Pre-Proposal

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

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Abstract

In 1996 the International Ocean Network (ION) committee launched a long-term (decadal) international plan to install long term seafloor geophysical observatories world-wide. A key component of this plan addresses the need to complement the land-based global seismic network with 20-25 seafloor sites, in order to achieve uniform global coverage for the study of deep Earth structure and earthquakes. It has now been established that in the oceans, borehole broadband seismometer installations provide superior data to many island stations and significantly better data than sensors on or just below the seafloor. The improved data quality makes possible a range of scientific investigations that otherwise could not go forward.

This proposal reviews the progress on existing ODP ION sites and outlines plans for ION related drilling in IODP. The long-term plan called for three phases: Phase I - pilot experiments, Phase II - prototype stations, and Phase III - establishment of the global ocean floor observatory network. Phase I is completed, Phase-II is nearing completion, and we are now in a position to start implementing Phase III . These borehole seismic observatories can share, where appropriate, power and data acquisition infrastructure and logistical support with other geophysical and oceanographic sensors installed nearby, on the seafloor or in the water column. Such facilities will constitute truly multidisciplinary long term observatories in the spirit of ION, as spelled out in its extended 2001 charter. Observatory siting and installation needs to be coordinated with other efforts which are aimed at developing and deploying such infrastructure (for example the DEOS programs in the US and UK, the proposed ARENA program in Japan, the MARS program in the US near MBARI, and various efforts being planned in the European Community such as ESONET).

This proposal focuses on the scientific motivations and siting priorities for drilling seafloor boreholes which will be dedicated to broadband seismic instrumentation. Another type of borehole observatory aims at observing geological processes in situ. While the latter are also part of the general ION goals, they are with some notable exceptions best considered in the framework of focused IODP missions. Sites appropriate from the perspective of global networks typically are chosen far from active geological and geophysical processes and, therefore, are not optimal for the latter goals. Also, noise considerations make it generally not desirable to combine broadband seismic instrumentation with many other geophysical/geological sensors in the same borehole, although it has been shown that combining broadband sensors with strainmeters and pressure sensors can be done successfully. Where there are opportunities for collocating global network observations with active process observations, ION investigators have done so.

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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. (Such measurements include those from chemical, biological and physical oceanographic sensors and arrays.)

IODP proposals for specific sites will be submitted separately and it is expected that they will go through normal IODP ranking procedures. While the overall scientific goals may change only modestly over the next decade, specific implementation plans will be updated with the results of experiments. 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.

1.1 What is ION?

The importance of establishing long term ocean observatories through international coordination and cooperation is recognized by the international scientific community. The International Ocean Network (ION) was formed in June 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 (e.g. Integrated Ocean Drilling Program, Global Ocean Observing System,...), to encourage the timely exchange of data, and to coordinate siting plans. ION is affiliated with the IUGG (International Union of Geodesy and Geophysics), primarily through IASPEI (International Association of Seismology and the Physics of the Earth's Interior)). The ION charter, as updated at Mt. Fuji in 2001, includes the following important statement:
"The ocean is an essential key to understand the interactions between the physical, chemical and biological processes governing Earth's system. Furthermore, to understand the dynamics of Earth's interior, it is necessary to instrument the two-thirds of the planet's surface covered by oceans. The international Earth and ocean sciences community recognizes the need for long-term observatories in the oceans, at fixed locations, in order to provide optimally sampled observations of global scale processes, in real-time when appropriate, and for the long-term monitoring of time dependent processes on the regional and local scales" . More information on ION (complete charter, history, steering committee representatives, objectives, etc) can be found at the ION web site (www.deos.org/ion).

1.2 Objectives and Recommendations of ION

The ION Steering Committee established a list of objectives and recommendation at meetings in Marseilles in 1995 and at Mt. Fuji in 2001. A complete list is on the web site, but the objectives and recommendations that are most relevant to IODP are listed here:
- Long term observations of a variety of phenomena are required on the seafloor and in the overlying water column to address a range of important problems in Earth systems science.
- Observatories must be sites where scientists can deploy diverse instruments and share infrastructure over inter-annual to decadal time scales and in which observations of several different phenomena are combined.
- ION must function as a clearing house for the exchange of information and for data exchange, and as an advocacy group to funding agencies.
- Data collected at the observatories must be made freely available to the global community of scientists.
- Initiation of permanent southern ocean observatories must be achieved over the next 10 years (by 2011).

1.3 ION Related Proposals Currently in the IODP Review System

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).

1.4 Quotes from Planning Documents

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])
- "Although it is possible to place seismometers directly on the seafloor, borehole installations are greatly preferred because they provide significant improvement in signal-to-noise ratio in the frequency band relevant to teleseismic body-wave studies (periods shorter than a few seconds). Borehole installations are necessary for the collection of critical data for body waves sampling the deep mantle (P waves) and the core (PKP, PKIKP)." (page 154 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])
- "IODP plans to continue the productive collaboration with seafloor observatory science programs, especially in the long-term monitoring of sub-seafloor physical parameters and seismicity, in active experiments and in regional-scale characterizations of sub-seafloor conditions. Future collaboration efforts will likely include instrument development, site selection, data transmission via fiber optic cables and data archiving. A firm foundation of observatory science both, as part of IODP and in coordination with other international programs, is a priority." (page 73 of [*Integrated Ocean Drilling Program*, 2001])
- "The scale of the monitoring effort needed depends on the scale of the process studied. For example, to image Earth's interior more accurately, seismometers need to be emplaced worldwide in seafloor boreholes at selected locations." (page 78 of [*Integrated Ocean Drilling Program*, 2001])
- "IODP will continue to be sympathetic to placing holes for seismic observatories in the world's oceans as part of the Global Seismic Network (GSN)/International Ocean Network (ION) programs. That record of collaboration within ODP over the past five years is clear." (page 107 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])

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.

2.1 Global Seismology

Issues involved in mapping departures from spherical symmetry accurately, whether they are lateral heterogeneity in elastic and anelastic structure or anisotropy are twofold: one is the theoretical problem of describing accurately how seismic waves of various frequencies interact with the inhomogeneities and the other is the question of uniform sampling. The latter is perhaps the most challenging issue, given the uneven distribution of earthquake sources and seismic stations on the surface of the Earth.

Lateral and radial resolution

Earthquake sources are essentially confined to plate boundaries, the most powerful being located along the "ring of fire" surrounding the Pacific Ocean. As for stations, they have traditionally been located primarily on continents, for natural logistical reasons. Recent efforts by the seismological community to fill gaps in the distribution of stations, in particular on the territory of the ex-Soviet Union, in Africa and now in South America, have gone a long way towards improving our capabilities of resolving the three-dimensional structure of the Earth's interior. Efforts have also been on-going in the past 10 years to instrument as many islands as possible. This has led to improved coverage in the Indian Ocean, and more recently in the Pacific Ocean. Nevertheless, 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 of in the central parts of the largest oceans.

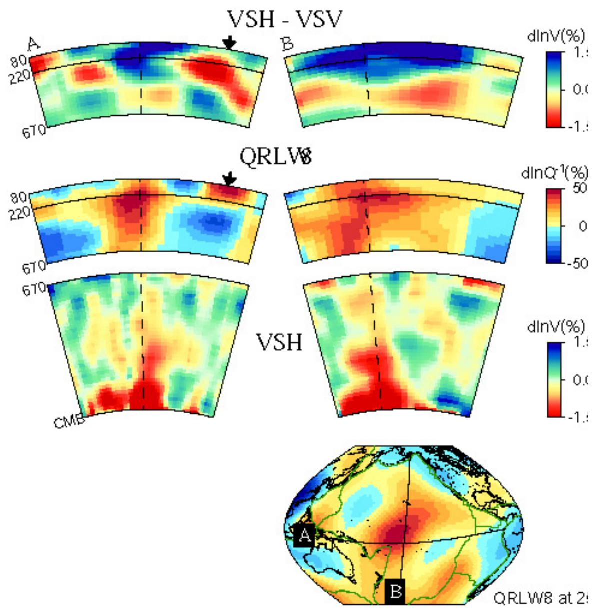

Figure 1. Bottom panel: Map view of attenuation model QRLW8 [*Romanowicz and Gung*, 2002] centered on the high attenuation peaks in the Pacific. Top panels: Depth cross-sections along profiles indicated in the bottom panels showing, for each profile (top to bottom), distribution of transverse anisotropy (V_{SH} -V_{SV})/V_{SH}, attenuation in the upper-mantle, and V_{SH} in the lower mantle. The upper mantle distributions are truncated at spherical harmonic degree 8, the lower mantle distributions are up to degree 24. 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. Adapted from [*Butler*, 1995; *Purdy and Dziewonski*, 1988;

Natural hazards

In addition to the fundamental question of the Earth's structure, the non-uniform distribution of seismic stations poses problems in the study of seismic sources, both natural and man-made. The present siting of seismic stations on continents and islands leads to large gaps in azimuthal coverage which in turn often introduces substantial uncertainty in the source mechanism of events. Seismic events in South America, for example, are observed primarily in the northern hemisphere, providing limited constraints on their source mechanism and rupture process properties such as directivity. Source mechanisms of the culturally important earthquakes in California could also be considerably improved by seafloor observations in the Pacific to the west. Similarly, although tsunami monitoring and research has benefited from seafloor pressure gauge measurements the additional information that broadband borehole seismic stations may provide is still unknown. In order to be useful for these purposes, it is necessary to provide real time transmission of seismic data to a central Internet-linked facility.

Scientific objectives

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. While down-going slabs appear to penetrate to depths of at least 1000-1200 km under some subduction zones [*van der Hilst et al.*, 1997], their continuity at greater depths, and their relation to the ring of fast velocities around the Pacific Ocean observed in S tomographic models of the core-mantle boundary (sometimes referred to as the "slab graveyard") is presently tenuous and subject to questions regarding vertical resolving power of the corresponding models. Seafloor observations might resolve this question. Likewise, some researchers have detected seismic phases scattered from fast-velocity bodies that may represent remnant subducted slabs in the lower mantle [*Kaneshima and Helffrich*, 1998; *Kaneshima and Helffrich*, 1999] and, more generally, there is an indication that the lower mantle may contain widespread smaller scale bodies (scatterers) as seen from the analysis of precursors to core phases [*Hedlin and Shearer*, 2000]. Again, resolution is presently limited by the sparse distribution of seismic stations in the oceans.

- **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 are the distinctive differences between slow and fast ridges?

- **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 "superswell", its concentration of hotspots, and its relation to mantle dynamics is yet poorly understood. Global seismic models indicate a correlation between hot spot locations and the velocity distribution at the base of the mantle at the longest wavelengths (degree 2 in particular) [*Hager et al.*, 1985] and in the transition zone for degree 6 [Montagner and Romanowicz, 1993]. It has been suggested that such a correlation also exists with the attenuation structure in the transition zone [*Romanowicz*, 1994]. More specifically, the low velocity structure at the base of the mantle beneath the south Pacific and African "superplume" regions (south Pacific and Africa) appears to extend vertically into the upper mantle, as inferred from attenuation tomography [*Romanowicz and Gung*, 2002]. 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. However, the resolution available from the global network data is again very poor, limited for attenuation to degrees 8 and lower (about 2500km). Progress on all these questions requires finer resolution, as can be obtained through the installation of seismic stations on the seafloor.

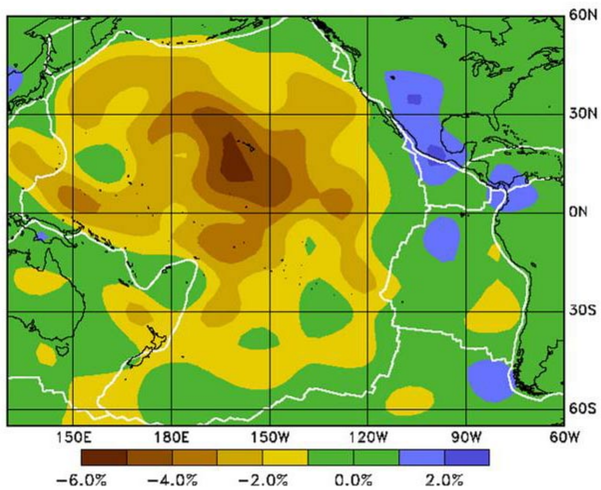

Figure 2. Variations in polarization anisotropy (V_{SH}-Vsv)/V_{SH} in percent) at 150 km depth under the Pacific ocean, in the model of Ekström and Dziewonski [*Ekström and Dziewonski*, 1998].

- 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. To first order, many important predictions of plate tectonic theory have long been verified through seismological observations in the ocean, e.g. the thickening of the oceanic lithosphere with age as inferred from surface-wave dispersion data [*Nishimura and Forsyth*, 1989], and the alignment of the fast axis of azimuthal anisotropy perpendicular to the mid-ocean ridge system [*Montagner and Tanimoto*, 1991]. However, some recent observations, mostly made possible by the increased quality of broadband seismic data collected on land in the last 10 years through the efforts of the Global Seismic Network, indicate significant and puzzling departures from the simple plate tectonic model. 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). Also, there appears to be significant variability in age-dependent thickening of the lithosphere from ocean to ocean, which may be related to differing spreading rates, but also to the available lateral resolution; for example, a transverse isotropy anomaly is visible in the western Indian Ocean in some models [*Montagner and Tanimoto*, 1991] but not in others [*Ekström and Dziewonski*, 1998].

- **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. The finding of anisotropy in the transition zone [*Montagner and Kennett*, 1996] might revive this debate. The geometry of hot upwellings must be better determined to improve understanding of the role of plumes in the global circulation. The structure of the mid-lower mantle is poorly resolved in global seismic models.

- **Structure at the core-mantle boundary (CMB).** The most intriguing part of the deep mantle is the D" region. This encompasses the last 200-300 km near the core-mantle boundary. Evidence for significant and laterally complex anisotropy has been accumulating, particularly in the Pacific Ocean [*Lay et al.*, 1998], but further characterization of this anisotropy is not possible with the present distribution of seismic stations: azimuthal coverage for S-diffracted waves is required in a specific distance range, attainable only through data collected on the ocean floor. Very strong and sharp transitions have been documented at the border of the African [*Ni et al.*, 2002] and of the Pacific [*Bréger and Romanowicz*, 1998] superplumes, but the distribution of sources and stations results in observations being available only over very limited portions of the plumes. Likewise, patches of ultra low velocity zones (ULVZ's) have been documented in various areas of the world, particularly in the west central Pacific [*Garnero et al.*, 1998], and it has been suggested that they could mark the roots of hotspots. Yet, this evidence is circumstantial and these ideas need to be further tested by the deployment of seafloor stations that sample parts of the lower mantle inaccessible to land-based stations.

- **Anisotropy in the inner core**. Inner core anisotropy was proposed 15 years ago to explain faster propagation of PKP phases on polar paths compared to equatorial paths, as well as anomalous splitting of core sensitive normal modes [*Morelli et al.*, 1986; *Shearer et al.*, 1988; *Woodhouse et al.*, 1986]. Simple models of constant transverse

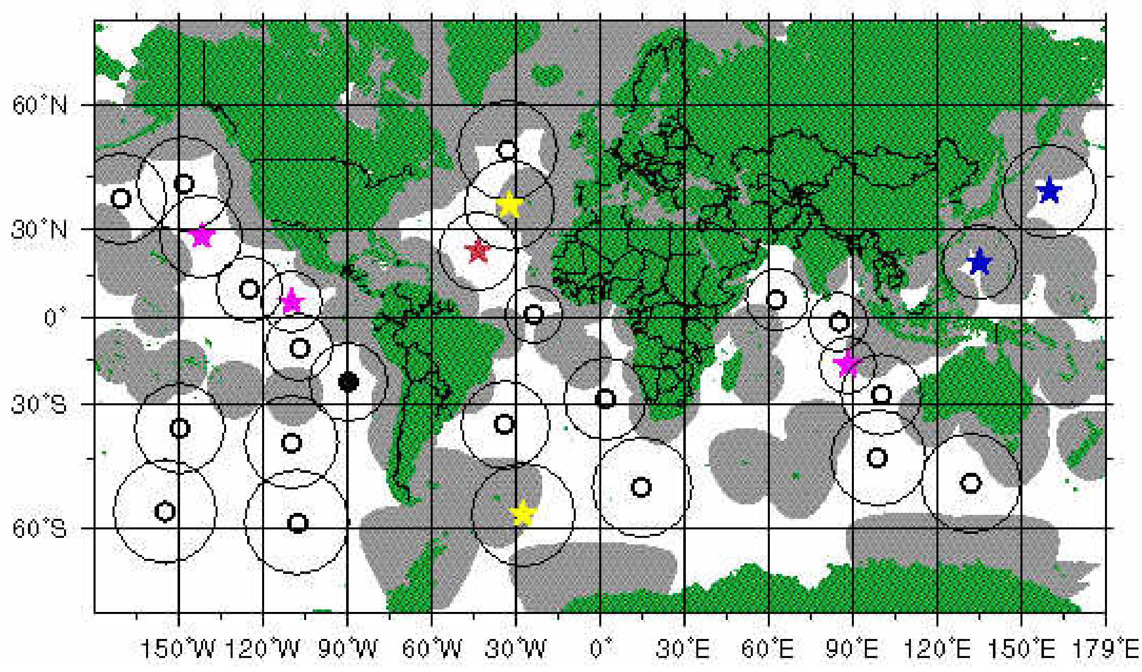

Figure 3: This figure summarizes the role of ocean borehole sites in global seismic coverage. The grey shaded regions indicate the surface coverage out to 1000km from continent and island stations. (These are distorted in the projection.) White spaces are gaps in the land based coverage. Existing and 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]

isotropy can explain the data to first order. However, as high quality broadband data have accumulated, a high level of complexity has emerged, with hemispherical variations in the trends of PKP travel times [*Creager*, 1999], as well as evidence for layering of anisotropy within the inner core. Very anomalous paths along the South Sandwich Island to Alaska corridor cannot be explained by any simple model of the inner core and the inner core origin of these anomalies has been questioned [*Bréger et al.*, 2000]. These authors have argued that the uneven distribution of observations on polar paths combined with strong heterogeneity at the base of the mantle could contaminate our view of inner core structure. The possibility of lateral heterogeneity in the outer core has also been invoked [*Ritzwoller et al.*, 1986; *Romanowicz and Bréger*, 2000], perhaps distributed as "sediments" in the immediate vicinity of the core-mantle boundary [*Rost and Revenaugh*, 2001]. To further distinguish the relative contributions of core-mantle boundary structure, outer-core heterogeneity and inner-core anisotropy requires a much more uniform sampling of polar paths around the globe, which implies installing stations in the northernmost and southern oceans.

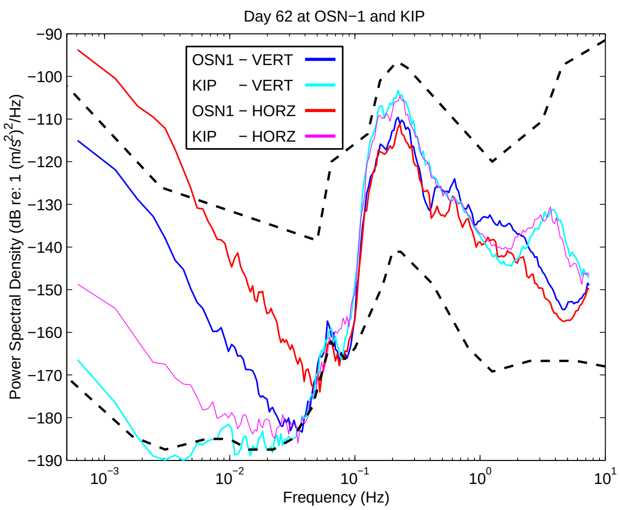

Figure 4: A comparison between the borehole sensor at OSN-1 and the GSN-GEOSCOPE station at Kipapa for the same time interval shows comparable noise levels from 0.03 to 1.5Hz on both vertical and horizontal components. This contradicts the assertion that seafloor stations should be noisier than island stations at short periods by up to 20dB [*Webb*, 1998]. 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. In contrast to many short period seafloor observations over the past 25 years, and even to the spectra at Kipapa, the horizontal components are quieter than the vertical components above the microseism peak for the seafloor borehole sensor. 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). In the noise notch below the microseism peak vertical component levels in the borehole approach the low noise model, with levels 80dB below the microseism peak at Kipapa.

- Super-rotation of the inner core. Glatzmaier & Roberts [*Glatzmaier and Roberts*, 1995a; *Glatzmaier and Roberts*, 1995b] predicted that the forces exerted on the inner core and mantle by the geomagnetic field leads to faster rotation of the inner core relative to the rotation of the Earth as a whole. Song & Richards [*Song and Richards*, 1996] provided evidence for super-rotation by analyzing changes in travel times of seismic waves traveling N-S through the core. This important finding is controversial, and the inferred rotational rates and direction are poorly constrained. 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

We can go very far towards resolving these issues by installing a modest network of high quality broadband stations in the deep ocean far from any accessible landmasses. Figure 3 is a first attempt to propose a set of sites which fill the most important gaps in the ocean coverage. 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 3 are also gaps for geomagnetic and geodetic observatories and that the possibility of sharing sites is strongly encouraged.

Early planning for ION on ODP 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 [*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.*, 1994a; *Vernon et al.*, 1994], and numerous tests under controlled conditions on land at the "Cecil & Ida Green Piñon Flat Observatory" [*Goldsborough et al.*, 1997; *Vernon et al.*, 1994]. 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 [*Collins et al.*, 2001; *Stephen et al.*, submitted; *Sutherland et al.*, submitted]. All three systems were exposed simultaneously to the same ambient noise environment and acquired data for the same earthquake events.

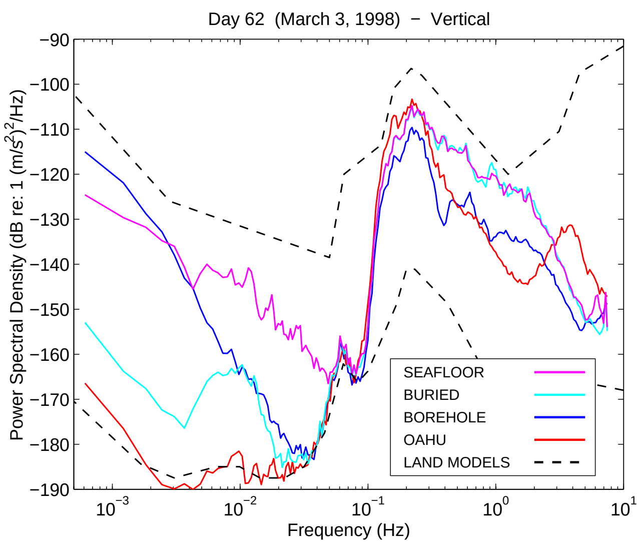

Figure 5: Vertical component spectra for the three broadband seismometer configurations deployed on the OSNPE (seafloor, buried and borehole) and the Kipapa GSN station on Oahu are compared with high and low noise USGS spectral models based on land observations. From 20mHz to 100mHz the borehole and buried sensors in the ocean are as quiet as any land sensor.

The ambient noise story on the OSNPE is summarized in Figures 4, 5, and 6. Figure 4 shows that the ambient noise field on the 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. Figures 5 and 6 compare the three seafloor configurations with Kipapa for vertical and horizontal components respectively. Above the microseism peak, the quietest sensor by 20 to 30dB was the borehole sensor. Below the microseism peak and down to the installation-related noise, the buried and borehole sensors had comparable noise levels.

The most meaningful test of the three configurations is a comparison of earthquake event detectability. This has recently been submitted for publication [*Sutherland et al.*, submitted]. 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. The borehole sensor was estimated to be able to 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 (a

Table 1: Summary of Holes Proposed for ION Prototype Stations

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

* - cable optional
** - operational March/03

comparable improvement over previous observations).

Phase 2. Prototype Stations 1998 ~ 2003

Table 1 summarizes eight sites that were identified for prototype stations by ION during ODP. The Japan Trench site had regional, active processes objectives, but the rest served to meet global seismology needs. These sites were not drilled based on their seismic priority alone. Other factors, such as proximity to cables for power and data telemetry, drill ship logistics, and ancillary science objectives played a role. All of the sites drilled are thoroughly documented in the ODP literature.

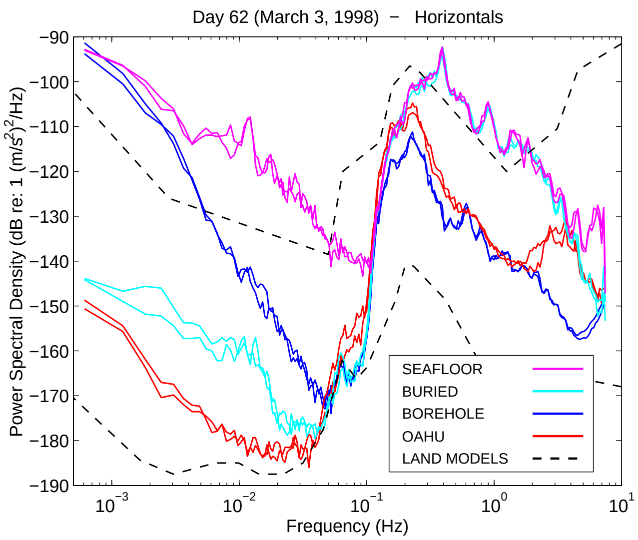

Figure 6: Horizontal component spectra for the three broadband seismometer configurations deployed on the OSNPE (seafloor, buried and borehole) and the Kipapa GSN station on Oahu are compared with high and low noise spectral models based on land observations. The borehole sensor has the quietest oceanic spectrum above 100mHz and the buried sensor has the quietest oceanic spectrum below 100mH.

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 7). 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 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. The Eastern Equatorial Pacific site was recently drilled on ODP Leg 203.

Following the successful experiments SISMOBS/OFM in 1992 at the Mid-Atlantic Ridge site (396B) [*Montagner et al.*, 1994a; *Montagner et al.*, 1994b], and the MOISE experiment in 1997 (not in an ODP borehole) [*Romanowicz et al.*, 1998; *Stutzmann et al.*, 2001] , 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 8 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]. 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.

Although it may appear that there has been slow progress in instrumenting the Phase 2 holes with prototype stations, major lessons concerning the advantages of borehole installations, as well as how to achieve low noise on horizontal components at long periods have been learned. 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*, 1999]. Although the data acquisition has occurred over too short a span to have led to significant discoveries yet, the pilot experiments have demonstrated that ocean floor stations can provide useful data for global seismological investigations. Broadband seismology has been one of the driving forces behind the Ocean Observatories Initiative in the US. 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 was among the strongest supporters behind the new Integrated Ocean Drilling Program. The pilot experiments were a necessary step preceding a more systematic deployment of borehole observatories, a goal which is now within reach in the framework of Phase 3.

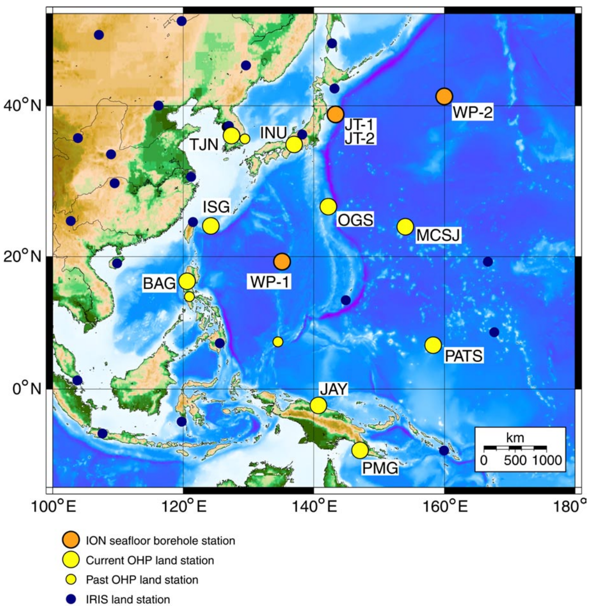

Figure 7: Location map of seismic station coverage in the northwest Pacific. Blue and yellow circles indicate land seismic stations. The orange circles are the OHP/ION/ODP seafloor borehole observatories. WP-1 and WP-2 were installed in August 2000 and April 2001 respectively. JT-1 and JT-2 were installed in July 1999. All four of the seafloor borehole sites are acquiring data at the time this report is being written.

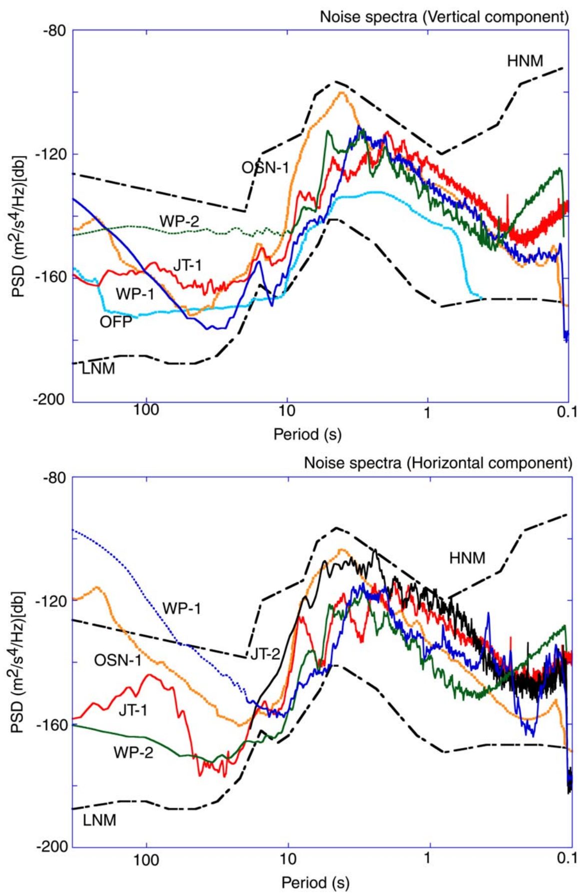

Figure 8: Ambient noise spectra are compared for the entire seafloor borehole data sets acquired to date. The dash-dot lines labeled HNM and LNM are the USGS high and low noise models based on a synthesis of land data. Seafloor borehole sites are as quiet as the quietest land sites at some frequencies and are only noisier than the noisiest land sites at some stations at very low frequencies on horizontal components.

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 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. Based on the list of potential sites given in Table 2, we propose to develop more specific plans and priorities for drilling at these sites. 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), sharing common infrastructure (Power, data acquisition, telemetry...). As reflected in the revised ION charter, 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 [*Orcutt*, 2003]. 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 borehole. It is therefore not too early for IODP to take the lead in this area.

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	Mid-Atlantic Ridge (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 Ridge (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

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