Seismic Observatories in Ocean Boreholes

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Introduction

The Sumatra-Andaman Earthquake of Dec. 2004 literally shook the world for days and caused Indian Ocean-wide tsunami disasters tolling over 230,000 lives and infrastructures for everyday life. This event is the largest earthquake since the seismological world has gone digital and has been linked over the Internet. Still, life-saving information of tsunami attacks did not reach people living near the coast. Clearly, there are immediate needs to establish a practical tsunami warning system in the Indian Ocean area and other areas in need. In a longer term, we need capabilities to precisely predict what to expect after a major rupture is initiated. A super computer at the top end is now capable of calculating seismic waves traveling through out the Earth as a whole. However, the computer simulation does not reproduce the actual observations. This means that linking the cause (earthquake) and effect (ground shaking) requires further refinement. This is a seismological problem and requires a 3-D model of the Earth at a higher resolution so that useful information can be delivered to people in danger. This requires ocean observatories (Figure 1).

The global coverage of seismic stations over the land area in the '60s and its shift to digital and broadband mode since the '80s considerably expanded the observational window to gather more useful information and enabled scientists to view the Earth in 3-D and interpret the seismological properties as dynamic properties such as mantle convections or plate motions. However, in reality the lack of seismic stations in the oceans is obstructing refining such views because oceans and continents behave differently beneath them deep into the Earth. For example, how do the plates and mantle convection couple? How does the plate subduction affect the seismic coupling and magma generation in areas like the Ring of Fire? Many more important questions remain unanswered and unverified.

We have been making steps towards establishing such stations and we are still in the experimental stage. However, the results so far show promising signs

will ?
should ?

so that ~~the~~ seismology would again experience a decade of rapid advancement through expansion of ocean seismic stations. In the following, we show where we are and our visions of future networking.

ION Vision and Pilot Experiments

The international scientific community recognizes the importance of establishing long-term ocean observatories through international coordination and cooperation. The International Ocean Network (ION) was formed in 1993 to foster synergies among different disciplines requiring long term observations in the ocean, to facilitate cooperation in the development of critical elements of observing systems, to encourage standards and best practices for shared maintenance of observatories, to develop common plans for the use of international resources, to encourage the timely exchange of data, and to coordinate location plans (www.deos.org/ion for more information). Multidisciplinary approach and multiple-purpose are considered important factors to bear in mind when constructing ocean network nodes (Figure 2).

Its actual implementations are a very difficult task due, firstly to the environmental hostile conditions prevailing at the bottom of the ocean, of secondly to the difficulty ~~to~~ maintaining stable long-period observations to V retrieve data in a timely manner, and to supply power continuously ~~for a long~~ ~~period of~~ time. Different workshops call for a three-phase approach (Purdy and Dziewonski, 1988; Lancelot and Montagner, 1995). In phase 1 (now completed), pilot experiments are proposed to address the fundamental problems of sensor coupling in holes, noise, devising solutions for power, data retrieval, and V reliability on a ~~the~~ multiple year time scale. In phase 2, a small number of prototype observatories are installed, immediately contributing data to the seismological community. Phase 3 would be the global network realization.

Earliest attempts to install ocean borehole seismographs were made by groups in USA between 1979 and 1982 before the era of digital broadband sensors during DSDP. Developments of digital and broadband stations occurred during ODP. Several groups in Japan, France and USA started preliminary experiments focused towards the goal of the installation of permanent seismic stations. These included the Japanese test in Hole 794D in 1989 in the Japan Sea

only borehole ?

Spell out

(Kanazawa et al., 1992; Suyehiro et al., 1992), the French SISMOBS seismometer test in 1992 at Hole 396B near the Mid-Atlantic Ridge (Beauduin et al., 1996; Montagner et al., 1994). The Japan Sea experiment recorded teleseismic events and obtained ~~the~~ broadband seismic noise spectra verifying ~~the~~ that ocean boreholes require the most sensitive sensor to be installed (Kanazawa et al., 1992).

In May 1992, the French pilot experiment OFM/SISMOBS was successfully conducted in the North-Atlantic Ocean and two sets of most sensitive broadband seismometers were installed inside and beside the DSDP Hole 396B (23°N, 43.3°W), operated for more than one week and recovered (Montagner et al., 1994). The experiment ~~made it necessary~~ required the simultaneous use of the oceanographic vessel NADIR, of the submersible NAUTILE, and the re-entry logging system NADIA. It was observed that the amplitude of noise decreased systematically and rapidly for the borehole sensor at long periods (>50s), which was not the case for the seafloor buried sensor. It was deemed that a longer duration experiment was desirable.

A more comprehensive test was the Ocean Seismic Network Pilot Experiment in 1998 which compared seafloor, shallow buried and borehole broadband seismometers at the same location (Site 843, SW of Oahu) for a duration of four months (Collins et al., 2001; Stephen et al., 2003; Sutherland et al., 2004). All three systems were exposed simultaneously to the same ambient noise environment and acquired data for the same earthquake events. The most meaningful test of the three configurations is a comparison of earthquake event detectability (Sutherland et al., 2004). They concluded that although burying a broadband sensor gave considerable improvement over a seafloor sensor at low frequencies, the best detector across the spectrum for teleseismic P, teleseismic S, Rayleigh and Love waves was the borehole sensor. In fact, the borehole seismometer outperformed the GSN station (KIP) on Oahu in all cases (Stephen et al., 2003). The borehole sensor was estimated to be able to detect teleseismic P-waves from earthquakes down to M (magnitude) 4.3 and to detect teleseismic S-waves and surface waves from earthquakes down to M 4.0.

Recent Developments and Findings

Table 1 summarizes eight sites that were identified for prototype stations

~~Table 1 summarizes eight sites that were identified for prototype stations~~ by ION during ODP (1998-2003). All of the sites drilled are thoroughly documented in the ODP literature.

Two boreholes were instrumented in the Japan Trench, JT-1 and JT-2 and one borehole each was instrumented in the Philippine Sea (WP-1) and the Northwest Pacific (WP-2) (Figure 3). These four sites, installed and maintained by Japanese scientists under their Ocean Hemisphere Network Project (1996-2001), use autonomous, battery powered recording and data packages are retrieved by ROV (Shinohara et al., 2002; Suyehiro et al., 2002) (Figure 4). There are cables near JT-1, JT-2, and WP-1 that could be used for power and data telemetry in future developments at these sites.

In order to understand the consequences of plate subduction, the data from land stations are ~~would be~~ insufficient simply because they cannot cover the fault zone. For example, across Northern Japan, the land covers only a portion of the whole plate subduction zone. Furthermore, large interplate earthquake slips occur basically seaward of the coastline. Therefore, it is necessary ~~requisite~~ that there be permanent offshore stations to monitor seismicity and crustal deformation (Sacks et al., 2000). Thus for JT sites, tiltmeters and strainmeters were also included in the installation. The installed tiltmeter measures the tilt of the ground to nanoradians (1 nanoradian is 1 mm tilt over 1000 km). The strainmeter measures down to picostrains (rocks fracture at 10^{-4}-10^{-5} strain).

Figure 5 summarizes ambient noise spectra from all of the broadband borehole seismic installations that have been instrumented so far (Shinohara et al., 2006). Except at very low frequencies on the horizontal channels of two stations the seafloor borehole spectra fall within the high and low noise models based on land stations. Ambient noise at seafloor stations is not in general noisier than at continental or island stations as previously suspected. At some frequencies some of the seafloor borehole stations are as quiet as the quietest land stations. Figure 6 schematically shows how borehole sensors can perform better than ~~superior to~~ seafloor sensors. However from the past borehole installations had important lessons had to be learned to properly emplac~~ing~~e highly sensitive sensors in boreholes so that they perform up to their expectations. Briefly summarized, boreholes are significantly quieter than ocean floor installations (even buried ones) at body wave frequencies, because they avoid signal generated noise from reverberations in the soft sediment layers. When properly installed, boreholes are also significantly quieter at low frequencies (surface wave and free oscillation band) because the sensors are less affected by tilts due to ocean currents (Araki et al., 2004).

Building a network in the oceans and accumulating natural earthquake data takes persistent effort and time. We show some recent preliminary results below to claim (demonstrate?) that the scientific reward will accelerate with increasing network density. The data from WP1 station in the middle of the Philippine Sea plate (Table 1) were used ~~for~~ to look~~ing~~ at mantle discontinuities immediately below (Suetsugu et al., 2005). Such velocity jumps are created by mineral phase changes caused by temperature and pressure conditions. They suggested lower-than-normal temperature at ~~the~~ boundary between upper ~~mantle and~~ lower mantle, ~~boundary~~ at around 660 km depth, caused by the cold subducted Pacific plate unable to penetrate down to lower mantle.

The data from WP2 show that M4.5 earthquakes can be clearly recorded similar to OSNPE result. There are modes (phases) of P and S waves that travel in the lithosphere for long distances and WP2 in its unique position to record seismic waves ~~with~~ for pure oceanic paths. It was found that such S phases persist~~ed~~ to 2500 km distance (Araki et al., 2003) (Figure 7). Explaining such arrivals requires several percent faster upper mantle than standard models. Furthermore, evidence from surface waves indicates meaningful discrepancies from the model constructed above. Reconciling these with uncertainties in mantle heterogeneities and anisotropy requires further data accumulation with more stations in the ocean. These results are strong indicators that our knowledge of mantle structure beneath the oceans still must be considered as largely unconstrained.

Observing the Earth from the Oceans

A modest network of high quality broadband stations in the deep ocean far from any accessible landmasses can go a long way towards addressing such important issues. The current spatial resolving power of global mantle tomographic models is reaching 1000 km in lateral extent. As resolving power improves more attention is given to the details that are critical in understanding ✓ how the Earth developed into its present day configuration in terms of physics and chemistry and further linking with geological understanding of the Earth's history.

? Figure 8 is a an first attempt to propose a set of sites, which fill the most important gaps in the ocean coverage not only for seismology but other oceanographic disciplines as well. Not all sites are equally important for all seismic studies. For example, the mid-Atlantic site (DSDP Site 396B) does not improve the already adequate coverage for surface waves but provides a valuable geometry for body-waves sampling both upper and lower mantles. It will be necessary for specific site proposals to take into account the broad spectrum of scientific problems being addressed, and the actual distribution of earthquake sources. It must be noted that all of the proposed sites in Figure 5 8 ? are also gaps for geomagnetic and geodetic observatories and that the possibility of sharing sites is strongly encouraged.

Although the data acquisition has occurred over too short a span to lead to significant discoveries yet, the pilot experiments have demonstrated that ocean floor stations can provide useful data for global seismological investigations. It is the results from these Phase 2 stations that have encouraged global seismologists to be excited about extending their networks to the seafloor and the global seismic community is among the strongest supporters behind the new Integrated Ocean Drilling Program and OOI/ORION, ESONET, or ARENA/DONET being planned in USA, Europe, and Japan.

Acknowledgements

Establishing long-term seismic observatories in ~~the~~ ocean boreholes is truly a new venture that involves many experiments and tests and developments after developments. So many people around the globe put their minds and times into various national but internationally coordinated efforts that it is impossible to list them as individuals. We believe that these endeavors by scientists, engineers, ship officers and crew, program managers, and all those who have had a part will lead to the emergence of a new view of the Earth from the oceans.

Figure Captions

Figure 1: NERO (Ninety-East Ridge Observatory) site was drilled by ODP 179 and awaits instrumentation for the first borehole observatory in the Indian Ocean.

Figure 2: Multi-disciplinary and multi-parameter observatory conceived by French group.

Figure 3: Location of Ocean Hemisphere Project observatories in the western Pacific. Stations are spaced at about 1000 km distance. Orange circles are the borehole stations, from which more than a few years' data have been obtained. IRIS is the Incorporated Institutes for Seismology, USA.

Figure 4: Observation platform at JT1 borehole observatory viewed from JAMSTEC ROV (remotely operated vehicle) "Hyper Dolphin", which is one of the ROVs that maintain the Japanese borehole stations.

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Figure 5: Comparison of ambient seismic noise~~s~~ among the borehole stations that operated. a) Vertical component. b) Horizontal component. See Table 1 for station identifications. HNM and LNM are the high and low noise models accepted by the seismological community. There is no horizontal record for OFP. See text for actual comparison. Since each installation differs in many aspects, it is important to recognize ~~each~~ the specific conditions~~.~~ of each.

Figure 6: Schematic view of how borehole sensors can outperform seafloor sensors.

Figure 7: Seismogram examples obtained at WP2 in the NW Pacific Ocean. See text for explanation.

Figure 8: This figure summarizes the role of ocean borehole sites in global seismic coverage. The grey shaded regions indicate the surface coverage out to 1000 km from continent and island stations. White spaces are gaps in the land based coverage. Existing and proposed ocean stations for global coverage are indicated by symbols surrounded by black circles at approximately 1000km radius. The different symbols show different levels of progress at the ocean sites: red star - the Mid-Atlantic Ridge test site, blue stars - presently operating borehole observatories (the Japan Trench regional sites are not shown), maroon stars - sites at which boreholes have been drilled but have not yet been instrumented, solid and open black circles -