Global Siting Plan for Borehole Geophysical Observatories in the International Ocean Network

1. Introduction

This proposal presents the scientific goals and the global siting plan for borehole geophysical observatories as planned in the framework of the International Ocean Network (ION). The focus is on sites that will extend the global broadband seismic network to the ocean floor in order to achieve more uniform coverage on the surface of the Earth for global structure and earthquake/seismicity studies. In many cases such sites will be collocated with complementary sensors on the seafloor and in the water column (e.g. geomagnetic, oceanographic) that would benefit from shared power and telemetry infrastructure, logistical support, and spatial/temporal sampling requirements. ION supports other observatory sites that are not discussed here which include boreholes used for local and regional geophysical studies (for example active margins) as well as sites for other long-term measurements that do not require boreholes. Boreholes are only one aspect of the infrastructure required for seafloor geophysical observatories and it will be necessary to coordinate specific siting plans and schedules with other organizations that are responsible for logistical support, observatory power, telemetry and data-logging.

Information on ION (complete charter, history, steering committee representatives, objectives, recommendations from planning meetings, etc) can be found at the ION web site (www.deos.org/ion).

ION supports at least three classes of observatories centered around seafloor boreholes: 1) permanent borehole observatories distributed around the globe to accomplish uniform coverage for global Earth studies, 2) regional observatories to address long-term time-dependent processes associated with active plate boundaries and local seafloor processes, and 3) test sites (for example, OSN-1). This document will focus primarily on borehole observatories to complete world wide seismic coverage. However ION is also supportive of such initiatives as a) the NantroSeize project, which already has an established drilling proposal, b) long-term borehole installations for local and regional hydrothermal studies (e.g., CORKS) and c) efforts to establish test facilities for seafloor observatories (with or without boreholes, for example MARS).

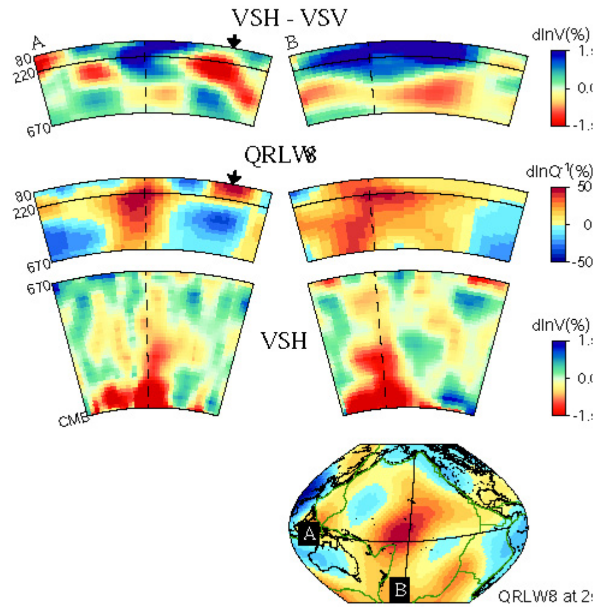

Figure 1. Bottom panel: Map view of attenuation model QRLW8 [*Romanowicz and Gung*, 2002] centered on the high attenuation peaks in the Pacific. Top panels: Depth cross-sections along profiles indicated in the bottom panels showing, for each profile (top to bottom), distribution of transverse anisotropy $(V_{SH} - V_{SV})/V_{SH}$, attenuation in the upper-mantle, and V_{SH} in the lower mantle. The location of the East Pacific Rise is indicated by the arrows. Note the position of the high attenuation regions in the transition zone above the lowermost mantle low velocity minima. Zones of positive $(V_{SH} - V_{SV})/V_{SH}$ in the uppermost mantle (blue) correspond to zones where the high attenuation regions are shifted horizontally with respect to their transition zone location.

The ION web site contains a list of quotations from planning meetings and workshop reports which emphasize the importance of seafloor borehole observatories. Some examples are:

- " A grand challenge of the twenty-first century will be to map the structural geology of Earth's deep interior and characterize how this dynamic region has functioned throughout geologic time. To what extent are hotspot island chains produced by plumes rising from the core-mantle boundary? Do subducting slabs pond at the base of the mantle? Although the convecting mantle and core are inaccessible to the drill bit, **ocean drilling will be essential for the installation of sub-seafloor seismic observatories needed to create a globally complete image of the lateral heterogeneity of the interior**. With technology currently available to the drilling program, it is possible to drill the boreholes necessary to install seismic observatories. In order to obtain global coverage, some of these boreholes will need to be in the extreme high latitudes of the Southern Ocean, where operations are very difficult." (Our bold font) (pages xiv-xv of [*JOI Inc.*, 1999])
- "To achieve that end, IODP will work with the International Ocean Network (ION) to install borehole seismometers to fill gaps in the Global Seismic Network, thereby improving the accuracy and resolution of global mantle tomography." (page 62 of [*Integrated Ocean Drilling Program*, 2001])

- "The ability to drill boreholes for the installation of sub-seafloor instruments will also be an essential requirement" (for seafloor observatories). (in the chapter on "Dynamics of oceanic lithosphere and imaging Earth's interior" on page 53 of [*Committee on Seafloor Observatories: Challenges and Opportunities*, 2000])

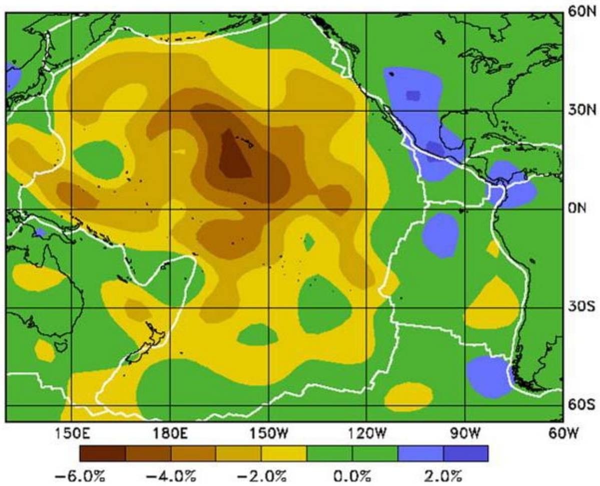

Figure 2. Variations in polarization anisotropy (V_{SH}-Vsv)/V_{SH} in percent) at 150 km depth under the Pacific ocean [*Ekström and Dziewonski*, 1998].

2. Scientific Rationale for Long Term Geophysical Seafloor Borehole Observatories

A white paper on the scientific rationale for long term geophysical seafloor borehole observatories is available on the ION website (www.deos.org/ion). In the following section we outline the highlights which apply specifically to global seismic coverage.

It is an inescapable fact that land masses are distributed unevenly on the Earth's surface. Consequently there is much denser sampling of the northern hemisphere, with particularly poor coverage in the central parts of the largest oceans. 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 detailed features of the models. Important issues include:

- **The character of the spectrum of lateral heterogeneity at various depths in the mantle.** This is important to constrain the convective regime of the mantle, since the configuration of convective cells will determine the spectral level of thermal heterogeneity in different depth ranges.

- Whether and where lithospheric slabs penetrate into the lower mantle? This question can only be resolved if the heterogeneity in the mantle can be determined with confidence at scale lengths smaller than 1000 km in a global sense.

- **What is the role of tectonic plates in the global deep circulation?** A controversial issue is, for example, the depth extent of mid-ocean ridges: are mid-ocean ridges directly related to the main upwellings of global mantle circulation, or are they passive features towards which the flow is driven by plate divergence?

- **What is the origin of hotspots and their role in the global circulation**? Current large-scale seismic models cannot resolve the deep structure of the numerous hotspots present across the oceans, fueling a vigorous debate on the origin of hotspots - are they shallow features, or do they originate in the lower or lowermost mantle? More generally, the nature of the south Pacific

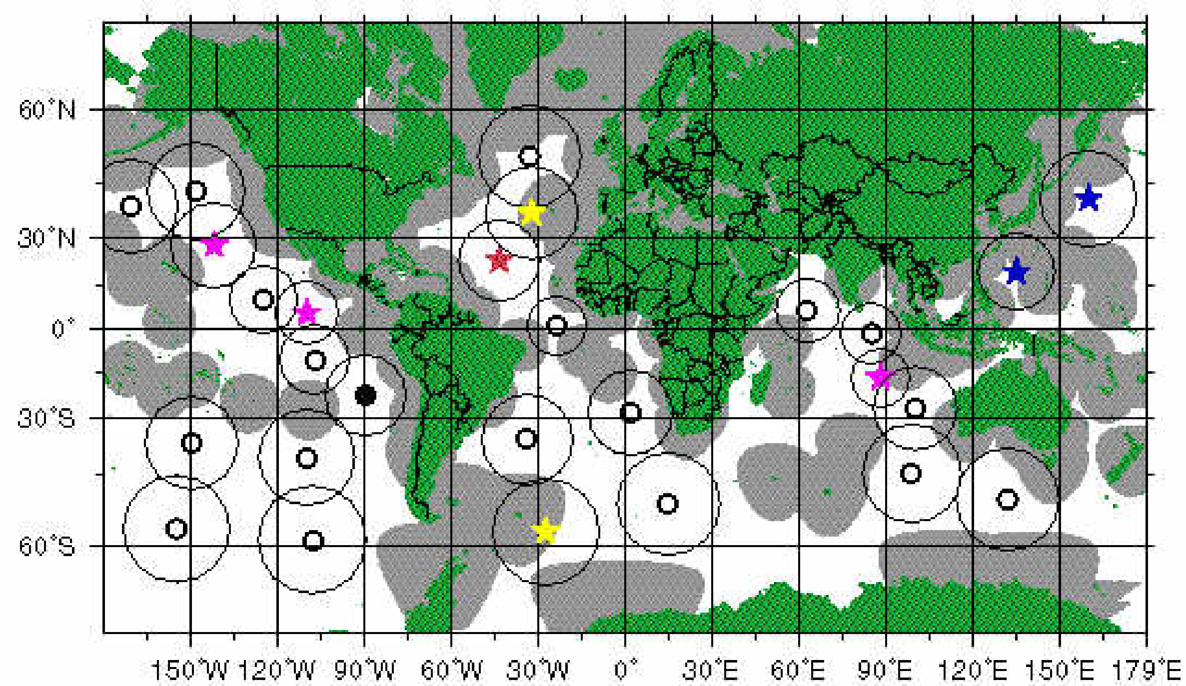

Figure 3: This figure summarizes the role of ocean borehole sites in global seismic coverage. The grey shaded regions indicate the surface coverage out to 1000km from continent and island stations. (These are distorted in the projection.) White spaces are gaps in the land based coverage. Existing and proposed ocean stations (Tables 1 and 2) are indicated by symbols surrounded by the black circles (at approximately 1000km radius). The different symbols show the different levels of progress at the ocean sites: red star - MAR test site (OSNPE and Japan Sea test sites not shown), blue stars - presently operating borehole observatories (Japan Trench regional sites are not shown), maroon stars - sites drilled but not yet instrumented, solid black circle - proposed phase 2 site which is not yet drilled, small open circles - phase 3 sites, yellow stars - phase 3 B-DEOS global sites (Reykjanes Ridge and Drake Passage B-DEOS regional sites are not shown). [*Butler*, 1995; *Purdy and Dziewonski*, 1988]

"superswell", its concentration of hotspots, and its relation to mantle dynamics is still poorly understood. High attenuation, indicative of a high-temperature anomaly, can be traced in the uppermost mantle under the central Pacific, extending roughly over the region of strong transverse isotropy (Figure 1), and is suggestive of significant lateral flow in the asthenosphere.

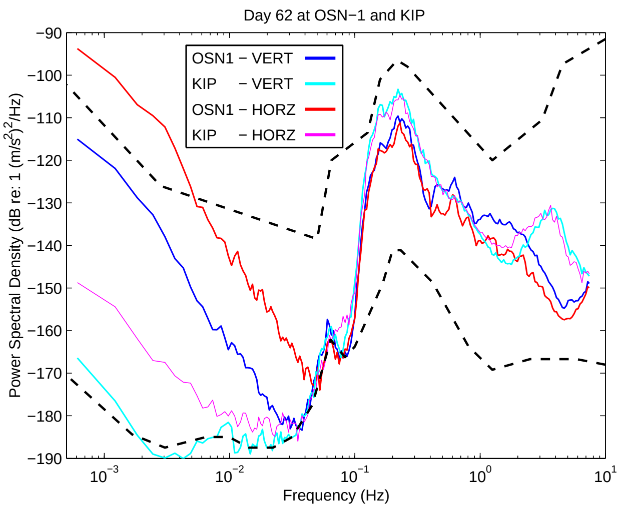

Figure 4: A comparison between the borehole sensor at OSN-1 and the GSN-GEOSCOPE station at Kipapa for the same time interval shows comparable noise levels from 0.03 to 1.5Hz on both vertical and horizontal components. This contradicts the assertion that seafloor stations should be noisier than island stations at short periods by up to 20dB. In fact, above 1.5Hz the seafloor station is about 20dB quieter than the island station, the latter being affected by cultural noise. Also the microseism peak itself is up to 6dB quieter in the oceanic basement at OSN-1 than at Kipapa. Below 0.01Hz on the horizontal component and below 0.03Hz on the vertical component the island station is considerably quieter than the seafloor borehole station. The borehole station appears to be subject to installation noise and is not responding to true Earth noise. Except for the horizontal components in the infra-gravity band, the noise levels for the seafloor borehole sensor fall within the USGS high and low noise models (dashed black lines).

However, the resolution available from the global network data is again very poor, limited for attenuation to degrees 8 and lower (about 2500km).

- **Upper mantle anisotropy.** Does upper-mantle anisotropy reflect the current flow pattern in the mantle or ancient flow "frozen" during the formation of the lithosphere? The current distribution of shear wave splitting measurements in the oceans is limited to islands, which have a clearly anomalous underlying local structure. The thickening with age of the oceanic lithosphere is itself being questioned: it is not equally visible in Rayleigh and Love fundamental-mode surface-wave data, as the signal is complicated by the presence of significant transverse isotropy, with horizontally polarized S waves traveling faster than vertically polarized ones, in the central Pacific [*Ekström and Dziewonski*, 1998] (Figure 2).

- **The style of mantle convection.** It is still a matter of controversy whether the primary circulation in the mantle involves the entire mantle in a "1 layer" system, or whether the upper and lower mantle convect separately.

- **Structure at the core-mantle boundary (CMB).** Evidence for significant and laterally complex anisotropy in the D" region has been accumulating, particularly in the Pacific Ocean, but further characterization of this anisotropy is not possible with the present distribution

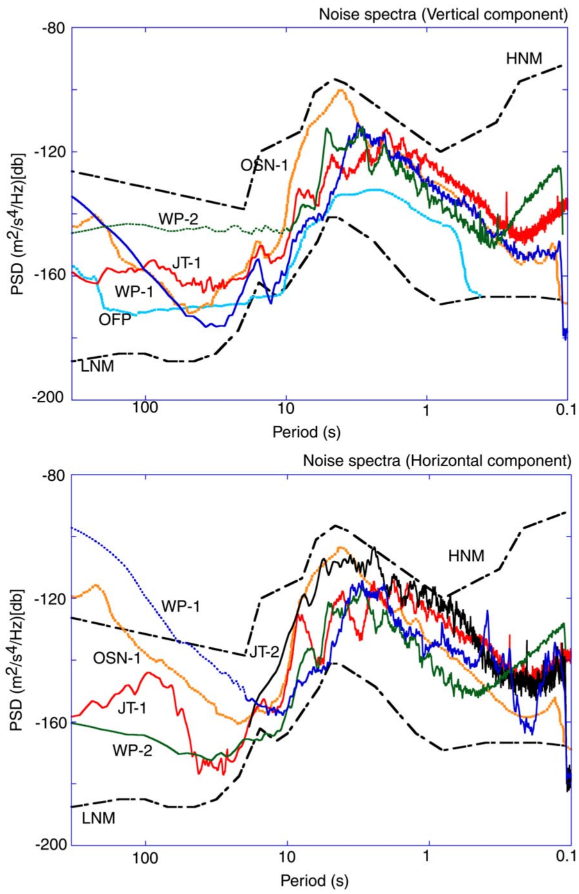

Figure 5: Ambient noise spectra are compared for the entire seafloor borehole data sets acquired to date. The dash-dot lines labeled HNM and LNM are the USGS high and low noise models based on a synthesis of land data. Seafloor borehole sites are as quiet as the quietest land sites at some frequencies and are only noisier than the noisiest land sites at some stations at very low frequencies on horizontal components. [*Shinohara et al.*, 2002]

of seismic stations.

- Super-rotation of the inner core. Song & Richards provided evidence for super-rotation by analyzing changes in travel times of seismic waves traveling N-S through the core. Confirming or refuting this requires building up the seismic observatory network in sparsely sampled high latitude regions (e.g. several sites in the extreme N Atlantic and S Atlantic/S Ocean).

3.0 Site requirements and the Phased Implementation Plan

Figure 3 is a summary of sites which fill the most important gaps in the ocean coverage. 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. Early planning for ION on ODP, however, identified three phases in the evolution of the ION network:

Phase 1. Pilot Experiments ~ 1997

It was expected that pilot experiments would be carried out through individual national efforts. These included the Japanese test in Hole 794D in 1989 in the Japan Sea, the French SISMOBS seismometer test in 1992 at Hole 396B near the Mid-Atlantic Ridge, and numerous tests under controlled conditions on land at the "Cecil & Ida Green Piñon Flat Observatory".

The most 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. All three systems were exposed simultaneously to the same ambient noise environment and acquired data for the same earthquake events. Figure 4 shows that the ambient noise field on the OSNPE borehole sensor is comparable to or quieter than the ambient noise at the GSN station Kipapa on Oahu above 0.08Hz for horizontals and above 0.03Hz for vertical components. Below these frequencies the borehole sensor was subject to noise due to installation problems. Tests at Piñon Flat have shown that this noise can be removed on future installations.

The most meaningful test of the three configurations is a comparison of earthquake event detectability [*Sutherland et al.*, submitted]. 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. It is estimated that the borehole sensor can detect teleseismic P-waves from earthquakes down to magnitude 4.3 (at least an order of magnitude better than previously published observations and predictions without borehole sensors) and to detect teleseismic S-waves and surface waves from earthquakes down to magnitude 4.0.

Table 1: Summary of Holes Proposed for ION Prototype Stations

Area	Data Recovery	Drilled (Leg/Site)	Instrumented
Active Processes			
Japan Trench (OHN-JT1,JT2)	Ship*	186/1150,1151	yes(2)**
Global Seismology			
Philippine Sea (OHN-WP1)	Ship*	195/1201	yes**
Northwest Pacific (OHN-WP2)	Ship	191/1179	yes**
Northeast Pacific (OSN-H2O)	Cable	200/1224	no
Center of Nazca Plate (OSN)	Ship	no	no
Eastern Equatorial Pacific (OSN)	Ship	203/1243	no
Ninetyeast Ridge (OFM-NERO)	Ship	179/1107	no
Existing Hole from DSDP			
Middle Atlantic (OFM-SISMOBS)	Ship	46/396B	yes

* - cable optional ** - operational March/03

Phase 2. Prototype Stations 1998 ~ 2003

Table 1 summarizes eight sites that were identified for prototype stations by ION during ODP. 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) which had regional active processes objectives. One borehole each was instrumented in the Philippine Sea (WP-1) and the Northwest Pacific (WP-2). These four sites, installed and maintained by Japanese scientists, use autonomous, battery powered recording and data packages are retrieved by ROV [*Shinohara et al.*, 2002; *Suyehiro et al.*, 2002]. At all four sites data are being acquired at the time of writing. 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.

Of the other sites in Table 1, the northeast Pacific site was drilled on ODP Leg 200 at the Hawaii-2 Observatory (H2O). There is a funded program in the US to install a borehole seismometer at this site in 2004. Power and data telemetry will be provided through the H2O cable to Oahu. The Eastern Equatorial Pacific site was recently drilled on ODP Leg 203. The Nazca Plate site is the only Phase 2 site that has not yet been drilled. Since there is no cable near this site, it would be an excellent candidate for an Ocean Observatory funded from the new US NSF initiative. Following the successful experiments SISMOBS/OFM in 1992 at the Mid-Atlantic Ridge site (396B) and the MOISE experiment in 1997 (not in an ODP borehole), an ODP borehole was drilled in 1998, close to the Ninety East Ridge (NERO - Ninety East Ridge Observatory). The installation of the broadband seismometers and the electromagnetic sensors will be performed in the framework of a French-Japanese cooperative program. The installation of sensors should take place in 2005.

Figure 5 summarizes ambient noise spectra from all of the broadband borehole seismic installations that have been instrumented so far [*Shinohara et al.*, 2002; *Suyehiro et al.*, 2002]. 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.

Phase 3. International Ocean Network 2003 ~

The goal of Phase 3 is to establish 20~25 permanent seafloor stations that will fill major gaps in the current distribution of global broadband seismic stations (Figure 3 and Table 2). The U.S. NSF Ocean Observatories Initiative (OOI) has been funded in the President's FY04 budget to begin in FY06 or earlier. The five year budget for the program is $209M and provides an opportunity for the vigorous pursuit of Phase 3. We propose to develop more specific plans and priorities for drilling at the sites listed in Table 2. Although each of the proposed sites can be equally justified scientifically for global seismology, priorities will be established in coordination with appropriate complementary programs that will provide the borehole sensors and their installation, as well as power and data acquisition and retrieval. In some cases, it will be advantageous to develop joint observatories with other geophysical and oceanographic communities (geodesy, geomagnetism, physical oceanography, biology, and geochemistry). The concept of long term observatories has gained significant ground in oceanographic communities beyond seismology and solid Earth geophysics. Such multi-parameter observatories are discussed, for example, in the framework of the DEOS program in the US and UK, which aims, among other things, at developing buoys suitable for providing long term power and telemetry capabilities in the open ocean. In addition the potential for scientific re-use of telephone cables that are being decommissioned in 2003 is currently under discussion. In any case, the completion of the seismological part of any of these observatories cannot proceed without a

Table 2: Phase 3 ION sites - modified from [*Butler*, 1995] and [*Purdy and Dziewonski*, 1988] with two new B-DEOS sites

Ocean	Site	Latitude	Longitude
North Atlantic	Mid-Atlantic Ridge	51.0	-33.0
North Atlantic	Mid-Atlantic Ridge	1.0	-24.0
North Atlantic	MAR (B-DEOS)	37.25	-32.5
South Atlantic	Argentine Basin	-36.0	-34.0
South Atlantic	Atlantic-Indian Ridge	-52.0	15.0
South Atlantic	Walvis Ridge	-28.0	2.0
South Atlantic	East Scotia Rdg (B-DEOS)	-57.5	-27.5
Indian	Carlsberg Ridge	6.0	63.0
Indian	Mid-Indian Ocean Basin	-2.0	85.0
Indian	Wharton Basin/ Broken Ridge	-27.0	100.0
Indian	Southeast Indian Ridge	-45.0	99.0
Indian	Southeast Indian Ridge	-51.0	132.0
North Pacific	Northeast Pacific Basin	43.0	-148.0
North Pacific	Northeast Pacific Basin	39.0	-171.0
Central Pacific	East Pacific Basin	10.0	-125.0
Central Pacific	East Pacific Rise	-11.0	-107.0
South Pacific	Peru Basin (not drilled on Phase 2)	-23.0	-90.0
South Pacific	East Pacific Rise	-41.0	-110.0
South Pacific	Southeast Pacific Basin	-59.0	-108.0
South Pacific	Southwest Pacific Basin	-37.0	-150.0
South Pacific	Pacific-Antarctic Ridge	-57.0	-155.0

borehole. It is therefore not too early for IODP to take the lead in this area.

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