is difficult to observe even with modern 'quasi-Lagrangian' floats and drifters. A recent description of the Labrador/Irminger Sea circulation from PALACE floats notes that 'no floats travelled southward to the subtropical gyre in the deep western boundary current, the putative main pathway of dense water in the meridional overturning circulation'. If the boundary current is concentrated to a narrow width, for example at the Flemish Cap, then these profiling floats may have difficulty staying within it; tracer observations assure us that the transport does in fact take place.

See also

Carbon Cycle. Current Systems in the Mediterranean Sea. Mediterranean Sea Circulation. Rossby Waves. Sub-sea Permafrost. Thermohaline Circulation.

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DEEP SUBMERGENCE, SCIENCE OF

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Introduction

The past half-century of oceanographic research has demonstrated that the oceans and seafloor hold the keys to understanding many of the processes responsible for shaping our planet. The Earth's ocean floor contains the most accurate (and complete) record of geologic and tectonic history for the past 200 million years that is available for a planet in our solar system. For the past 30 years, the exploration and study of seafloor terrain throughout the world's oceans using ship-based survey systems and deep submergence platforms has resulted in unraveling plate boundary processes within the paradigm of sea floor spreading; this research has revolutionized the Earth and Oceanographic sciences. This new view of how the Earth works has provided a quantitative context for mineral exploration, land utilization, and earthquake hazard assessment, and provided conceptual models which planetary scientists have used to understand the structure and morphology of other planets in our solar system.

Much of this new knowledge stems from studying the seafloor – its morphology, geophysical structure, and characteristics, and the chemical composition of rocks collected from the ocean floor. Similarly, the discoveries in the late 1970s of deep sea 'black smoker' hydrothermal vents at the midocean ridge (MOR) crest (**Figure 1**) and the chemosynthetic-based animal communities that inhabit the vents have changed the biological sciences, provided a quantitative context for understanding global ocean chemical balances, and suggest modern analogs for the origin of life on Earth and extraterrestrial life processes. Intimately tied to these research themes is the study of the physical oceanography of the global ocean water masses and their chemistry and dynamics, which has resulted in unprecedented perspectives on the processes which drive climate and climate change on our planet. These are but a few of the many examples of how deep submergence research has revolutionized our understanding of our Earth and ocean history, and provide a glimpse at the diversity of scientific frontiers that await exploration in the years to come.

Enabling Deep Submergence Technologies

The events that enabled these breakthroughs was the intensive exploration that typified oceanographic expeditions in the 1950s to 1970s, and focused development of oceanographic technology and instrumentation that facilitated discoveries on many

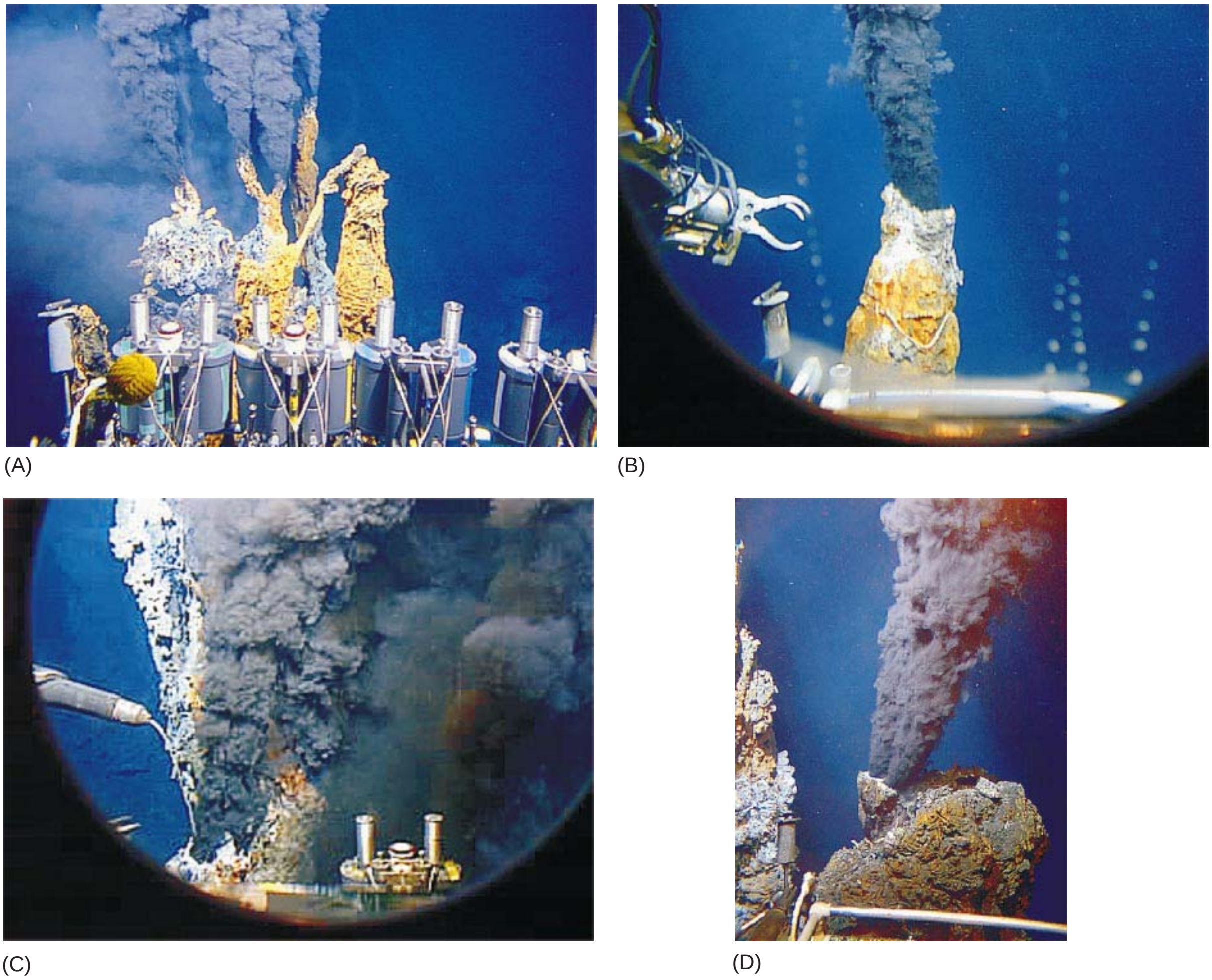


Figure 1 Hydrothermal vents on the southern East Pacific Rise axis at depths of 2500–2800 m. (A) Titanium fluid sampling bottles aligned along the front rail of *Alvin*'s basket in preparation for fluid sampling. (B) *Alvin*'s manipulator claw preparing to sample the hydrothermal sulfide chimney. (C) View from inside *Alvin*'s forward-looking view port of the temperature probe being inserted into a vent orifice to measure the fluid temperature. (D) Hydrothermal vent after a small chimney was sampled which opened up the orifice through which the fluids are exiting the seafloor. Photos courtesy of Woods Hole Oceanographic Institution – Alvin Group, D. J. Fornari and K. Von Damm and M. Lilley.

disciplinary levels. Significant among the enabling technologies were satellite communication and global positioning, microchip technology and the widespread development of computers that could be taken into the field, and increasingly sophisticated geophysical and acoustic modeling and imaging techniques. The other key enabling technologies which supplanted traditional mid-twentieth century methods for imaging and sampling the seafloor from the beach to the abyss were submersible vehicles of various types, remote-sensing instruments, and sophisticated acoustic systems designed to resolve a wide spatial and temporal range of ocean floor and oceanographic processes.

Oceanographic science is by nature multidisciplinary. Science carried out using deep submergence vehicles of all types has traditionally involved a wide range of research components because of the time and expense involved with conducting field research on the seafloor using human occupied submersibles or remotely operated vehicles (ROVs), and most recently autonomous underwater vehicles (AUVs) (**Figures 2–6**). Through the use of all these vehicle systems, and most recently with the advent of seafloor observatories, deep submergence science is poised to enter a new millennium where scientists will gain a more detailed understanding of the complex linkages between physical, chemical, biological, and geological processes occurring at and beneath the seafloor in various tectonic settings.

Understanding the temporal dimension of seafloor and sub-seafloor processes will require continued

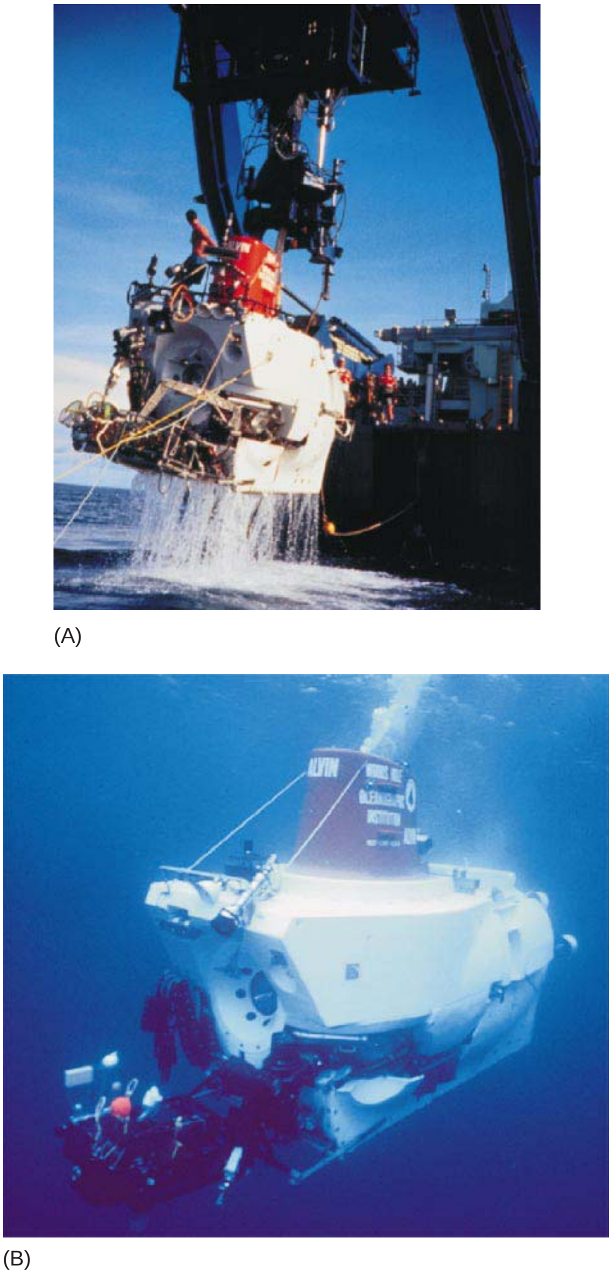


Figure 2 (A) The submersible *Alvin* being lifted onto the stern of R/V *Atlantis*, its support ship. (B) *Alvin* descending to the seafloor. Photos courtesy of Woods Hole Oceanographic Institution – Alvin Group and R. Catanach.

use of deep ocean submersibles and utilization of newly developed ROVs and AUVs for conducting time-series and observatory-based research in the deep ocean and at the seafloor. These approaches will provide new insights into intriguing problems concerning the interrelated processes of crustal generation, evolution, and transport of geochemical fluids in the crust and into the oceans, and origins and proliferation of life both on Earth and beyond.

Since the early twentieth century, people have been venturing into the ocean in a wide range of diving vehicles from bathyscapes to deep diving submersibles. Even in ancient times, there was written and graphic evidence of the human spirit seeking the mysteries of the ocean and seafloor. There is unquestionably the continuing need to take the unique human visual and cognitive abilities into the ocean and to the seafloor to make observations and facilitate measurements. For about the past 40 years submersible vehicles of various types have been developed largely to support strategic naval operations of various countries. As a result of that effort, the US deep-diving submersible *Alvin* was constructed.

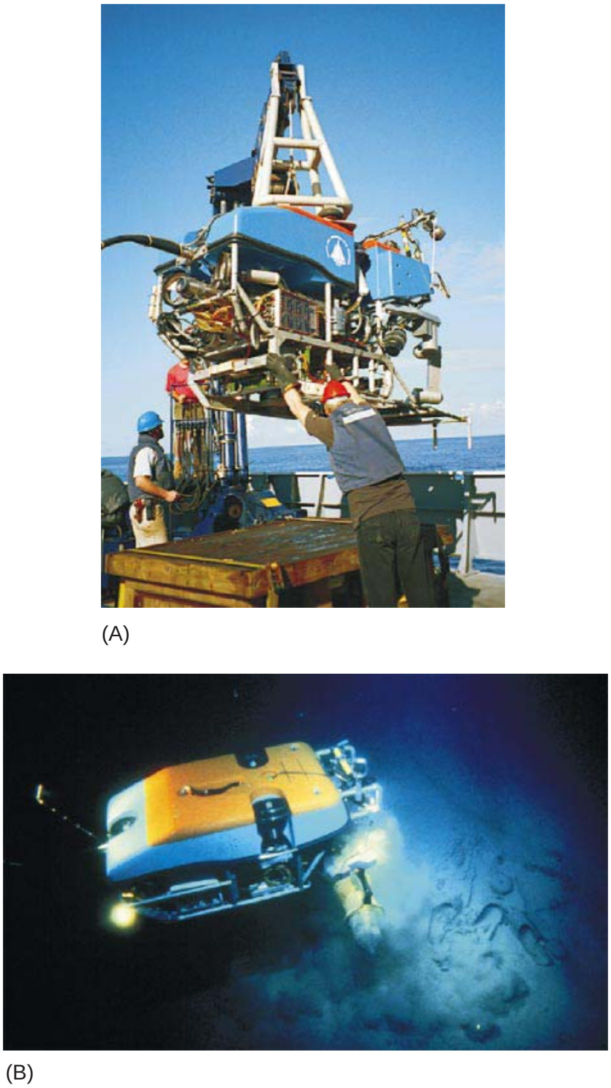
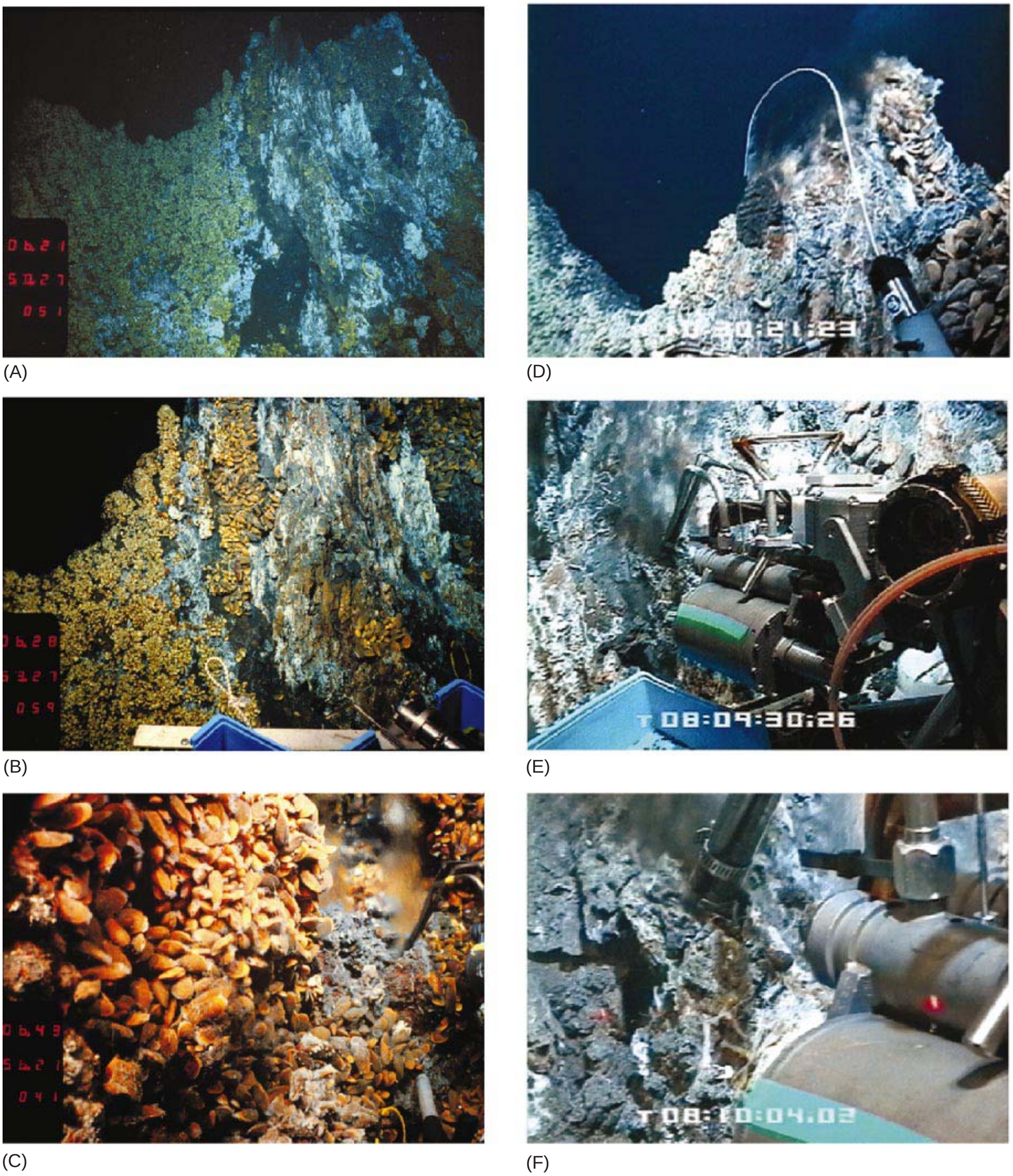


Figure 3 (A) The ROV *Jason* being lifted off the stern of a research vessel at the start of a dive. (B) ROV *Jason* recovering amphora on the floor of the Mediterranean Sea. Photos courtesy of Woods Hole Oceanographic Institution – Alvin Group and R. Ballard.



(A) (D) (B) (E) (C) (F)

Figure 4 Photographs taken from the ROV *Jason* at hydrothermal vents on the Mid-Atlantic Ridge near 37°N on the summit of Lucky Strike Seamount at a depth of 1700 m. All photographs are of a vent named 'Marker #4.' (A) Overall view of vent looking North. White areas are anhydrite and barite deposits, yellowish areas are covered with clumps of vent mussels. (B) Close-up of the side of the vent, *Jason*'s sampling basket is in the foreground. (C) Close-up view of mussels on the side of the hydrothermal chimney; the hydrothermal vent where hot fluids are exiting the mound is at the upper right, where the image is blurry because of the shimmering effect of the hot water. Nozzles of a titanium sampling bottle are at the middle-right edge. (D) Inserting a self-recording temperature probe into a beehive chimney. (E) Titanium fluid sampling bottles being held by *Jason*'s manipulator during sampling. (F) Close-up of nozzles of sampling bottle inserted into vent orifice during sampling. Photos (D)–(F) are frame grabs of *Jason* video data. Photos courtesy of Woods Hole Oceanographic Institution – ROV Group, D. J. Fornari, S. Humphris, and T. Shank.

(A)

(B)

Figure 5 (A) ROV *Tiburon* of the Monterey Bay Aquarium Research Institute (MBARI) in the hanger of its support ship R/V *Western Flyer*. This electric-powered ROV can dive to 4000 m. A steel-armored, electro-optical cable connects *Tiburon* to the R/V *Western Flyer* and delivers power to the vehicle. Electric thrusters allow fine maneuvering while minimizing underwater noise and vehicle disturbance. A variable buoyancy control system, together with the syntactic foam pack, enables *Tiburon* to hover inches above the seafloor without creating turbulence, to pick up a rock sample, or maneuver quickly to follow an animal. (B) ROV *Ventana* of the MBARI being launched from its support ship R/V *Pt. Lobos*. This ROV gives researchers the opportunity to make remote observations of the seafloor to depths of 1850 m. The vehicle has two manipulator arms – a seven-function arm with five spatially correspondent joints and another seven-function robot arm with six spatially correspondent joints. Both arms can use a variety of end effectors to suit the type of work being done. *Ventana* is also equipped with a conductivity, temperature and density (CTD) package including a dissolved-oxygen sensor and a transmissometer. Photos courtesy of MBARI.

Alvin is part of the National Deep Submergence Facility (NDSF) of the University National Oceanographic Laboratories System (UNOLS) operated by the Woods Hole Oceanographic Institution (**Figure** 7). Alvin provides routine scientific and engineering access to depths as great as 4500 m. The US academic research community also has routine, observational access to the deep ocean and seafloor down to 6000 m depth using the ROV and tethered vehicles of the NDSF (**Figure** 7). These vehicle systems of the NDSF include the ROV *Jason*, and the tethered optical/acoustic mapping systems Argo II and DSL-120 sonar (a 120 kHz split-beam sonar system capable of providing 1–2 m pixel resolution back-scatter imagery of the seafloor and phase-bathymetric maps with ~4 m pixel resolution (**Figure** 7). These fiberoptic-based ROV and mapping systems can work at depths as great as 6000 m.

Alvin has completed over 3600 dives (more than any other submersible of its type), and has participated in making key discoveries such as: imaging, mapping, and sampling the volcanic seafloor on the MOR crest; structural, petrological, and

Figure 6 The autonomous underwater vehicle (AUV) ABE (Autonomous Benthic Explorer) of the Woods Hole Oceanographic Institution's Deep Submergence Laboratory, which can survey the seafloor completely autonomously to depths up to 4000 m and is especially well suited to working in rugged terrain such as is found on the Mid Ocean Ridge. Photo courtesy of Woods Hole Oceanographic Institution.

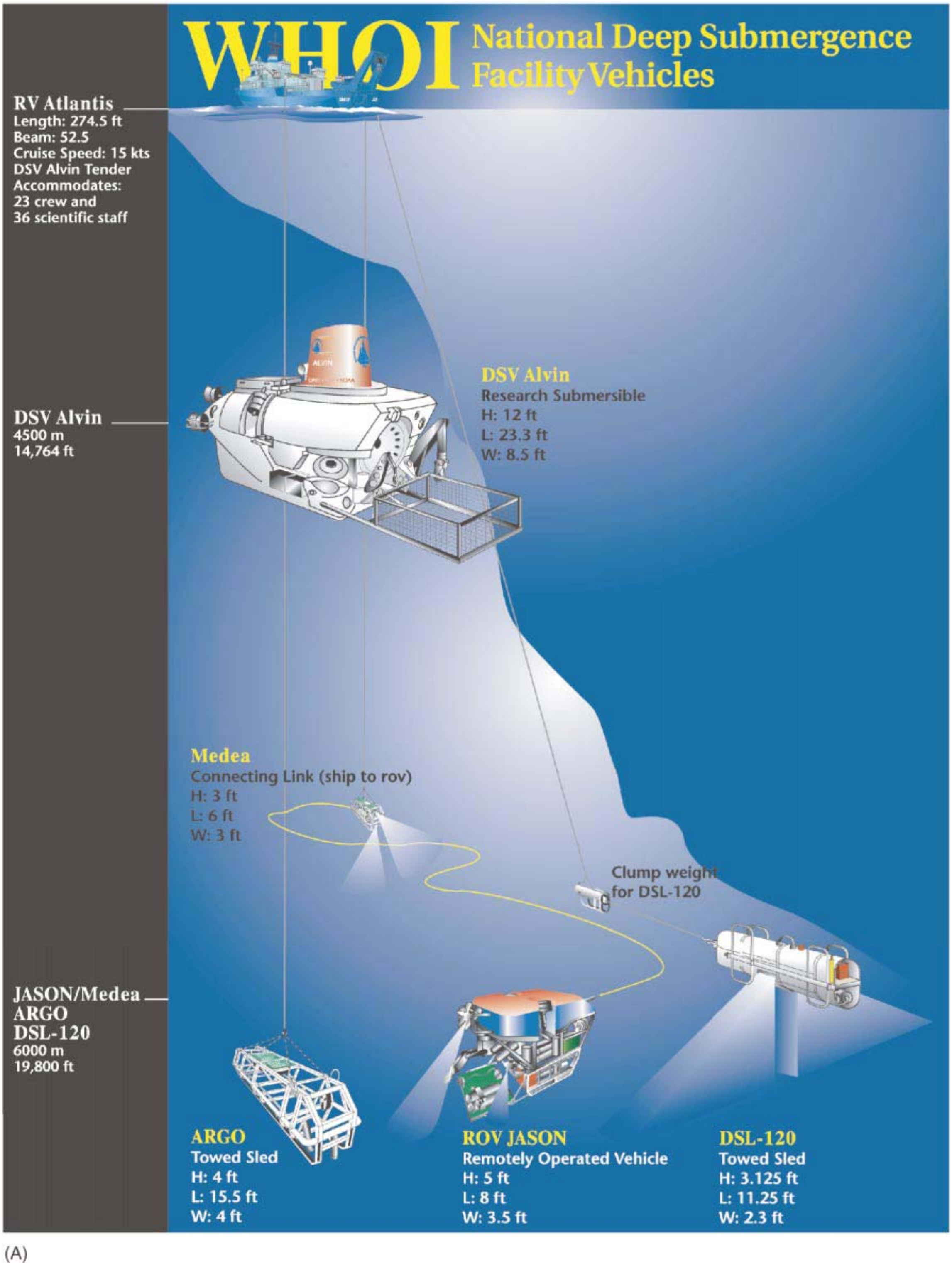
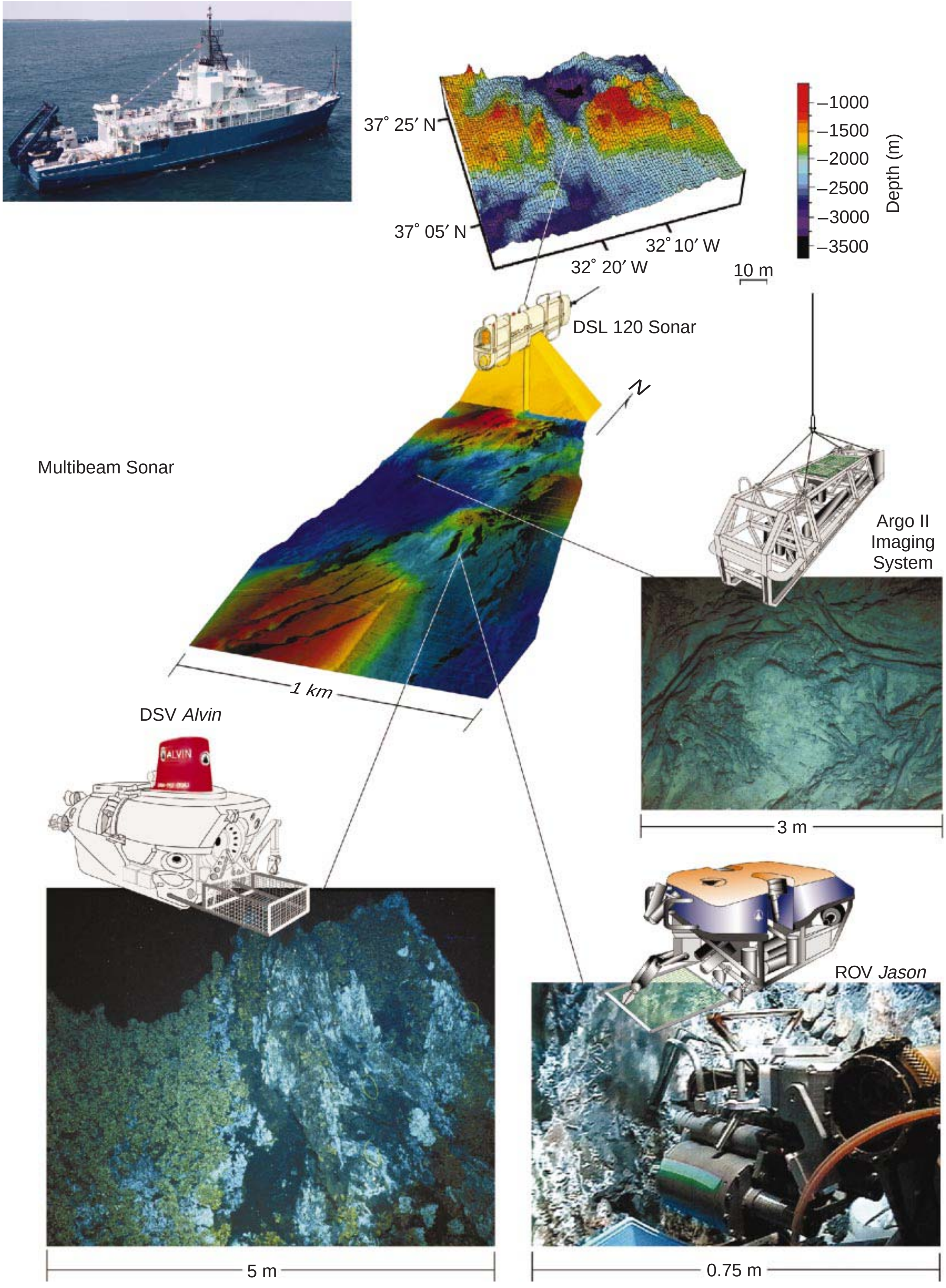


Figure 7 (A) Summary of the US National Deep Submergence Facility (NDSF) vehicles operated for the University National Oceanographic Laboratories System (UNOLS) by the Woods Hole Oceanographic Institution (WHOI). (B) Montage of the NDSF vehicles showing examples of the various types of data they collect. The figure also shows the nested quality of the surveys conducted by the various vehicles which allows scientists to explore and map features with dimensions of tens of kilometers (top right multibeam sonar map), to detailed sonar back scatter and bathymetry swaths which have pixel resolution of 1–2 m (DSL-120 sonar), which are then further explored with the Argo II imaging system, or sampled using *Alvin* or ROV *Jason*. Graphics by P. Oberlander, WHOI; photos courtesy of WHOI – Alvin and ROV Group.



(B)

Figure 7 *Continued*

geochemical studies of transforms faults; structural studies of portions of deep-sea trenches off Central America; petrological and geochemical studies of volcanoes in back-arc basins in the western Pacific Ocean; sedimentary and structural studies of submarine canyons, discovering MOR hydrothermal vents; and collecting samples and making time series measurements of biological communities at hydrothermal vents in many MOR settings in the Atlantic and Pacific Oceans. In 1991, scientists in *Alvin* were also the first to witness the vast biological repercussions of submarine eruptions at the MOR axis, which provided the first hint that a vast subsurface biosphere exists in the crust of the Earth on the ocean floor (**Figure** 7).

Deep Submergence Science Topics

Some of the recent achievements in various fields of deep submergence science include the following.

1. Discoveries of deep ocean hydrothermal communities and hot ($> 350^\circ$C) metal-rich vents on many segments of the global mid-ocean ridge (MOR);
2. Documentation of the immediate after-effects of submarine eruptions on the northern East Pacific Rise, Axial Seamount, Gorda Ridge and CoAxial Segment of the Juan de Fuca Ridge;
3. Utilization of Ocean Drilling Program bore holes and specialized vehicle systems (e.g. Scripps Institution's Re-Entry Vehicle) (**Figure 8**) and instrument suites (e.g. CORKs) (**Figure 9**) for a wide range of physical properties, fluid flow and seismological experiments;
4. Discoveries of extensive fluid flow and vent-based biological communities along continental margins and subduction zones;
5. Initial deployment of ocean floor observatories of various types which enable the monitoring and sampling of geological, physical, biological and chemical processes at and beneath the seafloor (**Figures 10** and **11**).

These studies have revolutionized our concepts of deep ocean processes and highlighted the need for more detailed, time-series, multidisciplinary research.

Within the field of biological oceanography, major recent advances have come from the study of the new life forms and chemoautotrophic processes discovered at hydrothermal vents (**Figure 10**). These advances have fundamentally altered biological classification schemes, extended the known thermal and chemical limits of life, and have pushed the search for origins of life on Earth as well as for new life forms on other planetary bodies.

Recent marine biological studies show that: (1) the biodiversity of every marine community is vastly greater than previously recognized; (2) both sampling statistics and molecular tools indicate that


(A)

Figure 8 (A) The Scripps Institution of Oceanography's Control Vehicle is a specialized ROV that can place instrument strings inside deep-sea boreholes, using a conventional oceanographic vessel capable of dynamic positioning and equipped with a winch carrying 17.3 mm (0.68 in) electromechanical cable with a single coax (RG8-type). The control vehicle is 3.5 m tall and weighs about 500 kg in water (1000 kg in air). It consists of a stainless-steel frame that contains two orthogonal horizontal hydraulic thrusters, a compass, a Paroscientific pressure gauge, four 250 W lights, a video camera, sonar systems, electronic interfaces to electrical releases and to a logging probe, and electronics to control all these sensors and handle data telemetry to and from the ship. Telemetry on the tow cable's single coax is achieved by analog frequency division multiplexing over a frequency band extending from 20 kHz to about 800 kHz. The sonars include a 325 kHz sector-scanning sonar, a 23.5 kHz narrow beam acoustic altimeter, and a 12 kHz sonar for long baseline acoustic navigation. This system was used successfully in the 1998 Ocean Seismic Network Pilot Experiment at ODP Hole 843B, 225 km south-west of the island of Oahu, Hawaii. In 1999, the control vehicle's analog telemetry module was converted into a digital system using fiberoptic technology thus providing bandwidth capabilities in excess of 100 Mbaud. (B) Cartoon showing the configuration of the control vehicle deployed from a research ship as it enters an Ocean Drilling Program bore hole to insert an instrument string. Photo and drawing courtesy of Scripps Institution of Oceanography – Marine Physical Laboratory, F. Spiess, and C. de Moustier.

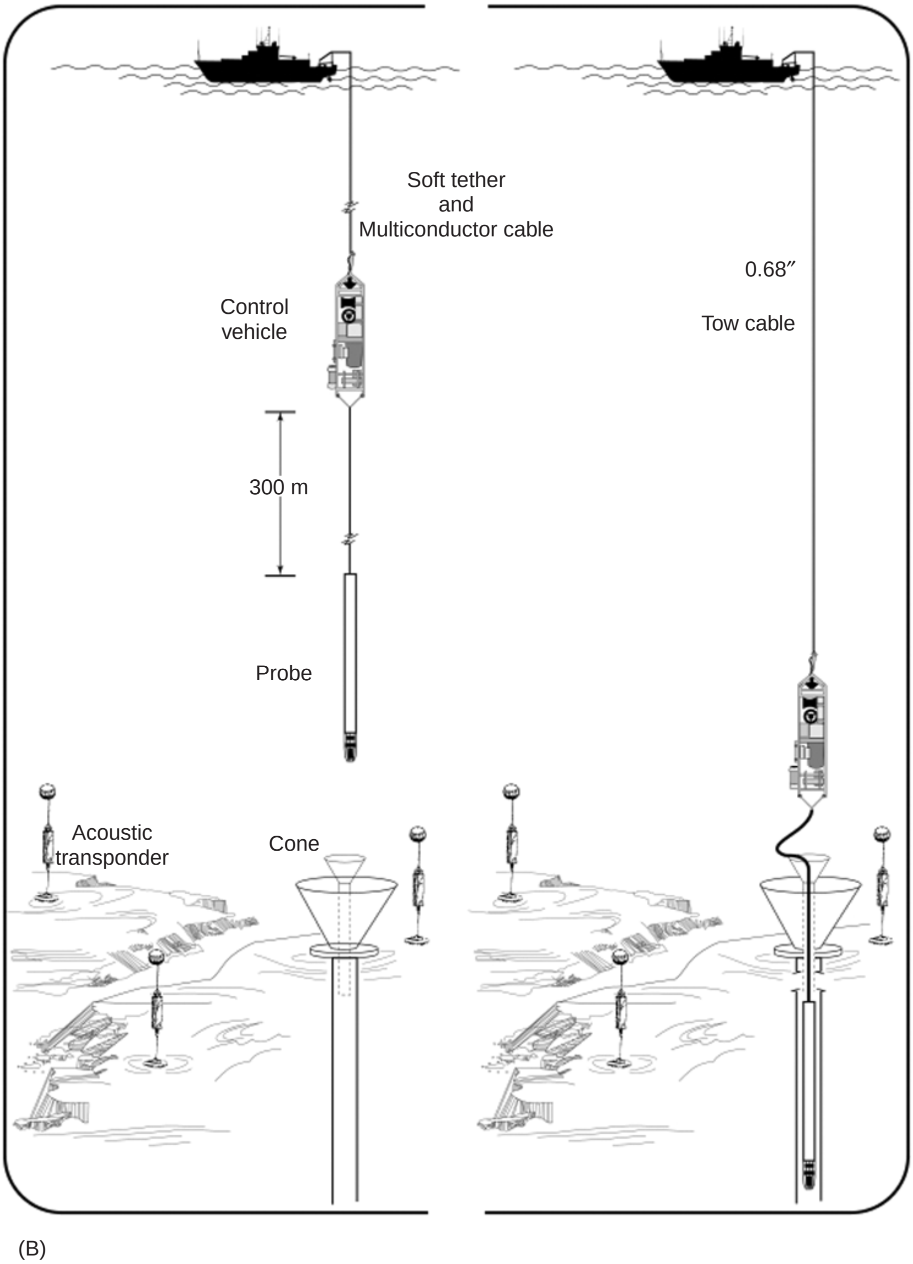
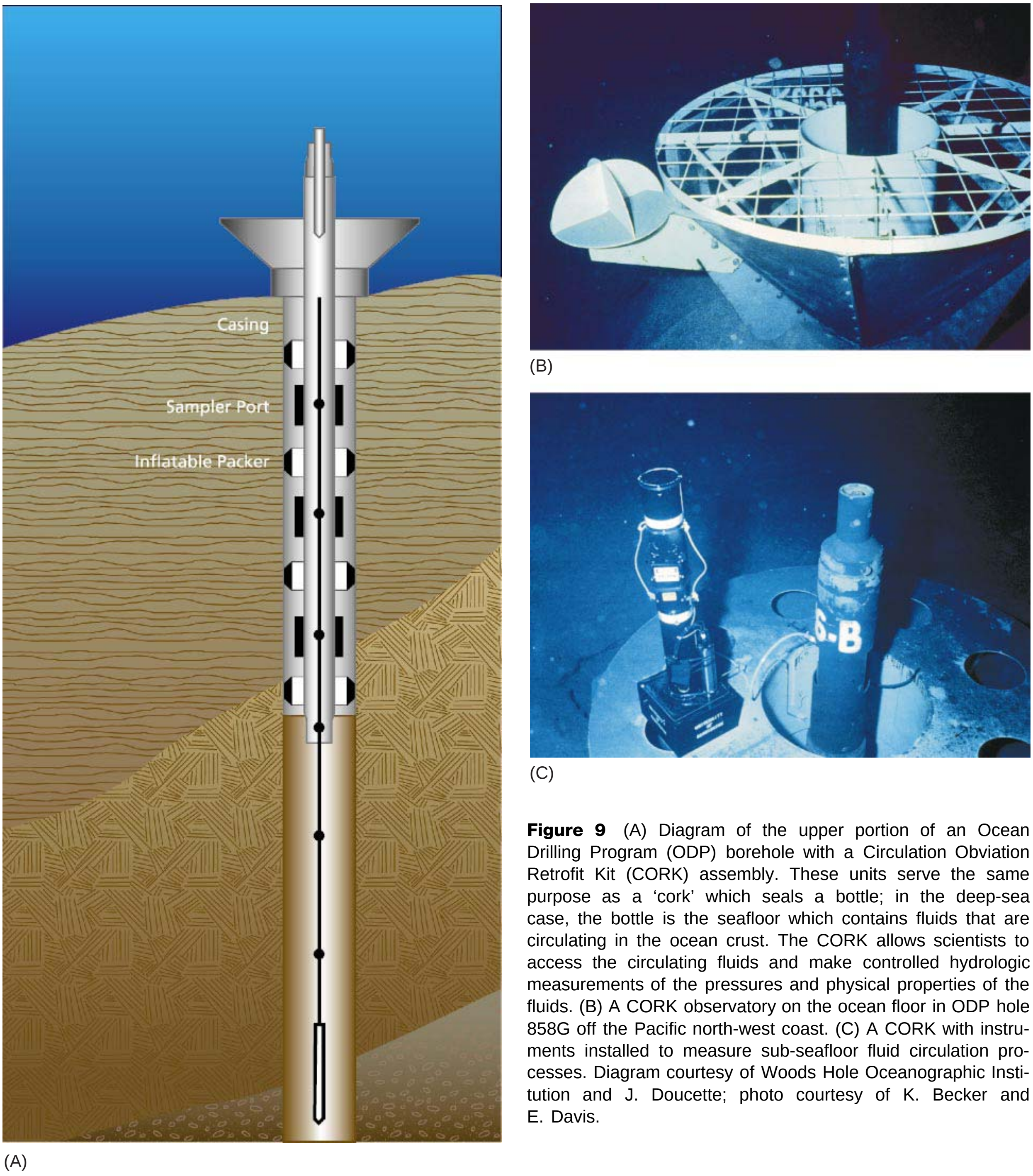


Figure 8 *Continued*

the large majority of marine species have not been described; (3) the complexity of biological communities is far greater than previously realized; and (4) the response of various communities to both natural and anthropogenic forcing is far more complex than had been understood even a decade ago. Focused studies over long time periods will be required to characterize these communities fully.

The field of marine biology is heading toward a more global time-series approach as a function of recent discoveries largely in the photic zone of the oceans and in the deep ocean at MOR hydrothermal vents. The marine biological, chemical, and physical oceanographic research which will be carried out in the next decade and beyond will certainly have a profound impact on our understanding of the complex food webs in the ocean which control productivity at every level and have direct implications for commercial harvesting of a wide range of resources from the ocean. Meeting the challenge of deciphering the various chemical, biological, and physical influences on these phenomena will require



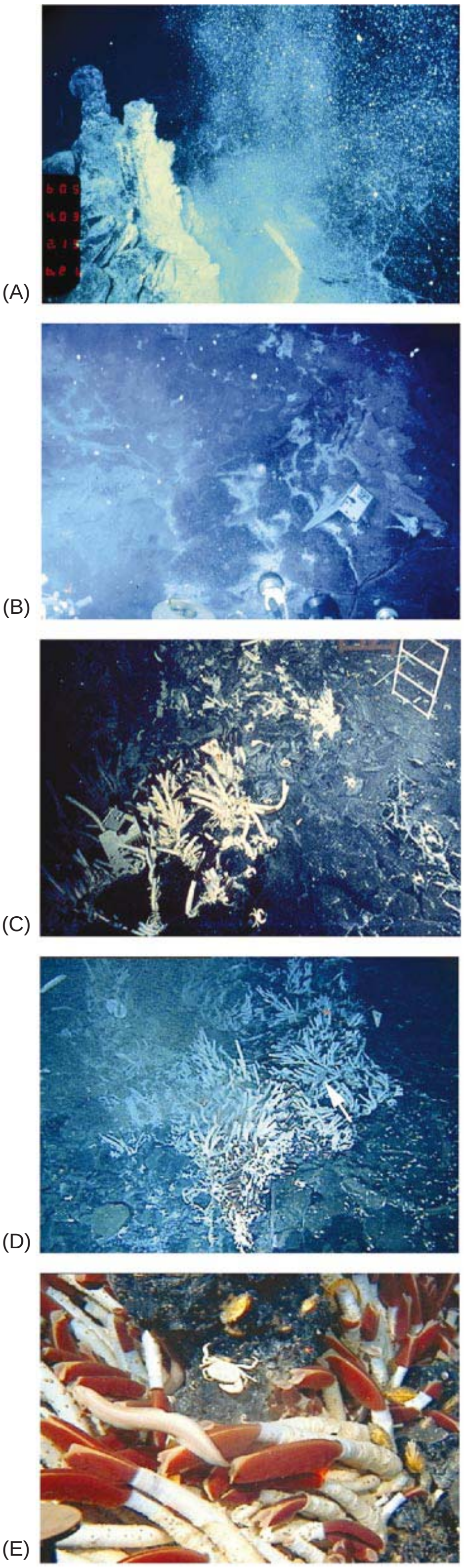
(A)

(B)

(C)

Figure 9 (A) Diagram of the upper portion of an Ocean Drilling Program (ODP) borehole with a Circulation Obviation Retrofit Kit (CORK) assembly. These units serve the same purpose as a 'cork' which seals a bottle; in the deep-sea case, the bottle is the seafloor which contains fluids that are circulating in the ocean crust. The CORK allows scientists to access the circulating fluids and make controlled hydrologic measurements of the pressures and physical properties of the fluids. (B) A CORK observatory on the ocean floor in ODP hole 858G off the Pacific north-west coast. (C) A CORK with instruments installed to measure sub-seafloor fluid circulation processes. Diagram courtesy of Woods Hole Oceanographic Institution and J. Doucette; photo courtesy of K. Becker and E. Davis.

a better understanding and resolution of the causes and consequences of change on scales from hours to millennia. Understanding ocean ecosystems and their constituents will improve dramatically in response to emerging molecular, chemical, optical, and acoustical technologies. Given the relative paucity of information on deep-sea fauna in general, and especially the relatively recent discovery of chemosynthetic ecosystems at MOR hydrothermal vents, this will continue to be a focus for deep ocean biological research in the coming decade and beyond. Time-series and observatory-based research and sampling techniques will be required to answer the myriad of questions regarding the evolution and physiology of these unique biological systems (**Figures 10** and **11**).



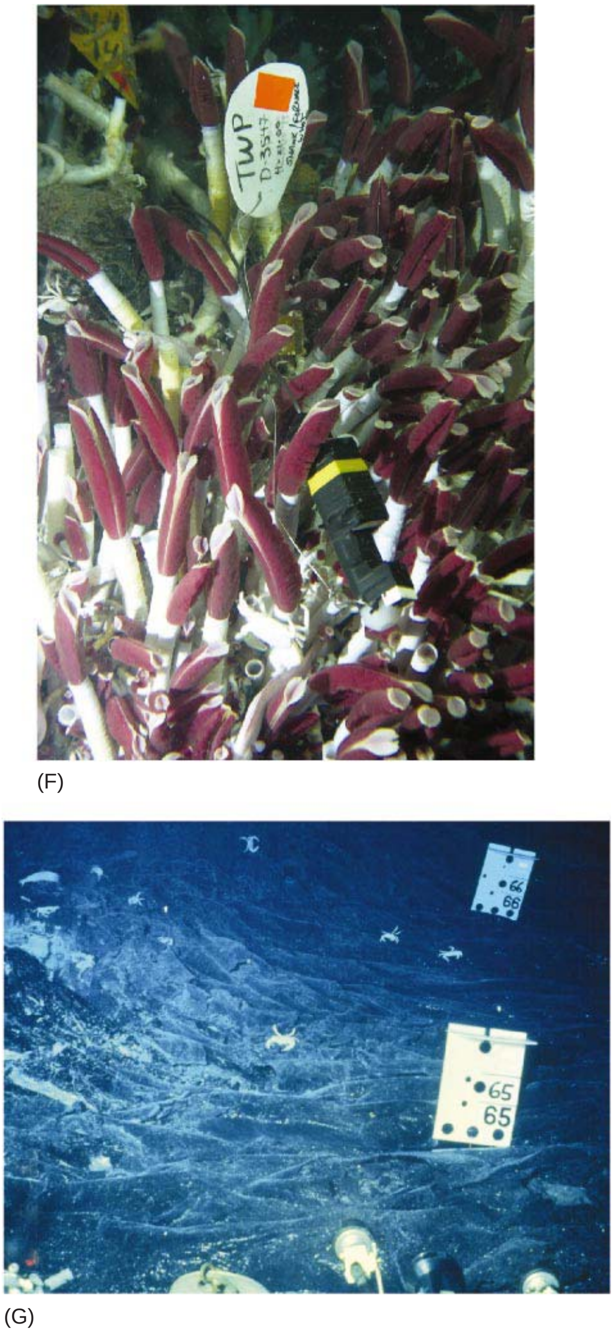
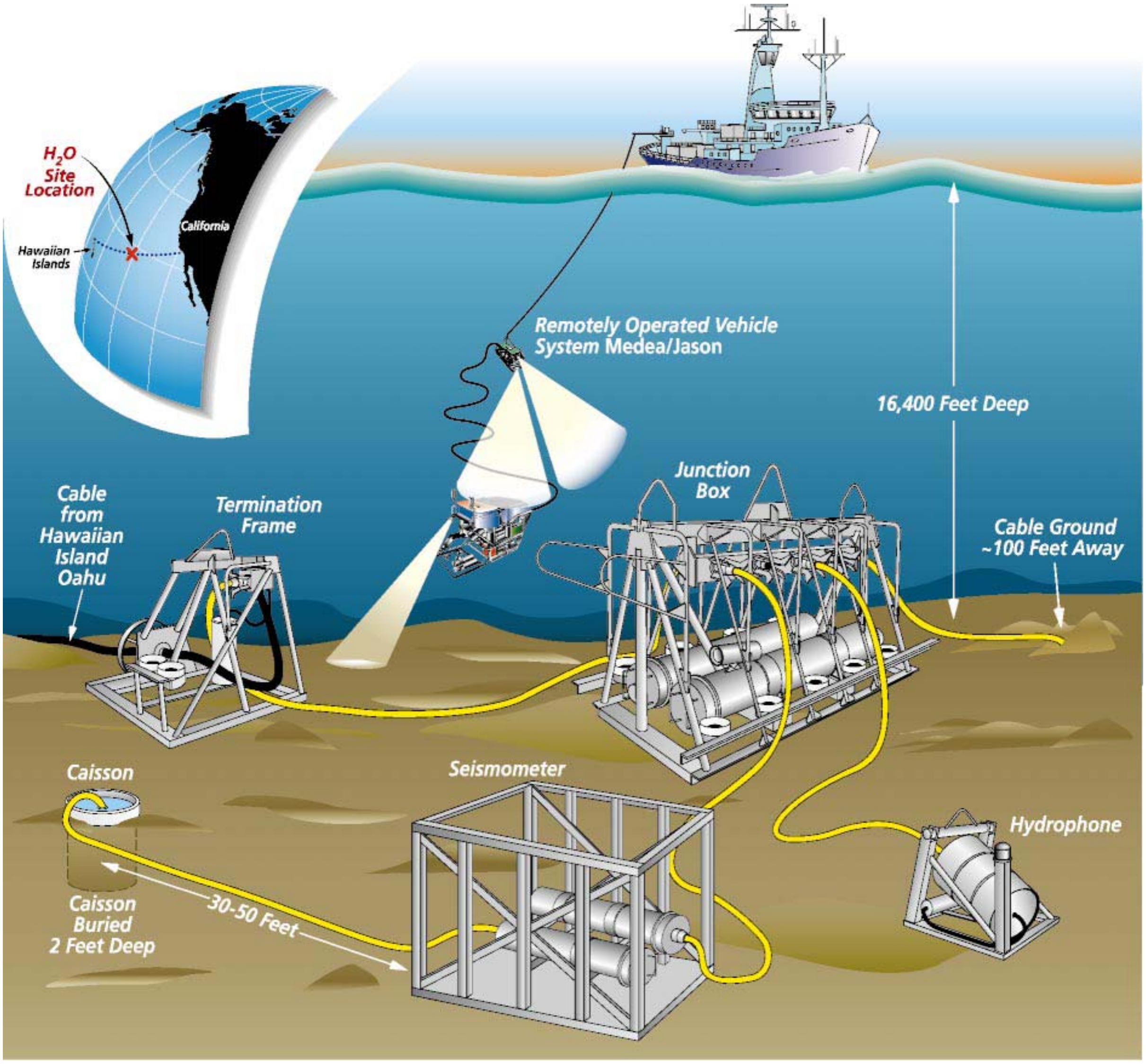


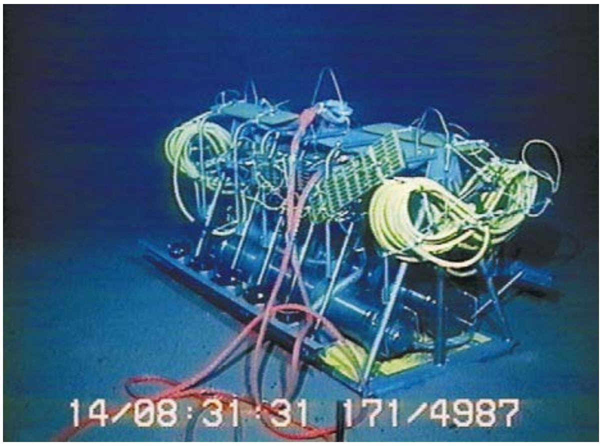
Figure 10 Time-series sequence of photographs taken of the same area of seafloor from the submersible *Alvin* of a hydrothermal vent site on the East Pacific Rise axis near $9^\circ 49.8'$N at a depth of 2500 m. (A) 'Snow blower' vent spewing white bacterial by-product during the 1991 eruption. (B) Same field of view as (A) about 9 months later. Diffuse venting is still occurring as is bacterial production. White areas in the crevices of the lava flow are juvenile tube worms. (C) Patches of Riftia tube worms colonizing the vent area ~ 18 months after the March 1991 eruption. (D) Tube worm community has continued to develop, and the venting continues over 5 years after the eruption. (E) Close-up photograph of zoarcid vent fish (middle-left), tube worms, mussels (yellowish oblong individuals) and bathyurid crab (center). (F) A time-series temperature probe (with black and yellow tape), deployed at a hydrothermal vent (Tube worm pillar) on the East Pacific Rise crest near $9^\circ 49.6'$N at a depth of 2495 m. The vent is surrounded by a large community of tube worms. (G) Seafloor markers along the Bio-Geo Transect, a series of 210 markers placed on the seafloor in 1992 to monitor the changes in hydrothermal vent biology and seafloor geology over a 1.4 km long section of the East Pacific Rise axis that have occurred after the 1991 volcanic eruption at this site. Photographs courtesy of T. Shank, Woods Hole Oceanographic Institution and R. Lutz, Rutgers University, D. J. Fornari and Woods Hole Oceanographic Institution – Alvin Group.



(A)

Figure 11 (A) Diagram of the deployment of the Hawaii-2 Observatory (H2O) one of the first long-term, deep seafloor observatories deployed in the past few years. Scientists used the ROV *Jason* to splice an abandoned submarine telephone cable into a termination frame which acts as an undersea telephone jack. Attached by an umbilical is a junction box, which serves as an electrical outlet for up to six scientific instruments. An ocean bottom seismometer and hydrophone are now functioning at this observatory. (B) The H2O junction box as deployed on the seafloor and photographed by ROV *Jason*. Drawing courtesy of Jayne Doucette, Woods Hole Oceanographic Institution (WHOI), A. Chave, and WHOI–ROV group.

Present and future foci for deep submergence science is MOR crests, hydrothermal systems, and the volcano–tectonic processes that create the architecture of the Earth's crust. Geochemists from the marine geology and geophysics community have emphasized the need for studies of: (1) the flux-frequency distribution for ridge-crest hydrothermal activity (heat, fluid, chemistry); (2) the role played by fluid flow in gas hydrate accumulation and determination of how important hydrates are to climate change; (3) slope stability; and (4) determination of how much of a role the microbial community plays in subsurface chemical and physical transformations. Another focus involves subduction zone processes, including: an assessment of the fluxes of fluids and solids through the seismogenic zone; long-term monitoring of changes in seismicity, strain, and fluid flux in the seismogenic zone; and determining the nature of materials in the seismogenic zone.



(B)

Figure 11 *Continued*

To answer these types of questions, the marine geology and geophysics community requires systematic studies of temporal evolution of diverse areas on the ocean floor through research that includes mapping, dating, sampling, geophysical investigations, and drilling arrays of crustal holes (**Figures 8, 9** and **11**). The researchers in this field stress that the creation of true seafloor observatories at sites with different tectonic variables, with continuous monitoring of geological, hydrothermal, chemical, and biological activity will be necessary. Whereas traditional geological and geophysical tools will continue to provide some means to address aspects of these problems, it is clear that an array of deep submergence vehicles, *in situ* sensors, and ocean floor observatory systems will be required to address these topics and unravel the variations in the processes that occur over short (seconds/minutes) to decadal timescales. The infrastructural requirements, facility, and development needs required to support the research questions to be asked include: a capability for long-term seafloor monitoring; effective detection and response capability for a variety of seafloor events (volcanic, seismic, chemical); adequately supported, state-of-the-art seafloor sampling and observational facilities (e.g. submersible, ROVs, and AUVs), and accurate navigation systems, software, and support for shipboard integration of data from mutiscalar and nested surveys (**Figures 7B, 11** and **12**).

As discussed above, the disciplines involved in deep-submergence science are varied and the scales of investigation range many orders of magnitude from molecules and micrometer-sized bacteria to segment-scales of the MOR system (10s to 100s of kilometers long) at depths that range from 1500 m to 6000 m and greater in the deepest trenches. Clearly, the spectrum of scientific problems and environments where they must be investigated require access to the deep ocean floor with a range of safe, reliable, multifaceted, high-resolution vehicles, sensors, and samplers, operated from support ships that have global reach and good station-keeping capabilities in rough weather. Providing the right complement of deep-submergence vehicles and versatile support ships from which they can operate, and the funding to operate those facilities cost-effectively, is both a requirement and a challenge for satisfying the objectives of deep-sea research in the coming decade and into the twenty-first century.

To meet present and future research and engineering objectives, particularly with a multidisciplinary approach, deep submergence science will require a mix of vehicle systems and infrastructures. As deep submergence science investigations extend into previously unexplored portions of the global seafloor, it is critical that scientists have access to sufficient vehicles with the capability to sample, observe and make time-series measurements in these environments. Submersibles, which provide the cognitive presence of humans and heavy payload capabilities will be critical to future observational, time-series and observatory-based research in the coming decades. Fiberoptic-based ROVs and tethered systems, especially when used in closely timed, nested investigations offer unparalleled maneuverability, mapping and sampling capabilities with long bottom times and without the limitation of human/vehicle endurance. AUVs of various designs will provide unprecedented access to the global ocean, deep ocean and seafloor without dedicated support from a surface ship.

AUVs represent vanguard technology that will revolutionize seafloor and oceanographic measurements and observations in the decades to come. Over approximately the past 5 years scientists at several universities and private laboratories have made enormous advances in the capabilities and field-readiness of AUV systems. One such system is the Autonomous Benthic Explorer (ABE) developed by engineers and scientists at the Woods Hole Oceanographic Institution (**Figure 6**). ABE can survey the seafloor completely autonomously and is especially well suited to working in rugged terrain such as is found on the MOR. ABE maps the seafloor and the water column near the bottom without any guidance from human operators. It follows programmed track-lines precisely and follows the bottom at heights from 5 to 30 m, depending on the type of survey conducted. ABE's unusual shape

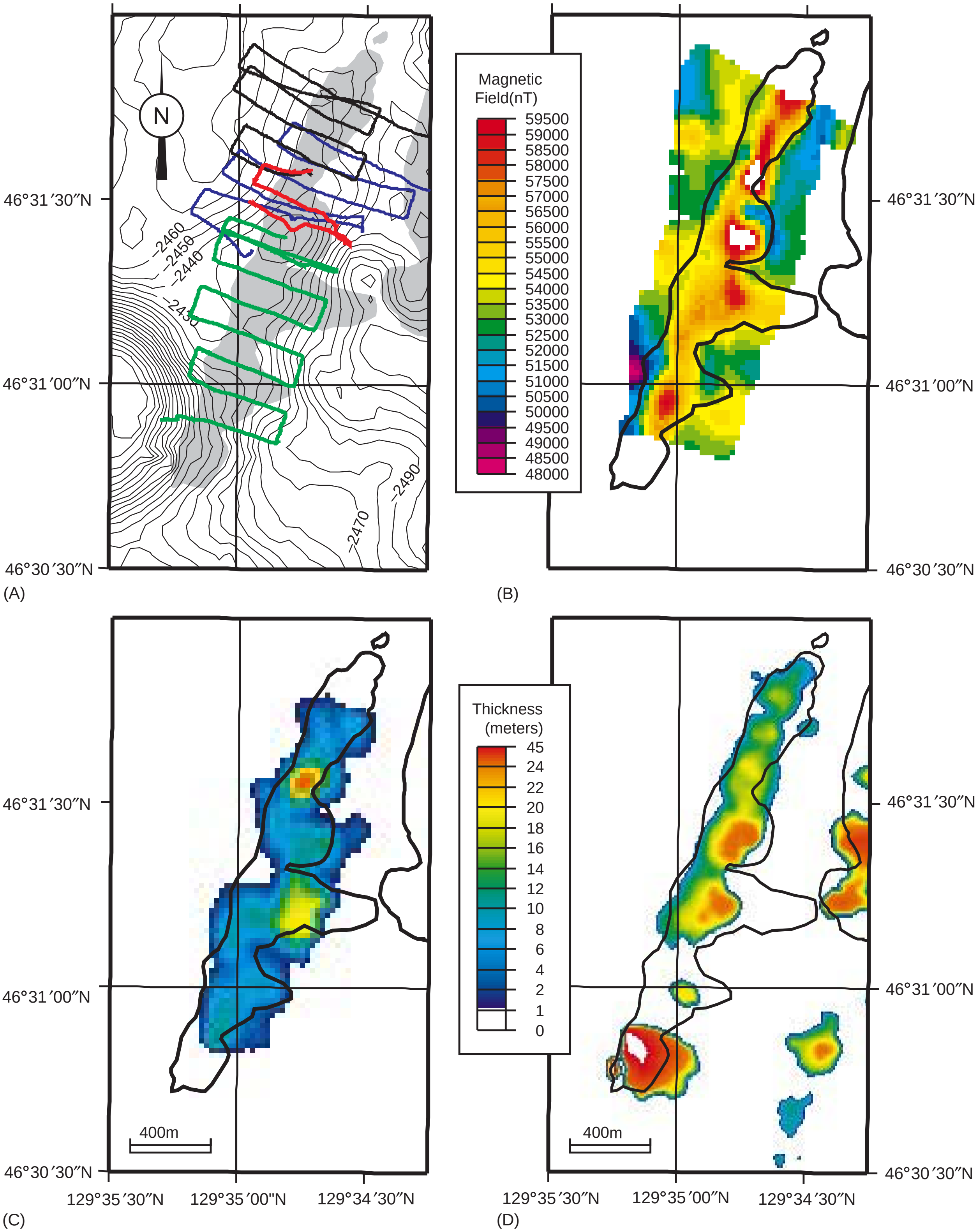


Figure 12 (A) Bathymetry map (contour interval 10 m) showing location of 1993 CoAxial lava eruption (gray) on the Juan de Fuca Ridge off the coast of Washington, and ABE tracklines (each color is a separate dive). (B) Magnetic field map based on ABE tracklines showing strong magnetic field over new lava flow. (C) Computed lava flow thickness assuming an average lava magnetization of 60 A/m compared with (D) lava flow thickness determined from differential swath bathymetry. Figure courtesy of M. Tivey, Woods Hole Oceanographic Institution.

allows it to maintain control over a wide range of speeds. Although ABE spends most of its survey time driving forward at constant speed, ABE can slow down or even stop to avoid hitting the seafloor. In practice, ABE has surveyed areas in and around steep scarps and cliffs, and not only survived encounters with the extreme terrain, but also obtained good sensor data throughout the mission.

Recently ABE has been used for several geological and geophysical research programs on the MOR in the north-east and south Pacific which have further proved its reliability as a seafloor survey vehicle, and pointed to its unique characteristics to collect detailed, near-bottom geological and geophysical data, and to ground-truth a wide range of seafloor terrains (**Figure 12**). These new perspectives on seafloor geology and insights into the geophysical properties of the ocean crust have greatly improved our ability to image the deep ocean and seafloor and have already fostered a paradigm shift in field techniques and measurements which will surely result in new perspectives for Earth and oceanographic processes in the coming decades.

Conclusions

One of the most outstanding scientific revelations of the twentieth century is the realization that ocean processes and the creation of the Earth's crust within the oceans may determine the livability of our planet in terms of climate, resources, and hazards. Our discoveries may even enable us to determine how life itself began on Earth and whether it exists on other worlds. The next step is toward discovering the linkages between various phenomena and processes in the oceans and in exploring the interdependencies of these through time. Marine scientists recognize that technological advances in oceanographic sensors and vehicle capabilities are escalating at a increasingly rapid pace, and have created enormous opportunities to achieve a scope of understanding unprecedented even a decade ago. This new knowledge will build on the discoveries in marine sciences over the last several decades, many of which have been made possible only through advances in vehicle and sensor technology. With the rapidly escalating advances in technology, marine scientists agree that the time is ripe to focus efforts on understanding the connections in terms of interdependency of phenomena at work in the world oceans and their variability through time.

See also

Autonomous Underwater Vehicles (AUVs). Cephalopods. Deep-sea Ridges, Microbiology. Manned Submersibles, Deep Water. Hydrothermal Vent Fluids, Chemistry of. Mid-ocean Ridge Geochemistry and Petrology. Remotely Operated Vehicles (ROVs). Seamounts and Off-ridge Volcanism.

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DEEP-SEA DRILLING METHODOLOGY

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Introduction

The technology developed and used in the Deep Sea Drilling Project and the Ocean Drilling Program include innovative drilling methods, sampling tools and procedures, *in situ* measurement tools, and seafloor observatories. Drilling technology for the new Program, Ocean Drilling in the 21st Century, is now under development for use by 2006. This new technology will be used to drill deeper into the seafloor than is currently possible in the Ocean Drilling Program. The first drilling target of Ocean Drilling in the 21st century is the seismogenic zone offshore Japan, a location deep in the Earth (10–14 km) where earthquakes are generated.

Drilling Technology

The Deep Sea Drilling Project and the Ocean Drilling Program use the same basic drilling technology, the open hole method. Drilling is the process of establishing a borehole. The open hole method uses a single drill pipe that hangs from the drill ship's derrick, a tall framework positioned over the drill hole used to support the drill pipe. The drill pipe is rotated using drilling systems the drill floor of the ship. Surface sea water is flushed through the center of the pipe to lubricate the rotating bit that cuts the rock and then flushes sediment and rock cuttings away to the seafloor (**Figure 1**). Open hole refers to the resulting borehole which remains open to the ocean during drilling. This method is also called a riserless drilling system. Important parts of the deep-water drilling system are a drilling derrick that is large enough to hang a long length of drill pipe reaching deep ocean and sub-seafloor depths (up to 8 km); a system that rotates the drill pipe; a motion compensator that isolates the ship's motion from the drill pipe; and a pump that flushes sea water through the drill pipe.

Open hole methods are successfully used in all of the Earth's oceans (**Figure 2**). The Ocean Drilling Program's achievements include drilling in very deep water (6 km) and to > 2 km below the seafloor (**Table 1**). Although there have been many achievements using these methods, there are also limitations. The open hole method cannot be used to drill depths > 4 km below the seafloor. Although the exact depth limit of the Ocean Drilling Program is not yet known, it is likely limited to 2–4 km. This limitation exists because when drilling deep into the seafloor, the drill fluid must be modified to a lower density so that the deep cuttings can be lifted from the bit and flushed out of the hole. In open hole methods, the drilling fluid density cannot be controlled. Another limitation of this method is that drilling must be restricted to locations where hydrocarbons are unlikely to be encountered. In an open hole, there is no way to control the drilling fluid pressure. In locations where oil and gas may exist, the formations are frequently overpressured (similar to a champagne bottle). If these formations were punctured with an open hole system, the drill pipe would act like a straw that connects this overpressured zone in the rock to the ocean and the ship. This type of puncture is called a 'blow-out' and is very dangerous. The explosion as gases are vented through the straw to the ship's drill floor could cause serious damage, or worse yet, the change in the density of the sea water as the gas bubbles are released into the overlying ocean could cause the ship to sink. With no system to control the pressure in the borehole using the open hole drilling method, there is no way to prevent a blow-out.

The new deep-sea drilling technology currently under development by Ocean Drilling in the 21st century is a closed system, also known as riser drilling. This technology has been used, in relatively shallow water, by the offshore oil industry to explore for and produce oil and gas.