1. BACKGROUND AND OBJECTIVES OF THE OCEAN SEISMOGRAPHIC NETWORK, AND LEG 136 DRILLING RESULTS[1]

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The primary objective of Ocean Drilling Program Leg 136 was to prepare a seafloor site for future experiments needed to develop the Ocean Seismographic Network (OSN). OSN-1 (ODP Hole 843B) has been established on the Hawaiian Arch, approximately 225 km south-southwest of the island of Oahu (Fig. 1). The hole was drilled through approximately 243 m of sediment and 70 m into the basaltic basement. It will provide a site for borehole seismometer experiments that include noise measurements, recording of data from teleseismic events for comparison with an existing, high-quality station on Oahu, and testing of new broad-band sensors and other instrumentation for long term deployment. The 5–10-yr goal of the OSN is to establish a global network of 15–20 permanent seismic observatories in the deep ocean, with the expectation that these facilities will be shared with other fields of geoscience requiring long-term observations on the ocean floor. OSN will revolutionize studies of global Earth structure, upper mantle dynamics and lithosphere evolution, earthquake source mechanisms, oceanic crustal structure, tsunami warning and monitoring, and deep ocean noise propagation and generation. A significant part of this report will be devoted to providing the reader with the background and objectives of the OSN.

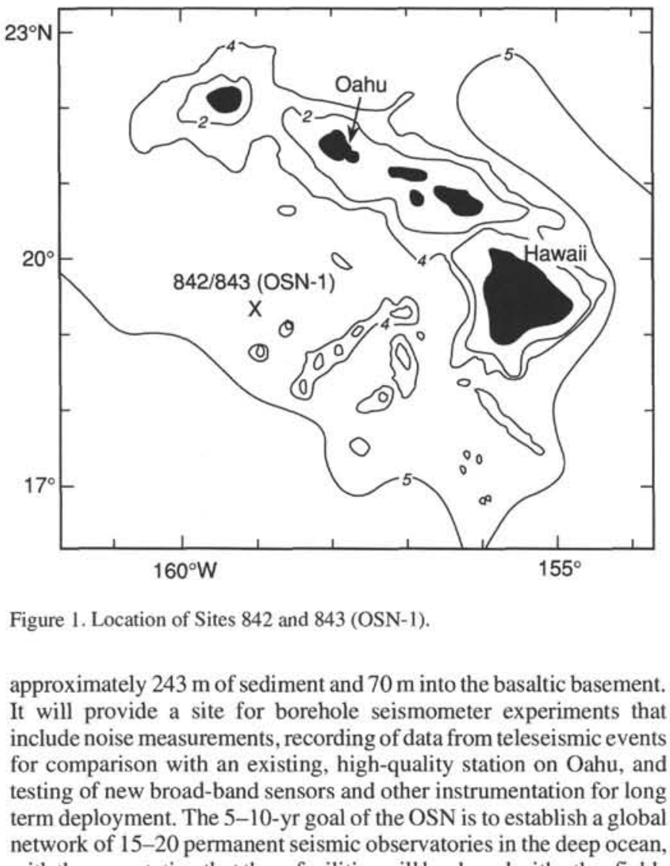

Figure 1. Location of Sites 842 and 843 (OSN-1).

Other issues were also addressed at Site 843. Two previous cruises, Leg 128 in the Japan Sea, and Leg 131 to the Nankai accretionary prism, have left long-term monitoring instruments in dedicated boreholes. A new and different type of instrument related to using ODP boreholes for long-time observations was tested during Leg 136: a reentry cone plug designed to seal boreholes for long-term temperature monitoring and fluid sampling. The experiments conducted during these three legs reflect a growing sentiment within the ocean drilling community that oceanic boreholes will play an increasingly important role as resources for future establishment of deep-water observatories.

Coring of the sedimentary and basaltic sequences at Site 843 and its nearby companion, Site 842, provided geological data that are important for several avenues of study. The sediments and basalts at the sites are analogs of the material through which Hawaiian lavas first erupted. Analysis of the chemistry and physical properties of this material will allow determination of the extent to which they contaminate Hawaiian magmas and will shed light on the role that the sediments underlying the volcanic edifices play in the mechanical behavior of Hawaiian volcanoes. Volcanic ash blown downwind from the Hawaiian Islands reflects the history and chemical evolution of the volcanic centers of the island chain. Paleomagnetic and biostratigraphic dating define the past 3.5-Ma history of ash and red clay sedimentation. Preliminary paleontologic dating (to be followed by isotopic studies) indicates a crustal age of approximately 95 Ma, the first basement age recovered in the region. Penetration 70 m into basement is the deepest in this part of the Pacific. Shipboard analyses indicate that the altered, well-cemented basalts that were recovered include a wide range of MORB compositions, from normal to enriched varieties.

OCEAN SEISMOGRAPHIC NETWORK

Background

Earthquakes are felt within a relatively small distance of their origin. The first seismographs were designed to record local events. In areas without instrumentation, however, major earthquakes were left undocumented. Also, information on deep-earth structure that could have been obtained by recording waves penetrating close to Earth's center, was not available.

The need for global seismograph coverage was recognized early in the history of modern seismology. The British Association for the Advancement of Science funded a network of 15 stations distributed throughout the British Empire during the first decade of this century. A turning point in the history of global seismology was the deployment of the World Wide Standard Seismograph Network in the early 1960's. Not only were all 125 stations of this network identically equipped, but there was a single depository for all seismograms, and researchers could order copies either of individual events or of complete sets of data.

Application of digital recording to global seismology began in the 1970's with the High-Gain Long-Period network. Modification of systems at some of the HGLP sites and addition of new stations called

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Seismic Research Observatories led to formation of the Global Digital Seismograph Network (GDSN). An important feature of this network was that 11 of its stations had seismographs placed in boreholes approximately 100 m deep. Borehole siting was shown to reduce noise on horizontal components by as much as 30 db, with significant improvement also on the vertical component. Another network developed in the 1970's is the International Deployment of Accelerometers (IDA). This network of LaCoste-Romberg gravimeters was designed to record very long-period signals, such as free oscillations of the Earth caused by large earthquakes.

An event of significant importance to the future of seismology, including the OSN project, took place in Germany in 1976: the opening of the Graefenberg Array, entirely composed of broad-band seismographs with a feedback system and relatively high-resolution digital recording. Most systems then in use had a peak response at a particular frequency: this was necessary when dealing with the small dynamic range of analog recording systems. In contrast, the broad-band instruments used in Graefenberg had a constant response to ground velocity between 5 and 0.05 Hz. In more recent applications this has been extended to 0.003 Hz, allowing us to see, in the same data stream, Earth tides, gravest modes of free oscillations, and short-period waves from local earthquakes. This instrumentation is commonly referred to as a very broad-band (VBB) system.

The French GEOSCOPE is the first global network to use a broad-band seismograph system. In addition to very long-period channels sampled once every 10 s, GEOSCOPE includes triggered broad-band channels, sampled five times per second. The first GEOSCOPE installation started recording in 1982 and the network now has 23 stations.

In the United States, the Global Seismographic Network (GSN) program within the Incorporated Research Institutions for Seismology (IRIS) was created in 1984. The design outlined a network of 100 globally distributed stations, each equipped with VBB seismographs and recording systems having a dynamic range of about 140 dB. GSN is being deployed and maintained in cooperation with the USGS.

Designs to deploy equipment of similar characteristics on national or regional scales were undertaken also by other countries. This led to formation in 1986 of the Federation of Digital Seismographic Networks (FDSN). The FDSN now has 10 member countries: Australia, Canada, China, France, Germany, Italy, Japan, Soviet Union, United Kingdom, and United States. In addition, ORFEUS — a consortium of 13 west-european countries — is also a member. The principal objectives of the FDSN are: to develop common equipment standards, to coordinate site selection by member networks, and to promote timely exchange of data. The FDSN is affiliated with the International Lithosphere Project and IASPEI. The FDSN has selected nearly 100 tentative sites of the "Federation Network," data from which will be distributed on CD-ROMs to all interested scientists.

With one exception, all of these stations, as well as those of IRIS, GEOSCOPE and other networks, are or will be deployed on land (including oceanic islands). The single exception is a broad-band station installed by Japanese seismologists at Site 794 of ODP Leg 128. While this experiment has resulted in valuable experience, the choice of site is not optimal from the standpoint of experiments required to initiate the OSN. Limits of coverage that can be obtained with land-based networks are shown in Figure 2. Because a uniform distribution of stations is preferred for studies of planetary scale effects, the Earth's surface has been divided into 128 elements of roughly equal area: 2000×2000 km. A light-shaded square indicates at least one existing, planned, or proposed Federation station within its boundaries. There are 81 such

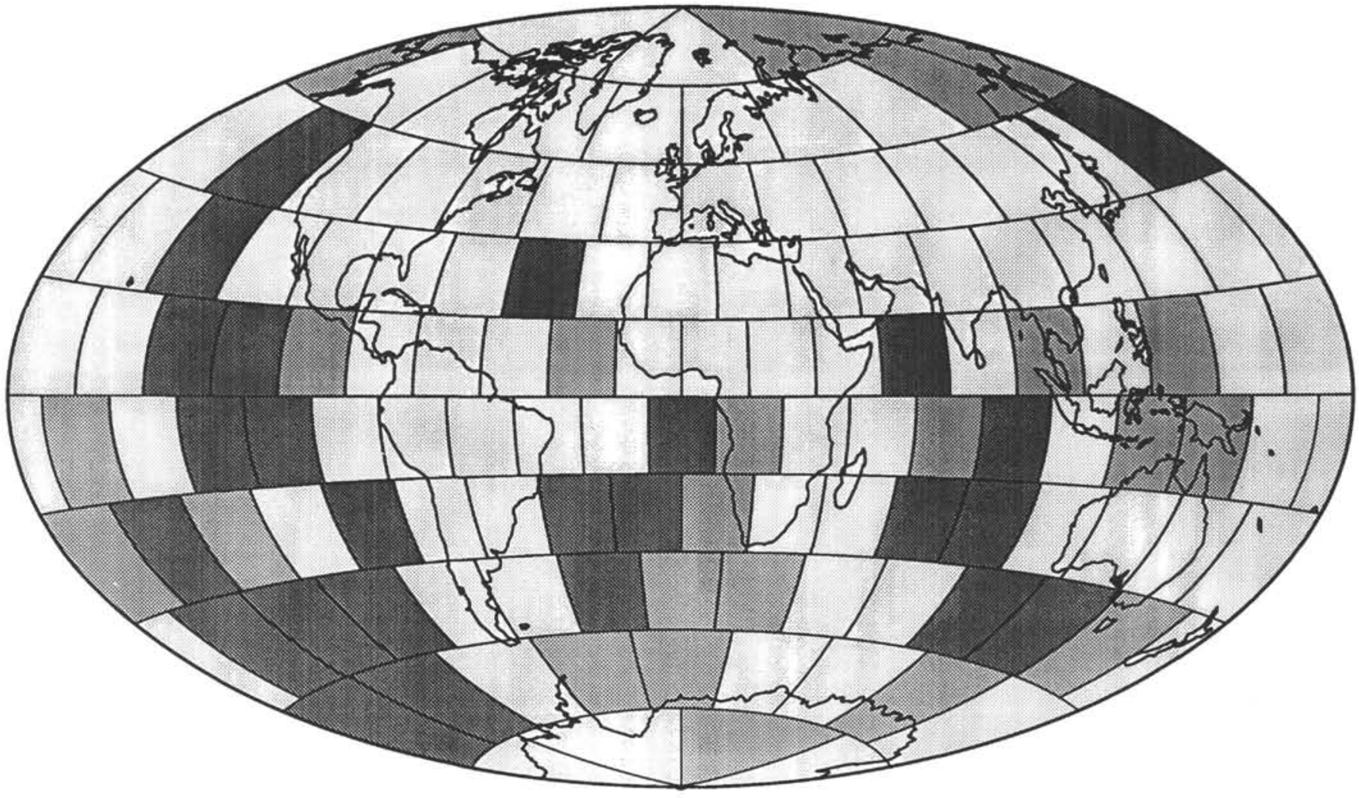

Figure 2. Potential global coverage with seismograph stations. The Earth's surface is divided into 128 roughly equal area elements of 2000×2000 km. Light shading indicates at least one existing, planned or proposed Federation site; medium shading shows areas where a standard station could be established. Dark-shaded areas identify squares in which permanent ocean bottom observatories are needed.

squares, some of which have as many as 15 stations (western Europe). Land masses or oceanic islands may fill another 22 squares; these are of medium shading. But even with this additional coverage, significant deficiencies are evident: a nearly continuous gap in the Eastern Pacific and large blank areas in the South Atlantic and Indian Ocean are represented on the figure with dark-shaded areas. These gaps in coverage significantly impede the resolution of planetary scale studies. For example, the band of gaps in the eastern Pacific Ocean makes monitoring of the tectonically active continental margin of North and South America less than satisfactory.

The need for permanent deployment of seismographic stations on the ocean bottom was presented during the Second Conference on Scientific Ocean Drilling (COSOD II) meeting held in Strasbourg in 1987. The recommendations of this conference read in part: "We also propose that several crustal holes be used as seismic observatories. Recent major advances have been made in improving upon radially symmetric models of the Earth's interior, both in the core and mantle.

These results provide fundamental information about the driving mechanisms of plate tectonics. The resolution of tomographic imaging of the Earth's interior, however, is severely limited by lack of seismological data from the ocean basins." Following this, a workshop on "Broad-band Downhole Seismometers in the Deep Ocean" was organized (Purdy and Dziewonski, 1988). The conference had significant international participation. Its principal recommendation was to conduct a series of pilot experiments in a borehole located on the Hawaiian swell. This choice was made on the basis of logistic considerations as well as of the opportunity for comparisons with data from an island site. A proposal for drilling in this area was submitted to JOIDES in the fall of 1988 and the Planning Committee approved Leg 136 in 1990.

Objectives

The long-term goal of OSN is to establish, during the next 5–10 yr, a permanent global network of 15–20 seismic observatories in the deep ocean. The objectives of such an effort encompass the most fundamental questions concerning Earth structure and dynamics. The following examples of key questions are grouped within several broad subject areas:

1. Global Earth structure: Is the inner core heterogeneous or anisotropic? What is the geometry of the core-mantle boundary? Are hotspots correlated with slow regions at the base of the mantle? What are the geometries of the 400-km and 670-km discontinuities?
2. Oceanic upper mantle dynamics and lithosphere evolution: Can seismic anisotropy be used to map flow in the upper mantle? What are the degree and spatial variations of lithospheric thinning beneath hotspot swells? What are the spatial variations in the depth extent of anomalous structures beneath ridges? Do oceanic plateaus have roots like continents? What is the form of small-scale convection beneath plates?
3. Earthquake source studies: Ocean floor stations are needed to improve source location (particularly depth), focal mechanism, and rupture process determinations. These measurements are critical to studies of the depth of the seismic decoupling zone, the depth extent of outer rise events, and the rheology of the oceanic lithosphere. Near-field data, in particular ocean floor recordings, are needed to improve the resolution of source mechanisms of events not caused by faulting but by slumping or magmatic injection. Such studies have important implications for estimation of long-term seismic hazards.
4. In addition, opportunities for study exist in the following areas: oceanic crustal structure, tsunami warning and monitoring, and sources and propagation of seismic noise.

Broad-band, long-term ocean floor observatories are needed for these studies. Generally, only seafloor stations can provide uniform global coverage in areas without islands. Seafloor installations are needed for regional studies of individual tectonic features and for sampling wave propagation in "normal" oceanic lithosphere.

At present, island seismic stations are the only places where permanent observatories exist in the oceans. Oceanic islands are, however, located on anomalous structures with thick crust and, in many cases, unusual upper mantle velocities. In addition to the objectives listed above, the following questions may be addressed with ocean floor observatories: How adequate are island-based stations? What role should they play in the global seismograph network? Would ocean-bottom observatories provide substantial improvements in broad-band signal-to-noise ratios? How does local structure influence seismic signals received on islands compared with an ocean floor site?

Before progress can be made toward the construction of a permanent global ocean floor network, thorough solutions to a number of experimental and technical issues must be found. Current understanding of sources and noise propagation mechanisms is insufficient to guide emplacement of permanent observatories. Measurements of inertial noise at intermediate frequencies (10–100 mHz) are very limited and at low frequencies (3–10 mHz) do not exist. A key parameter that remains unknown is the depth of sensor burial required (in various tectonic settings) to optimize the signal-to-noise ratio while minimizing required drilling penetration.

In addition, a large number of purely technical problems must be solved. One-Hz geophones are the lowest frequency sensors routinely used on the ocean floor. These geophones have little sensitivity to Earth noise below 50 mHz. An urgent priority, following the Japanese example, is to adapt a presently available broad-band sensor for operation on the ocean floor. How would a permanent global ocean floor network be operated in practice? With a data rate between 5 and 50 MB per day, the problems of both internal recording (with periodic data retrieval) or real-time telemetry are extremely challenging. Costs associated with use of fiber optic or existing telecommunication cables can be huge, but entirely remote packages produce the problem of power source. Completely new (micropower) sensors and data loggers may need to be developed.

Satisfactory solutions to all these questions can be established only by carrying out a series of pilot experiments. These experiments must be carried out at several locations in a variety of tectonic settings. The objective of this leg is to establish the first site at which these experiments, using wireline reentry from a conventional research vessel, can be performed over the next 1–2 yr. The experiments will be carried out by a variety of investigators and coordinated by a steering committee. Examples of specific objectives of such experiments are:

1. To prove the satisfactory and reliable operation of a low-power (and eventually micropower) broad-band ocean floor seismometer.
2. To measure and compare noise levels (in the band 3 mHz–50 Hz) downhole at various burial depths, with adjacent seafloor sensors, and with the island site on Oahu; and to understand the dependencies of the variations in these noise levels upon environmental parameters.
3. To establish the satisfactory and reliable operation of the required recording, telemetry, and timing systems.
4. To develop routine sensor emplacement and data package recovery schemes.
5. To obtain a sufficient number of high-quality broad-band recordings of teleseismic events to allow quantitative comparisons to be made with the data recorded on Oahu. These data could provide interesting new information on the upper mantle structure beneath the Hawaiian swell.

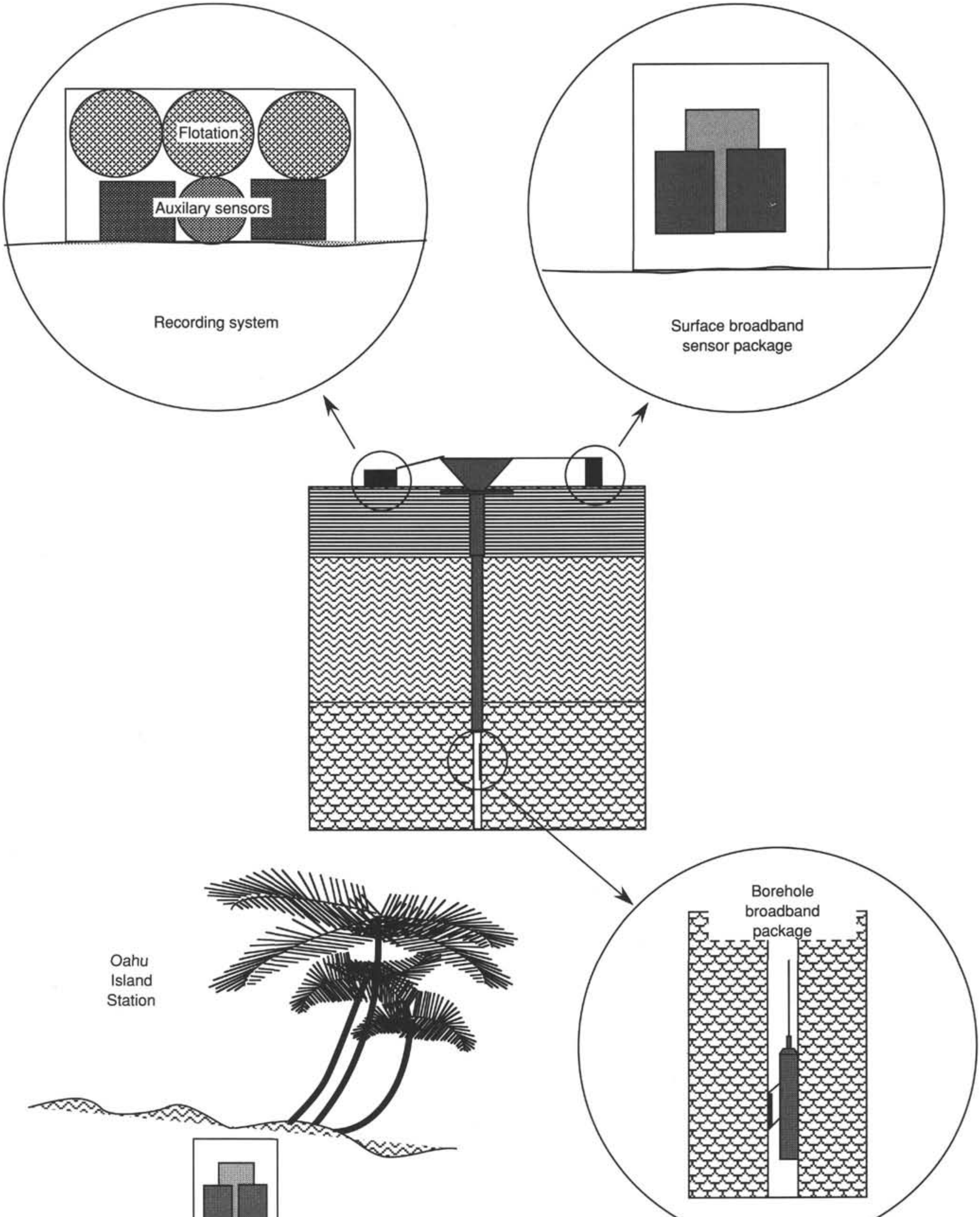

Figure 3. Possible configuration of an experiment in which data from a borehole and ocean bottom surface sensors are recorded simultaneously with data from an island station.

6. How deep do the drill holes need to be for sensor emplacement? We must measure variations in broad-band noise levels on a downhole sensor with depth below the ocean floor.

7. Do we need drill holes at all? Comparisons must be made between broad-band noise levels on a downhole sensor with identical seafloor and surficially buried broad-band sensors.

An example of the components of such a pilot experiment is shown in Figure 3. All of the above questions may be answered by experiments at the OSN-1 site.

REENTRY CONE SEAL

The first test of the ODP Borehole Seal was conducted during the last 2 days of Leg 136. The Borehole Seal assembly is a joint development effort of ODP, Canadian, and U.S. scientists designed to isolate ODP holes in which hydrogeological processes are a primary objective of scientific study. Although the prototype tested during Leg 136 consisted simply of the mechanical seal and housing, future deployments will incorporate instrumentation to log pressure and temperature within the borehole for at least 1 yr (Fig. 4). Additionally, a hydraulic feed-through will allow fluids to be drawn from the sealed hole for geochemical analysis and pump tests after conditions in the borehole equilibrate. The present assembly is designed to be deployed and retrieved by the *JOIDES Resolution,* but fluids and data will be accessible by ROV, submersible, or wireline reentry vehicle. Because the sensors and data logger can be removed, the seals will provide the opportunity for independent investigators to design and deploy future instrumentation in selected boreholes. Deployment of the seals will further the use of ODP boreholes as natural laboratories, a concept advocated in the COSOD I and II planning documents.

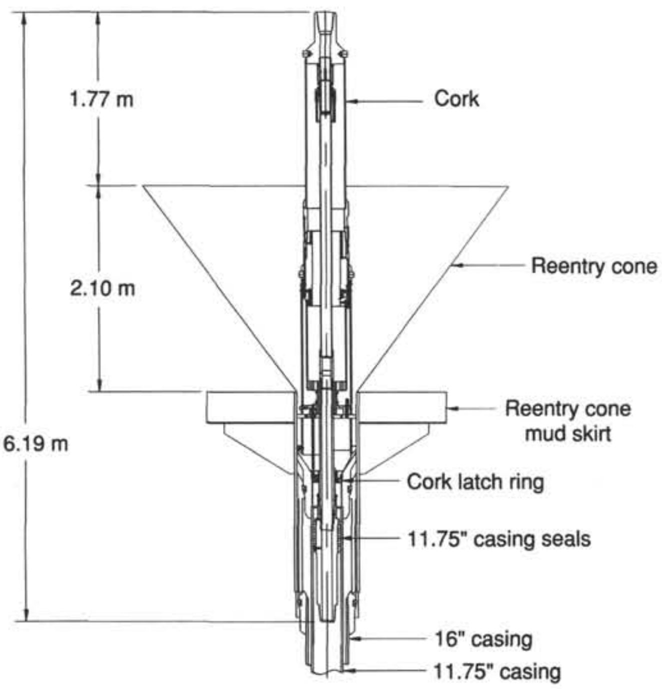

Figure 4. Engineering drawing of ODP Borehole Seal.

The first test of the ODP Borehole Seal consisted of several basic steps. The seal was locked into place by the drill string in the reentry cone at OSN-1 after logging and drilling operations were finished. The data logger was inserted through the drill string prior to detachment of the seal from the pipe. The drill pipe was then relatched onto the seal, the data logger retrieved, and the seal pulled from the reentry cone and returned to the surface. Success of the test was of critical importance to the first full deployment of the Borehole Seal, scheduled during ODP Leg 139 (sedimented ridges) in late summer 1991.

CORE ANALYSIS

Drilling of the OSN hole presented an excellent opportunity to characterize a poorly known part of the Pacific Basin. The Hawaii area is important because it is the type locality for oceanic, intraplate hotspots, and it is located well away from other tectonic and sedimentary influences. The upper 15 m of ash-rich, red clay sediments recovered at Site 842 spans approximately 3.5 m.y. of deposition (Fig. 5). Distinct ash horizons dated from between 1 and 3 Ma are probably the result of explosive volcanism related to volcanic centers on the islands of Maui and Oahu. In particular, it is possible that these ash deposits mark the emergence of volcanic centers from the sea. In contrast to the normally nonexplosive style of Hawaiian eruption, activity near the sea surface is marked by violent explosions and production of abundant ash, similar to that seen when the Icelandic volcano Surtsey emerged from the north Atlantic in 1963–1964. Not so easily explained are ash layers (now altered to clay and zeolites) found in older (middle Miocene-late Eocene) clay-rich sediments deposited when Site 842 was probably too far south to receive significant input from the Hawaiian Hotspot. These layers may record as yet unknown widespread central Pacific volcanic events.

Silicified mudstone and chert were first encountered at 35.7 m below seafloor (mbsf), marking the end of good core recovery. From the lower 200 m of the sediment column almost all of the recovered material consists of chert layers and chert breccia. A Santonian nannofossil ooze recovered from approximately 164 mbsf at Site 842 and Albian-Cenomanian nannofossils recognized directly above the basement contact at Site 843 (237.7 mbsf) suggest much higher rates of sedimentation at this site from the Late Cretaceous, but details are totally lacking due to poor recovery.

Approximately 12.5 m of core was recovered from a total penetration of 70 m of basaltic basement. Mildly altered pillow basalts at the sediment-basement interface were underlain by massive lavas that are locally brecciated with veins filled with calcite, pyrite, limonite, and clay. The fresher lavas range in composition from normal to enriched types of mid-ocean ridge basalt. Logging of the basement section included *p*-wave velocity, resistivity, density, spectral gamma-ray, geochemistry, formation microscanner, and borehole televiewer.

REFERENCE

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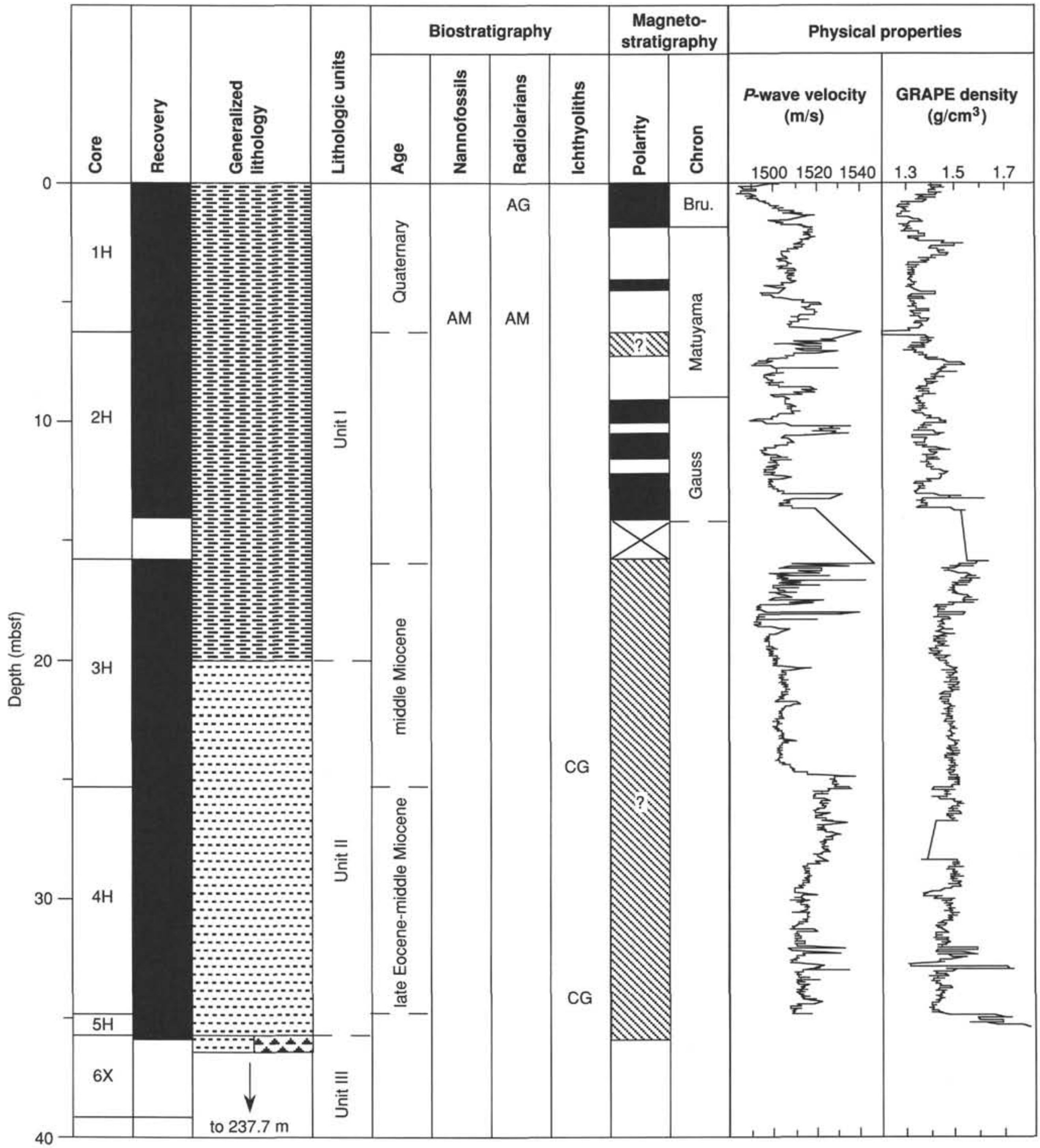

Figure 5. Summary diagram of top 40 m of Hole 842B.