A Future for Drifting Seismic Networks

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Earth models in which seismic wave speeds vary only with depth are sufficiently well constrained to accurately locate earthquakes and calculate the paths followed by seismic rays [*Engdahl et al.*, 1998]. The differences between observations and theoretical predictions of seismograms in such one-dimensional Earth models can be used to reconstruct the three-dimensional (3-D) wave speed distribution in the regions sampled by the seismic waves by a procedure known as seismic tomography, a technique akin to medical CAT scanning.

Caused by thermal, compositional, and textural variations, wave speed anomalies remain the premier data source to fully understand the structure and evolution of our planet [*Romanowicz*, 2003], from the scale of mantle convection and the mechanisms of heat transfer from core to surface to the interaction between the deep Earth and surface processes such as plate motion and crustal deformation.

Unequal geographical data coverage continues to fundamentally limit the quality of tomographic reconstructions of seismic wave speeds in the interior of the Earth. Only at great cost can geophysicists overcome the difficulties of placing seismographs on the two thirds of the Earth's surface that is covered by oceans [*Romanowicz and Giardini*, 2001]. The lack of spatial data coverage strongly hampers the determination of the structure of the Earth in the uncovered regions. Thus, all 3-D Earth models are marked by blank spots in areas, distributed throughout the Earth, where little or no information can be obtained (Figure 1).

Remediating this problem requires the observation of seismic waves in the oceans. Sonobuoys [*Reid et al.*, 1973] have had success in the past in recording local earthquake signals, but they have been too noisy to provide an acceptable signal-to-noise ratio for all but the strongest earthquakes [*Kebe*, 1981; *Cotaras et al.*, 1988]. Ocean bottom seismometers (OBS) [*Zhao et al.*, 1997; *Laske et al.*, 1999; *Stephen et al.*, 2003] and moored hydrophones [*Smith et al.*, 2004] are capable of addressing the coverage gap, but they are expensive to manufacture (~US$50,000 for a three-component OBS) and deploy (~$20,000 per day of ship time). Unable to communicate their recordings remotely without prohibitively expensive cabling, stationary underwater devices have to be retrieved at regular intervals for the data to be analyzed in the computer lab.

As a possible solution to gaining equal geographic data coverage, a prototype of a mobile receiver that will serve as a floating seismometer has recently been developed. This type of instrument could provide an easy, cost-effective way to collect seismic data in the ocean. The raw test data described in this paper were obtained in 2003 and 2004, but technical difficulties prevented their analysis. A grant obtained from the United Kingdom's Natural Environment Research Council (NERC) in 2005 allowed these problems to be addressed. This article may serve to alert the international community of the progress made in this field.

Design of a Mobile Receiver

Oceanographers have designed robotic floating instruments, floats that spend their lives at depth but surface periodically, using a pump and bladder, to make temperature and salinity profile measurements. Such low-cost (~$15,000) Sounding Oceanographic Lagrangian Observers (SOLO) [*Davis et al.*, 2001] can be equipped with a hydrophone to record water pressure variations induced by compressional (*P*) waves. Untethered and passively drifting, such a floating seismometer would surface upon detection of a useful (for global tomography) seismic event, determine a GPS (global positioning system) location, and transmit the waveforms to a satellite. The surfacing speed guarantees a location accuracy of the float at depth to within a few hundred meters. Operating costs are minimal: Their autonomy and low weight guarantee easy deployment from any vessel, and the data would be available in real time; what is left is the price of a satellite subscription.

However, design challenges are formidable because, pending alternative means of power generation, the success of the device depends on how long it can last before its batteries run out or before corrosion and barnacles take over. Life span is critically dependent on limiting power consumption by using a minimum of numerical operations to perform the detection and identification of the waveforms. Recent advances in signal processing have allowed this bottleneck to be addressed: Tests have demonstrated the success of so-called second-generation wavelets [*Sweldens*, 1996] to provide useful sensitivity and discriminating power, even in the presence of high levels of contaminating noise. Second-generation wavelets are no longer constructed from the Fourier transform, which leads to extremely fast and versatile algorithms. Interestingly, in an entirely different context, virtually identical algorithms can serve to trigger earthquake-damage warnings from seismometers on land [*Simons et al.*, 2006].

Proof of Concept

The prototype is nicknamed MERMAID, for 'mobile earthquake recorder in marine areas by independent divers' (Figure 2). The great promise of this technology was demonstrated by the prototype on its maiden voyage, 4–6 November 2003. A second test was conducted 11–12 September 2004. Submerged, and freely drifting for about 30 hours at 700 meters below the sea surface, in a canyon off the coast of La Jolla, Calif., MERMAID recorded a very promising signal, coming from a relatively faint (in global seismological terms) magnitude 6 earthquake near the west coast of Colombia, about 5000 kilometers away. Earthquakes of a magnitude larger than this occur at a rate of about 200 per year. The recording (Figure 3) shows a clear incoming *P* wave whose precise arrival time can be determined to within a fraction of a second. The demonstrated high sensitivity of the MERMAID platform clearly illustrates its likely contributions to global seismic tomography.

In addition to recording teleseismic *P* waves, such a system would pick up trapped waves propagating in the SOFAR (Sound Fixing and Ranging) channel. Such hydroacoustic phases are known as *T* waves. Although *T* waves have limited applicability for global tomographic studies, they have been shown to be useful in their own right, e.g., for studying the mechanisms of large, tsunamigenic earthquakes such as the 26 December 2004 Sumatran earthquake [*de Groot-Hedlin*, 2005].

The Future of Oceanic Data Collection

A worldwide array of MERMAID floating hydrophones, on the scale of the current international land-based seismic arrays, has the potential to progressively eliminate the discrepancies in spatial coverage resulting in poorly resolved seismic Earth models.

Through the development of the large-scale international Argo project (see http://www.

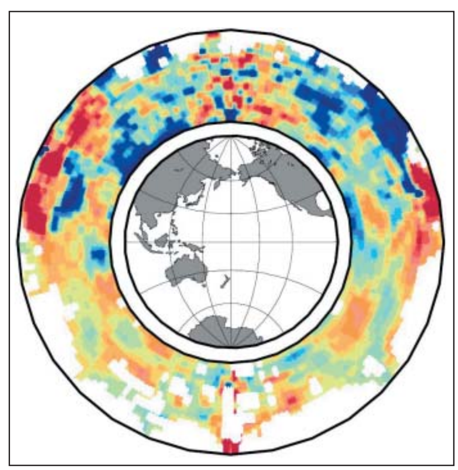

Fig. 1. Holes in the mantle: An example of poor resolution of mantle structure in the Southern Hemisphere and elsewhere due to the absence of seismic stations in the oceans. A polar cross section through a P *wave speed anomaly model [*van der Hilst et al., *1997] shows undersampled regions in white [*Boschi and Dziewonski, *1999].*

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argo.ucsd.edu), oceanographers have provided a clear model for emulation by the seismological community. As of August 2006, there were upward of 2500 SOLO floats measuring conductivity, temperature, and depth throughout the Earth's oceans, to understand and forecast climate. Added to future generations of the Argo project, MERMAID's regular resurfacings would provide useful corollaries to other disciplines, such as average current speeds at depth, spot depth soundings, and, with the ongoing miniaturization of marine technology, an additional payload of low-power instruments only limited by the imagination.

The future deployment of instruments like MERMAID will greatly aid with imaging the unmapped portions of the interior of the mantle. Many of the important dynamic processes in the deep Earth, in particular large-scale mantle upwellings known as plumes, seem located beneath the larger oceans in the Southern Hemisphere. The current absence of seismic observations in the southern oceans severely limits the ability to study these processes. Does the Earth's mantle convect as a whole, or is it layered? What is the contribution of mantle plumes to the transport of heat to the Earth's surface? What is the scale of mantle heterogeneity, and how does it originate? What are the nature and role of geochemical reservoirs? Is there an undifferentiated reservoir in the lowermost mantle? These questions, fundamental to Earth science, will only be answered once scientists can image the deep Earth with oceanic recordings from instruments such as MERMAID.

Seismic tomography provides primary models that are subsequently interpreted in an Earth systems framework involving geology, geodynamics and geochemistry. New developments in seismic theory improve mantle models in areas away from seismic rays. Ultimately, though, instruments in the right places will recover the data presently missing.

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Fig. 2. The MERMAID prototype. The hydrophone protrudes from the middle right. Thousands of similar drifters, though none capable of detecting earthquake signals, are currently afloat the seven seas in an effort to map the temperature and salinity of the upper 2000 meters of the ocean.

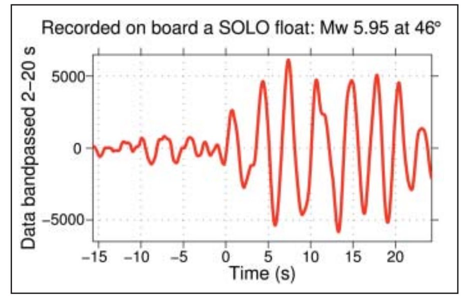

Fig. 3. The clear onset of a P *wave from a magnitude 6.0 earthquake at a distance of 46 degrees detected by the hydrophone on board the experimental MERMAID float on its trip adrift 700 meters below the sea surface. The waves from this teleseismic earthquake have sampled a hitherto uncharted volume of the Earth's mantle.*

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