ION GLOBAL OCEAN GEOPHYSICAL OBSERVATORIES (IGOGO)

Project Summary

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). It addresses some key scientific questions that are summarized in the chapter on Global and Plate-Scale Geodynamics in the OOI Science Plan ([*Spindel et al.*, 2005] , pages 37-42) and in the chapter on Earth Structure in the ORION San Juan Workshop Report ([*Schofield and Tivey*, 2005] ,pages 28-34). The focus of this proposal 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 in the borehole, on the seafloor and in the water column (e.g. geomagnetic, electromagnetic, geodetic, oceanographic) that would benefit from shared power and telemetry infrastructure, logistical support, and spatial/temporal sampling requirements. The ION plan comprises several elements: a) drilling of appropriate boreholes by the ODP/IODP (noting that there already exist several cased boreholes that have been drilled for ION and that are available to be instrumented), b) instrumenting the boreholes with broadband borehole seismometers, auxiliary sensors, and data acquisition and recording systems, and c) supporting the sites with buoys or submarine cables for power and telemetry. ION has historically played a pivotal role in coordinating these elements with international funding sources and a strategy for coordinating these elements in the context of ORION is proposed. Links to other programs such as IRIS/GSN and IODP will be made.

<u>Broader Impacts</u> - We will address broader impacts in at least four ways: 1) further the understanding of our planet, how it evolved and where it might evolve in the future, for the general public, 2) further the understanding of the impact of human activities on the environment, 3) further the understanding of catostrophic hazards such as earthquakes and tsunamis, and 4) introduce global seismology and geomagnetic research to the K-12 curriculum and to local, regional and state High School Science Fairs through such initiatives as the IRIS Seismographs in Schools Program and the Centers of Ocean Sciences Education Excellence (COSEE).

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Principal Investigators: R.A. Stephen, R. Butler, J. Collins, R. Detrick, B. Romanowicz and A. Schultz

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I. 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 in the borehole, on the seafloor and in the water column (e.g. geomagnetic, electromagnetic, geodetic, 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 in this "global proposal" which include boreholes used for local and regional geophysical studies (for example geodesy, active margin processes, deep hydrology/biosphere) as well as sites for other long-term measurements that do not require boreholes (for example, some chemical, biological and physical oceanographic sensors and arrays).

We anticipate that proposals for specific sites or groups of sites will be submitted separately and that they will go through normal ranking procedures similar to IODP. While the overall scientific goals may change only modestly over the next decade, specific implementation plans will be updated with the results of experiments. ORION provides only one aspect of the infrastructure required for seafloor geophysical observatories and it will be necessary to coordinate specific siting plans, site surveys and schedules with other organizations that are responsible for drilling boreholes (IODP) and supporting global seismic acquisition and data management systems (for example, IRIS)

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. the Integrated Ocean Drilling Program and the 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), as an Inter-Association body co-sponsored by IASPEI and IAPSO. 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 recommendations 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 ORION 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 data 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 in the IODP and ORION Systems

This document focuses primarily on borehole observatories to complete world wide seismic and geomagnetic coverage. The rationale for borehole seafloor seismic installations will be developed below. However ION is also supportive of such initiatives as a) the NantroSeize and MOMAR projects, 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 OSN-1 and MARS). ION also supports observatory sites that do not require boreholes but these are not addressed in this proposal.

This "umbrella" proposal gives a prioritized list of global observatory sites that meet ION goals. We are aware that this proposal overlaps the "Open-Ocean Observatories: Earth Structure and Geodynamics (OOOESG)" proposal but feel that a separate proposal is necessary to represent the uncompromised, distinct goals of ION as an international global geophysical effort. The selection of observatory sites by OOOESG takes into consideration broader multi-disciplinary issues from a U.S. national perspective. In addition, some issues, for example the acquisition of broadband borehole seismometers and pressure cases, could be common among US global sites and could be justified in an omnibus, rather than site specific, fashion. Consequently there are sites identified for seafloor/borehole geophysical instrumentation in this proposal that are not found in the OOOESG document. For each site, however, separate proposals will be necessary to address site-specific engineering and technical issues as well as to address other multi-disciplinary scientific objectives (for example, the MOMAR ORION Conceptual Proposal).

1.4 Links to Scientific Justification in Key Planning Documents

Some key scientific questions addressed by a global distribution of seafloor geophysical observatories are summarized in the chapter on Global and Plate-Scale Geodynamics in the OOI Science Plan ([*Spindel et al.*, 2005] , pages 37-42) and in the chapter on Earth Structure in the ORION San Juan Workshop Report ([*Schofield and Tivey*, 2005] ,pages 28-34). The ION web site contains a list of quotations from other planning meetings and workshop reports that 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])

- "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]))

2. SEAFLOOR SEISMIC OBSERVATORIES

2.1 Uniform Global Coverage and Lateral and Radial Resolution

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.

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 landmasses 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.

2.2 Real-Time Acquisition and 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 as hazards, both natural and man-made. The present siting of seismic stations on continents and islands leads to large gaps in azimuthal coverage that 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 plate to the west.

Many ION global science objectives are focused on global earth structure and processes and do not require real-time data telemetry. Land and island based GSN-style stations, however, provide the "first detection" of catastrophic and tsunamigenic earthquakes and real-time sea floor stations will obviously contribute to this database. Seafloor stations can play an additional role. Since the seafloor deforms under the loading of surface gravity waves, a seafloor IRIS/GSN sensor will respond to a tsunami traveling overhead and could contribute useful real-time data to a tsunami warning system. For example, a westward traveling trans-Atlantic tsunami (for example from the Cumbre Vieja Volcano in the Canary Islands [*Ward and Day*, 2001]) could be detected on broadband, seafloor seismometers near the Mid-Atlantic Ridge. The IRIS/GSN nominal period band is 0.0017-16.67minutes (0.1-1000sec) compared to the tsunami period band of about 2-60minutes, so traditional "tsunami bottom pressure recorders" (TBPR - very low frequency pressure sensors, [*Eble and Gonzalez*, 1991]) would still be required. Since the power and data telemetry requirements for TBPRs are relatively small it would be a good idea to include TBPRs at all ORION global and regional sites.

2.3 Borehole Seismic Observatories

In the early stages of ION 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

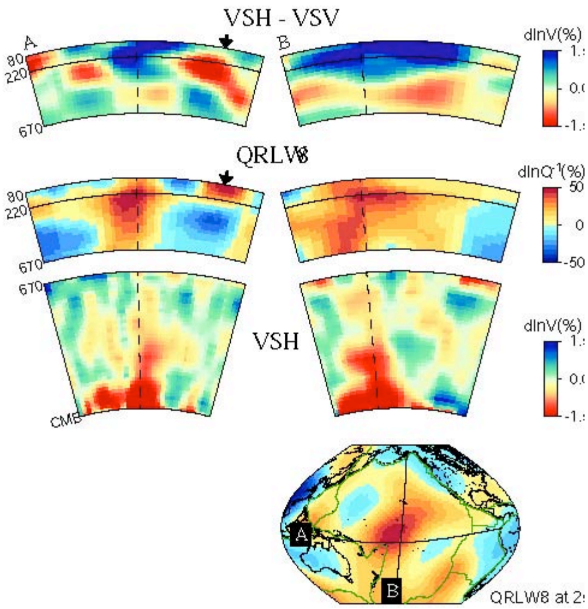

Figure 1. Bottom: Map views of attenuation model QRLW8 .Top: Depth cross-sections along profiles indicated in the bottom showing, for each profile (top to bottom), distribution of transverse anisotropy (V_{SH}-Vsv)/V_{SH}, attenuation in the upper-mantle, and V_{SH} in the lower mantle. The East Pacific 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}-Vsv)/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. [*Romanowicz and Gung*, 2002]

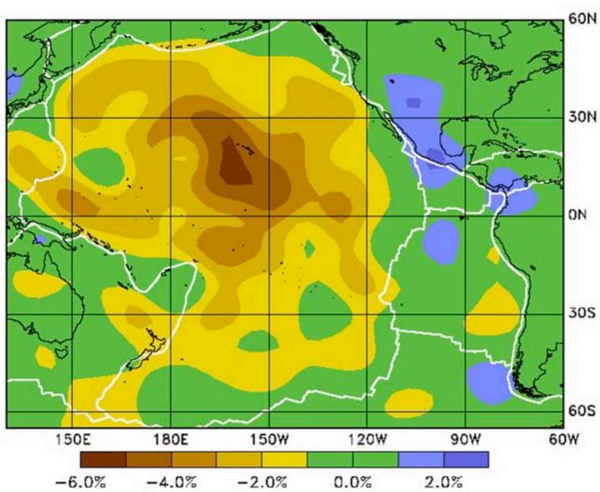

Figure 2. Variations in polarization anisotropy (VSH-Vsv)/VSH in percent) at 150km depth under the Pacific ocean, in the model of Ekström and Dziewonski [*Ekström and Dziewonski*, 1998].

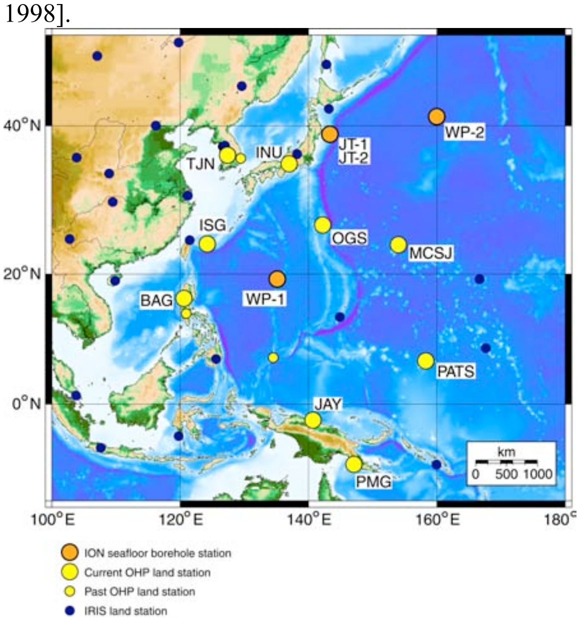

Figure 3. Location map of seismic station coverage in the Northwest Pacific. Blue and yellow circles indicate land seismic stations. The orange circles are the OHP/ION/ODP seafloor borehole observatories.

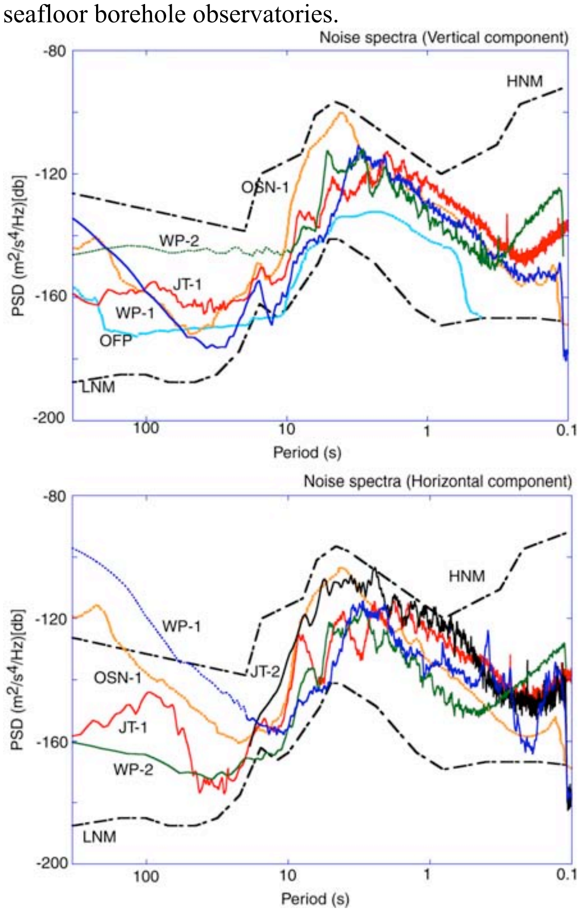

Figure 4: Ambient noise spectra are compared for the seafloor borehole sites installed to date.

[*Beauduin et al.*, 1996; *Montagner et al.*, 1994a], 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 (ODP 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 ambient noise story on the OSNPE is summarized in Stephen et al [*Stephen et al.*, 2003]. Figure 20 of that paper 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 21 and 22 of that paper 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 signal to noise ratios on the three configurations is a comparison of earthquake event detectability as discussed by Sutherland et al [*Sutherland et al.*, 2004]. They concluded that "the best system to record high quality teleseismic P waves at the OSN1 site was the borehole seismometer that was coupled to the basalt at the base of the sediments. The preferred system to record teleseismic S- and Love waves was the buried broadband OBS which had the best horizontal noise performance at frequencies below 0.04 Hz. For observing Rayleigh waves, both the buried and the borehole seismometer performed comparably. The seafloor broadband sensor had the highest detection threshold for each of the four types of measurements made. When compared to nearby island stations, the borehole system provided similar results for the magnitude detection thresholds for teleseismic P, S, Rayleigh and Love waves, while the buried broadband sensor gave improved detection thresholds for teleseismic S, Rayleigh, and in particular, Love waves but significantly higher detection thresholds for teleseismic P waves."

2.4 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 at the base of the mantle (sometimes referred to as the "slab graveyard" [*Grand*, 2002; *Gu et al.*, 2003; *Masters et al.*, 2000; *Ritsema et al.*, 2004]) is presently tenuous and subject to questions regarding vertical resolving power of the corresponding models. Observations are currently biased on the continent side of subduction zones. Seafloor observations might thus help to resolve this type of 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 [*de Hoop and van der Hilst*, 2005; *Foulger*, 2002; *Montelli et al.*, 2004]? 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 of structure in the oceans, through the installation of seismic stations on the seafloor.

- 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; *Ni et al.*, 2005] and of the Pacific [*Bréger and Romanowicz*, 1998; *To et al.*, 2005] 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. Some evidence for heterogeneity at the top of the outer core has also been suggested [*Rost and Revenaugh*, 2001]. 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 from land.

- **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 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]. 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.

- 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 [*Laske and Masters*, 2003]. 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. SEAFLOOR MAGNETIC AND ELECTROMAGNETIC OBSERVATORIES

The global geomagnetic observatory network is the oldest worldwide, internationally-coordinated observatory system, predating the mid-19th century. The length and quality of geomagnetic time series provides Earth scientists with an exceptional resource for studying geodynamic processes, yet the geomagnetic community is hampered severely by the biased spatial sampling inherent in a system devoid of seafloor stations. To achieve their full potential, such seafloor stations must be operated on decadal scale or longer, and comply as closely as possible with international standards as defined by the INTERMAGNET consortium. The modern (electro)magnetic observatory network is run by national programs, but coordinated through international bodies, with data archived and distributed through long-established channels including national agencies, the World Data Center system and INTERMAGNET. The INTERMAGNET consortium was established in 1989 following recommendations made in Ottawa in 1986. It exists to coordinate modern digital magnetic observatories equipped with satellite telemetry. Presently of the approximately 200 observatories operated around the globe, 92 stations in 39 countries are run to INTERMAGNET standards. We propose to adhere as closely as possible to these standards. In practical terms this means the permanent seafloor (electro)magnetic observatory installations must be provided adequate power so they may use sensors capable of establishing stable baseline measurements of the geomagnetic field rather than variations about an unknown and drifting baseline value, and they must support near real-time telemetry. ORION makes this possible,

The recognition of the importance of a seafloor element to such large-scale observatory efforts can be traced to many sources. As summarized in the SCOTS Report (2002) with regard to cabled, seafloor electromagnetic observatories–

"…In the geomagnetism realm, we don't really know what causes Earth's magnetic field to reverse. Magnetic and electrical data from remote areas of the Earth would help us find out. (2) What are the properties of the core-mantle boundary? Is the layer directly above this boundary the source of mantle plumes and hot spots? Is it the graveyard for subducted plates? Are the long-wavelength geoid anomalies created by undulations in the core-mantle boundary? (3) What is the extent and structure of mantle convection? How is convection modified by subducted slabs? How much coupling is there between the tectonic plates and convection in the mantle? What is the role of mantle plumes in convection? What is the role of lithospheric roots under continental blocks in convection? How rapid is convection? How complete is mantle mixing?"

The SCOTS report was not the first to recognize that real-time seafloor observatories would be a major component of future EM research. US National Research Council studies spanning more than a decade have concluded such a capability was required (NRC 2000, 2003; National Geomagnetic Initiative 1993). Clark (2003) and the DEOS Global Working Group (1999) made similar recommendations.

Investigations providing stable measurements of the Earth's internal geomagnetic field and views of electrical conduction in the oceanic mantle can address the geodynamic questions summarized above, and can also provide data complementary to other investigations of relevance to ORION. The proposed global seafloor (electro)magnetic observatory array accomplishes several long-term objectives. First, it substantially reduces the geographic bias found in the existing continental, and northern hemisphere-centric global observatory distribution, making it possible to construct models of the internal and internally-induced geomagnetic fields to spherical harmonic degree and order 8-10, globally. Regionally, it will be possible to extend to even higher order harmonics. This will permit us to refine our existing 3-D models of the variation of electrical conductivity of the mantle, to provide a spatial resolving power capable of resolving the large-scale features of mantle convection processes. This will also provide a set of deep "anchor points" about which higher-resolution regional-scale studies may be conducted.

On the plate scale, the pattern of spatial variability in electrical conduction within the lithosphere and asthenosphere is governed by convection beneath the plate, the upwelling of mantle materials beneath the ridge crest, and the subduction and recycling of the slab into the mantle. This pattern is mapped into electrical conductivity through the sensitivity of mantle and crustal electrical conduction to temperature, composition, degree of partial melt, presence of fluids and volatiles. Mantle convection might also result in anisotropic electrical conduction, as mineral grain boundaries are aligned along flow paths. By mapping out the 3-D variations of electrical conductivity in the mantle, we can construct models of the geodynamical processes that underlie these observations. Such data are complementary to seismic methods. Seismic interpretation leads to constraints on the elastic properties and the density of Earth materials, rather than the electrical properties of those materials. ORION therefore provides a powerful tool, enabling joint interpretation of EM and seismic models, since our stations will be collocated with broadband seismometer sites. Joint rather than individual interpretation of EM and seismic data can much better constrain the geodynamic processes that are the ultimate scientific target.

This proposal complements international activity in magnetic field satellite missions. Approximately a half dozen international magnet satellites have operated over the past decade, and more are in the pipeline both for pure research, and for applications including national security. Permanent seafloor magnetometry also aids interpretation of aero and marine magnetic studies of crustal magnetization, both onshore and offshore, providing stable baseline measurements of immediate utility to these investigations. The proposed EM observatory sites will provide important new information on the internal magnetic field, of great use to studies of the circulation of outer core fluids driving the geodynamo, and of research in coupling between the geosphere and hydrosphere of relevance to studies of climate change. These research areas are enumerated below.

a) Electromagnetic Induction Imaging of the Mantle. The convection of the mantle is the underlying mechanism that drives plate tectonics – yet the controls on thermal and compositional convection, as well as the chemical variability within the mantle remain poorly understood. The heterogeneity detected in mantle electrical conductivity, and the correspondence between patterns of heterogeneity and tectonic regime, has stimulated the development of new analytical and numerical tools for modeling the mantle. The effort to construct a 3D view of the

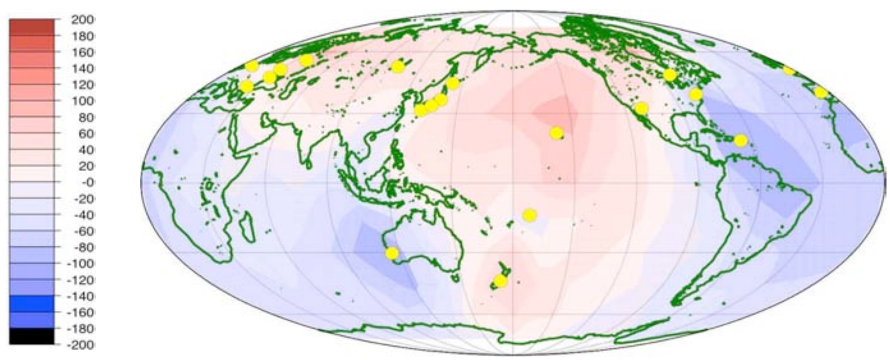

Figure. Variation of mantle conductivity for 2nd of 4 shells in Schultz & Pritchard (1999) model, shell depth of 436-774 km. Color represents % perturbation around baseline of 0.31 S/m – red is conductive, blue is resistive. Yellow dots are locations of magnetic observatories used in this study.

mantle's electrical properties (e.g. related to temperature, composition, volatiles, melt) is in transition. The earliest models were based on the datasets of the mid-1980's. Such data were limited in both geographical distribution, and interpretation. Despite these limitations, the first 3D mantle conductivity models (Schultz & Pritchard, 1998) show remarkable similarity to shear wave tomographic velocity distributions. There is no *a priori* reason why these very different approaches should provide a mutually coherent picture. That they do implies that important new bounds on mantle conditions should, in future, arise from joint interpretation of seismic tomography and 3D electromagnetic induction imaging.

New methods of modeling (Uyeshima & Schultz, 2002; Kuvshinov *et al*, 2005; Velimsky & Martinec, 2005) and of extracting information from the geomagnetic fields have been developed more recently (Fujii & Schultz, 2003) that now make it possible to model the electrical structure of the mantle in 3D from pole-to-pole, with a quality that depends on the spacing between observatory points on the Earth's surface. Our ability to extract higher resolution views of 3-D mantle conductivity structure is no longer limited by theory – only by the absence of adequate global coverage. It is essential that INTERMAGNET-compliant electromagnetic observatory systems are now installed on the seafloor.

Passive seafloor electromagnetic observations (magnetic plus electric field) have been carried out at on the seafloor at basin sites and also along a number of mid-ocean ridge systems. We propose to augment the permanent magnetic observatories with electric dipole receivers. This can be done at low marginal cost, and provides an additional data set that can be used to provide higher resolution data in the upper-most mantle immediately beneath the observatory site. For instance, Jegen & Edwards (1998) were the first to identify a magma lens under the Endeavour segment, Juan de Fuca Ridge. The MELT experiment on the East Pacific Rise (EPR) at 17ºS combined seismic and MT observations to determine the geometry of partial melting and the pattern of upwelling beneath the fast spreading ridge system (Evans *et al.*, 1999). An asymmetric structure is seen, more conductive to the west of the ridge axis than to the east. This was interpreted to be a consequence of asymmetric spreading rates and a westward migration of the ridge axis, suggesting distinct styles of melt formation and delivery in the mantle beneath the two plates. Marine MT measurements were also carried out at four sites at the EPR at 9º50'N using a recently developed broadband MT instrument (Key & Constable, 2002), revealing a conductive zone in the crustal section that agrees well with seismic tomography data. A crustal melt fraction of 1-20% can be derived beneath the ridge from the EM data. MT measurements on the Reykjanes Ridge, at 57º45' N are in good agreement with seismic data, and provide clear evidence for a crustal magma chamber with a melt fraction within the body of at least 20% (MacGregor *et al*., 1998). The EM data suggest that the process of melt extraction and migration at the Reykjanes Ridge is episodic rather than steady state. Long-term observations from eight sites have also been collected recently along a line crossing the central Mariana Trough parallel to the present spreading direction (Baba *et al*., 2004). A transition in conductivity at 60-70km depth was interpreted in terms of redistribution of water due to partial melting beneath the spreading axis.

Other long-period seafloor MT experiments aimed at deeper penetration of the mantle to depths of hundreds of km and greater have been conducted by measuring the electric fields using dipoles built from decommissioned submarine telephone cables, e.g. in the mid-plate north Pacific between Hawaii and California (Lizzaralde *et al*, 1995). These early submarine cable measurements used nearby island or continental magnetic observatory data, and provided a view of conductivity within a partially hydrated upper mantle, although with spatial resolving power limited by the long averaging scale of the electric field measurements and the distance between those sites and the magnetic observatories.

Recently, Motabayashi *et al* (2004) analysed nearly a year of seafloor MT data from the Japan backarc region, and identified a possible source of plate dehydration in the mantle, complementing seismic tomographic efforts in a region proving otherwise difficult to interpret. While the utility of electric field measurements for sub-seafloor electrical investigations is frequency band-limited at long periods by the EMFs generated by water motions, and at short periods by the electromagnetic shielding effects of the conductive water column, it should be feasible to strip off motional induction effects and to extend the useful frequency band for conductivity investigations into longer periods for those observatories collocated with higher density physical oceanographic monitoring installations. At those sites, mesoscale water motions can be modeled, and the EM effects of those motion removed from the (electro)magnetic observatory data.

b) The Geodynamo and Geomagnetic Field. While we have long known that the Earth's magnetic field is largely of internal origin, there are fundamental gaps in our understanding of the dynamo process that generates that field. Understanding the changes in the geomagnetic field over the annual-to-decadal scale is important for a broad range of problems in Earth science of interest to a wide community. Examples include geochemical interests in the variation in the rate of production of beryllium and carbon isotopes in the upper atmosphere by cosmic rays that result from variations in the intensity of the geomagnetic field.

Understanding changes in the angular momentum of the core is important if we are to remove the contribution to the total angular momentum of the Earth system due to the core, so that long term variations in the angular momentum of the hydrosphere can be isolated. This provides a possible marker of the effects of global change on the hydrosphere. The long-term geographic drift of the geomagnetic field measures such core rotations.

Geomagnetically-detected torsional oscillations of the Earth's core provide a constraint on the magnetic field within the outer core which is not otherwise available. These observations allow us to determine the relative contributions from inertia and from friction in the dynamics of the outer core. Magnetic "jerks" constitute another set of observed phenomenon. These are abrupt changes, apparently occurring in less than one year, in the rate of secular variation of the

Earth's magnetic field. The physical process that gives rise to these events is unknown, with proposed mechanisms including magnetic flux instabilities in the outer core. While the dynamical processes in that cause these field accelerations are of intrinsic importance, they are of practical interest as well since they restrict our ability to forecast the magnetic field. Our observations of all of these phenomena are hampered severely by the lack of seafloor observatories.

Satellite observations of the geomagnetic field have become more common in recent years for space and ionospheric physics investigations, and for solid Earth research. These provide a very detailed snapshot of the field at every position the satellite overflies, but one that is contaminated by electrical currents flowing in the ionosphere beneath the satellite orbits – with the added complication that such current systems must be modeled and their effects removed from the satellite data in order to understand the short term variations in the geomagnetic field. These measurements are also aliased, temporally, since the field behavior can change rapidly before the satellite returns to the same location in its orbit, usually several days later. The ORION EM array in concert with regional terrestrial geomagnetic variometer arrays (e.g. Polaris, Canopus, USArray and others) will provide this capability for interpreting satellite data obtained from over-flights of the relevant areas. Thus, satellite data and geomagnetic observatory data on both land and at the seafloor are highly complementary.

The effects of crustal fields represent a nearly constant offset in permanent magnetic observatory data. As a result, temporal first differences of observatory data are almost completely free of crustal contamination. With satellite data such differencing cannot be so simply accomplished. Unfortunately, permanent magnetic observatory data are currently of only limited use for this because of the near absence of coverage of oceanic regions. The ORION EM array, in concert with the aforementioned terrestrial arrays, can provide data to improve interpretation of regional aeromagnetic and ship-based magnetic surveys.

The accuracy of the International Geomagnetic Reference Field is hampered by the biased permanent magnetic observatory distribution, and would benefit substantially from the establishment of a seafloor observatory network. Stable measurements are needed of the secular variations in the vector components of the magnetic field. This requirement has driven the design of our observatory program, where we have included both a suspended dIdD sensor to establish absolute vector magnetic field readings, and a geodetic sensor to reference changes in inclination and declination into absolute baseline values. In this way, when the seafloor platform undergoes small rotations and translations in geodetic terms as the seafloor deforms and sediments settle, the ability to re-measure the geodetic reference system automatically and on a regular sampling interval will re-establish these coordinates and provide for stable baseline measurements.

Measurements of electrical potential across submarine cables have long been used to estimate a quantity V*-bar, which is a function of the shear-independent (barotropic) ocean velocity field. In order to transform this to a measure of barotropic transport, it is necessary to establish the leakage of electrical currents from the sea into the Earth below. By determining the electrical conductivity cross-section of the observatory sites by MT investigation, this quantity becomes known, and barotropic transport can be determined (Tyler, 1998). This has been carried out successfully for many years of monitoring the Gulf Stream by using a submarine cable between Florida and the Bahamas (Larsen & Sanford, 1985) and elsewhere. The EM observatory array can provide complementary estimates of barotropic transport using this method.

4. SITING STRATEGY

4.1 Background

Figure 5 summarizes the progress in establishing ION "Phaase 2" prototype stations during the ODP (up to 2003). Holes have been drilled at the sites indicated by red, blue and maroon stars. 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.

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). The Japan Trench sites had regional, active processes objectives, but the rest served to meet global seismology needs. These four sites, installed and maintained by Japanese scientists, use autonomous, battery powered recording and the data packages are retrieved by ROV [*Shinohara et al.*, 2002; *Suyehiro et al.*, 2002]. All four sites have proven to be capable of acquiring data although there are gaps in the data coverage due to trade-offs between the available power and ship and ROV scheduling. 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 borehole sites in Figure 5, the northeast Pacific site was drilled on ODP Leg 200 at the Hawaii-2 Observatory (H2O) and the Eastern Equatorial Pacific site was drilled on ODP Leg 203. There is a funded program in the US to install a borehole seismometer at the H2O site where power and data telemetry will be provided through the H2O cable to Oahu. The Nazca Plate site (black dot) is the only ION Phase 2 site that has not yet been drilled.

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.

Figure 4 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.

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]. 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.

Figure 6 shows sites discussed in the OOOESG proposal. Table 1 gives a progress summary of the twenty-seven ION sites and gives the closest associated OOOESG site. The OOOESG plan requests five borehole sites at locations 1, 5, 6, 12 and 13 and differs from the scenario in the previous paragraph only in the choice of the equatorial Atlantic borehole site (5) in place of one of the Southern Ocean sites. The OOOESG proposal further requests seven shallow-buried broadband seismometer sites (2, 3, 8, 9, 14, 15, 16), which will help to fill-in the ION global coverage, plus two additional shallow-buried seismometer sites (7 and 10, not included in Table 1). (Shallow-buried systems could of course be upgraded with borehole systems in the future as resources permit.) This leaves 11 of the ION sites for a future phase.

We are aware of an ORION proposal for an extensive program at the Mid-Atlantic Ridge near the Azores (MOMAR). A global seismic station on MOMAR would fill a substantial hole in the North Atlantic coverage, but at the moment is not included in either this proposal or the OOOESG proposal. The "fifth borehole site" could be MOMAR, equatorial Atlantic (OOOESG #5), or a second southern ocean site (ION). One solution would be to extend our request to seven borehole systems. Another solution would be to use an additional shallow-buried system at MOMAR.

5.0 Power and Telemetry Requirements

Although there are strategies for picking particular events and transmitting only small subsets of data in near real-time, we assume here that a broadband, borehole seismic system on ORION will transmit data in real-time continuously. We further assume that although the standard "bandwidth" for a GSN station is 0.001-10Hz (20sps sampling), the ION/ORION borehole stations will have an extended bandwidth to 100Hz (250sps sampling). The borehole system will consist of a single package of three-component sensors. It may be necessary to have two sensors for each component - one "broadband sensor" (0.001-10Hz) and 1 "VLF" sensor (1-100Hz). All channels will be digitized at 24bits. Systems will be designed to acquire at least one year of autonomous data and buffering strategies will be implemented so that no data is lost if the cables or moorings are inoperative.

Prototype borehole seafloor stations have been built and installed but none of them have met all of the requirements of an ION/ORION system. Further each site may have its own site specific requirements. For example, since we require ION/ORION systems to be installed in igneous basement, the depth of the sensor below the seafloor will vary and this will impact the power budget required at the seafloor due to transmission losses in the cable. As a rule of thumb we estimate that the power required for a 24 bit system will be 4Watts per channel and for the controller and telemetry unit will be 5Watts each. Thus a six channel system (3broadband plus 3 VLF channels) will require 24Watts of continuous power at the seafloor plus 10Watts for the controller/telemetry. Allowing a 33% factor to allow for losses in power conversion and transmission we estimate that an ION/ORION node will draw about 50Watts.

For telemetry, 24 bits/sample x (250 +20)sps x 3channels x 1.33 (overhead factor for error checking, time stamps, scan counts, SOH info,...) gives about 26Kbits/second uncompressed. This is roughly 280Mbytes (1byte=8bits) per day or 102Gbytes/year.

6.0 Education, Outreach, and Broader Impacts

We will address broader impacts in at least four ways: 1) further the understanding of our planet, how it evolved and where it might evolve in the future, for the general public, 2) further the understanding of the impact of human activities on the environment, 3) further the understanding of catostrophic hazards such as earthquakes and tsunamis, and 4) introduce global seismology and geomagnetic research to the K-12 curriculum and to local, regional and state High School Science Fairs through such initiatives as the IRIS Seismographs in Schools Program and the Centers of Ocean Sciences Education Excellence (COSEE).

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