of the buffer that contained signal* removed *prior to spectral density computation.*

correlation between ocean-wave forcing at 0.21–0.23 Hz, derived from the WAVEWATCH III (2019) ocean model , and acoustic noise recorded by MERMAID between 0.36–0.38 Hz reaches as high as 0.845. The well-known *double-frequency* mechanism of microseismic noise generation (Gualtieri et al., 2013, 2014, 2020; Longuet-Higgins, 1950), is observed by MERMAID *in situ*, which has become an *environmental* sensor.

One more MERMAID float (R067) was recovered, and we are working with the relevant authorities to repatriate the data memory card. This proposal will enable to us to analyze and make available its full buffer.

5.6 Direct Spectral Recovery — The *Stanford* MERMAID Model

Figures 5–6 showed the unanticipated "bycatch" from worldwide MERMAID records (designed for short segments containing *P* waves, as in Figure 4). Pipatprathanporn & Simons (2022) showed the rich source of information obtainable from **spectral-density** data products from our records, supported by this this proposal. Their analysis will benefit our understanding of earthquake detection thresholds (*Earth in Time* Q4), and has potential for revealing atmosphere-ocean-surface-water-column-solid-earth interactions (e.g., Babcock et al., 1994; Bradner et al., 1970; Brown et al., 2014; Kibblewhite & Wu, 1989a,b; Rhie & Romanowicz, 2004; Tanimoto, 2005; Webb, 1998). **Ambient noise** is of interest in the community, both for what it tells us about the *meteorological environment* (Gualtieri et al., 2018) and for its potential in *Earth imaging* in the absence of impulsive (earthquake) sources (Bensen et al., 2007; Shapiro et al., 2005), where an understanding of source homogeneity, directionality, and seasonality are recognized as being of substantial importance.

The *seven* Stanford MERMAIDs (deployed 2021) whose data stream we *monitor* and *manage* as part of the operations supported by this proposal (collaborator Lucia Gualtieri, see *Letter of Collaboration*) were a new fourth-generation model type (see Section 2), 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. With this proposal we will review, quality-control, package, and offer these data to the EarthScope DMC.

5.7 Earthquake Association: *Value-Added* Metadata

A MERMAID waveform available from the EarthScope DMC is a time series of acoustic pressure. Georeferenced and accurately timed, as supported by this proposal—but 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 Simon et al. (2020) accomplishes this procedure. To date, 3,631 earthquakes have been matched to 10,248 traces recorded by 53 MERMAIDs, likely some 90% of the total, see Figure 7. This proposal supports this ongoing work.

Every triggered waveform already comes tagged with *statistical* information (the metadata briefly mentioned in Section 5.3) about exactly what flagged it: sample number, STA/LTA ratio, and a probabilistic

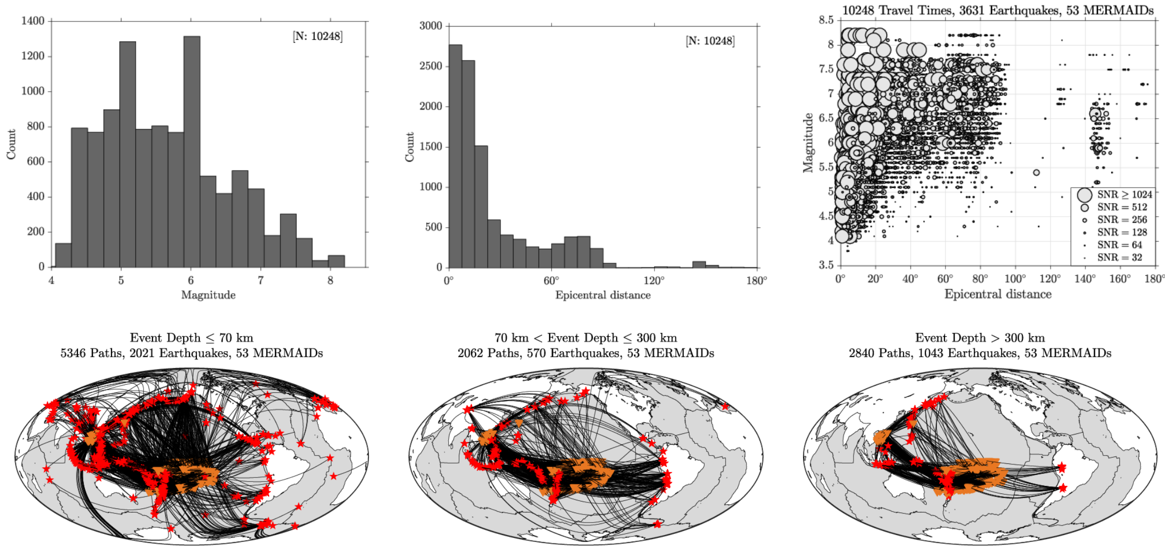

Figure 7: *The current catalog of* associated *events. Princeton and Géoazur waveforms are already available from the EarthScope DMC. Chinese, Japanese, and Brazilian data will follow as part of* this proposal*. Ray-theoretical travel-time residuals are computed for tomographic imaging, as a cumulative data product supported by* this proposal*.*

score of the likelihood that the record indeed contains a *teleseismic* earthquake phase, derived from wavelet analysis according to Sukhovich et al. (2011, 2014). *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** of the form (data products as in the Supplementary Material accompanying Simon et al., 2020):

```
Filename m18.20130702T074818.sac | IRIS ID 4221326 | NORTHERN SUMATRA, INDONESIA |JDS multiscale phase picks: 3 scales at 5 Hz
Last updated 2019/03/22                                                       | Phase  Time    Tres      SNR        Mu   2Sigma
            Date        Time       Latitude Longitude  Depth Distance Magnitude  |   P   90.40   -3.88 3.271E+00  -0.01   2.78
Initial: 2013/07/02 07:37:05.75    4.6907    96.5824  25.40  88.0221    6.1      |   P   93.00   -1.28 5.083E+00   0.00   1.62
Updated: 2013/07/02 07:37:05.09    4.6907    96.5824  25.40  88.0221    6.1   MW  | PcP  98.20    2.13 8.967E+00   0.00   0.89
GeoAzur phase pick: P                                                          | PcP  96.60    0.53 2.732E+01   0.02   0.41
```

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 5.8) that accompany our waveform records already hosted by the EarthScope DMC. These data have formed and will form the basis of research projects by interested groups worldwide. Additionally, we will evaluate the contribution of MERMAID data to improve ISC's location results.

Figure 8 shows waveform onsets (Simon et al., 2022), used to obtain **travel-time residuals and uncertainty estimates** referenced to water-layer-adjusted `ak135` models, and with the red vertical our "pick".

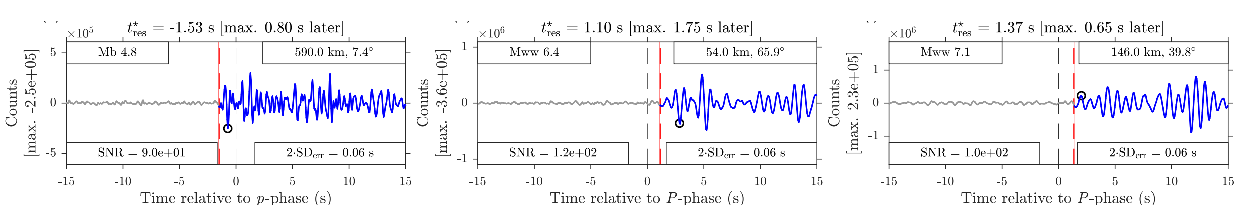

Figure 8: *Travel-time residuals of first-arriving compressive P waves. Seismograms (filtered to 1–5 Hz) show detail in a 30 s window aligned on the theoretical first-arriving phase in* `ak135` *models adjusted for bathymetry and* MERMAID *cruising depth (Simon et al., 2022), with uncertainties estimated via the AIC-based method of Simon et al. (2020).*

5.8 Phase Matching and *Validation* through Terrestrial Network Analysis

The geographical extent spanned by the Pacific MERMAIDs comprises 6.5% of Earth's surface. EarthScope lists just 19 island seismometers with data after 2018, of which five Raspberry Shakes (Anthony et al., 2019; Bent et al., 2018; Calais et al., 2019). Six short-period seismometers in the Réseau Sismique Polynésien do not report to EarthScope (Reymond et al., 2003; Talandier et al., 2002, 2016; Wright et al., 2008) .

The distribution of MERMAID *P*-wave residuals in Fig. 9b agrees well with that from traditional seismometers in Fig. 9a, and to a lesser extent with Raspberry Shake stations in Fig. 9c. 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. These findings demonstrate that MERMAID data are useful for seismic tomography (Simon et al., 2022). This proposal sustains (and innovates, see Section 5.9) the **seismological analysis** and validation of the incoming data. Inasmuch as they are not already available, we deposit the data used for comparative analysis with the EarthScope DMC also.

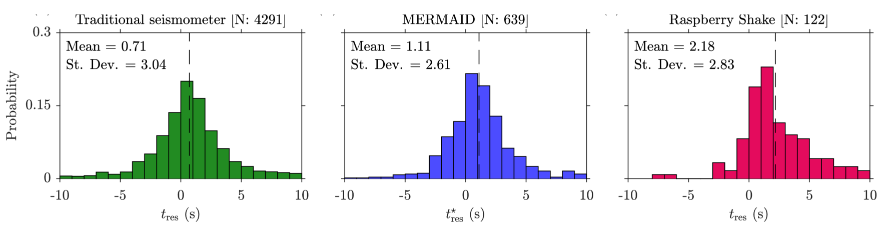

Figure 9: *P-wave travel-time residuals from traditional (green),* MERMAID *(blue), and Raspberry Shakes.* MERMAID *data match those of traditional stations. Uncertainties and SNR compare favorably to Shakes.*

5.9 Waveform Modeling of MERMAID Data—Synthetic Data Products

MERMAID was designed (Simons et al., 2006b, 2009) to detect, identify, and report teleseismic *P* waves, and, since 2018, has been collecting a growing database of thousands (see Figure 7) of high signal-to-noise 20 Hz waveforms in 250 s segments (see Figure 4). We match the incoming data stream (on average, a MERMAID resurfaces every 6.25 days) with phase predictions based on global earthquake catalogs (see Section 5.7), and determine recording location and time (see Section 5.1) to arrive at accurate travel-time residuals (see Section 5.8). These are the "core" **data**, **metadata** and **data products** from this proposal.

MERMAID seismograms are being and have been (Nolet et al., 2019) used for travel-time tomography, but modeling the entire waveform, to move beyond first-arriving arrival-time picks, has remained elusive. What prevents the application of Full-Waveform Inversion (FWI) to hydroacoustic seismograms (Fernando et al., 2020; Lecoulant et al., 2019) is that simulating *seismic* wave propagation in a 3-D globe with an ocean in which *acoustic* waves propagate 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. Our solution (Pipatprathanporn & Simons, 2023) 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. This proposal further develops and carries this out on all waveforms in the ESO data base as it continues to acquire new event-MERMAID pairs.

We precompute elastic Green's functions using `Instaseis` to obtain 2 Hz displacement seismograms within a 1-D reference earth model. We then use `SPECFEM-2D` 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.

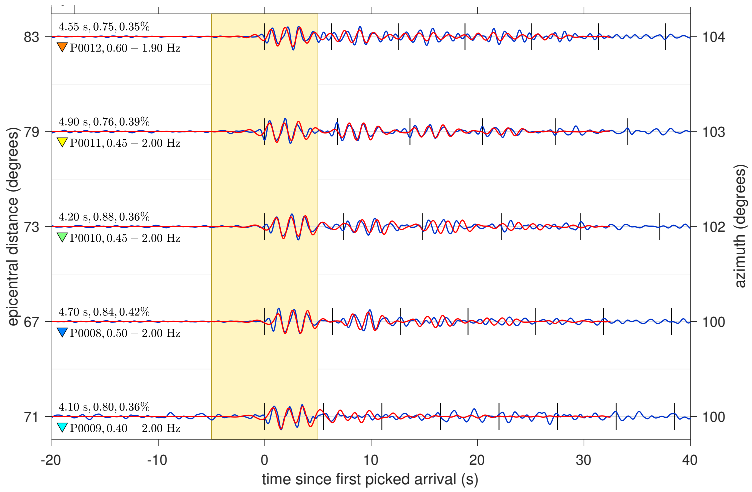

Figure 10: *Waveform modeling of* MERMAID *records of CMT event C201808171535A, magnitude 6.50, depth 529 km. Adaptive frequency selection has effectively and optimally split the record in a noise and a signal segment with high signal-to-noise ratio. Observations are in black, synthetics modeled via our innovative procedure (Pipatprathanporn & Simons, 2023) 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.*

The correlation between synthetics and observations in our test data set (3,887 seismograms, 682 earthquakes) is high (max 0.98, median 0.72), and very coherent across the array (Figure 10). 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 EarthScope DMC to host such non-primary data, a small but not unprecedented (see, e.g., *ShakeMovie*) departure from their usual holdings.

5.10 MERMAID as a Tsunamometer? | The JAMSTEC/Kobe Model

Hydrophones can record tsunami (e.g., Okal et al., 2007)—at periods too long for the current response of MERMAID-III. Firmware on *one* of the Japanese-owned units (R050) was changed for the static (absolute) pressure sensor to be logged directly (instead of merely being used for depth control). Since MERMAID is neutrally buoyant, a passing tsunami wave might also induce a cruising depth change (Winant, 1974), which would be compensated by the active depth control pump mechanism. Early experiments with the modified R050 appeared to pick up mostly tidal signals—no tsunami yet—and further research is ongoing. Absolute **pressure time series** are a future data product supported by this proposal, and we will work with our Japanese colleagues (Masayuki Obayashi and Hiroko Sugioka, see *Letters of Collaboration*) to further support exploring this intriguing possibility, from a management and operations standpoint.

In October 2025 JAMSTEC and Kobe are scheduled to deploy 5 new MERMAID units around the Hawaii-Emperor seamount chain, using data collection and service software supported by this proposal.

5.11 MERMAID as an *Indirect* Ocean Thermometer? | The Caltech/WHOI Collaboration

The groundbreaking proof-of-concept by Wu et al. (2021) which showed that earthquake-generated tertiary *T* phases contain measurable sensitivity to ocean-temperature variations over long temporal and spatial baselines spurred the search for temperature-sensitive signals recorded by MERMAID. A recent collaboration with Caltech and WHOI (see *Letter of Collaboration*) has produced evidence (Ervik et al., 2024) that mobile marine sensors hold promise to map the ocean's **mesoscale temperature field** from indirect (acoustic) measurements. As part of this proposal the ESO DCC will follow up by procuring hundreds of seismic *T* phases from the MERMAID buffers for further analysis. This is an area of exciting innovation: MERMAID has traditionally *deprioritized* sending *ocean*-sensitive *hydroacoustic* (e.g., *T*) phases in favor of *earth*-sensitive *seismic* phases (e.g., *P*). We will work out a feasible data recovery procedure to serve the oceanographic community without compromising on the scientific goals of the geophysical community.

5.12 MERMAID as a *Direct* Ocean Thermometer! The deep ocean is a vast receptacle of heat and a major factor in regulating Earth's climate. Few direct observations of the time-evolving temperature of its deep currents exist. The impact of CTD (conductivity-temperature-depth) data from the ARGO program on ocean modeling has been monumental (Roemmich et al., 2009). However, ARGO sampling continues to be largely limited to the upper 2,000 m of the ocean. Collaboration with the Japan Agency for Marine-Earth Science and Technology (Masayuki Obayashi, Shigeki Hosoda) and Kobe University (Hiroko Sugioka) resulted in a **4,000 m** MERMAID-IV model that added a SeaBird (41/61) **conductivity-temperature-depth** (CTD) sensor. *Two* instruments with combined acoustic sensing and **deep hydrographic profiling** capability were deployed in the Pacific in June 2023. This proposal ensures that their data collection and quality assurance meet ARGO protocols, continues their remote management, and prepares for anticipated fleet additions.

5.13 MERMAID as a *Lander* to Monitor *Regional* Seismicity. In 2023 a consortium from Brazil's Observatório Nacional (Sergio Fontes) and the University of São Paulo (Marcelo de Bianchi) joined EarthScope-Oceans. They will take delivery of 8 MERMAID-IV models equipped with ocean-floor *landing* capability, which, in the Spring of 2024, they will deploy in 2 km deep water along the southern Brazilian margin, together with 4 ocean-bottom-seismometer (OBS) sensors. Their objectives are to study local upper-mantle structure, locate passive-margin earthquake events, monitor the **soundscape** of acoustic noise levels (sound is an *Essential Ocean Variable*) and identify their sources, and develop ways to integrate MERMAID into their permanent network. The tectonic evolution of the Brazilian passive margin relates to the development of the marginal basin and its hydrocarbon reservoirs, and the area is marked by a high seismic rate relative to the rest of Brazil, with many earthquakes of moderate size, whose depth (in the sediments, or in the crust?) and location the MERMAID records will help constrain. Supported by this proposal the ESO DCC will contribute operational and management expertise to their deployment, and develop the necessary tools and procedures to help meet their scientific objectives. Marcelo de Bianchi will join ESO's *Steering Committee*.

5.14 Other Collaborative Endeavors. The **International Seismic Centre** (Dmitry Storchak, Tom Garth, James Harris) is a standard-setting scientific research center that collects, archives and processes seismic bulletins, and prepares and distributes the definitive summary of world seismicity. Supported by this proposal, the ESO DCC will continue the work of training ISC staff in the task of earthquake association with hydroacoustic MERMAID data. The new records improve ISC's **earthquake location estimates** in the important focus area of the Kermadec-Tonga subduction zone in the Southwest Pacific (Namjesnik et al., 2023). Closing the azimuthal gap and allowing to obtain "free" depth estimates for key events on the basis of MERMAID data recorded in the near field, especially when *P* and *S* waves can be identified, is an objective for which the ESO DCC will formulate new buffer requests. The ISC will become the final repository for EarthScope-Oceans data **products** (MERMAID-derived earthquake associations and catalogs) which currently fall outside of the scope of the EarthScope DMC to host. At the **Colorado School of Mines**, Ebru Bozdağ and graduate student Rachel Willis have developed a MERMAID de-reverberation filter that the ESO DCC will evaluate and consider as a future data product. Bozdağ (NSF CAREER grant 1945565) and postdoc Masaru Nagaso are exploring alternative (to the procedure described in Section 5.9) ways to incorporate MERMAID waveforms into **full-waveform inversion** for global earth models. Aided by this proposal, the ESO DCC will contribute data, tools, and training. At **Virginia Tech**, Ying Zhou and former graduate student Shuyang Sun are working on evaluating the contribution of MERMAID data to enhancing seismic resolution of the lithosphere-asthenosphere boundary from *SS* precursors. Under this proposal the ESO DCC will help them assemble a MERMAID data set. **Géoazur** will remain a major partner for the ESO DCC. MERMAID-I was developed by the PI with Guust Nolet at Princeton (Simons et al., 2006b, 2009), MERMAID-II was built by Teledyne Webb Research and developed by Guust Nolet and Yann Hello at Géoazur (Hello et al., 2011), and MERMAID-III was developed by commercial company OSEAN SAS (from Le Pradet, France) from engineering design by Yann Hello at Géoazur (Hello & Nolet, 2020). Karin Sigloch, a member of the *Steering Committee*, is heading the Brazilian cooperation, and supervising electronics engineer Sébastien Bonnieux, whose model-based application-switching MERMAID-language (MeLa) (Bonnieux et al., 2019, 2020) will form part of future models and deployments supported by the ESO DCC under this proposal. This will usher in the era of the "multi-MERMAID" with additional configurable sensors, e.g., for whale census research, and biogeochemical sensors. The ESO DCC will contribute expertise to all these future data products and tools. **SUSTECH** (Youngshun John Chen and Yong Yu) continues to be the largest and most important data partner, with the over 50 MERMAID units under their ownership followed by the ESO DCC, including in novel geographical areas (Yu et al., 2023). This proposal continues the training of their staff in fleet management and earthquake association. The ESO DCC will develop and contribute software to facilitate mantle tomography using MERMAID data, and, crucially, will shepherd their data into the EarthScope DMC.

6 Approximate Timeline. A MERMAID never sleeps. Data collection and reporting are going on as we write this. This proposal assumes the **data collection and quality analysis** tasks for the EarthScope-Oceans consortium. All are equally distributed over the years, but we anticipate **delivering data** from all MERMAIDs in our *entire* network (including from our partner institutions) at the end of each budget year, a timing coincident with our annual Consortium meeting, which we will organize as we have in prior years (2016 San Francisco, 2017 Shenzhen, 2018 Princeton, 2019 San Francisco, 2020–2022 on Zoom, 2023 in Vienna). Innovative **software tools** are continually updated on their `GitHub` pages, with periodic **doi citable releases**. The development of new data products, **training** and the handling of **user requests** will be ongoing activities. By the end of the first year we should have established a pathway for the **novel data products** into the EarthScope DMC and ISC data bases, continuing to feed those throughout Years 2 and 3.

7 Broader Impacts

This proposal focuses on data collection and quality analysis for (inter)disciplinary science done by others. It establishes the **EarthScope-Oceans** (ESO) **Data Collection Center** (DCC) as an innovative cyberinfrastructure resource, and continues the transformation of the international MERMAID arrays into a **community experiment**. Within a few hours of their surfacing, our data server makes MERMAID position data available to the public over the Web. Within a few weeks of their ingestion, the data are ready for archiving with the EarthScope DMC. The public will be able to see data availability and instrument position, which will help with planning by other science groups. With a maximum delay of two years, the **acoustic data** acquired with funding by this project will be released to the public through the EarthScope DMC. In practice, we aim for a **yearly release** of all data in December of each calendar year. The indirect **temperature measurements** and direct, deep (4,000 m) **hydrographic** conductivity-temperature-depth (CTD) **profiles** will be invaluable for the oceanographic community. The determination of **sound speed profiles** that these enable are of great importance for seafloor geodesy. Other **data products** and **software tools** will serve a wide audience. The EarthScope DMC and ISC provide detailed reports on access statistics, and MERMAID data have their own FDSN seismic network code (MH), hence all MERMAID data will be doi citable (Evans et al., 2015; Kohler et al., 2020; Staats et al., 2023), as are the periodic software releases (through `GitHub` and `Zenodo`). Hence we will report **engagement metrics** annually.

EarthScope-Oceans offers opportunities for outreach and education. The **Adopt-A-Mermaid** initiative, first proposed by PI Simons at the 2004 ORION workshop in San Juan, Puerto Rico (Schofield & Tivey, 2004), and formally launched by Géoazur in Nice in early 2017 (Bigot-Cormier & Berenguer, 2017), allows teachers of elementary and middle-school classes to follow MERMAID floats in real-time and use their data for in-house science projects. The *Adopt-A-Float* iOS app, developed by the PI with undergraduate computer science students, has been released on the Apple Store. Its development continues as part of this proposal. Besides the global classroom that can be reached via the World Wide Web, our face-to-face target audience continue to be the students of NJ-PA-area schools and their teachers. Department of Geosciences instructors Danielle Schmitt and Laurel Goodell are on hand to help with material development and to make the program available elsewhere through Princeton's QUEST teacher preparation program.

References

Allen, R. V., 1978. Automatic earthquake recognition and timing from single traces, *B. Seismol. Soc. Am.*, **68**(5), 1521–1532.

Anthony, R. E., Ringler, A. T., Wilson, D. C. & Wolin, E., 2019. 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), 219–228, doi: 10.1785/0220180251.

Babcock, J. M., Kirkendall, B. A. & Orcutt, J. A., 1994. Relationships between ocean bottom noise and the environment, *B. Seismol. Soc. Am.*, **84**(6), 1991–2007.

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

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

Bigot-Cormier, F. & Berenguer, J.-L., 2017. How students can experience science and become researchers: Tracking MERMAID floats in the ocean, *Seismol. Res. Lett.*, **88**(2A), 416–420, doi: 10.1785/0220160121.

Bonnieux, S., Mosser, S., Blay-Fornarino, M., Hello, Y. & Nolet, G., 2019, Model driven programming of autonomous floats for multidisciplinary monitoring of the oceans, in *OCEANS 2019-Marseille*, pp. 1–10, doi: 10.1109/OCEANSE.2019.8867453, IEEE.

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

Bradner, H., de Jerphanion, L. G. & Langlois, R., 1970. Ocean microseism measurements with a neutral buoyancy free-floating midwater seismometer, *B. Seismol. Soc. Am.*, **60**, 1139–1150.

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

Burky, A., Irving, J. C. E. & Simons, F. J., 2021. Mantle transition zone receiver functions for Bermuda: Automation, quality control, and interpretation, *J. Geophys. Res.*, **126**(3), e2020JB020177, doi: 10.1029/2020JB020177.

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

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

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

Evans, P., Strollo, A., Clark, A., Ahern, T., Newman, R., Clinton, J. F., Pedersen, H. & Pequegnat, C., 2015. Why seismic networks need digital object identifiers, *Eos Trans. AGU*, (96), doi: 10.1029/2015EO036971.

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

Fomel, S. & Claerbout, J. F., 2009. Guest editors' introduction: Reproducible research, *Comput. Sci. Eng.*, **11**, 5–7.

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

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

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

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

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

Harig, C., Lewis, K. W., Plattner, A. & Simons, F. J., 2015. A suite of software analyzes data on the sphere, *Eos Trans. AGU*, **96**(6), 18–22, doi: 10.1029/2015EO025851.

Hello, Y. & Nolet, G., 2020, Floating seismographs (MERMAIDS), in *Encyclopedia of Solid Earth Geophysics*, edited by H. K. Gupta, Encyclopedia of Earth Sciences, pp. 1–6, doi: 10.1007/978–3–030–10475–7_248–1, Springer, New York.

Hello, Y., Ogé, A., Sukhovich, A. & Nolet, G., 2011. Modern mermaids: New floats image the deep Earth, *Eos Trans. AGU*, **92**(40), 337–338, doi: 10.1029/2011EO400001.

Joubert, C., Nolet, G., Bonnieux, S., Deschamps, A., Dessa, J.-X. & Hello, Y., 2016. *P*-delays from floating seismometers (MERMAID), Part I: Data processing, *Seismol. Res. Lett.*, **87**(1), 73–80, doi: 10.1785/0220150111.

Kibblewhite, A. C. & Wu, C. Y., 1989. The generation of infrasonic ambient noise in the ocean by nonlinear interactions of ocean surface waves, *J. Acoust. Soc. Am.*, **85**(5), 1935–1945, doi: 10.1121/1.397847.

Kibblewhite, A. C. & Wu, C. Y., 1989. A reexamination of the role of wave–wave interactions in ocean noise generation, *J. Acoust. Soc. Am.*, **85**(5), 1946–1957, doi: 10.1121/1.397848.

Kohler, M. D., Hafner, K., Park, J., Irving, J. C. E., Caplan-Auerbach, J., Collins, J., Berger, J., Tréhu, A. M., Romanowicz, B. & Woodward, R. L., 2020. A plan for a long-term, automated, broadband seismic monitoring network on the global seafloor, *Seismol. Res. Lett.*, **91**(3), 1343–1355, doi: 10.1785/0220190123.

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

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

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

Longuet-Higgins, M. S., 1950. A theory of the origin of microseisms, *Phil. Trans. R. Soc. London, Ser. A*, **243**(857), 1–35, doi: 10.1098/rsta.1950.0012.

Nakata, N., Gualtieri, L. & Fichtner, A., 2019. *Seismic Ambient Noise*, Cambridge Univ. Press, Cambridge, UK.

Namjesnik, D., Sigloch, K., Bonnieux, S., Hello, Y., Storchak, D., Simons, F. J., Simon, J. D., Harris, J. & Garth, T., 2023. 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*.

Nolet, G., Hello, Y., van der Lee, S., Bonnieux, S., Ruiz, M. C., Pazmino, N. A., Deschamps, A., Regnier, M. M., Font, Y., Chen, Y. J. & Simons, F. J., 2019. Imaging the Galápagos mantle plume with an unconventional application of floating seismometers, *Sci. Rep.*, **9**, 1326, doi: 10.1038/s41598–018–36835–w.

Nolet, G., Simon, J. D. & Bonnieux, S., 2023. How accurately are MERMAID seismograms located?, *Seismol. Res. Lett.*, p. submitted.

Okal, E. A., Talandier, J. & Reymond, D., 2007. Quantification of hydrophone records of the 2004 Sumatra tsunami, *Pure Appl. Geophys.*, **164**, 309–323, doi: 10.1007/s00024–006–0165–4.

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

Pipatprathanporn, S. & Simons, F. J., 2023. Waveform modeling of hydroacoustic teleseismic earthquake records from autonomous MERMAID floats, *Geophys. J. Int.*, p. submitted.

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

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

Roemmich, D., Johnson, G. C., Riser, S., Davis, R., Gilson, J., Owens, W. B., Garzoli, S. L., Schmid, C. & Ignaszewski, M., 2009. The Argo program: Observing the global ocean with profiling floats, *Oceanography*, **22**(2), 34–43, doi: 10.5670/oceanog.2009.36.

Schofield, O. & Tivey, M. K., 2004, A report of the workshop held January 4–8, 2004, San Juan, Puerto Rico, Tech. rep., ORION: Ocean Research Interactive Observatory Networks.

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

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

Simon, J. D., Simons, F. J. & Irving, J. C. E., 2021. A MERMAID miscellany: Seismoacoustic signals beyond the P wave, *Seismol. Res. Lett.*, **92**(6), 3657–3667, doi: 10.1785/0220210052.

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

Simon, J. D., Yu, Y., Obayashi, M., Simons, F. J. & Irving, J. C. E., 2023. Hunga Tonga-Hunga Ha'apai—as heard by MERMAID, *Geophys. J. Int.*, p. submitted.

Simon, J. D., Yu, Y., Obayashi, M., Sugioka, H., Simons, F., Irving, J. C. E. & Consortium, T. E.-O., 2023. 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.*.

Simons, F. J., Dando, B. D. E. & Allen, R. M., 2006. Automatic detection and rapid determination of earthquake magnitude by wavelet multiscale analysis of the primary arrival, *Earth Planet. Sci. Lett.*, **250**(1–2), 214–223, doi: 10.1016/j.epsl.2006.07.039.

Simons, F. J., Nolet, G., Babcock, J. M., Davis, R. E. & Orcutt, J. A., 2006. A future for drifting seismic networks, *Eos Trans. AGU*, **87**(31), 305 & 307, doi: 10.1029/2006EO310002.

Simons, F. J., Nolet, G., Georgief, P., Babcock, J. M., Regier, L. A. & Davis, R. E., 2009. On the potential of recording earthquakes for global seismic tomography by low-cost autonomous instruments in the oceans, *J. Geophys. Res.*, **114**, B05307, doi: 10.1029/2008JB006088.

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

Staats, M., Aderhold, K., Hafner, K., Dalton, C., Flanagan, M., Lau, H., Simons, F. J., Valée, M., Wei, S. S., Yeck, W., Frassetto, A. & Busby, R., 2023. Inconsistent citation of the Global Seismographic Network in Scientific Publications, *Seismol. Res. Lett.*, p. doi: 10.1785/0220230004.

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

Sukhovich, A., Irisson, J.-O., Perrot, J. & Nolet, G., 2014. 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), 6469–6485, doi: 10.1002/2013JB010936.

Sukhovich, A., Bonnieux, S., Hello, Y., Irisson, J.-O., Simons, F. J. & Nolet, G., 2015. Seismic monitoring in the oceans by autonomous floats, *Nat. Commun.*, **6**, 8027, doi: 10.1038/ncomms9027.

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

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

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

Tepp, G. & Dziak, R. P., 2021. The seismo-acoustics of submarine volcanic eruptions, *J. Geophys. Res.*, **126**(4), e20912, doi: 10.1029/2020JB020912.

Thurin, J., Tape, C. & Modrak, R., 2022. Multi-event explosive seismic source for the 2022 M_{w} 6.3 Hunga Tonga submarine volcanic eruption, *The Seismic. Rec.*, **2**(4), 217–226, doi: 10.1785/0320220027.

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

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

Webb, S. C., 1998. Broadband seismology and noise under the ocean, *Rev. Geophys.*, **36**(1), 105–142, doi: 10.1029/97RG02287.

Winant, C. D., 1974. The descent of neutrally buoyant floats, *Deap-Sea Res.*, **21**, 445–453.

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

Wu, F. V., Borisov, D., Simons, F. J. & Williamson, P., 2021, Waveform inversion for shear velocity and attenuation via the spectral-element adjoint method, in *SEG Tech. Prog. Expanded Abstracts*, pp. 697–701, doi: 10.1190/segam2021–3581151.1, Soc. Explor. Geophys., Denver, Col.

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

Yu, Y., Chen, Y. J., Guo, Z. & Ge, Z., 2023. Long-term seismic network in South China Sea by floating MERMAIDs, *Sci. China Earth Sci.*, **66**, 1979–1993, doi: 10.1007/s11430–022–1100–3.

Zhang, Z., Irving, J. C. E., Simons, F. J. & Alkhalifah, T., 2023. Seismic evidence for a 100 km mantle discontinuity under the Pacific, *Nat. Commun.*, **14**, 1714, doi: 10.1038/s41467–023–37067–x.

Zheng, Y., Hu, H., Spera, F. J., Scruggs, M., Thompson, G., Jin, Y., Lapen, T., McNutt, S. R., Mandli, K., Peng, Z. & Yuen, D. A., 2023. Episodic magma hammers for the 15 January 2022 cataclysmic eruption of Hunga Tonga-Hunga Ha'apai, *Geophys. Res. Lett.*, **50**(8), e2023GL102763, doi: 10.1029/2023GL102763.