tools have also been used to measure pressure and fluid flow properties of sediment and rock.

Deep Seafloor Observatories

The CORK (Circulation Obviation Retrofit Kit) is a seafloor observatory that measures pressure, temperature, and fluid composition – important parameters for the study of the dynamics of deep-sea hydrologic systems. CORKs are installed by the Ocean Drilling Program for measurements over long periods of time (months to years). Since 1991, observatories have been installed on the deep seafloor in different settings, for example at mid-ocean ridge hydrothermal systems and at active margins.

The CORKs are installed by the drill ship. After a borehole is drilled, a CORK is installed to seal instruments in the borehole away from the overlying ocean (**Figure** 7). The CORK has two major parts: the CORK body that provides the seal and an instrument cable that hangs from the CORK into the borehole. A data recorder is included with the instrument cable. The data recorders have sufficient battery power and memory for up to 5 years of operation. Data are recovered from CORKs using manned submersibles or remotely operated vehicles. The instruments in the CORK measure pressure and temperature spaced along a cable that extends into the sealed borehole. The CORK also includes a valve above the seal where borehole fluids can be sampled.

The Ocean Drilling Program installs another type of long-term seafloor observatory for earthquake studies. Seismic monitoring instruments are installed in deep boreholes located in seismically active regions, e.g. off the coast of Japan. These data are used to help established predictive measures to prevent loss of life and damage to cities during large earthquakes.

Deep-sea seismic observatories contain a strainmeter, two seismometers, a tilmeter, and a temperature sensor. The observatories have replaceable data-recording devices and batteries like CORKs, and are serviced by remotely operated vehicles. Eventually real-time power supply and data retrieval will be possible when some of the observatories are connected to nearby deep-sea fiber-optic cables.

Summary

Deep-sea drilling applies innovative sampling, instrument, and observatory technologies to the study of Earth system science. These range from the study of Earth's past ocean and climate conditions using high-quality sediment cores, to the study of earthquakes and tectonic processes using logging tools and seafloor observatories, to exploring gas hydrates (a potential future energy source) using specialized sampling tools.

The Ocean Drilling Program continues until 2003. A successor international scientific ocean drilling program will begin in 2003 with the operation of at least two specialized ships: a riser drill ship, operated by Ocean Drilling in the 21st century in Japan and a non riser drill ship, operated by a US organization.

See also

Deep Submergence, Science of. Deep-sea Drilling Results. Manned Submersibles, Deep Water. Remotely Operated Vehicles (ROVs).

Further Reading

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DEEP-SEA DRILLING RESULTS

J. G. Baldauf, Texas A&M University, College Station, TX, USA

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Introduction

Modern scientific ocean drilling commenced over forty years ago with the inception of Project

Mohole. This project was named for its goal of coring a 5–6 km borehole through thin oceanic crust, continuing through the Mohorovicic Discontinuity and into the earth's mantle. Project Mohole was active from 1957 through 1966. Although it did not achieve its objective, the Project demonstrated the means for coring in the oceans for scientific purposes and in doing so planted the seed for future decades of scientific ocean drilling.

The current era of scientific coring commenced with the creation of the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) in 1964. In 1965, JOIDES completed its first scientific drilling program on the Blake Plateau using the drilling vessel *Caldrill*. This initial experiment led to the development of the Deep Sea Drilling Project (DSDP) managed by Scripps Institution of Oceanography, California. The scientific objective of DSDP was expanded, compared to that of Project Mohole, and included the recovery of sediments and rocks from throughout the World Ocean to improve the understanding of the natural processes active on this planet. Central to DSDP was the scientific research vessel *Glomar Challenger* (**Figure 1**) operated by Global Marine Inc.

During the 15 years (1968–1983) of operations, DSDP advanced the scientific frontier by completing 96 scientific expeditions throughout the World Ocean (**Figure 2**). These expeditions contributed to advancement of the earth sciences. For example, DSDP confirmed Alfred Wegner's theory of continental drift, and provided fundamental evidence in support of plate tectonics, established the timing of northern and southern hemisphere glaciations, documented the desiccation of the Mediterranean Sea, documented the northward migration of India and its collision with Asia, determined the history of the major oceanic gateways and their impact on ocean circulation, and improved the understanding of oceanic crust formation and subduction processes.

The overwhelming success of DSDP and the numerous scientific questions still remaining provided the framework for the current scientific drilling program, the Ocean Drilling Program (ODP). This new program, established in 1984, continues to explore the history of the earth as recorded in the rocks

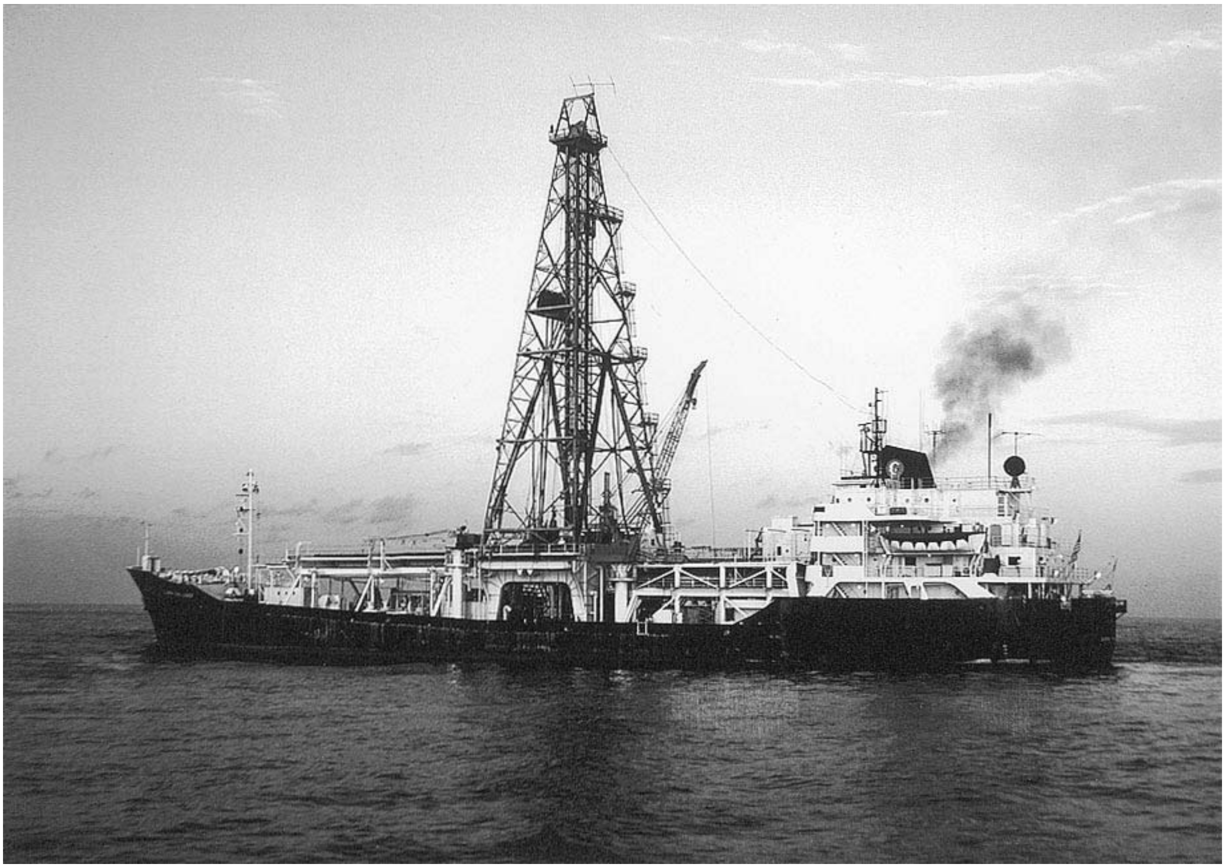
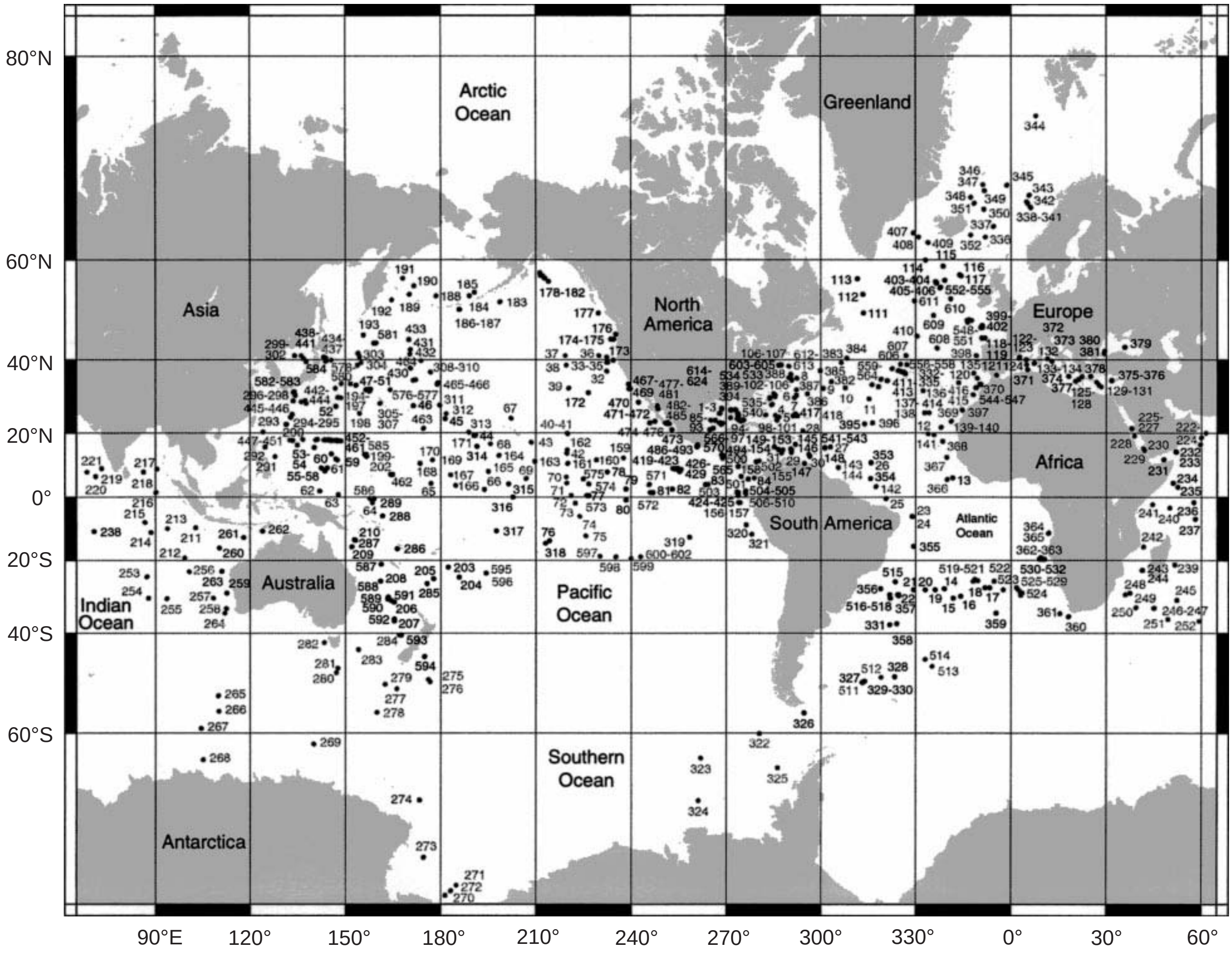


Figure 1 Scientific Research Vessel *Glomar Challenger* operated by Global Marine Inc. for the Deep Sea Drilling Project from 1968 to 1983.



DSDP Legs 1–96, Sites 1–624

Figure 2 Geographic location of the sites occupied during scientific expeditions of the Deep Sea Drilling Project from 1968 to 1983.

and sediments beneath the World Ocean. The centerpiece of ODP is the scientific research vessel *JOIDES Resolution* (**Figure 3**) operated by Transocean SedcoForex for Texas A&M University. To date 92 scientific expeditions have been completed by ODP (**Figure 4**).

Science Initiatives

The earth system is complex and dynamic with numerous variables and a multitude of forcing and response mechanisms. The sediments preserved beneath the World Ocean record the tempo and variation of the climate system at annual to millennial scales. Likewise, oceanic crust records the environment at the time of its formation. The understanding of these variables and the naturally occurring process active in the Earth's environment and in the Earth's interior continue to evolve based on results from scientific ocean drilling. The partitioning of the Earth's processes into these two themes is in part arbitrary as the external environment is closely linked to that of the Earth's interior.

Dynamics of the Earth's Environment

The Earth's climate system consists of processes active in and between five regimes, space, atmosphere, ocean, cryosphere, and crust (**Figure 5**). For example, variation in incoming solar radiation influences the atmosphere-ocean coupling through changes in precipitation, evaporation and heat exchange. In addition, ice-sheets (and in turn sea level), sea ice, albedo, and terrestrial and oceanic biomass also respond to solar radiation changes.

Similarly, variations in the dimensions and shape of the ocean basins, through crust formation on

Figure 3 Scientific Research Vessel *JOIDES Resolution* operated by Transocean SedcoForex for the Ocean Drilling Program 1984 to present.

destruction or the opening or closing of oceanic gateways, influence oceanic circulation, as well as the salinity and temperature of specific water masses. These changes subsequently impact the distribution of nutrients, regional climates, and the Earth's biomass.

The complexity of the climate system is only now beginning to be realized, in part through the ground truthing of climatic models and the historical perspective at various (annual to millennial) scales provide through ocean drilling. ODP's contributions to understanding the Earth's environment are extensive. For example, coring off northern Florida provided evidence to support the Cretaceous/Tertiary Boundary meteorite impact theory and its causal impact on widespread extinction of the Earth's biota. Numerous other cruises have provided insight as to the complexity of the climate system, investigating scientific themes such as the desertification of Africa, implications on climate of the uplift of Tibet plateau, refinement of the glacial history of both hemispheres, including the climate periodicity in icehouse and greenhouse worlds, and understanding of the history of sea level.

In addition, ODP continues to investigate the extent of the biosphere based on evidence of organisms deep within Earth's crust. The discovery of organisms in volcanic crust is significant as it extends the depth of the biosphere and indicates that life is possible in extreme environments.

Three scientific themes associated with the dynamics of the Earth's environment continue to be explored by ODP. These themes include understanding the Earth's changing climate, the causes and effects of sea level change, and fluids and bacteria as agents of change.

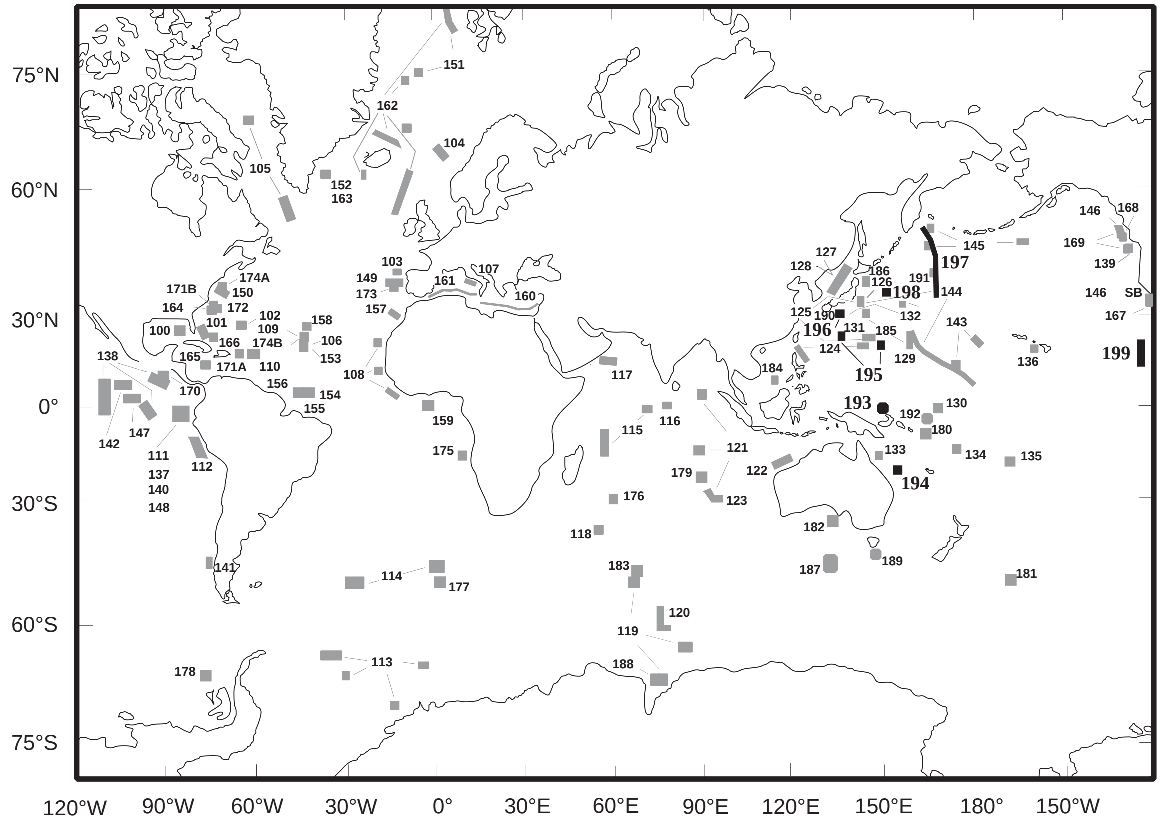


Figure 4 Geographic locations of the 91 scientific expeditions currently completed by ODP from 1984 to the present. Legs indicated in black were completed in 1990 and 1991.

Dynamics of the Earth's Interior

The global cycling of mass and energy in the Earth's interior and the extrusion of this material into the Earth's exterior environment impacts global geochemical budgets (**Figure 6**). For example, the formation of oceanic crust at the mid-ocean spreading centers plays an important role in mantle

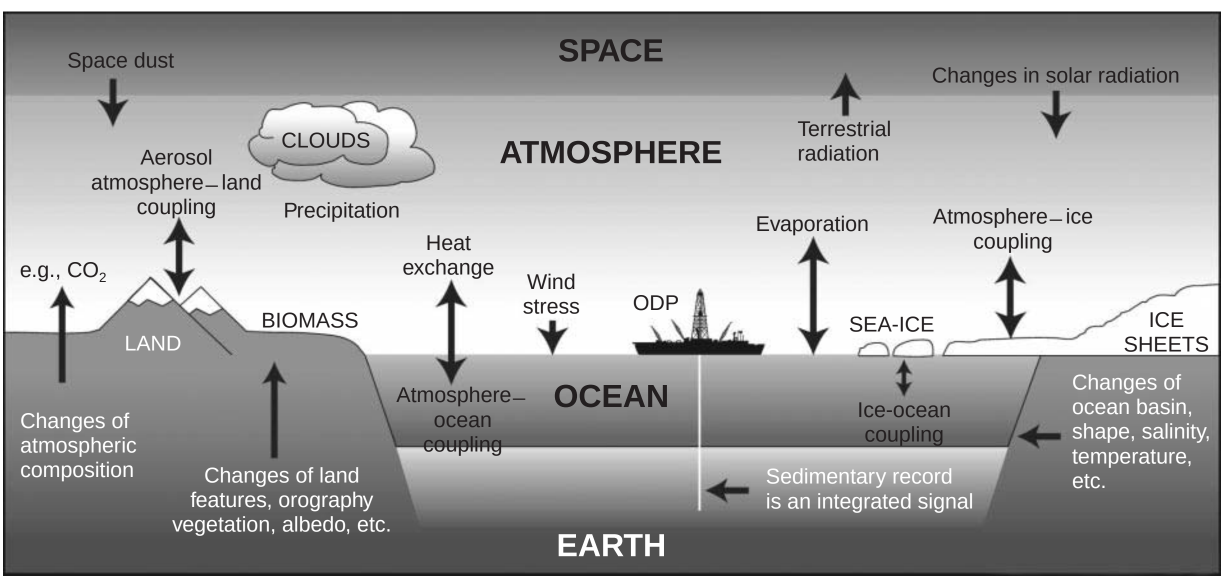


Figure 5 Schematic representation of the major components of the earth's climatic system. (Adapted from Crowley and North (1992) and the ODP long-range plan (1996).)

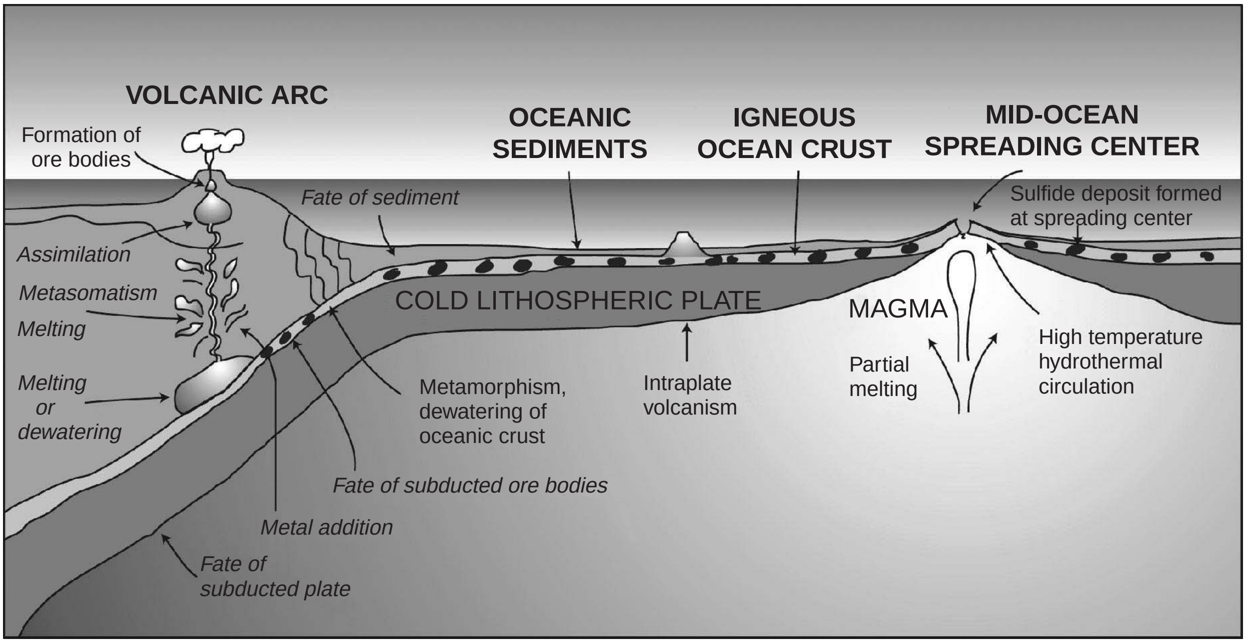


Figure 6 Schematic representation of the major components of the earth's tectonic cycle. (Adapted from the ODP long-range plan 1996.)

dynamics, geochemical fluxes, and heat exchange within and between the Earth's internal and external environments. Similarly, the subduction of a lithospheric plate at a convergent margin results in the melting of the plate, which in turn contributes to the composition and circulation dynamics of the mantle. Associated with subduction zones are volcanic systems through which magma and gases are extruded to Earth's exterior, contributing to the chemical fluxes of the oceans and atmosphere.

Understanding of the processes associated with crustal formation and plate subduction has been enhanced through the recovery of crustal rocks from beneath the oceans. For example, ODP has improved the understanding of the chemical flux by coring within subduction zones to understand the processes associated with subduction, including chemical and mass balances and fluid flow associated with the interface between the two plates, referred to the Decollement zone.

Coring of large igneous provinces (LIPs) such as the Kerguelen Plateau and the Ontong Java Plateau has also provided insight into the mantle dynamics and chemical fluxes. These LIPs formed from the injection of magma through volcanic hotspots. Obtaining crustal samples from these regions enhances the understanding of chemical composition and fluxes, mantle dynamics, and the impact of the formation of these features on oceanic and atmospheric chemistry.

ODP has also recovered over 500 m of gabbro from a single hole on the South-west Indian Ridge. This sequence represents the most continuous stratigraphic sequence of lower crust from oceanic basement, allowing insight into the chemical composition and structure of oceanic crust.

Two other areas of interest for ODP have been the processes associated with the formation of ore bodies and the formation of gas hydrates – frozen methane crystallized with water. Of particular interest is the origin and history of such deposits and their potential influence on global chemical fluxes.

Two scientific themes remain central to ODP investigations: exploring the transfer of heat and material to and from earth's interior and investigating deformation of the lithosphere and earthquake processes.

Technological Advances

Scientific advances made through ocean drilling are closely linked to advances in technology. New tools such as the development of seafloor observatories, enhanced coring and logging prototypes, seafloor equipment, and state-of-the-art laboratory equipment have provided new opportunities to advance the scientific frontier.

Seafloor Observatories

A reentry cone seal, also referred to as CORK, has been developed and used to seal an ODP hole, thus

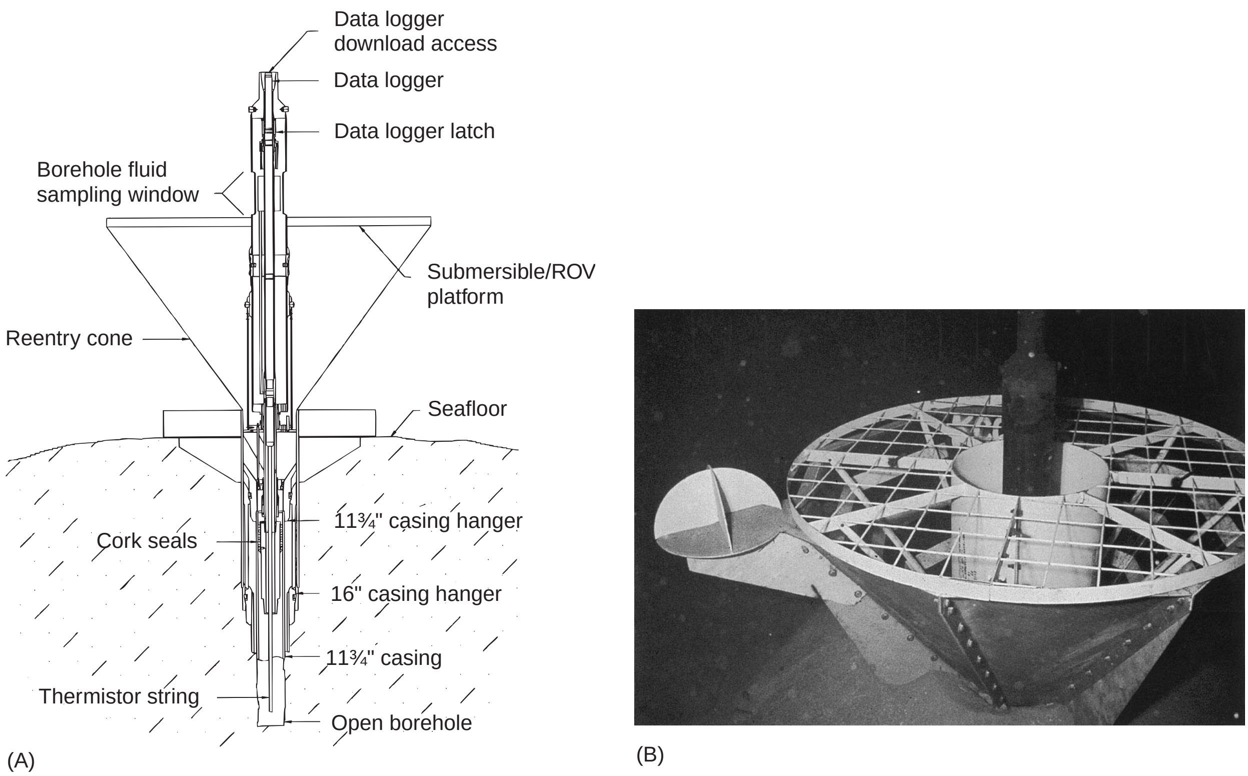


Figure 7 (A) Schematic of a reentry cone seal, also referred to as a CORK. The tool provides a means for monitoring borehole temperature and pressure as well as recovery of borehole fluid samples. (B) Underwater view of the CORK landed in a reentry cone.

preventing flow into or out of the borehole. The CORK provides a means for monitoring borehole temperature and pressure as well as recovery of borehole fluid samples. A typical CORK configuration (**Figure 7A** and **B**) is characterized by the thermistor string used for the collection of pressure and temperature data, a borehole fluid sampler for collection of borehole fluids, and a data logger for the recording and storage of data from the thermistor string until it can be downloaded via a submersible. The next-generation borehole seals, known as the ACORK, are currently being developed. The ACORK will allow subdivision of the borehole into isolated segments, allowing monitoring of fluid flow for given horizons or intervals.

Coring and Logging Tools

Advanced piston corer (**APC**) This is a hydraulically actuated piston corer designed to recover undistributed core samples from soft sediments with enhanced core quality and core recovery. Initially developed during the latter phases of DSDP and enhanced during ODP, the APC has become the mainstay for the recovery of high-resolution sedimentary records for paleoceanographic and climate studies.

Pressure core sampler (**PCS**) The PCS was developed for the retrieval of core samples from the ocean floor while maintaining near *in situ* pressures up to 10 000 psi (69 MPa). This tool continues to be critical for investigating gas-bearing sediments, such as gas hydrates, for the analysis of biogeochemical cycling.

Formation microscanner (**FMS**) Adapted from industry, this logging tool provides an oriented, two-dimensional, high-resolution image of the variations in microresistivity around the borehole wall. Collected data allow the correlation of coring and logging depth, orientation of cores and location of the cored sections when recovery is less than 100%, mapping of sedimentary structures, and interpretation of depositional environments.

Seafloor Equipment

Seafloor equipment such as a reentry cone and the hard rock guide base have been developed and implemented to achieve scientific objectives at specific sites. The reentry cone is a permanent seafloor installation, which serves as a conduit for reentry of the borehole and a platform for supporting various casing strings. Often the drill pipe is pulled from the hole to replace coring bits or to change coring tools. A temporary reentry cone referred to as a 'free fall funnel' is also used to allow bit changes.

The hard rock guide base (HRGB) was developed to focus the direction of the drill bit into hard, irregular seafloor surfaces that are otherwise undrillable. The difficulty in drilling is both the inability to spud or start a hole as insufficient weight could be applied to the bit and the tendency of the bit to 'walk' downhill when trying to start a hole on a sloping surface. The HRGB, when placed on the seafloor, provides support for the drill string to start a hole. Recent technological development of the Hard Rock Reentry System (HRRS) allows a cased reentry hole to be established in bare hard rock without the use of the HRGB.

Laboratory Equipment

Mutisensor track (**MST**) The MST allows measurements of cores at centimeter scales for examination of changes in physical parameters resulting from changes in lithology, composition, porosity, density, and magnetic susceptibility of the sediment collected. Changes in these properties result from changing oceanographic conditions at the time of deposition or from postdeposition processes. The high-resolution records obtained with the MST also allow correlation of data sets from offset holes to ensure completeness of the geological record. In addition, the high-resolution data collected (100–1000 y) can be correlated to data collected through the logging of the borehole to allow direct correlation of laboratory measurements with those from the borehole.

Facilities

The scientific research vessel *JOIDES Resolution* is a dynamically positioned drilling vessel capable of maintaining position over specific locations while coring in water depths down to 8200 m. The vessel was built in Halifax, Nova Scotia, Canada in 1978 and has a length of 143 m, a breadth of 21 m, a gross tonnage of 7539, and a derrick that towers 61.5 m above the water line. A computer-controlled automated dynamic positioning system regulates 12 thrusters in addition to the main propulsion system to maintain the position of the vessel directly over the drill site. *JOIDES Resolution* was originally operated as an oil exploration vessel. In 1984, ODP converted the vessel into a scientific research vessel by removing the shipboard riser system and adding scientific laboratories. Operating statistics of the *JOIDES Resolution* are shown in **Table 1**.

Unique to this vessel is the 7-story laboratory structure housing state-of-the-art scientific equipment for use in the studies of geochemistry, microbiology, paleomagnetism, paleontology, petrology, physical properties, sedimentology, downhole measurements, and marine geophysics. This structure also includes support facilities for electronic repair, computers, photography, database management, communications, and conference facilities.

Cores and data collected during each scientific cruise are stored at shore-based facilities for future research by members of the international scientific community. ODP maintains four core repositories, three in North America and one in Europe. The North American repositories include the East Coast Repository (ECR) at Lamont Doherty Earth Observatory (LDEO), which stores cores from the Atlantic Ocean through Leg 150; the Gulf Coast Repository (GCR) at Texas A&M University (TAMU), Texas, which houses cores from the Pacific and Indian Oceans, and the West Coast Repository (WCR) at Scripps Institution of Oceanography, California, which houses cores from the Pacific and Indian Ocean collected during the Deep Sea Drilling Project. The Bremen Core Repository at the University Bremen, Germany, houses cores obtained from the Atlantic since Leg 151. Data collected during each cruise are stored in one of two locations.

Table 1 Significant operational highlights of the *JOIDES Resolution* from 1985 to 1999 (Leg 100–183)

Deepest hole penetrated	2111 m below the seafloor – Holes 504B completed during Leg 148, eastern Pacific.
Shallowest operational water depth	37.5 m – Leg 143, north-west Pacific.
Deepest operational water depth	5980 m – Leg 129, western Pacific.
Most core recovered during a single expedition	8003 m – Leg 175, south-east Atlantic.
Total number of sites visited	535 – ODP Legs 100–183.
Total number of holes cored	1417 – ODP Legs 100–183.
Total core cored	251 017 m – ODP Leg 100 through Leg 183.
Total core recovered	170 770 m – ODP Leg 100 through Leg 183.

Downhole measurement (logging) and site survey data are housed at LDEO. All other data collected during a cruise are housed at TAMU.

Scientific Expeditions

Using the *JOIDES Resolution,* ODP recovers sediments or rocks from beneath the World Ocean. Typically two types of coring tools, the Rotary Core Barrel (RCB) and the Advanced Piston Corer (APC), are used to cut the oceanic sediments and rocks. The RCB, typical of the petroleum industry, is used for penetration of hard rocks or sediment, while the APC is used in the less-indurated, softer sediment. The APC tool is typically used to recover the upper several hundred meters of the sediment sequence, with the subsequent sequence cored using the RCB. Once collected, the cores are returned to the ship via a wireline. Once on board the 9.5 m cores are sectioned into 1.5 m lengths for ease of handling within the shipboard laboratories.

Following coring operations, the borehole is often logged using standard industrial tools. Logging provides data on the variation in the physical and chemical properties of the sediments and rocks directly from the walls of the borehole. Seafloor laboratories may also be established by instrumenting a borehole with thermistors, water samplers, or seismometers for long term, multiyear monitoring.

Each cruise addresses a specific scientific theme based on a rigorous review of proposals submitted by members of the international science community. The duration of a leg depends on the specific objective. Generally each leg is two months in duration.

The ship crew consists of about 106 individuals of whom 51 are members of the scientific party. The remaining contingent supports ship and coring operations. The scientific party consists of international scientists from participating member countries and a technical support staff from TAMU.

International Partnership

Eight international members representing 22 countries currently provide funding for the Ocean Drilling Program. The budget for the program is about US$46 million annually with the US National Science Foundation contributing about 66% of the required funds. The remaining funds are provided by five additional full members, each contributing about US$3 million annually, and two associate members each contributing between US$0.5 and 2 million annually.

Full members of the program are the Australia/Canada/Korea/Chinese Taipei Consortium for Ocean Drilling, the European Science Foundation Consortium for Ocean Drilling (Belgium, Denmark, Finland, Iceland, Ireland, Italy, Norway, Portugal, Spain, Sweden, Switzerland, and The Netherlands), Germany, Japan, the United Kingdom, and the United States. Associate members include France and the People's Republic of China.

Management Structure

The ODP management team consists of the Prime Contractor, Joint Oceanographic Institution (JOI), the Science Operator at Texas A&M University, and the Wireline Operator at Lamont Doherty Earth Observatory (**Figure 8**). As the prime contractor from the National Science Foundation, JOI is responsible for overall management of the program, including scientific planning, operations, and responding to recommendations from the science advisory structure.

Texas A&M University is subcontracted through JOI to implement the scientific program developed by the science advisory structure. As Science Operator, TAMU is responsible for shipboard operations, including cruise staffing, maintenance and support of shipboard laboratories, data acquisition, engineering development, publication, core curation, and shipboard logistic (clearance, safety review, etc.)

Lamont Doherty Earth Observatory is subcontracted through JOI to implement the wireline-logging program for each scientific cruise. As Wireline Operator, LDEO is responsible for standard logging, specialized logging, and log analysis support services and database. LDEO is also responsible for the ODP Site Survey Data Bank at LDEO, which archives and distributes site survey data for ODP.

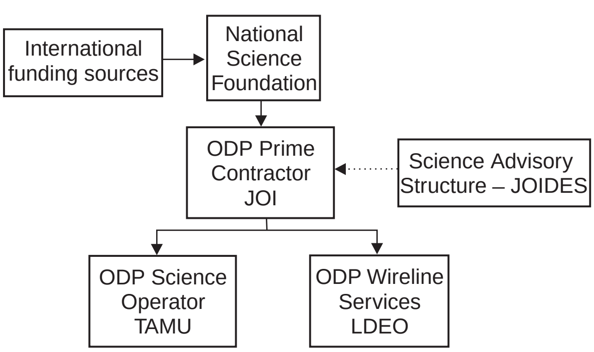


Figure 8 ODP management structure including the National Science Foundation, Joint Oceanographic Institutes (JOI), Texas A&M University (TAMU) and Lamont Doherty Earth Observatory (LDEO). Science advice is provided to JOI through the Joint Oceanographic Institutes for Deep Earth Sampling (JOIDES) panels.

Advisory Structure

The ODP advisory structure (**Figure 9**) provides advice on the scientific program and on logistical activity and program facilities. Scientific guidance is provided by two JOIDES advisory panels, one focused on the Earth's environment and the second focused on Earth's interior. The remaining advisory panels provide guidance for shipboard operations and logistics, such as shipboard laboratories, pollution prevention and safety, and site locations.

Scientific Guidance

The success of ODP is in the bottom-up approach when it comes to determining the scientific programs most likely to advance the scientific frontier. Individuals or groups of scientists in the international community submit a proposal to answer specific scientific questions. Each proposal is reviewed by the Science Advisory Panels (SSPS) and recommendations are made to the Science Committee (SCICOM), which is responsible for ranking each proposal based on the overall contribution the proposed program would make to understanding Earth history. SCICOM forwards to the Operations Subcommittee (OPCOM), the highest-ranked proposals for scheduling consideration, taking into account available budget, weather constraints, and efficiency of scheduling when comparing days on site versus days in transit between sites. OPCOM sends back to SCICOM a proposed schedule, which is then ratified by SCICOM and forward to the Executive Committee (EXCOM) for approval. Upon approval, EXCOM forwards the schedule to JOI and subsequently to the TAMU and LDEO for implementation.

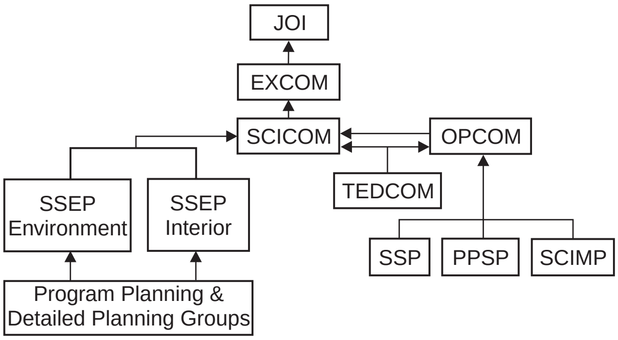


Figure 9 JOIDES Advisory structure consisting of two science panels (SSEP) and four additional panels technology TEDCOM, Site Survey (SSP), pollution prevention and safety (PPSP) and shipboard measurements (SCIMP) providing guidance and advice to the SCICOM committee (SCICOM) and the Operations subcommittee (OPCOM). Recommendations of SCICOM are forwarded to the Executive committee (EXCOM) for endorsement and to JOI for implementation.

Logistics/Infrastructure

In addition to science planning, the JOIDES Advisory structure provides recommendations on site locations, pollution prevention and safety, shipboard measurements and technological developments. The Site Survey Panel (SSP) is responsible for reviewing all site location data and forwarding recommendations to OPCOM concerning the state of readiness of proposals under consideration for implementation. Similarly, the Pollution Prevention and Safety panel reviews each proposal for safety concerns. This panel is focused on reducing risks associated with the potential occurrence of hydrocarbons to an acceptable level. Both SSP and PPSP make recommendations to OPCOM for consideration when considering proposals for scheduling.

The Scientific Measurements Panel (SCIMP) provides advice and guidance on the shipboard laboratories, primarily pertaining to data acquisition, database storage, and data retrieval. In addition, this panel provides recommendations on publications and databases.

The Technology Committee (TEDCOM) works closely with the Engineering development teams at TAMU and LDEO to provide guidance on technological developments.

Future Directions

Like the Deep Sea Drilling Project before it, the present ODP has a defined duration, with the present program ending 30 September 2003. Although the program as currently configured will end, the need for continued scientific research through ocean drilling remains great. Recognizing this continued demand, the international partners are actively planning for a new program of scientific ocean drilling.

The future program is envisioned to utilize multiple platforms, with both Japan and United States providing platforms for the Integrated Ocean Drilling Program (IODP). Japan will provide a new raiser vessel capable of completing deep (>3 km) stratigraphic holes. The United States will provide a nonriser vessel to continue work similar to that currently completed by the *JOIDES Resolution*. In addition to these two platforms, additional alternate platforms will be included for operating in regions not accessible by the other two vessels, such as the Arctic Ocean, shallow water continental margins, and coral reefs, among others. It is envisioned that this new era of scientific ocean drilling will commence in late 2003.

See also

Deep Submergence, Science of. Deep-sea Drilling Methodology. Manned Submersibles, Deep Water. Remotely Operated Vehicles (ROVs)

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DEEP-SEA FAUNA

P. V. R. Snelgrove, Memorial University of Newfoundland, St John's, Newfoundland, Canada
J. F. Grassle, Rutgers University, New Brunswick, New Jersey, USA

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Overview

The deep sea covers more of the Earth's surface than any other habitat, but because of its remoteness and the difficulty in sampling such great depths, our sampling coverage and understanding of the environment have been limited. There has been a common misperception that the deep sea is species poor, and a commonly used 'desert' analogy is hardly surprising given that early sampling found few organisms, and the first deep-sea photographs revealed large plains of rolling hills covered in sediment with little obvious life (**Figure 1**). Indeed, all lines of evidence suggested that the deep sea is a very inhospitable environment. Temperatures are low ($\sim 4°C$), ambient pressure is extremely high (hundreds of times greater than on land), light is completely absent, and food is generally in very low abundance. But within the last few decades, quantitative samples have revealed what primitive sampling gear and photographs could not – that sediments in the deep sea are teeming with a rich diversity of tiny invertebrates only a few millimeters in size or smaller. These benthic (bottom-dwelling) organisms may reside just above the bottom but closely associated with it (hyperbenthos), on the sediment surface (epifauna), or among the sediment grains (infauna).

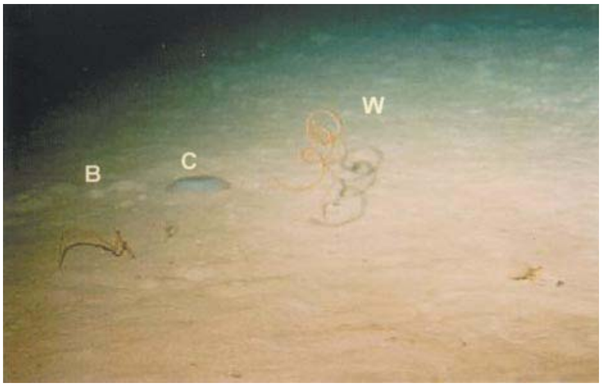

Figure 1 Photograph of a typical deep-sea landscape. This photo is from 750 m near St Croix, US Virgin Islands. Infaunal burrows (B), a sea cucumber (C) and a sea whip (W) are visible.