Report from a Workshop

"Requirements for Robotic Underwater Drills in U.S. Marine Geologic Research"

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Texas A&M University
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Steering Committee:

William Sager (chair)
Henry Dick
Patricia Fryer
H. Paul Johnson

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SUMMARY

Twenty-five scientists and engineers, representing a variety of academic institutions and scientific interests, met on November 3 and 4, 2000, to discuss how to bring about ready access to robotic underwater drills for scientists engaged in academic research. Although there were attendees from Europe and Canada, the primary focus was on the needs of U.S. marine geologic research. After listening to keynote presentations about past or existing drill systems, the attendees addressed the following questions:

- What science problems require or would benefit from robotic underwater drills?
- What drill capabilities and specifications are required to accomplish the science goals?
- How many and what types of drills are needed?
- How should robotic drills and their technical staff be supported?
- How can a new drill become a "proven" tool?

A broad spectrum of science applications was represented, including sampling of the ocean crust at ridge-crests, transform faults, and megamullion complexes, sampling of seamounts and large igneous provinces, acquisition of oceanic paleomagnetic data, sampling of hydrothermal deposits, continental margin sedimentary deposits, carbonate banks, gas hydrate, and sediment cores for paleoceanographic studies. Some scientists spoke of using arrays of small holes for installation of seismometers and strainmeters for earthquake investigations, instruments to measure fluid flow in hydrothermal and other hydrologic cells, as well as geochemical studies of vent effluents. One scientist wished to use a robotic drill for coring beneath the Antarctic ice sheets. Others were interested in samples of microbes inhabiting the sedimentary or igneous layers just beneath the seafloor. In many cases, seafloor samples might be obtained using a drill ship, but the drill ship is inefficient, inappropriate, or unavailable. Robotic underwater drills can augment U.S. marine geoscience programs in two fundamental ways. First, a portable, robotic, wireline drill can operate in some places and in some lithologies that a drillship cannot or is ineffective. Examples are shallow carbonate banks, the inner-continental shelf, lakes, and rivers, as well as ice-covered seas. Current drill ships do not core well in fractured igneous rocks, friable carbonate rocks, alternating hard-soft layers, and hydrothermal deposits. With a small core diameter and kerf, along with diamond bits and an absence of heave, robotic wireline drills can likely do better. For similar reasons, microbiologists see robotic drills as an answer to difficulties in sampling the water-rock interface. Second, during the Ocean Drilling Program (ODP), there was far more worthy science than can could be addressed by a single drill ship. That is unlikely to change even with the transition to two drill ships in the successor program, the Integrated Ocean Drilling Program (IODP). In fact, with more and more science programs seeking 2D, 3D, and 4D characterization, the need for more holes and more cores will only increase.

Most attendees had a similar vision for underwater "robotic drills" -- a device that can be launched from the deck of a ship (or another platform) and which is lowered to the seafloor where it lands, drills cores, and is raised back to the surface. We call such a device a "ROBO-drill" (Robotic Ocean Bottom drill). It was noted that several ROBO-drills have been built

previously, but for one reason or another they were unavailable to the U.S. scientific community, their capabilities did not allow them to address some significant scientific problems, or they were not considered a "proven" tool. After considerable discussion, the group reached a consensus that there should be a large drill (Big ROBO) that would address most scientific problems and two to three smaller, "niche" drills that are cheaper and more transportable for special applications. The Big ROBO drill was envisioned with the capability to drill in water depths of 3500-4500 m, to core 50-100 m beneath the seafloor, to take either hard rock or sediment cores, to install casing, and to be transportable and usable on the largest academic research ships. A smaller 3-5 m ROBO drill, designed to be simpler to use and handle, cheaper to operate, and more easily transported, would address science problems that do not require deep penetration. At the smallest, cheapest end of the spectrum, several mini ROBO drills, with ~1 m penetration capability, were envisioned to be a part of the shipboard equipment pools of several academic institutions for easy availability. These drills would be used primarily for programs where only small samples were needed, or where logistics and costs dictated that the drilling was an ancillary activity on a particular cruise. Finally, a ROV-mounted drill was seen as a necessary element of the robotic drill fleet because none of the other drills would be able to core vertical or steeply-dipping outcrops and because some applications would require a highly maneuverable drill with excellent imaging capabilities. Greatest support was for the largest and smallest drills. The 3-5 m drill fits the niche for which a scientist requires cores longer than 1 m, but logistics or costs make large drill use infeasible. Such a drill would gain greater support if a large drill were never built, but would lose support if the smallest drills could be stretched to several meters penetration capability. Currently, two investigators are proposing construction of an ROV drill and a mini drill. We know of no academic efforts to build a larger drill.

The issue of how to support robotic drills was one of wide concern. To be successful, robotic drills must be routinely maintained, must be operated by trained technicians, and must be properly administered to ensure availability and continuity. The attendees placed a high value on open access and capable maintenance. It was agreed that this is generally not possible with sporadic support to an individual investigator or small group of investigators. Therefore, the consensus was that there should be a robotic drill facility that would house, maintain, and operate the large ROBO drill and 3-5 m ROBO drill. Furthermore, the technicians employed by this entity would be a resource for expertise in maintenance and improvements of the mini ROBO drills and ROV drills, which would be part of different equipment pools. Conference attendees also expressed concern about the high hurdles to drill development in a conservative, peer-review system. High expectations for immediate success and short grant durations might force a drill developer to bring a drill online that is not-yet-ready for routine operations, potentially giving the impression that the drill does not work properly and making continued support difficult to obtain. A realistic, long-term plan to build one or more drills is necessary to develop them properly.

INTRODUCTION

Seafloor sampling has changed little in a generation or more. A marine geologist can chose from a timeworn tool-box that includes dredges (which have changed little in a century), wax corers, and submersibles with manipulator arms for hard rocks, piston cores, gravity cores, and similar tools for soft sediments. For high profile projects requiring deep penetration, the Ocean Drilling Program provides a drill ship; with IODP the plan is to have two, one with a riser and one without. Each of these tools has its limitations. For example, dredges and wax corers only knock off surface samples, so relationships with deeper units and structural data are lacking. Orientation is usually impossible. Dredges typically scrape samples from a large area, while wax corers return small sample volumes. Submersibles and ROVs can pick up samples with their manipulator arms, and provide geologic context with their video cameras, but they are limited to samples that are broken off or only loosely attached to an outcrop. All of these methods are frustrated by even a thin mantle of sediment and none can routinely sample more than a few centimeters below the surface.

Scientists using gravity and piston cores, or their relatives, are faced with similar problems. Long coring techniques in the U.S. can presently recover cores to about 15 m in hemipelagic sediments, limited by wire strength on UNOLS vessels. Four sets of piston coring gear have been lost in the past decade from UNOLS vessels due to this limit (two by WHOI and two by OSU). The longest conventional piston core ever recovered is 55 m, recovered aboard a French vessel (*Marion Dufresne*). Using non-U.S. facilities is one option for scientists, but involves a degree of complexity that limits use. Although corers such as these work well enough in soft, homogeneous sediments, even in the best of conditions core pentration of more than about 30 m is rare, yet many science programs, such as paleoceanographic and geotechnical studies, would greatly benefit from two or three times that. Furthermore, hard layers and certain sediment textures, such as sand or gravel, can stop the penetration of a piston corer and possibly damage it. This limits the usefulness of such corers on the continental margins, an area of current scientific focus. As with other samplers, piston core orientation is rare.

Scientific ocean drilling is a partial answer to some of these needs. The drill ship *JOIDES Resolution* can penetrate hundreds of meters into either hard or soft rock. Indeed, its APC (advanced hydraulic piston corer) cores are arguably the best for high-resolution paleoceanographic study. But the drill ship has significant limitations as well, not the least of which is availability. Only about one in twenty proposals to the Ocean Drilling Program has come to fruition and the process of fielding a winning proposal is a long and arduous one. As a result, only those programs with wide appeal and persistent proponents are drilled. Many scientifically important projects never make it. Furthermore, logistics come into play because the ship only operates in one region at a time. If a program is not drilled when the drill ship is in a particular region, it may be 7-10 years before the ship returns to the region.

In addition to the difficulties with getting a drilling program accepted and scheduled, there are still many localities and lithologies that are not well suited for the existing drilling technology. The *JOIDES Resolution* cannot drill safely in shallow water, making it impossible to address interesting problems that are found on the inner continental shelves, rivers, or atoll lagoons. This limitation has frustrated attempts to examine the shallow water portions of sequence stratigraphic transects (for example, the New Jersey margin transect). It also frustrates investigators who would drill shallow water carbonate banks. Indeed, this difficulty lead to the formation of a workshop and working group to find ways to address this problem (Quinn and Mountain, 2000). Other regions are off -limits to the *JOIDES Resolution*. These include ice covered seas and seas with frequent ice, for example the high Arctic Ocean, bodies of water without access for a large ship, such as lakes and rivers, and places where there is no liquid water, such as drilling beneath the Antarctic ice cap.

These are all problems caused by limits to where drill ship can go, but despite three decades of improvements to the drilling technology, there are still lithologies that the *JOIDES Resolution* cannot drill and core effectively. Antartic diamictons are notoriously hard to core, owing to their density and erratics. The same can be said of continental margin sands, which tend to stop piston corer penetration and wash away when rotary cored. Alternating soft and hard layers, such as chert/chalk sequences give low recovery for several reasons. Roller cones work by crushing the rock they penetrate, so the drill bit destroys the soft layers while crushing the hard ones. Furthermore, drill string heave causes large weight-on-bit fluctuations that also cause crushing and fracturing. Another problem is the high volume of fluid pumped out the drill bit to flush away cuttings. In hard/soft formations this can also wash away the material one would like to recover. Carbonate rocks, too, are extremely sensitive to pulverization caused by weight-on-bit fluctuations, resulting in poor recovery with the *JOIDES Resolution*. Fractured rock formations, such as those near the ridge crests are difficult because the cutting fluids are lost in the formation and loose pieces bind the drill string. What is more, starting holes on hard rock outcrops is a major undertaking because the drill string is unstable until its head becomes buried and the hole provides lateral support. Although ODP developed a hammer-in casing system to begin such hard rock holes, it does not recover core and so the problem is not entirely solved.

Many of these problems can be solved by using portable, robotic, underwater drills. Such a drill could be shipped virtually anywhere and operated at less cost than a drill ship, the lesser cost leading to wider application. Such a drill could operate on land (e.g., in a lake or river), beneath the ice (beneath sea ice in the Arctic Ocean or a glacier in Antarctica), in shallow water, and in deep water. Moreover, robotic drills offer a solution for those problems that require drilling, but do not require deep penetration, for example high resolution paleoceanographic cores between 30-100 m length, gas hydrate samples from shallow accumulations, dense sample grids of igneous rocks from the ridge crest, samples of seamounts and large igneous provinces mantled with weathered zones or manganese crusts. Indeed, a robotic drill can be applied to many problems that are envisioned for “alternate platforms” in the current Integrated Ocean Drilling Program plan (Pisias and Delany, 2000). In addition, a robotic drill will likely improve recovery in problematic lithologies for several reasons. It can maintain a more constant weight on bit (it is not bobbing on the sea surface like the drill ship). The bits do not need as much flushing fluid as the *JOIDES Resolution* drill string because the bits, drill pipes, and casing for a robotic drill are much smaller. And because the drill string is small and light, drilling parameters, such as weight on bit, can be more easily monitored and tailored to the formation being drilled.

If robotic underwater drills are such a fantastic idea, why are U.S. scientists complaining about lack of access? Almost a decade ago, Paul Johnson outlined a vision for underwater drills that is startlingly similar to the recommendations of this workshop (Johnson, 1991). The problem has not been in the vision, but the execution. Though robotic underwater drills have been around for about two decades, they are complex machines and exist at the leading edge of underwater technology. They are expensive tools that require reliable, continuous maintenance, a situation that does not fit well within the proposal-driven U.S. science funding system. As a result, recent attempts to develop drills have largely taken place outside the U.S. and many of these efforts have been driven by priorities other than science, resulting in tools that are not as widely useful as desired by the scientific community. Indeed, this was one of the main reasons for this workshop, to construct a vision for what robotic drills are needed to accomplish today's important science problems.

Existing Robotic Drills and Why New Drills Are Needed

Several robotic drills exist today, so why do we need more? Wouldn't it be better to let some institution, one that has already invested in drill construction, pay the bills? That sounds like a good approach, but it has not paid off. Here is why.

A single institution has difficulty in raising capital for construction of a drill and in garnering an uninterrupted stream of funds for its upkeep. For example, Paul Johnson contracted with Williamson and Associates in 1989 and 1990 to build a 3-m robotic drill (Fig. 1; Johnson, 1991). The construction funding came from several sources, including the U.S. Navy and Sea Grant. For several years, Johnson worked to build and test the drill, but in 1991 the instrument was lost on a cruise when the dynamic positioning system on the R/V *Melville* malfunctioned. This caused the drill to be dragged across the ocean bottom and torn off the its cable. Johnson was unable to retrieve the drill and later elected not to rebuild it because of the effort required to raise construction funds once again and because of the difficulty he had getting enough funding to support a technician to work on the drill. Lesson: in an environment where capital is hard to raise (i.e., today's universities) and where research funding is extremely competitive, it is unrealistic to expect a single investigator to be able to construct and maintain a robotic drill effectively.

A different dilemma results from a "commercial" drill. If a drill constructed by an entity that does not specialize in basic, academic research may not be readily available to the science community or may not have the tools and specifications that community requires. Two examples are drills constructed by Williamson and Associates for non-U.S. groups. One is the Benthic Multicoring System (BMS; Fig. 2), constructed in 1996 for the Metals Mining Agency of Japan. This drill has a 30-m drilling depth capability and a 12-km umbilical cable. The problem for U.S. investigators is that it is permanently installed on the MMAJ research vessel, *Haurei Maru No. 2* and is not offered to scientists outside of Japan. Another, similar drilling system, the Portable Remotely Operated Drill (PROD; Fig. 3), also partly constructed and designed by Williamson and Associates, is under development by Benthic GeoTech Pty., Ltd., an Australian consortium. The PROD can potentially drill even deeper, up to 100 m, but it is limited to 2000 m water depth by cable strength considerations and by the housings for its electronics. Because of this depth limitation, the system is not suitable for many important scientific programs, for example, drilling ocean spreading ridges. Furthermore, the drill has not been completely tested and proved. It underwent sea trials in 2000, during which it successfully cored sediments, but hard-rock drilling was scrubbed owing to environmental concerns over hydraulic fluid leaks. In addition, the drill currently lacks a launch and recovery system that would make ready for routine use at sea. Still another potential difficulty is the cost. Currently, the system lease price is >$20,000 per day, not including mobilization/demobilization and shipping costs. This means that PROD is expensive enough that its use will be exceptional, not routine. Lesson: if someone other than the scientific community constructs and operates the robotic drill, it will be designed for their purposes, on an uncertain schedule, and may be dearly expensive owing to cost recovery and profit seeking.

Even drills built for academic purposes may not be routinely used if the institutional infrastructure is not geared for open use. One example is the ROV drill built by Debra Stakes at MBARI with assistance from Leon Holloway at the Ocean Drilling Program (Fig. 4). These two investigators have spent a number of years perfecting the drill design, including mounting the unit on several ROVs and DSRV *Alvin*. Although the unit works, and Stakes has been helpful loaning and modifying it for investigators outside of MBARI, there is insufficient institutional support to pay for costs associated with making the unit available on a routine basis. Another example is two robotic drills built in the U.K. and administered by the British Geological Survey. One drill can core up to 5-m deep (Fig. 5), but it is limited by lack of imaging capabilities and it cannot go deeper than 2000 m because of its cable. This means that many sites of interest to marine investigators cannot be drilled. It is also a problem that the drill cannot image the seafloor so operators can be sure whether it has landed on a suitable outcrop. The other BGS drill is a small unit with a 1-m penetration capability (Fig. 6). This drill can go to a depth of 4000 m, can orient cores, and has been used successfully on at least one drilling expedition (Allerton and Tivey, 2001). In applications where there is no sedimentary cover or weathered zone to penetrate, this drill may be a useful tool. However, owing to its limited penetration capability, there are many programs for which it would not work well. Although BGS encourages the use of this system by outsiders, a hurdle for U.S. investigators is that there is no routine interface for an investigator to devise a schedule and work out cost details. Currently each program is ad hoc. Lesson: without an organizational infrastructure designed to support the robotic drill, to respond to academic science interests, and act as link to investigators, it is unlikely that drill capabilities will match needs and drill use will be sporadic.

In summary, although there are a several robotic drill that exist today, none is both readily available to U.S. investigators or having capabilities and specifications to permit use on a wide range of programs. Therefore, the U.S. science community should consider building and operating a drill that can address a wide range of cutting-edge science programs, is easy for a scientist to access and put to use, and which is not so expensive (to the individual investigator) as to preclude its frequent usage.

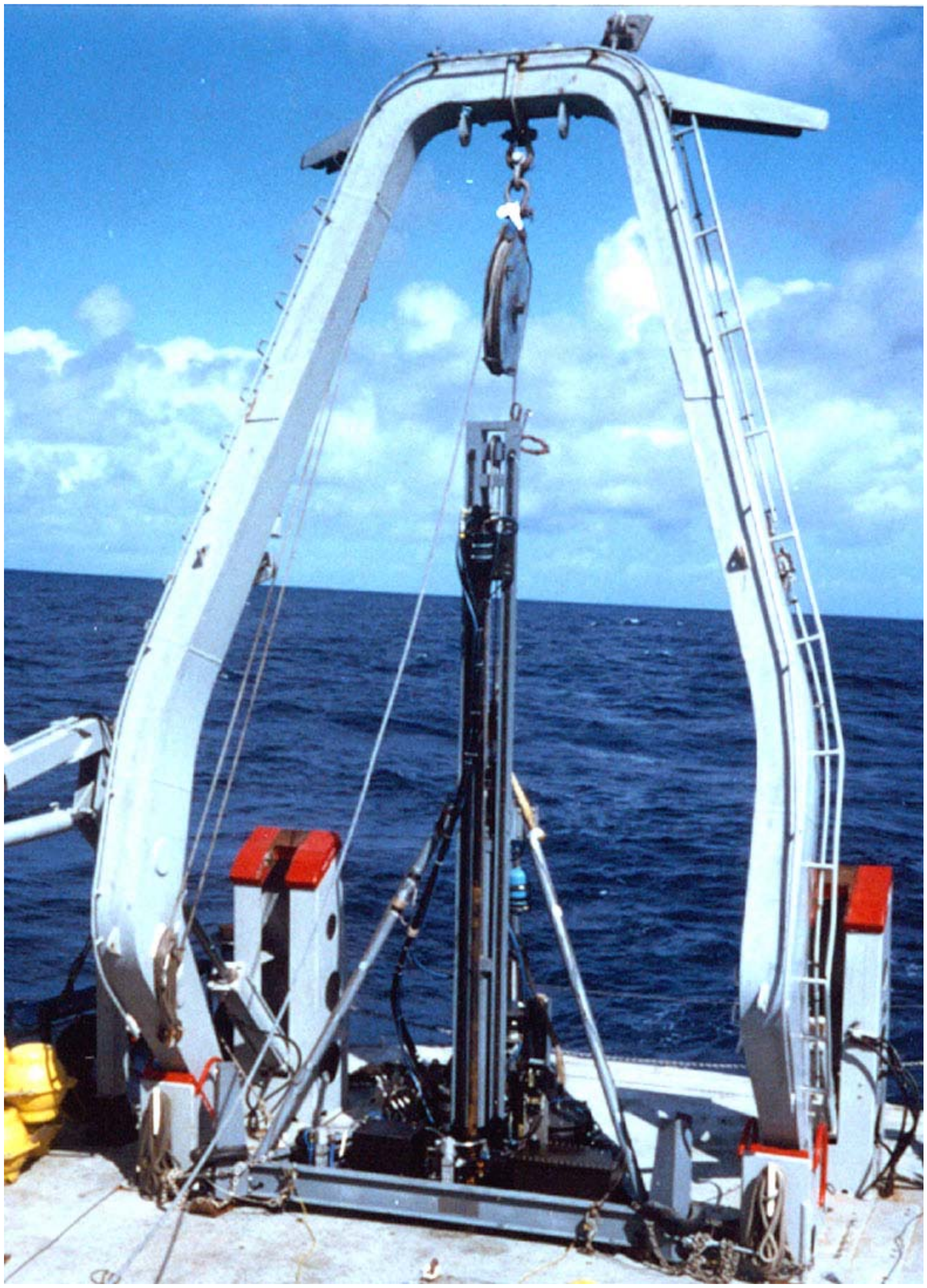

Figure 1. The University of Washington 3-m rock drill, onboard the old R/V *Thomas G. Thompson*, circa 1990 (Johnson, 1991).

Figure 2. Benthic Multicoring System (BMS) drill, built by Williamson and Associates, Inc. for the Metals Mining Agency of Japan. The BMS is 5.9 m in height and weighs 5 tons in air. It is designed for up to 6000 m depths and can take 20 m of 48-mm diameter core in 2.2 m sections.

Figure 3. Portable Remotely Operated Drill (PROD), constructed by Benthic GeoTech Pty, Ltd. (Australia) in cooperation with Williamson and Associates, Inc. This drill is 5.8 m in height and weighs approximately 10 tons in air. It can drill up to 100-m penetration depth by assembling a drill string from pipe segments carried in a rotary magazine. (see http://www.bgt.com.au/prod.htm)

Figure 4. ROV-mounted drill designed and built by Debra Stakes, Monterey Bay Aquarium Research Institute, and Leon Holloway, Ocean Drilling Program

Figure 5. British Geologic Survey 5-m Seabed Rockdrill and vibrocorer.

Figure 6. British Geologic Survey 1-m BRIDGE drill. The device is approximately 1.5 m in height and weighs 900 kg in air. It operates from a standard 0.68-in coaxial cable, can recover a 35-mm diameter core ~1m in length, and has been used to depths of 4500 m (see Allerton and Tivey, 2001; MacLeod et al., 2002).

EXAMPLES OF SCIENTIFIC PROGRAMS REQUIRING ROBOTIC DRILLS

In general, robotic underwater drills complement existing sampling programs in two key ways. First, robotic drills can sample formations that cannot be drilled or cored efficiently with drill ship technology. Second, ODP drilling represents a massive investment by the scientific community and is only available for programs that have exceptionally broad scientific community support. Many critical scientific problems require having dense grids of samples to define geologic information in three dimensions, but ODP is not a feasible way to accomplish such programs. In the following sections, examples of the impact of robotic underwater drills on high-priority science programs are discussed. The list was compiled by workshop attendees and is not intended to be exhaustive. However, it seems clear from these examples that robotic underwater drills would greatly augment virtually each and every science focus area discussed in the ODP COMPLEX report (Table 1; Pisias and Delaney, 2000).

Subsurface Biosphere

The shallow crust is the largest unexplored portion of the biosphere, and the fragmentary information available to date suggests that it may host as much biomass as the surface biosphere (Whitman et al., 1998). What is more, the ridge crest environment is a candidate for the font of life on this planet (Baross and Hoffman, 1985). The ocean crust provides a wide range of environments for the deep biosphere: sediments, igneous rocks, altered sediments and rocks, aquifers, and hydrothermal deposits. Although existing ocean drilling technology provides access to some crustal environments, such as oceanic sediments and deep-water massive rocks, robotic drilling will furnish new opportunities to study environments that cannot be reached by standard techniques. In addition, robotic drilling has the potential to be a better biologic sampling tool for many sites accessible to shallow drilling. Many biologically important locations are beyond the reach or capabilities of the current and envisaged drill ships for the IODP. Hard substrates in shallow water are currently off-limits owing to limitations in drill ship positioning and heave compensation, but these factors are not a problem for a tethered, robotic drill. Other locations, notably those in volcanic or continental interior locations are also out of reach for a drill ship, yet these extreme environments are potentially important biologic environments. In addition, robotic drills can also improve sampling in hard substrates in all water depths near the tops of outcrops, where biological gradients tend to be strongest, or in friable, biologically-active substrates such as sulfide or carbonate precipitates. Furthermore, a robotic drill can be more cost-effective and more available than a drill-ship as a method of making a biologic survey of the uppermost oceanic crust, using the robotic drill to make many shallow holes.

One of the highest priority environments in which to examine subsurface life is at the crests of spreading ridges. For many years now, scientists have known that the ridge crests are sites for voluminous cycling of fluids through the crust. New ocean crust at the ridge axis is possibly one of the most hospitable subsurface habitats on Earth as well as a potential analog for volcanically-fueled extraterrestrial habitats. The upper ocean crust at the ridge is highly porous (Gilbert and Johnson, 1999) and hydrothermal fluids and seawater mix within it to provide an environment rich in microbial energy (McCollom and Shock, 1997). Evidence indicates that microorganisms inhabit these energetic mixing environments, based on culture of indicator microbes from seafloor effluents (Holden et al., 1998; Summit and Baross, 2001) as well as observation of flocculent sulfur after eruptive events (Haymon et al., 1993; Taylor and Wirsen, 1997; Delaney et al., 1998). Other less understood axial crustal microenvironments, such as those tapped by event plumes, also contain microorganisms. However, little else is known about the different habitats created in axial oceanic crust or the microbial communities that reside in them. Direct sampling and borehole observatories are required to advance our understanding of ridge-axis microbial communities and the environment they inhabit.

Extensive drilling in the upper axial crust is needed to compile more complete knowledge of the types and ranges of organisms that live in the crust and the physical environment that they live in. Currently, most information is indirect: structure is inferred from seafloor observations and geophysical data; temperature and chemistry are inferred from vent fluids and mixing models; and, biology is sampled from effluents that are contaminated by exposure to bottom waters. Robotic drills can be used to acquire biologic and geologic samples from the upper crust as well as making holes for physical properties and fluid flow tests. Boreholes would be used to understand the structure and permeability distribution of the upper crust (which likely controls the thermal and chemical environment) through downhole logging, hole-to-hole packer flow tests, and surface-to-hole active microseismic experiments. Relatively solid formations would allow installation of borehole observatories, packed off and instrumented at intervals, allowing measurement of in-situ temperature and chemical parameters, osmotic sampling for shore-based chemical analysis, and biological experiments to determine community composition and activity of microorganisms within the seafloor

Remote drilling to sample the crust will inevitably lead to microbial contamination of samples, a factor which must be considered when conducting biological studies of subsurface samples. This adds a level of complexity to subsurface sampling, but does not pose insurmountable problems. The amount and microbial make-up of contamination can be monitored as samples are collected, and the extent of contamination can be quantified, for example, as developed on ODP Leg 185 (Smith et al, 2000). In fact, robotic drills can furnish samples with less contamination than seen in drill ship cores owing to the lesser flushing required of the smaller bits and the use of bottom water. Fluids used for flushing will be based on bottom seawater, which contains 10% to less than 1% of the microbial abundance of surface seawater, which is used for flushing by a drill ship. Because there is no heave to contend with, cored rocks will be less fractured and therefore less contaminated. Certainly not least in the list is that smaller diameter holes should lead to less flushing of the formation, important when the hole might be used to install a long-term biological observatory.

Hydrothermal Mineral Deposits and Fluid Circulation in the Upper Crust

Discovery of active seafloor hydrothermal venting at spreading ridge crests about 25 years ago has provided important insight into the transfer of energy and mass between the lithosphere and the hydrosphere. Among the phenomena at hydrothermal vents are massive sulfide deposits that form on the seafloor and are important geochemical laboratories that contribute to our understanding of the formation of ore deposits that supply much of the copper, zinc, gold and silver used by modern societies. The opportunity to sample hydrothermal fluids that are actively depositing sulfides has advanced our understanding of ore deposit genesis. Unfortunately, sampling by submersible and ROV is restricted to chimneys exposed above the seafloor. Study of the geochemistry of active systems and ancient analogs has shown that many of the important geochemical interactions occur below the seafloor. The only means for sampling this part of these systems is by drilling.

The importance of these problems to the scientific community is demonstrated by the fact that the Ocean Drilling Program has addressed four legs (139, 158, 169, 193) to investigate the formation of seafloor hydrothermal deposits. Core recovered on Legs 139, 158, and 169 provided samples from the interior of active sulfide mounds that were otherwise unattainable, and changed our understanding of massive sulfide deposits (Davis, Mottl, Fisher, et al., 1992; Humphris, Herzig, Miller et. al. 1996; Fouquet, Zierenberg, Miller, et al., 1998). We now recognize the importance of shallow subsurface circulation of seawater through these deposits as a controlling factor in determining mineral precipitation. For example, deposition of anhydrite in the TAG mound is an important control on the fluid flow and mineralogical composition of that system. However, anhydrite is removed by later dissolution from the cooler portions of hydrothermal mounds and is rarely preserved in ancient deposits. Examination of core from the active TAG mound (Fig. 7) lead to the realization that the extensive development of breccias in ancient massive sulfide deposits results from collapse following anhydrite dissolution (Humphris et al., 1995), not hydrothermal explosions as previously speculated.

Spatial zoning of metals in ancient massive sulfide deposits is a widely observed but poorly understood phenomenon. Observations from Middle Valley confirmed that subseafloor replacement, dissolution, and reprecipitation of minerals is a critical process leading to the geochemical zoning of ore deposits (Mottl, Davis, Fisher, et al., 1994; Zierenberg et al., 1998). Understanding this "zone refining" process has important implications for the economics of mining on land deposits, as well as implications for the geochemical budgets of the oceans.

As important as these discoveries are, progress in this area has been significantly hampered by the poor core recovery that results from trying to drill massive sulfide deposits with modified oil field technology. On land massive sulfide drilling is conducted by diamond drilling using narrow-kerf, high rotational speed bits with low weight on bit. Core recovery is typically greater than 90% and important lithologies including sedimentary contacts, veins with intact margins, and faults are often recovered intact. In contrast, the majority of holes drilled by ODP in massive sulfide have typically had less than 5% recovery. The most recent effort to drill massive sulfides in an arc-related environment was Leg 193, which saw the first tests of the Advanced Diamond Core Barrel (ADCB). Although this leg returned valuable samples of mineralized and altered silicic volcanic rock, no massive sulfide was recovered. In fact, the average 5% recovery reported in the ODP *Initial Reports* volumes is significantly biased on the high side because much of the "core" recovery is actually drilling rubble that makes in situ relationships difficult to impossible to constrain. The recovery figures are also highly biased by drilling at Middle Valley, where a phenomenal thickness of 100 m of older, inactive massive sulfide was encountered (Zierenberg and Miller, 2000). Much of this material was hydrothermally recrystallized and was more amenable than active mounds to rotary core drilling. No targets of equivalent thickness are known from active deposits. Large sulfide mounds on the seafloor are on the order of 25 to perhaps 50 m thick, and recovery from the uppermost part of these systems by ODP drilling has been very poor. An experimental, downhole-powered diamond coring device, the Navidrill, tested on Leg 158, proved more successful in recovering intact core and indicates that high rotational speed, narrow-kerf diamond drilling systems are needed to successfully recover core in massive sulfide mounds.

Many important scientific problems related to massive sulfide genesis and geochemistry could be investigated by a robotic seafloor drill using diamond-coring technology, capable of recovering core in the upper 25 to 50 meters of a sulfide mound. Even basic information on the size and grade of these deposits is extremely speculative when extrapolated from widely space holes with 5% core recovery. Indeed, the minerals industry tends to dismiss such speculative data as unusable. A systematic grid of boreholes drilled on a sulfide mound would allow the first true constraints on the size and grade of these deposits for comparison to on-land ore deposits. The geochemical zoning of deposits is formed by zone refining in response to thermal and chemical gradients in the subseafloor. These relate to relative roles of advective and diffusive transport of heat and solutes in the shallow subsurface. More continuous core recovery is needed before we can constrain these processes. Critical relationships, such as sulfide-sediment contacts, vein paragenesis, and wall rock alteration envelopes around veins, that are critical to understanding the processes that form these deposits are unlikely to be recovered by standard ODP coring.

Two of the most controversial questions discussed by scientists studying hydrothermal systems in the 1990s are (1) the role of diffuse versus focused fluid flow in transporting heat and matter in seafloor hydrothermal systems (e.g. Schultz et al., 1992) and (2) the depth extent of microbial life at mid-ocean ridges. Diffuse fluids (or shimmering waters) may play a much larger role in transporting mass and heat than focussed fluid discharge through black smokers. Diffuse fluids are generated by processes of fluid cooling and mixing in the subsurface of hydrothermal vent fields. Subsurface cooling of hydrothermal fluids and mixing with entrained seawater results in massive subsurface deposition of minerals, and may provide habitats for microbial organisms similar to those found within deposits at the sea floor. Drilling would allow us to explore the chemistry, mineralogy, and biology of the crust underneath areas of diffuse fluid flow. Such work would be crucial in examining (1) microbial communities and their metabolic diversity in the subsurface of hydrothermal deposits, (2) processes of fluid mixing and mineral precipitation and their role in regulating chemical fluxes into the ocean.

As important as good core recovery is to understanding these deposits, one can argue that the hole from which the core is removed is as valuable as the core itself. Experimentation in active hydrothermal systems requires the presence of stable drill holes, and often requires the ability to case drill holes. Understanding the subsurface hydrology of these systems is critical for understanding where various mineral phases will precipitate. Shallow subsurface hydrology also controls the development of subsurface microbiological communities. The spectacular communities of vent specific organisms occur primarily in diffuse flow zones that are the seafloor expression of subsurface mixing zones. The ability to drill a nested series of holes cased and screened to different depths would provide the first quantitative information on the shallow hydrology of these systems. Instrumentation of drill holes using packers, flow meters, and pressure, temperature and geochemical sensors will revolutionize our understanding of this environment. Active experimentation using these cased and instrumented drill holes will be possible using submersibles and remotely operated vehicles. As the RIDGE community moves towards seafloor observatories, stable and cased drill holes will become critical for installation of a variety of sensors, from long term fluid samplers and chemical sensors to seismometers and tilt meters. Some of these needs can be met by shallow penetration drilling conducted from submersibles or ROV's, but understanding the three dimensional flow in these systems will require the ability to recover core from, and experiment in, hole drilled to several tens of meters.

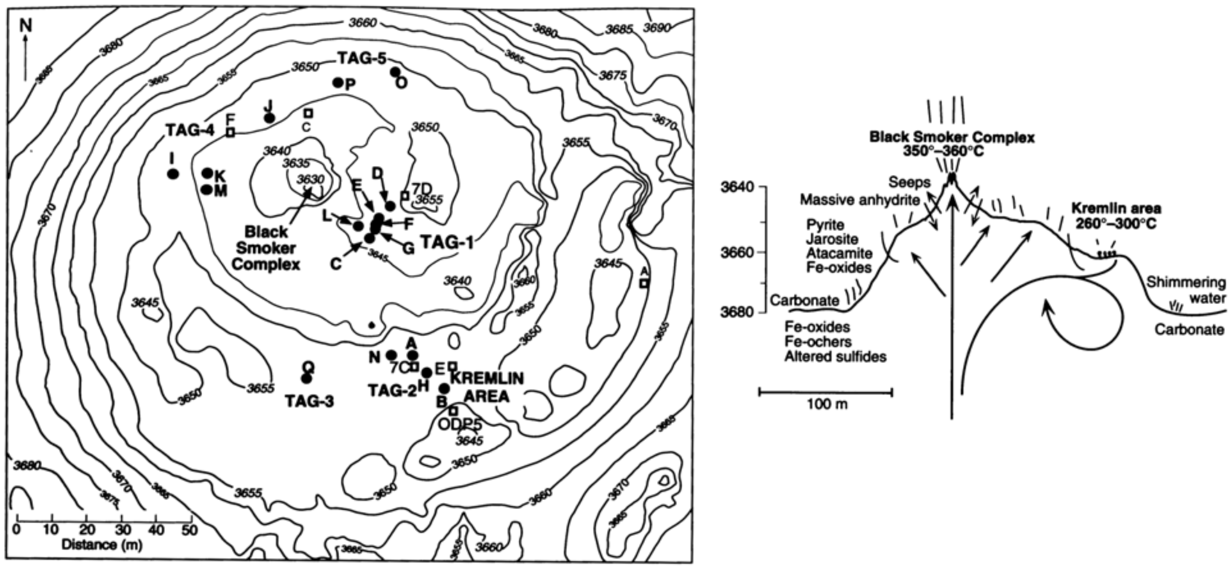

Figure 7. The Trans-Atlantic Geotraverse (TAG) hydrothermal mound drilled during ODP Leg 158 [Humphris et al., 1996]. Left: Bathymetry map of the TAG mound, with 5-m contours, showing the locations of ODP coring locations. Right: Cartoon showing a transect of the hydrothermal mound. The deepest hole drilled by ODP on this mound penetrated 128 m and all the rest were ~50 m or less. This program could have been accomplished with a 100-m ROBO-drill.

Crustal Hydrology

The flow of fluids within the seafloor is responsible for most processes that are considered important to understanding water/rock interactions. Although prior studies have been largely limited to measurements at the water/rock interface, it has become clear that active fluid flow within the seafloor occurs in many areas previously considered static or impermeable (Fig. 8). In near-shore sedimented areas, fresh water has been shown to migrate substantial distances from subaerial sources. On continental margins, both fluid and gas flow upward from a source layer sediments, sometimes through a solid hydrate phase, and finally into the water column. In the unsedimented regions of active mid-ocean ridge spreading centers, heat from lower intrusive rocks drives vigorous hydrothermal circulation cells that penetrate hundreds of meters, and perhaps kilometers, into the igneous crust. Circulating hydrothermal fluids drive many of the alteration processes that affect the evolving oceanic crust after formation, and largely determine the physical properties of the seafloor at almost any age. Recent studies of the hydrology of ridge flank crust have shown that such crustal fluids have Darcy velocities of meters/week or meters/day, rather than the leisurely meters/year previously assumed. Further, the warm crustal fluid has also been shown to travel tens and perhaps hundreds of kilometers in the horizontal dimension, upwelling into the water column through seamounts that penetrate the overlying sediment cover.

One of the more exciting recent discoveries related to crustal hydrology is that the warm, actively circulating crustal fluids sustain an active sub-surface biosphere consisting of abundant populations of microbes of surprising diversity, capable of living in a wide range of chemical and physical environments. Obtaining uncontaminated fluid samples from within warm, porous upper crustal rocks at a range of geologically diverse sites is, for many marine biologists and chemists, an extremely high priority. Although ODP-style drilling can (and has) occasionally penetrated into this environment, drilling from a surface ship with rotary cone bits and high flushing rates makes sampling difficult and precludes the taking of uncontaminated fluid samples. The alternate method of sampling crustal fluids from hydrothermal vents using ROVs or submersibles is similarly unsatisfactory, because the water/rock interface is a notoriously difficult surface to sample, being porous, brittle, extremely uneven and heavily populated with non-crustal biota. Placing a sampling tube even a meter below the water/rock interface, using a small seafloor drill with tightly-controlled drilling parameters, would resolve many contamination issues.

Another recent discovery regarding crustal hydrology is that the circulating hydrothermal fluids respond dramatically to external environmental forcing. Recent studies have shown that small individual earthquakes can increase the temperature of nearby hydrothermal vents (Fornari et al, 1998; Sohn et al., 1998). Larger earthquake swarms can cause the thermal flux from vents to increase by a factor of ten over an entire ridge segment (Johnson, et al, 2000). Larger (but still small by seismic standards) earthquakes can impact hydrothermal circulation cells over a 100 miles distant from the epicenter (Johnson et al, 2001). Although this hydrological "far field effect" has only been seen in igneous crustal rocks, anecdotal reports (B. Carson, personal communication, 2000) indicates that it has also been observed in sediment regions on the continental margin, where porous aquifers allow rapid fluid flow within the sediments.

The essential hydrological measurements that would allow us to develop models that explain the above "disturbed-system" phenomena suffer from the same difficulties as the sub-surface biosphere studies. Co-registered measurements of fluid flow and temperature taken from surface vents are extraordinarily difficult to make, due to the nature of the water/rock interface. These data are also contaminated because of the porous and permeable nature of the rocks that compose the uppermost surface, rendering surficial data of limited usefulness. Penetration into the igneous crust by ODP-style drilling can provide useful data, but is limited by the need to (1) penetrate into bare rock outcrop and (2) obtain many measurements over a wide range of geological sites. The former is difficult with a long drill string and the latter is not feasible owing to availability limits on the drill ship.

Drilling with a small rock drill would solve many of these technical difficulties. A rock drill sits on the seafloor, and is inherently more stable than drilling from the surface. This stability allows the effective use of diamond bits. Diamond drilling is much less abusive to the rock being drilled (less surface shattering and fracturing), and hole size, bit weight and RPM can be varied in real time, as drilling progresses. Flushing of the bit by water can be controlled (and eliminated during the final stages of penetration). If not possible to eliminate altogether, flushing water can be tagged with chemical tracers, allowing contamination to be quantitatively detected (and it can be determined when, in the post-drilling period, this contamination has finally been eliminated). When drilling using a diamond bit, the drill string can be abandoned within the hole when penetration is complete – leaving behind a 'soda straw' tube for later crustal fluid sampling (Fig. 9). In addition to all these new capabilities, the use of small rock drills deployed from standard research vessels would allow a wider range of hydrological projects to be undertaken, including many that could not be otherwise contemplated given limitations on drill ship technology and availability.

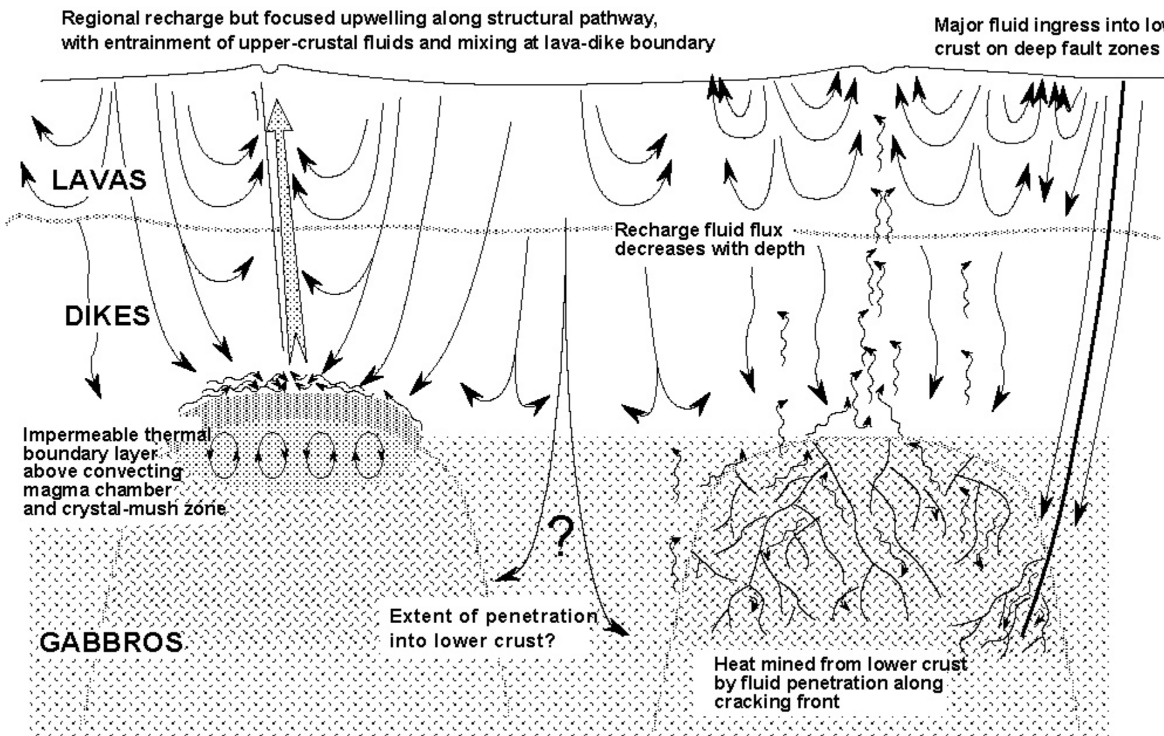

Figure 8. Cartoon showing possible fluid flow regimes in the upper ocean lithosphere. Right and left halves of cartoon show different models for ridge-crest hydrothermal circulation. At left, the cartoon displays recharge through the upper crust having a high bulk permeability and focused discharge. At right, it shows recharge focused through faults and other conduits, with diffuse discharge. [From Delaney and Pisias, 2000].

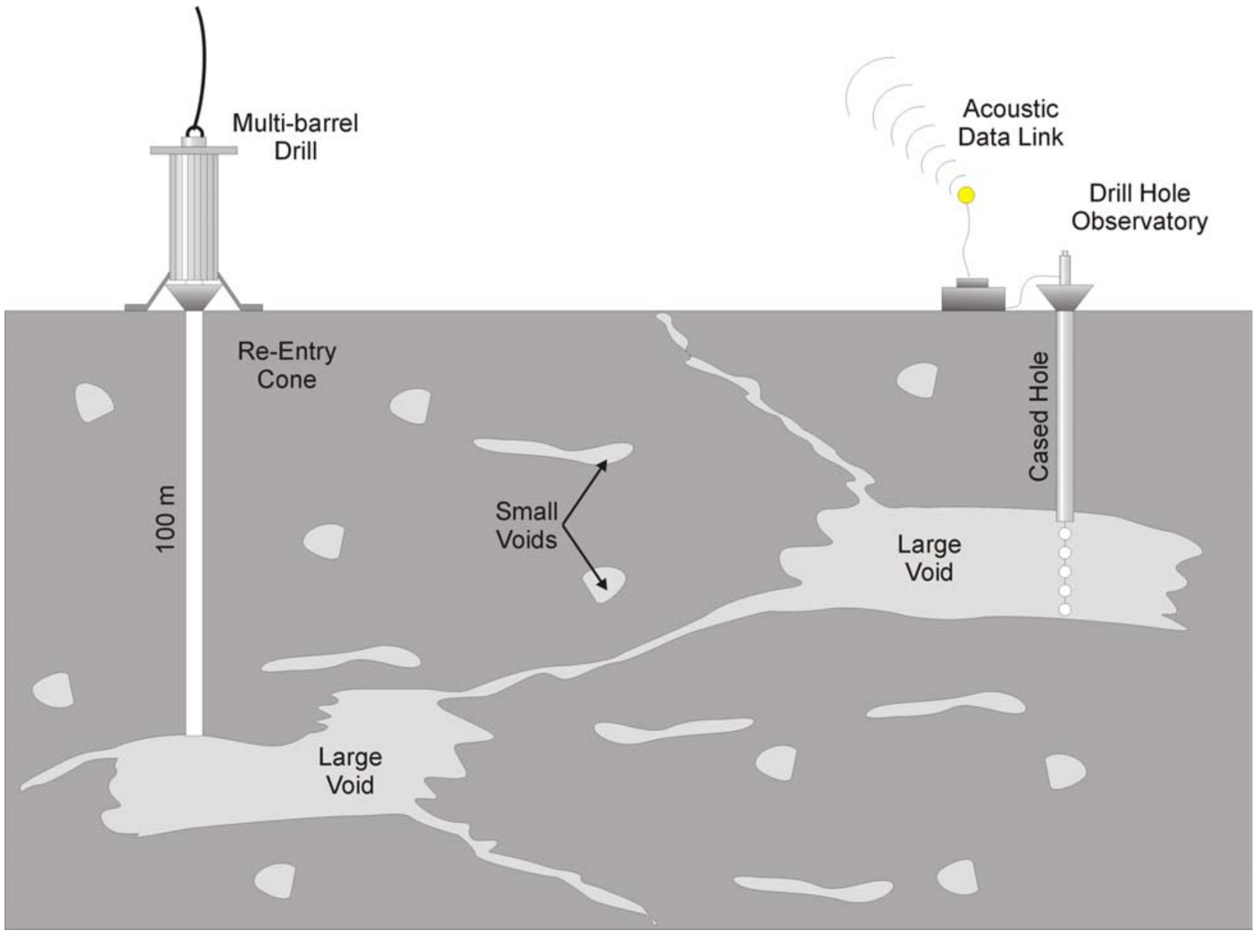

Figure 9. Cartoon showing ROBO-drill used to core into voids within the crust for hydrology study

Drilling Ocean Lithosphere

Drilling into the oceanic lithosphere is a high priority for scientists studying accretionary processes at ocean ridges (Fig. 10 [Delaney and Pisias, 2000]). Drilling adds two important dimensions largely unavailable to the community: time and stratigraphy. At present, most of the ocean crust is covered by a thin veneer of sediment that prevents coherent sampling of even its shallowest layer beyond a few million years of age. Yet when one looks at modern bathymetric maps of the oceans, sea floor morphology shows many complex patterns with respect to the ocean ridge segmentation and proximity to hotspots. These patterns change with inferred crustal age, and clearly reflect changes in the mantle processes accompanying seafloor spreading. It is now known from many sources [e.g., Schilling et al., 1983; Dick et al., 1984; Klein and Langmuir, 1987; Michael, 1985] that the composition of abyssal basalts reflect systematic variations in the pressure and temperature of mantle melting, and mantle composition. Thus abyssal basalts provide a means of interpreting the evolving patterns of mantle flow and mantle composition underlying the ocean ridges, and can therefore be used to interpret how variations in sea floor morphology are responding to changes in the dynamic environment.

At present, however, earth scientists are largely restricted to study of near zero age basalts dredged along ocean ridge axes, and thus to a single snapshot of the relationships between ridge morphology and mantle composition and thermal structure. The only reliable means of sampling the critical dimension of time is by using the *JOIDES Resolution*, or its successor ships. Both the demands on the *Resolution*'s time by numerous disciplines and the scale of its operations make it both unsuitable, and unavailable for the large scale sampling needed to address questions of how crustal composition varies with seafloor morphology through time. What is needed are inexpensive, accessible rock drills capable of penetrating a hundred meters of sediment or more, and drilling some ten to 20 meters into the basaltic crust. In many cases, a drill which would penetrate much less sediment, and only 50 cm of basalt would be adequate for studies of the basaltic crust out to several million years.

The other critical dimension, stratigraphy, is critical for the interpretation of plutonic rocks from the seafloor. At the present time there is little direct information on the composition and structure of the lower ocean crust, and how it varies in space and time with seafloor spreading rate, proximity to mantle hotspots, and local tectonic variables, such as ridge segmentation and proximity to fracture zones. Both marine geophysics and studies in ophiolite complexes (fossil ocean crust) show that the architecture of the ocean crust must vary dramatically with these many variables. Recent ODP drilling results from holes in the lower crust, at fast spreading ridges tectonically exposed at Hess Deep and from the East Pacific Rise, and from the ultra-slow spreading Southwest Indian Ridge at Atlantis Bank, show that lower crustal structure and composition vary dramatically with spreading rate [e.g., Gillis et al., 1993; Dick et al., 2000]. Moreover, it is evident that large-scale variations exist along axis with respect to position within a ridge segment and proximity to transform faults that cannot be resolved by a few deep drill holes. Mapping of such variations require systematic, three dimensional sampling around deep drill sites in large tectonic windows into the ocean crust, such as are found at the tips of propagating ridges like Hess Deep in the Pacific, or the large oceanic core complexes exposed by detachment faulting at slow spreading ridges such as Atlantis Bank in the Indian Ocean [Tucholke et al., 1997; 1998].

A major problem, however, in studying oceanic core complexes is that deformation and alteration along the footwall of the detachment faults on which the lower crust and mantle rocks are exposed dramatically modifies and obscures their primary features. At Atlantis Bank, moreover, it has been found that a thin layer of sheared talcose peridotite covers the uneroded detachment fault surface over many kilometers, completely hiding the large underlying gabbro massif beneath. The peridotite appears to have been intruded along the detachment faults from where they cut the crust-mantle boundary down axis near the transform. Thus, exposure of the gabbros, which are at least 1.5 km thick at ODP Hole 735B, occurs only where the footwall is heavily eroded, or cut by latter faults and landslips. Thus, if tectonic windows are to be used to study the lateral variability of the lower ocean crust, suites of relatively shallow drill holes (5- to 200 m) are needed.

A second critical problem for the study of plutonic rocks is that, unlike basalts, their interpretation is critically dependant on their internal stratigraphy, layering and cryptic chemical variations which reflect the processes of their formation. These cannot be studied in small bits of unoriented dredged rocks. For example, while the gabbros drilled by ODP at Hess Deep are strikingly different from those drilled at the SW Indian Ridge in Hole 735B, layered cumulates inferred to have formed at fast spreading ridges, similar to those found in many ophiolites, were not recovered. Until these are found, no ophiolite can be reliably used to infer further details of the stratigraphy of fast spread ocean crust. Even cores of only several tens of meters would be sufficient to establish whether or not there are layered cumulates exposed on the sea floor at Hess Deep. Dredging, on the other hand, simply cannot provide adequate samples to do this, and despite a large suit of such samples from Hess Deep, their study has not provided convincing evidence of the presence of layered cumulates there.

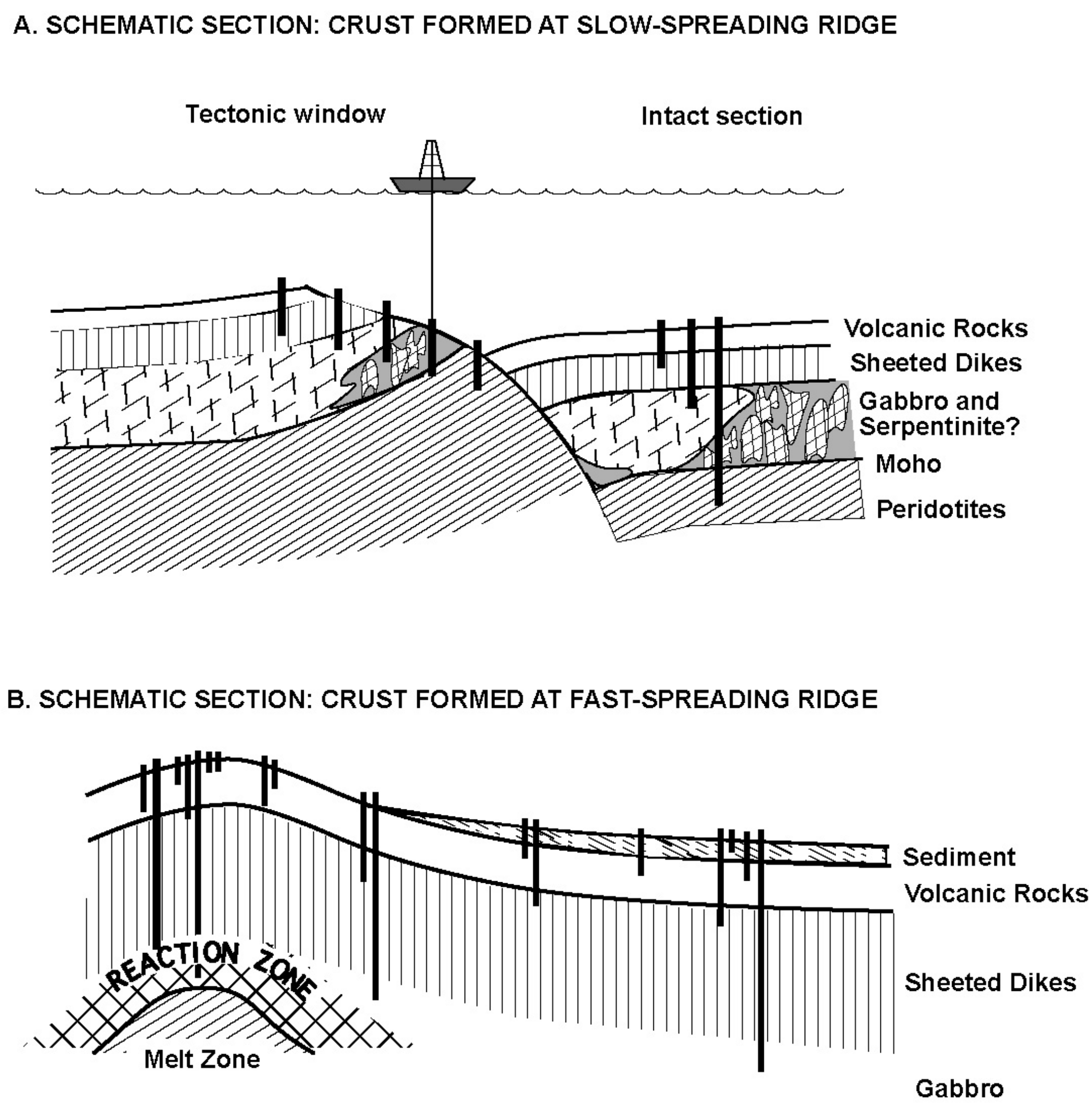

Figure 9. Cartoon of two strategies for drilling oceanic crust sections. Top: Drilling across tectonic windows can sample deep crustal sections that are exposed by tectonic unroofing. These sections can be sampled with a series of short offset drill holes. Bottom: Drilling a section of intact ocean crust to obtain information on spatial and time

variabililty. The strategy here is to combine many short holes with several deep holes drilled by ODP. [From Delaney and Pisias, 2000]

Finally, drilling is needed to obtain oriented cores for determining paleo-orientations for tectonic studies. There are numerous tectonic problems in the oceans that could be addressed if there were a reliable means of obtaining such cores, such as the evolution of microplates and oceanic core complexes. The recent success of the British Geological Survey at Atlantis Bank in obtaining a suite of 11 oriented half-meter diamond cores across a magnetic reversal in lower crustal gabbro [Allerton and Tivey, 2001] both confirmed that such reversals can be recorded in the lower crust and that the gabbro section drilled in Hole 735B has been back-tilted some 20° to the south. This was accomplished with the relatively inexpensive BGS BRIDGE drill (Fig. 6), showing that coring and orientation with a small drill is possible with present technology.

Drilling at Convergent Margins

The wide variety of environment types in convergent margins makes for diverse uses for drills and broadens the range of drill types needed for research such settings. Robotic ocean bottom drills can enhance research on convergent margins by allowing a more detailed approach to understanding the workings of the "Subduction Factory". Four major tectonic environments are currently under investigation in convergent margins. These are the outer trench rise, where the downgoing plate is deformed prior to subduction, the forearc region between the trench axis and the active volcanic arc (Fig. 11), the volcanic arc from the frontal volcanoes to the distal edifices in cross-chains, and the active spreading ridges that form in the backarc basins associated with rifted island arcs.

Oceanic Plate Applications: The deformation in the down-going plate that occurs prior to subduction can expose deep sections of the oceanic lithosphere. Access to fault-scarp exposures provides the opportunity to obtain oriented cores of deep sections of the oldest part of the lithosphere. The potential contribution to understanding the sources of input to the Subduction Factory is enormous. We know from dredging of fault scarps on the outer trench rise from several convergent margins that exposures of deep crustal materials are accessible in such locations. Drills mounted on a deep-diving submersible or ROV, or offset drilling by seafloor lander drills, could potentially provide a far better picture of the composition of the oceanic crust than can standard ODP-style efforts. A series of drill samples from a well-characterized outcrop surveyed prior to drill sampling can give a detailed two-dimensional picture of local variability in composition of the crust. ODP efforts often give only point source information from a single hole. The approach of using a combined submersible or ROV survey and drilling effort can provide information on effects of both stratigraphic variability and the influences from intrusives (dikes, sills) on the overall composition of the down-going plate. With carefully chosen sections of the outer trench rise it would be possible to obtain three-dimensional data on plate composition. What would be needed would be relatively simple horizontal drills mountable on a submersible or ROV that could drill sufficiently deep into an outcrop to get beyond potential effects of fault zone alteration (a few meters at most)

Forearc Applications: Convergent margins fall into two categories, accretionary and non-accretionary. At the outer edge of the overriding plate, sediments are either off-scraped from the down-going plate or transported along the forearc from terrigienous sources. The accretionary wedges that form by off-scraped sediment from the subducted plate provide some of the best opportunities to investigate channeling of fluids within convergent margins. The mechanism of channeling or of diffuse flow of fluids bears significantly on the physical properties of the accretionary wedge and thus on both the stability of continental slopes and of seismic hazard of the convergent margins. The mechanisms of slope failure and its link to seismicity in such environments could easily be studied with carefully controlled coring efforts and with deployment of pressure sensors or specialized down-hole seismometers. The flow of fluids through the accretionary wedge is a first order problem that cannot be solved with single deep holes. This problem will require 2-D arrays of holes to pin down the dynamics of chemical changes associated with activation of faults, changes in volumes of diffuse flow, or other factors linking faulting with distribution of fluids in accretionry prisms. These environments are also likely areas for the development of gas hydrates. The difficulty with research into gas hydrate formation, stability, and distribution is that these are dynamic deposits affected by temperature fluctuations and by changes in sea level. The study of gas hydrates will rely critically for maximum effectiveness on the ability to perform in situ experimentation and observation. One of the best ways to accomplish this would be to deploy an array of drill holes linked with down-hole instrumentation that can be monitored over appropriate time-frames. Time-series experiments such as these could be best accomplished by seafloor observatory sites whose data can be sent to shore via ocean bottom cables or ROVs or AUVs.

The biological activity of shelf regions adjacent to subaerial portions of the arcs and on the slope regions of the forearc margins is poorly understood in terms of both diversity and biomass. The evaluation of the environmental controls over establishment of various food chains depends critically on the understanding of nutrient cycling and biological forcing functions that can only be evaluated with an understanding of the water sediment interface and at depths great enough to be beyond the potential for contamination by bioturbation (tens of meters). The types of cores needed for biological studies will need to be large enough to provide uncontaminated materials.

Slope and sediment stability controls on convergent margins are poorly understood and have potentially great impact on hazard assessment and management problems for coastal regions. Large slumps may be seismically generated or formed as a consequence of storm effects. Such slumps are important to humankind because they may cause tsunamis. These must be studied in detail in order to assess potentially disasterous effects on coastal areas. The phenomena of slope instability events requires detailed analysis of slumping history and can be assessed by obtaining sufficiently deep cores (50-100m) to characterize a long enough period of geologic history on selected continental slope regions prone to repeated failures.

In nonaccretionary convergent margin settings the applications for drilling focus mainly on the through-put of the Subduction Factory. Forearc regions of nonaccretionary convergent margins lack the sediment cover that causes slab-derived fluids to interact chemically with the highly heterogeneous sediment blanket and lose the slab-signature that can tell much about the nature of dehydration reactions in the down-going plate. Convergent margins that have high degrees of deformation, and thus contain numerous faults that provide pathways for slab-generated fluids, offer unprecedented opportunities for tracing the dehydration history of the slab from shallow through intermediate depths of up to 30 kilometers. It has been demonstrated that samples collected from active springs have a far stronger signal of the slab-derived fluids than do areas of diffuse flow from a few meters away. Therefore the problem of accurately locating a drill over a specific seep or spring site requires a drill capable of providing near real-time video pictures and equipped with thrusters to adjust position before beginning drilling.

The dynamic deformation of convergent margins is a problem relevant to mechanisms of the subduction process and seismicity in subduction zones. Studies of convergent margin tectonics require deployment of a wide variety of monitoring instrumentation. Arrays of instruments are the best mechanism for monitoring 3-D and 4-D processes, thus sufficient down-hole instrumentation is necessary for geophysical, geochemical, and biological processes. The holes produced must be sufficiently large to accommodate various tools. Well-located drill holes that can be cased and instrumented are ideal for these kinds of monitoring efforts. The potential for deep biosphere investigations in forearc environments in which there is proven circulation of material from the subducted slab to the surface involves the possibility of tracing cycling of actual microbial forms through the Subduction Factory.

The origin of continental lithosphere is still unresolved, but theories of accretion of island arcs onto continents during tectonic collisions suggest that this is a major factor in the development of continental cratons. The evaluation of the structure and composition of island arc crust is critical for determining the average composition of arcs. There are localities in various submarine arcs where deep fault exposures provide access to deep sections of the arc crust including mid- to lower-crustal level intrusives. A series of offset drill holes deployed on fault slopes could provide significant information regarding crustal architecture and provide sufficient samples to define average compositions. The need to understand the stratigraphic relationships of the sites requires work with a drill system that is tethered or operated from a ROV.

Arc and Backarc Basin Applications: The island arc in intraoceanic convergent margins includes the frontal arc volcanoes and active edifices that stretch into the backarc regions along lineaments at high angles to the strike of the arc system. Drilling on the edifices and between them will provide the most detailed history of volcanic growth of the arc system and provide a more complete history of magmagenesis in the Subduction Factory. Compartmentalization of arcs leads to profound faulting of the arc massif. In arcs such as the Aleutians, deep faulting exposes the subvolcanic structure of the volcanic front. The mechanisms of deposition of volcanic products from individual eruptive centers vary with type of magma and with structure of the arc. The distribution of pyroclastic materials (from ignimbrites to volcaniclastic debris flows) in the marine environment is still not well characterized and bears critically on both the structure of the arc crust and on the distribution of potentially valuable ore deposits within the arc environment. Drilling such deposits would provide information regarding timing of these events, nature of deposits and the relationships to hydrothermally produced ore deposits. The rifting and spreading centers of actively extending backarc basins have many of the same attributes as mid-ocean ridges, but also have very important differences. The volcanic processes of these basins require an approach similar to that required for the study of spreading centers world-wide. The ability to drill unsedimented backarc ridge crest sites would enable us to determine magma variability along strike and thus trace chemical changes that could reflect various forcing mechanisms (subduction of ridges, changes in dip of slab, variation in degree of sedimentation of the down-going plate, etc.). It is clear that the nature of spreading in backarc basins is complex and intimately interrelated to arc structures. It is also clear that magma genesis in backarc spreading centers changes through time, from that characteristic of the early stages of extension to that which forms in the mature backarc spreading stages. The distribution of volcanic products could best be determined by detailed drilling and age dating. Variations in composition at different stages of the rifting and spreading process in backarc basins is related to the periodicity of extension in the convergent margin. This in turn responds to changes in such controls as variations in convergence rate, changes in direction of convergence, and collisions of the convergent margin with plateaus and seamount chains. The timing of such events and the effects on the rates of spreading in backarc basins can only be verified by establishing accurate rates of spreading with stratigraphically-controlled samples. Drilling is the best way to obtain such samples. Backarc basin spreading centers differ from mid-ocean ridges in the nature of the hydrothermal systems and the types of ore deposits formed in the two environments. The backarc basins are hosts to Koroko-type deposits, remarkably rich and voluminous ore resources that are enhanced by the rapid sedimentation rates typical of the arc environment. Drilling in an active arc/backarc system to determine the systematics of hydrothermal activity and their development of Koroko-type deposits are important for the evaluation of resource potential in active systems.

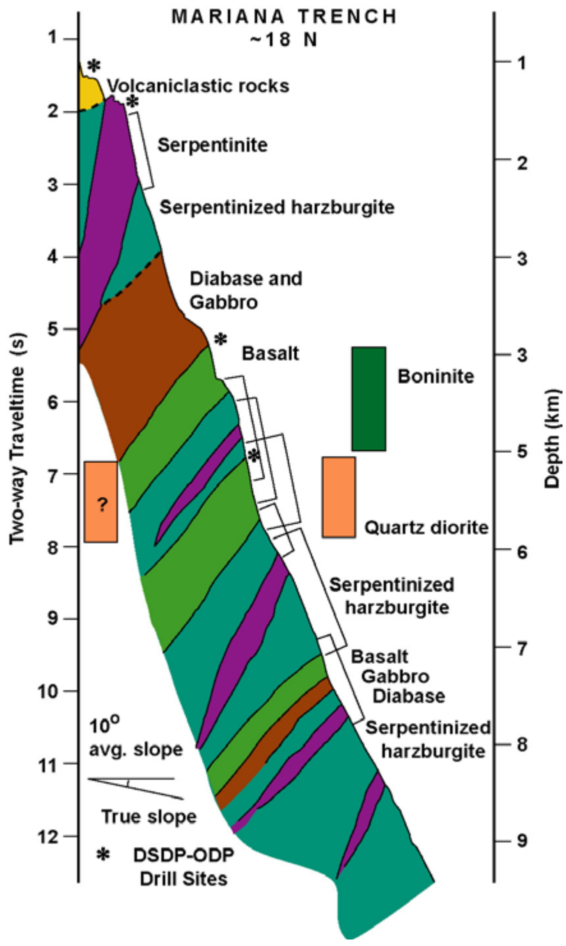

Figure 11. Interpretive sketch showing the heterogeneity of the inner slope of the Mariana Trench near 18°N latitude. Such high spatial variability requires much greater sampling capacity than provided by current and planned drill ships. ROBO-drills would contribute significantly to understanding of the complex geology in this setting. [From Pisias and Delaney, 2000]

Magnetic Structure of Ocean Crust.

Knowledge of the spatial patterns of seafloor spreading and lateral variations in ridge segmentation have reached a new level of maturity over the last 10 years thanks to swath mapping and detailed imagery of the seafloor and ocean crust. Now the focus is changing and questions are being asked about the vertical structure of the ocean crust with regard to the upper crustal volcanic lavas and dikes as well as the deeper gabbro and mantle sections. The internal architecture of the ocean crust is a record of crustal accretion and tectonic evolution at the midocean ridge. In particular, the magnetic properties of ocean crust provide both isochrons through the crust (using polarity reversals), and directional information using the vector information of the magnetic remanence that constrains the burial and tectonic rotation of the crust [e.g., Schouten, 2002]. The use of directional data from the seafloor is in its infancy at the present time, but the potential impact of obtaining such information would have tremendous implications for models of oceanic crustal accretion and its tectonic evolution through time.

Thus, one of the most important goals of remote seafloor drilling should be to obtain oriented cores from outcrops of oceanic crust. There are a number of questions concerning the accretion history and style of formation of oceanic crust that can be directly addressed by drilling and the recovery of oriented samples. For example, the internal architecture of the extrusive and dike layers that form the upper oceanic crust provide important constraints on the style of crustal accretion at a midocean ridge, e.g., where the lava is being supplied, how narrow is the supply region (dike injection zone), how often lava escapes the axial valley and how far the flows extend off-axis, and how the extrusive lava layer thickens and evolve through time. Recent concepts of this process envision progressive lava burial and subsidence with age. Progressive lava burial can be accommodated by either systematic overlap and pivoting or bending of the flows leading to rotation of the lava flow sequence, or by near-vertical faulting that has little or no rotation associated with it. Vertical faulting will steepen isochrons without rotation of the lava and the magnetic vectors recorded in the lava, wheras lava burial and bending also steepen isochrons, but has an associated rotation of the lava sequence. This post-depositional rotation of the lava sequence, or lack thereof, can be estimated by measuring the magnetic inclination of the remanent lava magnetization. Orientation data can provide constraints on post-accretionary block rotation and tectonic deformation and could also be used to determine lava or dike flow direction using AMS techniques. For testing emplacement models of the lower crust, a fundamental type of measurement is to follow isochrons through the crust and determining the amount of rotation of the magnetic vectors. Such data are also critical for addressing a variety of tectonic questions ranging from the formation of corrugated fault surfaces ("megamullions") and the uplift of rift valley walls at midocean ridges.

Sampling of oceanic crust outcrops is probably best done mainly with a drill attached to an ROV. Lander-type robotic drills will be suitable for some outcrops, and their longer, larger diameter cores could yield better samples. But such drills require nearly flat surfaces upon which to land whereas many outcrops suitable for sampling the interior of the ocean crust are steep fault surfaces. Although ROV drills are limited in core diameter and penetration, the ROV makes up for this drawback with increased mobility, the ability to drill nearly horizontal cores, and excellent imaging capabilities. Providing a video image of what is being drilled is critical to successful drilling, especially for those sampling studies that require a detailed geologic context for the samples.

Oceanic Paleomagnetic Pole Data

Paleomagnetic data are hard to obtain from the oceans because samples retrieved from on or below the ocean bottom are difficult to orient accurately. Indeed, the apparent polar wander path for the Earth's largest plate, the Pacific, consists mainly of paleomagnetic poles calculated from seamount magnetic anomalies, calculations of magnetic lineation asymmetry (skewness), and azimuthally-unoriented data from DSDP and ODP cores [Cox and Gordon, 1984; Sager et al., 1988; Petronotis and Gordon, 1999]. The latter are arguably more reliable than magnetic anomaly data, but play a lesser role in determining the polar wander path because there are not many drill sites that produced good data sets and because the lack of azimuthal orientation results in poor constraint of paleomagnetic pole positions in one direction [Cox and Gordon, 1984]. Nevertheless, paleomagnetic data from ocean areas are important because data from ocean plates are needed for paleomagnetic studies of apparent polar wander paths, true polar wander, and the long-term average shape of the geomagnetic field. Most of these studies require data with a wide global distribution, in which ocean areas cause large gaps. Moreover, oceanic plates often move more rapidly than continental counterparts, so they may contain more detailed records of the motion of the plates relative to the mantle (hotspots) and such data are required for studies of hotspot fixity and true polar wander.

Aside from the problem of gathering oriented samples from beneath the water, ocean plates contain many basaltic outcrops, frequently on seamounts, and basalt samples are often regarded as the best samples for paleomagnetic study and radiometric dating. Were they more readily available, ocean data could make it possible to refine and fill gaps in existing polar wander paths. Samples garnered from DSDP, ODP, or their successor are not the best answer because the drill ship is expensive, oversubscribed, and difficult to obtain for a given program. Paleomagnetic programs are only very rarely the driving force behind ODP legs (indeed, ODP Leg 197 was the first "paleomagnetic" leg). Futhermore, a reliable orientation system has not been developed for hard rocks drilled using the rotary coring apparatus. A better approach is to use a cheaper robotic drill with an orientation mechanism.

Currently, only one robotic drill has an orientation mechanism, the BGS BRIDGE drill. This small drill has a non-rotating inner sleeve that is attached to the frame so it can be oriented by sensors on the drill frame. The sleeve scribes an orientation line on the samples as they are drilled. The system was used successfully on a recent study of the paleomagnetism of Atlantis Bank on the Southwest Indian Ridge (Fig. 12, Allerton and Tivey, 2001).

A robotic underwater drill may also be more efficient at sampling basalts than a drill ship. The drill ship does a good job of drilling a deep hole, but a better strategy for sampling basalts from a seamount is to drill many, shallow holes with broad aerial distribution. This is because lava flows in any particular location are likely to show serial correlation owing to many flows being emplaced at that site in a short time [Cox and Gordon, 1984]. A widely distributed sampling grid is more likely to gather data from flows constructed during different eruptions, thereby giving a greater time sampling for averaging paleosecular variations.

Sampling from basalt outcrops for paleomagnetic data will probably require a drill that can core at least several meters into the outcrop. A shorter drill may not be able to get past intensely weathered exteriors or thick manganese crusts. Most any diameter over about an inch is appropriate as paleomagnetic samples do not need to have large volumes. A reliable orientation system is essential and this may limit paleomagnetic sampling to short drill barrels that can have a rigid inner sleeve. Longer, rotary core barrels with no attachment to the drill frame may prove difficult to orient. For paleomagnetic sampling, high quality video imaging is necessary and the ability to maneuver the drill as it hovers over the seafloor is desirable. The former will allow the scientist to see the outcrop being sampled and to judge whether or not it is suitable, whereas the latter would will allow the position of the drill to be adjusted to place the drill at the optimum location for sampling.

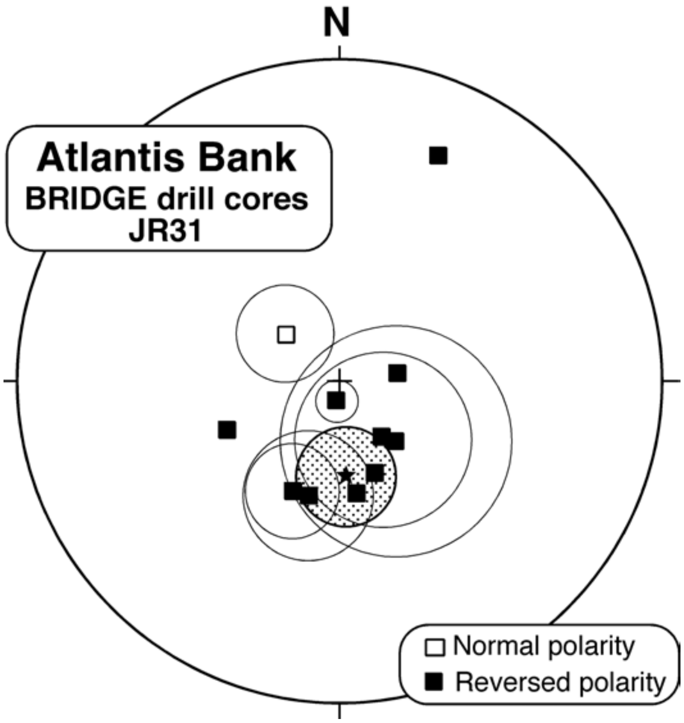

Figure 12. Azimuthally-oriented ocean paleomagnetic data collected using a robotic drill. Cores were collected from Atlantis Bank using the BGS 1-m BRIDGE drill. Open and filled squares represent magnetic directions; large open circles are 95% confidence regions. Star and stippled circle show the mean direction and its confidence region. Stereographic plot with north pole at center. This study shows that the concept of using underwater drills to collect paleomagnetic data is feasible. [Modified from Allerton and Tivey, 2001].

Origin and Evolution of Seamounts

Seamounts are ubiquitous features of the ocean lithosphere, yet their origin and evolution are not well understood. Many are thought to be formed near the ridge crests, either from the axial magma chamber and related magma pockets or from mantle plume volcanism [e.g., Batiza, 1977]. Other seamounts form by mid-plate volcanism, which is itself poorly understood. Some of these may be related to ancient hotspot chain volcanism [e.g., Epp, 1984] whereas others may be related to more unusual widespread magmatic episodes, such as plume head eruptions [Coffin and Eldholm, 1994]. Still others form on island arcs, related to the process of subduction. Much of our knowledge of basaltic volcanoes, for example, come from a few large, subaerial edifices in possibly unusual settings, for example the Hawaiian-Emperor Chain, Iceland, the Galapagos Islands, and the Canary Islands [e.g., Clague and Dalrymple, 1989; Staudigel and Schminke, 1984]. These volcanoes may not be good analogs for the smaller, possibly simpler edifices scattered around the ocean basins.

The study of seamounts is important because these volcanoes record processes of crustal construction and mantle magma reservoirs [e.g., Floyd, 1991]. They provide comparative geochemical and isotopic data on hotspots and other forms of volcanism. In addition, they constrain mantle convection and compositional domains. Geochemical and isotopic data in addition to radiometric dates from seamounts are crucial for understanding the origin and evolution of the seamounts themselves, as well as their mantle reservoirs [e.g., Staudigel et al., 1992; Koppers et al., 1998]. The geochemical and isotopic trends reflect upon the depth, size, and evolution of the magmatic source. Radiometric dates are critical for understanding the timing of the volcanism, how fast the magmas were emplaced, and whether or not there were multiple volcanic epsiodes.

Although the DSDP and ODP drill ships have proved invaluable for coring basalts from seamounts, such ships are inefficient for the purpose. The expense and difficulty in obtaining a drill ship for a geochemical/isotopic study discourages investigators from using this method. Instead, the tool of choice is still the dredge. Dredging itself has improved in recent years owing to pingers, dynamic positioning, and multibeam bathymetry data, but this method still relies upon luck because the dredge scrapes the surface to collect loose or easily dislodged rocks. Sample locations are not pinpointed to their source outcrop and many tons of samples are often collected to find suitable samples. With a robotic ocean bottom drill, it would be possible to pinpoint the sampling location accurately. Furthermore, because the drill could penetrate a thin overburden, samples could be retrieved from many locations that cannot produce good dredge samples, for example, outcrops covered with thick manganese crusts. A drill that could core at least several meters below the seafloor would be suitable for many sampling programs, and a drill that could core several tens of meters would satisfy even more. Core diameter is not critical, but larger is generally better to gather samples with greater volume. Because seamounts are topographic highs, a drill suitable for their study would be adequate with a depth capability of 4500-3500 m.

Oceanic Plateau Formation

Like seamounts, the mechanism by which many Large Igneous Provinces (LIPs) form is poorly known, even though LIPs are widespread (Fig. 13). One class of LIP, oceanic plateaus, are large, basaltic undersea mountains that many scientists believe formed by rapid, voluminous eruptions, the oceanic equivalent of continental flood basalts [e.g., Coffin and Eldholm, 1994]. Many also believe that such large ocean plateaus are formed by eruptions from the bulbous head of a nascent plume as it reaches the base of the lithosphere after rising through the mantle [Richards et al., 1989; Duncan and Richards, 1991]. An implication of this hypothesis is that a huge amount of volcanic material is emplaced in a short time. Given the implied flux of magma and volatiles, such eruptions may produce global environmental effects [Larson, 1991; Coffin and Eldholm, 1994].

Although widely accepted, the plume head hypothesis has yet to be adequately tested. Geochemical, isotopic, and radiometric age data are needed from ocean plateaus to understand their formation and test hypotheses about their origin. The geochemical and isotopic data can be used to infer the depth of magma reservoir, mixing with lower mantle, the mantle domain from which the magmas arose, and the evolution of the magma source. Radiometric dates indicate when the ocean plateau formed, how long the eruptions occurred, and whether there were significant gaps in the volcanic history. Such data are critical for testing the plume head model and alternatives.

Igneous rock samples are needed to investigate plateau formation. Because many plateaus are Cretaceous in age, they are frequently covered with a thick mantle of sediments and outcrops are badly altered and encrusted with manganese crusts. As a result, dredging produces poor quality samples. To address this problem, the JOIDES community has proposed a series of LIP-drilling legs, the first of which were Leg 183 (Kerguelen Plateau) and Leg 192 (Ontong Java Plateau). The problem with this strategy is that it is unlikely that any other plateaus will be drilled in the foreseeable future. Because they knew it unlikely that plateau drilling projects could get more than 2-4 legs, scientists on the science steering committees decided to focus on just these two plateaus. On the two recent ODP legs, both plateaus surprised investigators with unexpected results, making it likely that additional data will be needed from each one. To better understand Kerguelen and Ontong Java plateaus, as well as other poorly-studied plateaus such as Shatsky Rise, Hess Rise, Manihiki Plateau, Magellan Plateau, and others, another way of acquiring samples is needed. Robotic ocean bottom drills may partly fill this need.

Although many plateaus are covered with extensive and sometimes thick accumulations of sediment, outcrops are frequently found. Where sediments are thin or absent, a robotic drill that can penetrate several to several tens of meters can obtain valuable igneous rock samples. A robotic drill would have the advantage of being more readily available for projects, allowing some LIPs to be drilled that might not otherwise be studied. Furthermore, a robotic drill would be vastly cheaper than a drill ship.

A robotic drill can easily move laterally to provide a wide aerial distribution of samples. Because of surface weathering and manganese crusts, it is desirable that the drill be able to penetrate at least several meters into the outcrop. Several tens of meters would be better still. Geochemical studies and radiometric dating require relatively large sample volumes, so a large-diameter core (more than 2 inches) is preferred. Depths of operations would typically be between about 2500 to 4500 m because many plateau summits are this deep, but the best outcrops are likely to be on the middle to upper flanks, rather than the deep, lower flanks.

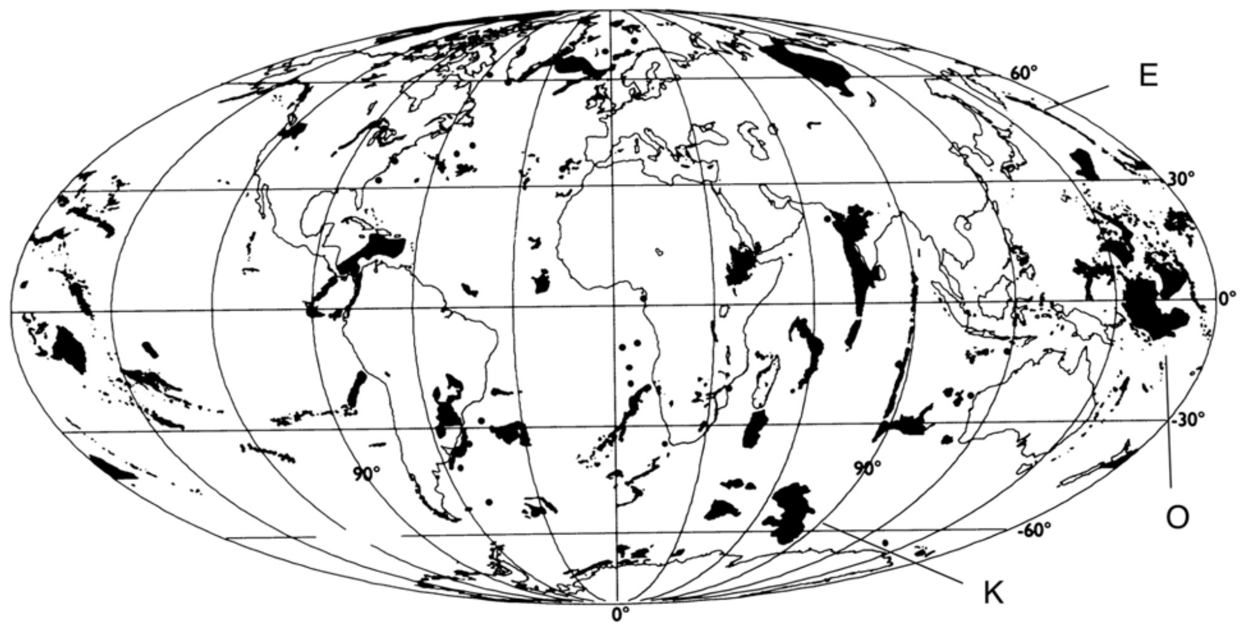

Figure 13. Large Igneous Provinces (LIPs) around the world (dark areas). Because of limitations on drill ship availability, only a small handful of LIPs have been investigated systematically. "O" and "K" denote Otong Java and Kerguelen plateaus, which were drilled on recent ODP legs (192 and 183, respectively). ODP Leg 197 drilled a series of short holes on seamounts of the northern Emperor chain ("E") in 2001. This program is one that might have been done more effectively and less expensively using a big ROBO-drill. [modified from Delaney and Pisias, 2000]

Paleoceanography

Understanding variations in the Earth's climate is one of the main goals of the Ocean Drilling Prgram [Long Range Plan, 1996]. The key to establishing a high-resolution record of paleoceanographic and paleoclimate variability is sampling sedimentary strata with high deposition rates that create an expanded record for a time interval of interest (Fig. 14). Only with high-resolution records can alternate hypotheses about climate oscillations be properly tested [e.g. Ramsdorf et al., 1995 versus Toggweiler and Samuels, 1992]. The problem for paleoceanographers is that there is at present only one way to get such samples in the ocean, drilling by *JOIDES Resolution*. ODP hydraulic piston coring is effective at recovering continuous sequences of soft sediments (typically to 150-200 m), and ODP is capable of deep rotary drilling, but the cost, lead-time, and effort involved in an ODP leg is formidable. Not all worthy projects can be accommodated by ODP.

Although piston-coring techniques have improved over the years, present capabilities have important limitations. Currently, recovery of long cores on U.S. vessels is limited to about 15 m length owing to the wire strength of standard coring winches. Indeed, four sets of piston coring gear have been lost in the past 7 years from UNOLS vessels due to this limit (two by WHOI and two by OSU). The longest conventional piston core ever recovered is 55m, taken aboard a French vessel (*Marion Dufresne*), but this is an unusual result and most long cores are limited to ~30 m or less by lithology or coring difficulties. Using non-U.S. facilities, such as *the Marion Dufresne*, is one option for U.S. scientists, but involves a degree of complexity that limits use.

Thus, there is a gap in sampling capabilities desired by marine scientists who wish to sample more than 10-15 meters of sediment, but cannot mount an ODP drilling leg for each desired sample.

The potential for filling this sampling gap comes from a class of seafloor drills with the capability of recovering sediment cores several tens of meters in length. Examples of this technology are the PROD and BMS systems mentioned in the introduction. These devices use rotary drilling or hydraulic piston coring from a seafloor lander to collect cores up to 100 m in length. Seafloor drills can be deployed from ships of opportunity, including larger UNOLS vessels, at a fraction of the cost of a drill ship. This new technology offers a quantum leap in our ability to sample the seafloor owing to its portability and potential availability coupled with potentially substantial cost savings relative to drilling.

Seafloor drills make it possible to core high sedimentation rate sections without mounting an ODP drilling leg to do so. In addition to taking longer cores than other non-ODP coring methods, seafloor drills eliminate a problem inherent in ODP style drilling -- ship heave that makes for variable bit pressure, limiting recovery and disturbing sediment. ODP has spent millions of dollars on heave compensation, and although partially successful, shipboard heave compensation will never be perfect. A robotic drill can land on the seafloor, and is decoupled from the ship. Thus, it is not influenced by heave, and can apply pressure as needed while being monitored in real-time by the drilling operator. The result is superior recovery of essentially pristine sediments, possibly even in messy "hard-soft" alternating lithologies. In addition, smaller drill-strings used with robotic drills can potentially do a better job of coring difficult lithologies, such as sediments containing sand and gravel, owing to the smaller bit size, better control of weight on bit, and a lesser requirement for flushing fluids. Robotic drills, therefore, offer a cost effective method of increasing the availability of high-resolution cores for paleoceaongraphic study.

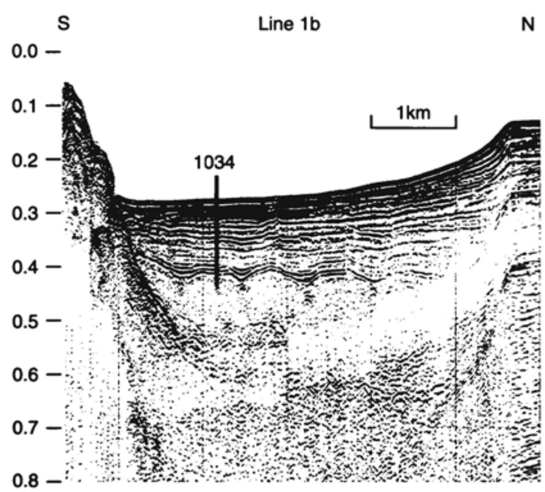

Figure 14. Seismic section from Saanich Inlet, British Columbia, showing ODP Leg 169S coring location. The objective of the drilling at this location was to sample an expanded Holocene sedimentary section. Because the deepest penetration was 118 m, this project could have been accomplished with a big ROBO-drill. (from Bornhold and Firth, 1998)

Gas Hydrate

One of the main research themes of current and future scientific drilling is to investigate the occurrence of gas hydrate world-wide [Long Range Plan, 1996]. Most data on gas hydrate in continental margins are derived from "bottom simulating reflectors" (BSR's) evident in seismic profiles [Shipley et al., 1979; Hyndman and Spence, 1995]. It is thought that this reflector is generated by the seismic velocity contrast at the base of the solid hydrate layer in the sediment with a possible layer of free gas trapped below. The BSR is frequently buried by hundreds of meters and can only be sampled with a drill-ship. In contrast, where hydrocarbon gasses are focused along fluid pathways, often on tectonically disturbed continental margins, gas hydrate can form layers or massive bodies at or near the seafloor. In such environments, drilling with seafloor robotic drills can be an important method for sampling gas hydrate. As with other types of seafloor sampling, having to use a drill ship limits the number and distribution of samples. However, wide sampling of gas hydrate is necessary to understand gas hydrate formation in differing parts of the gas hydrate stability zone as well as rates and mechanisms of methane oxidation in formation fluids. Thus, drilling with seafloor drills can an important component of the overall gas hydrate program. Moreover, a robotic seafloor drill could enhance in several ways the scientific return from shallow gas hydrate coring. The smaller kerf diamond bits would disturb gas hydrate less during drilling. This type of drill would also require lesser volumes of fluids, which might destabilize the in situ gas hydrate, to be pumped into the hole to flush cuttings. In addition, a diamond bit with light weight-on-bit is preferred for drilling hard-soft formations, such as occur around gas vents where hemipelagic sediments, gas hydrate, and authigenic carbonate are typically interlayered.

Gas hydrate is important for understanding a number of scientific questions. Destabilized gas hydrate beneath the seafloor could have broad implications for regional sediment stability, as well as for global climate change [Kvenvolden, 1988, MacDonald, 1990: Gornitz and Fung, 1994]. The effect on global climate of the massive methane source under continental margins remains largely speculative. This is because relatively little is known about actual dissemination or concentration of hydrates in the sediments, the effects of changes in the hydrate layer on slope stability, the input to the bottom water via hydrate decomposition, and the biogeochemical fate of the methane released to the water column. This ignorance is acute in focused flow settings because there are rarely BSRs that can be used to predict the location of gas hydrate. Sampling the sediments and hydrates with seafloor drilling can potentially address these questions. Recovering the gas hydrate presents technical challenges, since in-situ condition preservation is desired. Pressure core samplers are needed, as well as innovative devices, such as core thermal scanners, to document the distribution of hydrates in the sediments cores. Nevertheless, pressure samplers and other tools can be developed or adapted for robotic drill deployment from existing tools once a drill is available.

WORKSHOP RECOMMENDATIONS

Workshop participants strongly supported the construction of a large robotic ocean bottom drill (ROBO-drill) capable of tens of meters of penetration into the sea bed. Nevertheless, participants also recognized that such a drill would not address all perceived science needs and it would be desirable to have several smaller, less expensive “niche” drills. Recommended drills and their specifications are outlined in the following sections.

Big ROBO-drill

Much of the interest in robotic underwater drills at the workshop centered around a vision of a large drill system similar to the Benthic Multicoring System (BMS) built by Williamson and Associates, Inc., for the Metals Mining Agency of Japan and the Portable Remotely Operated Drill (PROD) built by an Australian consortium (that included Williamson and Associates). When asked about core diameter and penetration depth for their science needs, most workshop attendees responded “larger” and “deeper”. This indicates that the limiting factors determining how large to make the drill are the practical limitations such as cost, instrument size, cable strength, deck space, and shipping weight. Most workshop attendees felt that a drill larger than the PROD (100-m proposed maximum penetration) was not currently feasible, whereas a drill with the capability of the BMS (30-m maximum penetration) was the minimum. Thus, the consensus vision was a drill with a core diameter greater than 2 inches and a penetration capacity of 50-100 m (Table 1). Although many scientific uses for the ROBO-drill call for rotary coring of igneous or hard sedimentary rocks, it was also envisioned that the drill would be able to take sediment cores and insert casing strings. Both the BMS and PROD utilize core-rod technology, which results in longer drilling time owing to the assembly and take-down of core barrels. This type of drill string system also makes the installation of casing and use of logging tools more difficult. Consequently, the workshop attendees felt it important to investigate another method of lowering and pulling tools in the hole, such as wireline technology.

A specification of critical importance for robotic drills is the length of the cable that provides electrical power and a tether to the ship. A cable too short makes it impossible to reach deep targets, whereas a long cable stretches the limits of weight, cost, and power transmission in existing cables. A number of scientists noted that the depth limitations of PROD and the British Geological Survey 5-m drill (2000 m water depth) did not allow those tools to be used on important science objectives found in deeper water. In contrast, the 12-km cable assembled for the BMS is probably impractical owing to size, cost, and power loss. The compromise is a consensus that the large ROBO-drill should be able to reach targets in water depths as great as 3500-4500 m, which would allow most ridge crests, seamounts, continental margins, and plateaus to be cored.

Other constraints envisioned for the big ROBO-drill were that the system should be designed to be shipped long distances and deployed from the larger, dynamically-positioned UNOLS ships, so that it can be used most anywhere. Moreover, it should have a launch/retrieval system that allows use in moderate seas (6-8 ft) and it should have emergency recovery systems to allow retrieval in case of power failure or cable malfunction. It should have levelling capability so that it can drill on a moderate slope (<15°) with some roughness (±1 m). Desirable options include thrusters for maneuverability, full-frame video of the drill operations and seafloor, a core barrel for pressured samples, the ability to emplace a re-entry cone, control of fluids, control of weight on bit, and sample orientation.

It was realized that the big ROBO-drill would be big, heavy, complex, and expensive to build and operate. Such a device would likely need about six technicians (three each on two sea-going rotations) as well as periodic maintenance ashore, engineering maintenance and improvement design, and administrative oversight for scheduling and funding. The consensus was that it would cost about $1.5-2.0 million per year to run such an operation.

Medium ROBO-drill

Workshop participants considered it useful to have another drill that could be used where cost or platform considerations made it difficult to use the big ROBO-drill. The rationale behind the medium ROBO-drill is that it could be more easily shipped, it would be small enough to operate on a wider variety of research vessels, and it would be operated at less cost by a smaller seagoing technical staff. This would allow more projects to benefit from robotic drill sampling. The medium ROBO-drill would likely be the instrument of choice for projects where penetration depth is not critical, but cost and ease of handling are.

For simplicity and ease of construction, this drill was envisioned with a single core barrel, rather than the "gatling-gun" rotary core handlers on the big ROBO-drill. This limitation would limit the penetration of the medium ROBO-drill to 3-5 meters, similar to the existing British Geological Survey drill. However, unlike the existing drill, the small ROBO-drill would have greater capabilities. It would have high-quality, full-frame video cameras. It would have a cable of sufficient length to allow it to reach the seafloor in water up to 5500-6500 m deep (Table 1). It is desirable that the medium ROBO-drill be able to take cores approximately 2 inches in diameter. It should be able to drill on slopes up to about 15°. It should be easily shipped and deployed from medium and large research vessels.

Desirable features for the small ROBO-drill are core orientation and directional movement control. Orientation may be more easily accomplished for a single-barrel drilling system because a sleeve in the barrel can be attached to the frame to provide an azimuthal reference. Thrusters on the drill could allow it lateral movement, controlled from the surface, making it possible to move the drill lander to avoid hazards or position itself at a particular place on an outcrop.

Because of its smaller size, lesser complexity, and lesser requirements for operators at sea, the workshop participants felt that the medium ROBO-drill could be operated with a staff of about 3 technicians at a cost of about $0.6 million per year. It might be shipped in a single container and operated from existing fiber optic cables in the research fleet.

Mini ROBO-Drill

Many workshop participants saw a need for a small, simple drilling device that would be available on a few of the U.S. research vessels. This device would have limited capabilities, but would be of low cost and maintenance overhead. It would be small and simple to minimize fabrication and maintenance costs. Thus, the workshop participants envisioned several such units being built and consigned to different research vessels in the U.S. academic fleet as part of the normal equipment pools. These mini drills would be operated by non-specialist seagoing technicians and maintained by the normal technical staffs of the institutions that operate the ship they are on. Because of their low operation cost, these drills would be frequently used on projects where cost is a major factor. Furthermore, they would allow the use of drilling equipment for projects in which drilling is ancillary, such as piggy-back projects, or projects where many small, short cores are required.

As envisioned, the mini drill would operate from a small conducting cable, such as standard UNOLS CTD or trawl cables (0.34 and 0.68-in diameter). Its core diameter might only be an inch or a little more, and the penetration capability would likely be about one meter (Table 1). This drill may only have slow-scan video capability owing to the limited bandwidth of standard conducting cables, but this would allow scientists and operators to take a picture of the seafloor to see if the drill is in an appropriate place or position. The mini drill would be able to orient its cores and like its larger brethren, it would be capable of drilling on a slope up to 15°. It would also be designed to withstand depths >6500 m so that the practical limit to operations would be the length of the available cable.

ROV-Drill

Although the ROBO drills are versatile, certain scientific problems require a drill attached to a ROV. The ROBO drills all use a similar approach: they are lowered to the seafloor where they land on legs, are leveled, and drill a vertical core. They may be able to work on seafloor slopes up to about 15°, but steeper outcrops will require a drill that can core sub-horizontally. In addition, there will be projects where maneuverability and excellent imaging capabilities are required, for example, when an investigator is exploring unknown seafloor, making a geologic map, and collecting samples simultaneously. Such applications call for a drill mounted on a ROV, with maneuverability provided by thrusters and low weight/power ratio and imaging provided by multiple cameras.

The ROV drill should take core diameters of up to two inches, but penetration will likely be limited to about 0.5 m because of limitations to vehicle stability and weight carrying capacity. Operational depths should be as deep as possible, certainly in the 5500-6500 m range (Table 1). It is desirable that the drill be removable and adaptable to more than one ROV; although, in practice it may prove efficient to limit its use mainly to a single, widely avaiable vehicle. Another desirable feature is a system for orienting cores.

Robotic Drill Facility

If one or more robotic drills is constructed, proper support is required to insure the investment is not squandered. A large robotic drill must have good maintenance, must be periodically updated, must have skilled operators, and should be available to a broad community of scientists. Today, many instruments are built by single investigators or small investigator teams, often at a single institution. This method is unlikely to provide the necessary support nor promote the desired wide usage of the robotic drill. Such a drill represents a large expense for construction and a steady stream of funds to support the technical staff to run and maintain it. For example, the large ROBO-drill will likely cost $2-3 million to build and will need approximately 6 technicians in addition to administrative oversight, all of which will cost about $0.6-1.0 million per year. Even the small ROBO drill is likely to need several technicians for support, so it might cost $0.4-0.6 million per year to maintain. These are amounts not easily generated by a single investigator, or even a single institution.

Given the current competitive funding environment, drill support by a single investigator or institution will limit its use. When a device is built by under these circumstances, there is a tendency for the use of the instrument to be restricted to investigators at the home institution. Moreover, when the budget for a robotic drill is added to a scientific project budget, perhaps including overhead associated with the home institution, the additional expense can make the program difficult to fund.

To make sure the robotic drills are properly maintained and can be easily and widely used, it is necessary to have a drill facility funded directly by NSF. A facility would administer the drills and it technical staff. An investigator would apply for use of a particular drill in the manner currently used to obtain *Alvin, Jason*, and similar facility instruments. The facility would make shipping arrangements and handle mobilization and demobilization. Furthermore, the facility would provide the technical staff to operate and repair the drill during a project. Because the facility is open to all investigators, the drills would be used by many different investigators from a variety of institutions, as is *Alvin* today. With the funding provided directly by NSF, funding gaps would not destroy the continuity of the technical staff and it would be possible to hire top-notch personnel. Adequate maintenance and updates would be assured. In addition, if an individual P.I.'s budget did not have to reflect the cost of the drill, the quality of the proposed science would be the issue for reviews, not the cost of the drill.

Workshop participants felt that the facility should be the repository for the big and medium ROBO-drills. In addition, the technicians and engineers associated with the facility would provide expertise for the maintenance of the mini drills and ROV drill, which would belong to other institutions.

Testing ROBO-drill

In testing past versions of robotic underwater drills, there has been an unfortunate tendency to push the drill into operation before it was ready. This is usually driven by the need to begin generating an inflow of funds as the development funds run out. Such an approach is unfortunate because it gives robotic drills a reputation as unreliable. Workshop participants strongly felt that the development of one or more robotic drills should contain enough support for proper testing and tweaking of the instrument prior to full-scale undertaking of scientific projects. Proper testing may take a year or more, beginning with static tests on land, moving to logistically-simple ocean tests once the drill was deemed ready. Funding drill development through a facility may help because the pressure may be less than that on a single investigator attempting to write proposals to keep support coming in.

Table 1. Desirable Specifications for Future Robotic Drills.

Name	Required	Desired	Comments
Big ROBO-Drill	Penetration 50-100 m Water depth ~4500 m Core diameter > 2 inches Full frame video of seafloor and drill pipe Tolerates slopes to 15° Can be deployed from class 1 AGOR Can insert casing Transports in standard shipping containers Control of weight on bit and rotation rate	Core orientation Wireline technology Thrusters for maneuverability Logging capable ROV compatible Pressured cores Hole re-entry Fluid control Sample isolation Downhole motors	Existing drills need greater depth capability and better launch and retrieval systems; drills are either high cost or unavailable. Not one has drilled cores routinely.
Medium ROBO-Drill	Penetration 3-5 m Water depths ~6500 m Core diameter ≥ 2 inches Full frame video of seafloor Tolerates slopes to 15° Can be deployed from class 2 AGOR Transports in standard shipping Containers Fiber-optic cable compatible	Core orientation Thrusters for maneuverability	Existing drills need greater depth capability, better imaging, greater reliability.
Mini ROBO Drill	Penetration ~1 m Water depths ~8500 m Core diameter > 1 in Slow scan video of seafloor Tolerates slopes to 15° Deployed with 0.68 cable	Core orientation Penetration >1 m Full frame video	Envisioned as tool in equipment pool of UNOLS vessel; for non-dedicated projects; Inexpensive shipping and operation
ROV-Drill	Penetration ~0.5 m Water depths ~6500 m Core diameter ~1 in Easily shipped Easily adapted to ROV	Core orientation	Envisioned as tool in ROV facility equipment pool; assumed that ROV will provide capability for video and maneuvering

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Appendix 1.
Requirements for Robotic Underwater Drills
in U.S. Marine Geologic Research
Agenda

Day 0 (Thursday, 2 November)
Attendees arrive in College Station
Dinner on own

Day 1 (Friday, 3 November)
0830 Intro and Overview by Steering Committee
0850 Keynote #1 – MBARI ROV drill - Debra Stakes
Keynote #2 – Drill development at Williamson & Associates – Tim McGinnis
Keynote #3 – PROD drill tests – Chris Goldfinger
Break (20 min)
Keynote #4 – Other drill systems - Leon Holloway
Keynote #5 – Lake drilling developments at DOSECC – Don Thomas
1150 Lunch break (catered in)
1315 Discussion: "What scientific problems require underwater robotic drills?"
Purpose: define the scientific rationale for developing and using robotic drills
Drilling the oceanic crust – Henry Dick
Magnetic structure of ocean crust – Maurice Tivey
Drilling hydrothermal and massive sulfide deposits – Robert Zierenberg
Paleoseismology using robot drills – Chris Goldfinger
Drilling for microbiology – Martin Fisk
Paleomagnetic poles for oceanic plates – Will Sager
Drilling Large Igneous Provinces (LIPS) – Will Sager
Coring sediments and gas hydrate on continental margins – Chris Goldfinger
Paleoceanographic science with robot drills – Chris Goldfinger
Coring carbonate platforms – Andre Droxler
Drilling subduction zones with robot drills – Patty Fryer
Crustal hydrology and microbiology – Paul Johnson
1500 Break (20 min)
1520 Discussion: "What kinds of robotic drills are needed"
"How do existing drills satisfy needs"
"Design and operational constraints on robotic drills"
"What constitutes a working drill"
"Support of drilling science"
1730 End for day
900 Dinner at Epicures, College Station

Day 2
0900 General Discussion
Continue with discussion of types of drills and drill specifications
1030 Break (20 min)
1050 Continue discussion
1200 Lunch break (catered in)
1315 Wrap up
1400 End of general meeting

Appendix 2
Robotic Drills Workshop
List of Participants

Steering Committee

Dr. William W. Sager (Chair)
Department of Oceanography
Texas A&M University
College Station, Texas 77843-3146
979/845-9828 - Telephone
979/845-6331 - Fax
wsager@ocean.tamu.edu

Dr. H. Paul Johnson
School of Oceanography
Box 357940
University of Washington
Seattle, Washington 98195-7940
206/543-8474 - Telephone
206/543-0275 - Fax
johnson@ocean.washington.edu

Dr. Patricia Fryer
Hawaii Institute for Geophysics and Planetology
University of Hawaii at Manoa
2525 Correa Road
Honolulu, Hawaii 96822
808/956-3146 - Telephone
808/956-6322 - Fax
pfryer@soest.hawaii.edu

Dr. Henry J. B. Dick
Geology and Geophysics Department, MS #22
Woods Hole Oceanographic Institution
360 Woods Hole Road
Woods Hole, Massachusetts 02543-1050
508/289-2590 - Telephone
508/457-2187 - Fax
hdick@whoi.edu

Dr. William R. Bryant
Department of Oceanography
Texas A&M University
College Station, Texas 77843-3146
979/845-2880 - Telephone
979/845-6331 - Fax
wbryant@ocean.tamu.edu

Dr. André W. Droxler
Department of Geology and Geophysics, MS-126
Rice University
6100 Main Street
Houston, Texas 77005-1892
713/348-4885 - Telephone
713/348-5214 - Fax
andre@ruf.rice.edu

Dr. Martin R. Fisk
College of Oceanic and Atmospheric Sciences
104 Ocean Administration Building
Oregon State University
Corvallis, Oregon 97331-5503
541/737-5208 - Telephone
541/737-2064 - Fax
mfisk@oce.orst.edu

Dr. Chris Goldfinger
College of Oceanic and Atmospheric Sciences
104 Ocean Administration Building
Oregon State University
Corvallis, Oregon 97331-5503
541/737-5214 - Telephone
541/737-2064 - Fax
gold@oce.orst.edu

Participants:

Mr. Andrew D. Bowen
Deep Submergence Laboratory, MS #07
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543
508/289-2643 - Telephone
508/457-2191 - Fax
abowen@whoi.edu

Mr. George L. Holloway
Drilling Services Department
Ocean Drilling Program
Texas A&M University
College Station, Texas 77843-3469
979/845-2294 - Telephone
979/845-2308 - Fax
holloway@odpemail.tamu.edu

Dr. Thomas Kuhn
Freiberg University of Mining and Technology
Institute of Mineralogy
Department of Economic Geology
Brennhausgasse 14
D-09596 Freiberg, GERMANY
49-3731-39-3398 - Telephone
49-3731-39-2610 - Fax
kuhnto@orion.hrz.tu-freiberg.de

Ms. Amy J. Lamarche
Department of Oceanography
Texas A&M University
College Station, Texas 77843-3146
979/845-5346 - Telephone
979/845-6331 - Fax
aj@ocean.tamu.edu

Dr. Charles E. Lesher
Department of Geology
University of California at Davis
One Shields Avenue
Davis, California 95616-8605
530/752-9779 - Telephone
530-752-0951 - Fax
lesher@geology.ucdavis.edu

Mr. William H. Martin
School of Oceanography
Box 357940
University of Washington
Seattle, Washington 98195-7940
206/616-3998 - Telephone
206/685-7436 - Fax
bmartin@ocean.washington.edu

Mr. Tim Mcginnis
Williamson and Associates, Inc.
4200 23rd Avenue West
Seattle, Washington 98199
206/285-8273 - Telephone
206/285-8291 - Fax
timm@wassoc.com

Dr. Duane J. Miller
Science Services Department
Ocean Drilling Program
Texas A&M University
College Station, Texas 77843-3469
979/845-2197 - Telephone
979/845-0876 - Fax
miller@odpemail.tamu.edu

Mr. Marshall Pardey
QD Tech, Inc.
4558 South Kayland Circle
Salt Lake City, Utah 84117
801/558-5262 - Telephone
801/972-3694 - Fax
mpardey@qdtech.com

Mr. Thomas L. Pettigrew
Drilling Services Department
Ocean Drilling Program
Texas A&M University
College Station, Texas 77843-3469
979/845-2329 - Telephone
979/845-2308 - Fax
pettigrew@odpemail.tamu.edu

Dr. Tommy J. Phelps
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831-6036
865-574-7290 - Telephone
865-576-8543 - Fax
phelpstj@ornl.gov

Mr. Eugene C. Pollard, Jr.
Drilling Services Department
Ocean Drilling Program
Texas A&M University
College Station, Texas 77843-3469
979/845-2161 - Telephone
979/845-2308 - Fax
pollard@odpemail.tamu.edu

Mr. Matthew J. Pruis
School of Oceanography
Box 357940
University of Washington
Seattle, Washington 98195-7940
206/543-8474 - Telephone
206/543-0275 - Fax
mpruis@ocean.washington.

Dr. Reed P. Scherer
Department of Geology and Environmental Geosciences
Northern Illinois University
DeKalb, Illinois 60115
815-753-7951 - Telephone
815/753-1945 - Fax
reed@geol.niu.edu

Dr. Peter Schultheiss
GeoTek
Nene House, Drayton Fields
Daventry, Northants NN11 5EU
United Kingdom
44-1327-311666 - Telphone
44-1327-311555 - Fax
Peter@geotek.co.uk

Dr. Alexander N. Shor
Division of Ocean Sciences
National Science Foundation
4201 Wilson Boulevard, Room 725N
Arlington, Virginia 22230
703/292-8581 - Telephone
703/292-9085 - Fax
ashor@nsf.gov

Dr. Debra S. Stakes
Monterey Bay Aquarium Research Institute
7700 Sandholdt Road
Moss Landing, California 95039-0628
831/775-1710 - Telephone
831/775-1620 - Fax
debra@mbari.org

Dr. Melanie Summit
Department of Earth and Planetary Sciences
Campus Box 1169
Washington University
St. Louis, Missouri 63130
314/935-8555 - Telephone
314/935-7361 - Fax
summit@zonvark.wustl.edu

Dr. Frederick W. Taylor
Institute for Geophysics
The University of Texas at Austin
4412 Spicewood Springs Road
Austin, Texas 78759-8500
512/471-0453 - Telephone
512/471-8844 - Fax
fred@utig.ig.utexas.edu

Dr. Donald M. Thomas
Hawaii Institute of Geophysics and Planetology
University of Hawaii at Manoa
2525 Correa Road
Honolulu, Hawaii 96822
808/956-6482 - Telephone
808/956-3188 - Fax
dthomas@soest.hawaii.edu

Dr. Maurice A. Tivey
Geology and Geophysics Department, MS #24
Woods Hole Oceanographic Institution
360 Woods Hole Road
Woods Hole, Massachusetts 02543-1542
508/289-2265 - Telephone
508/457-2150- Fax
mtivey@whoi.edu

Mr. Eddie L. Wright
Drilling Services Department
Ocean Drilling Program
Texas A&M University
College Station, Texas 77843-3469
979/845-3207 - Telephone
979/845-2308 - Fax
ewright@odpemail.tamu.edu

Dr. Robert A. Zierenberg
Department of Geology
University of California at Davis
One Shields Avenue
Davis, California 95616-8605
530/752-1863 - Telephone
530-752-0951 - Fax
zierenberg@geology.ucdavis.edu

Feasibility Study for

Remotely Operated Seafloor Drilling Equipment for the

US Scientific Community

Submitted to:

Texas A&M University
Dept. of Oceanography

College Station, TX 77843-3146 USA
Contact: William Sager
Tel: 979-845-9828
Fax: 979-845-6331
wsager@ocean.tamu.edu

Submitted by:

University of Washington
Applied Physics Lab

1013 NE 40th St.
Seattle, WA 98105-6698
Contact: Tim McGinnis
Tel: 206-543-1346
Fax: 206-543-6785
tmcginnis@apl.washington.edu

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{Add executive summary}

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Tables

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Record of Document Versions

Date	Version	Description, Reason for change
Jan 21, 2003	draft	Draft for Review
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Contact for revisions and proposed changes:

Tim McGinnis
tmcginnis@apl.washington.edu

1.0 Introduction

On November 3-4, 2000, a workshop was held at Texas A&M University titled “Requirements for Robotic Underwater Drills in Marine Geologic Research”. This workshop brought together twenty-five scientists and engineers to discuss the issues involved with making the capabilities of these drills more available to the US and international academic research community.

The workshop group reached a consensus that drills in the following categories need to be considered:

1. A “large” drill capable of drilling in water depths of 3500-4500 m and recovering hard rock and sediment cores from depths of 50-100 m beneath the seafloor.
2. A “small” drill that would be relatively simple and inexpensive to operate that could recover cores from 3-5 m beneath the seafloor.
3. A “micro” drill that could be operated as part of standard shipboard equipment by on-board technicians and could recover cores from 1m beneath the seafloor.
4. A ROV drill that could recover cores from a variety of formations including vertical outcrops.

The results of this workshop were published in a report [1].

Several robotic drills have been built and operated that are similar to the drills mentioned above. Many of the capabilities of and technologies required by these drills currently exist, have previously been demonstrated or require combining existing components or technologies. It is thought that the engineering challenges involved with implementing the “small”, “micro” and “ROV” drills are modest and present no major challenges. On the other hand, the “large” drill presents a number of challenges – several of the capabilities either do not exist or exist in a form that needs significant work to adapt for use by remote control on the deep seafloor.

The purpose of this study is to investigate some of the issues involved with implementing the large drill mentioned above.

2.0 System Capabilities

This study will investigate several specific capabilities that were identified as desirable in a deep sea robotic coring system. For each of these capabilities, the goal will be stated followed by a discussion of the issues involved, whether that goal is achievable, how the goal might be achieved and what some of the trade-offs or alternatives would be.

2.1 Operating Depth and Coring Depth

GOAL: Operating depth to 4500m – consider trade-offs between depth, umbilical size/weight, power capability, system weight (vehicle, tools, samples), etc.

GOAL: 50-100 m sub-seafloor capability - what are the trade-offs for determining a maximum depth capability

Most of the issues related to water depth involve the cable – primarily cable weight, strength and power transmission capability. For steel armored cables in deep water, the self-weight of the cable can be a large fraction of the total load.

There are no other major engineering challenges foreseen with building a drilling system for use in deep water. The BMS drill was built with for an operating depth of 6000 m and has been used as deep as 4000m [1].

Tables 1 and 2 below show the total cable load different:

Cable weights & strengths
Tool diameters & weights (NQ size tools were used as a constant)
Water depths (affects cable weight)
Coring depths (affects tool & sample weight)

Parameter	Units	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6	Cable 7	Cable 8
Water Depth	m	1000	1000	3000	2500	2300	1500	1500	2000
Coring Depth	m	30	30	100	100	100	50	75	100
Vehicle Weight in H_2O	kg	4500	4500	4500	4500	4500	4500	4500	4500
Tool Size		NQ	NQ	NQ	NQ	NQ	NQ	NQ	NQ
Hole Diameter	mm	75.8	75.8	75.8	75.8	75.8	75.8	75.8	75.8
Core Barrel Wieght in H_2O	kg/m	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Rod Weight in H_2O	kg/m	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Total Tool Weight in H_2O	kg	390	390	1301	1301	1301	650	976	1301
Core Diameter	mm	50.5	50.5	50.5	50.5	50.5	50.5	50.5	50.5
Sample Density in H_2O	kg/m^3	1500	1500	1500	1500	1500	1500	1500	1500
Sample Weight in H_2O	kg/m	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Total Sample Weight	kg	90.1	90.1	300.4	300.4	300.4	150.2	225.3	300.4
Pullout Force	kg	200	200	200	200	200	200	200	200
Cable Strength		steel	steel	steel	steel	steel	aramid	aramid	aramid
Cable Diameter	mm	17.3	23.7	29.7	33.1	65.4	38.0	38.1	43.2
Cable Weight in H_2O	kg/m	0.905	1.75	2.6	3.4	8.37	0.438	0.746	1.01
Total Cable Weight	kg	905	1750	7800	8500	19251	657	1119	2020
Cable Breaking Strength	kN	205	325	560	640	1014	449	498	600
Cable Working Load	kN	62.3	75.6	142	151	254	62	71	85
Cable Working Load	kgf	6357	7714	14490	15408	25918	6327	7245	8673
Cable Safety Factor		3.3	4.3	3.9	4.2	4.0	7.2	7.0	7.1
Total Load at Sheave	kg	6085	6930	14101	14801	25552	6158	7020	8321
Cable Load Margin	kg	272	784	389	607	366	169	225	352

Table 1 - Water Depth, Coring Depth, Cable Type for N Tool Size

Note: Several vendor specification sheets use the unit of kilograms-force (kgf) as a metric unit of weight/force (equal to the weight of 1 kg at sea level) that is readily understandable and convertible to/from the English weight/force unit of pounds (lbs). For convenience, this document will use the same convention of equating mass to force, although not strictly correct.

These assume a vehicle weight of 4500 kgf and sample density of 2500 kg/m^3 (basalt). The parameters were adjusted to result in a "Cable Load Margin" – the difference between the cable load at the sheave and the cable Safe Working Load - of a few hundred pounds. This does not allow for any dynamic loading but should be reasonable for preliminary design. The loads are greatest in deep water with a large amount of cable deployed and this long cable length provides some absorption of shock and dynamic loads.

Table 1 compares several standard cables and for each cable, shows a case with maximum water depth and coring depth for NQsize wireline coring tools (as opposed to conventional coring tools). This table shows that the longest cores and deepest water depth that can be achieved are provided by Cable 3 in Table 1. Table 2 compares several different tool sizes with Cable 3 and shows the maximum water depth and coring depth that can be achieved for each tool size. There are cables shown in Table 1 that are stronger (Cables 4 & 5) but the strength-to-weight ratio is not as good. This cable comparison is not exhaustive and it is probable that there is another more optimal cable configuration.

These table shows that a robotic coring system, using a cable similar to Cable 3, depending on the tool size, can potentially recover core lengths of 50-100 m in water depths of 3200-3500 m. It turns out that the safe working load (SWL) of Cable 3 is close to the SWL of the A-Frame of the R/V Thomas G. Thompson. This indicates that these coring limits may be on the order of what is possible with AGOR-23 class vessels such as the Thompson.

The ROPOS System that is operated by the Canadian Scientific Submersible Facility has used Cable 3 to depths of 3200+ m. The ROPOS vehicle weighs 2700 kg in air and is neutral in water. The ROPOS cage/tether management system weighs 5000 kg in air and approximately 4300 kg in water. The PROD Drill has also used this cable to depths of several hundred meters. PROD weighs approximately 7000 kg in air and 6000 kg in water.

Tool Size	Units	AQ	BQ-LW	BQ	NQ	HQ
Water Depth	M	3500	3300	3300	3200	3200
Coring Depth	M	100	100	100	80	50
Vehicle Weight in H_2O	Kg	4500	4500	4500	4500	4500
Hole Diameter	Mm	48.0	60.1	60.1	75.8	96.2
Core Barrel Wieght in H_2O	kg/m	2.1	3.7	3.7	6.2	11.4
Rod Weight in H_2O	kg/m	3.3	4.3	5.2	6.8	10.0
Total Tool Weight in H_2O	Kg	544	797	893	1041	1071
Core Diameter	Mm	30.5	40.6	40.6	50.5	63.5
Sample Density in H_2O	kg/m^3	1500	1500	1500	1500	1500
Sample Weight in H_2O	kg/m	1.10	1.94	1.94	3.00	4.75
Total Sample Weight	Kg	109.6	194.2	194.2	240.4	237.5
Pullout Force	Kg	200	200	200	200	200
Cable Diameter	Mm	29.7	29.7	29.7	29.7	29.7
Cable Weight in H_2O	kg/m	2.6	2.6	2.6	2.6	2.6
Total Cable Weight	Kg	9100	8580	8580	8320	8320
Cable Breaking Strength	kN	560	560	560	560	560
Cable Working Load	kN	142	142	142	142	142
Cable Working Load	Kgf	14490	14490	14490	14490	14490
Cable Safety Factor		3.9	3.9	3.9	3.9	3.9
Total Load at Sheave	Kg	14454	14272	14368	14301	14328
Cable Load Margin	Kg	36	218	122	189	161

Table 2 - Water Depth, Coring Depth, Tool Type for Cable 3 in Table 1

2.2 Core Diameter

GOAL: Core Diameter > 2" – list of standard size coring tools and discussion of trade-offs with size, power requirements and weight

The primary considerations for core diameter are:

1. The power required to provide the torque required to rotate the bit with a sufficient rotation rate (RPM) and bit weight to maintain a reasonable rate of advance.
2. The weight of the coring tools and the recovered core samples.
3. The flow capacity of the flushing water pump.
4. The size and weight of the storage magazine and handling equipment.

It should be possible to design the drill equipment to be able to handle a variety of tool sizes – possibly up to H size. The larger tools may be used with reduced water depth or coring depth and then smaller tools could be used for deeper water and/or deeper cores. This could involve changing the carousel and possibly some of the jaws or other components but the hydraulics, water pump and other critical components would be designed to handle the range of sizes or be adjustable.

2.3 Seafloor Types

GOAL: Capability for diamond rotary rock coring and hydraulic piston coring (HPC) - switchable while on the seafloor or on-board the vessel

As described in Section 3.1 below, diamond rotary rock coring is significantly less challenging to accomplish than sediment hydraulic piston coring. A Hydraulic Piston Core Assembly "HPC" is a core sampling tool for soft, unconsolidated formations, typically sediments. The HPC can be attached directly to the end of a rod string with conventional, non-wireline techniques or be deployed as an inner assembly on a wireline system. There are two basic alternatives for recovering sediment cores using and HPC.

The first type utilizes a piston that is fixed at the bottom of the core barrel by a rod. During the coring process, the inner barrel is pushed into the sediment to collect the core. The piston stays fixed at the top of the sediment sample and supplies hydraulic pressure to pull the sample into the core tube, which results in a higher quality core. The downside of this type of coring is that, with the fixed piston, once the core tube is extended, the length of the core barrel is increased by the length of the core sample – if the tube were retracted, the sample would be pushed out by the rod. This is not a problem with normal wireline system where the core barrel is recovered to the surface where operators can handle it but it is a problem with a robotic system because of the difficulty of handling and storing the longer core barrel. If the core barrels will not fit back into the magazine, an alternate storage rack would need to be used which would require a more complicated tool handling system. It is likely that this external storage rack could only hold a few core barrels which would limit the number of sediment sample that could be taken on a deployment.

The second type utilizes a floating piston. The position of the piston is maintained by using an external hydraulic piston to draw a volume of water out of the top of the core tube that exactly matches the volume of water that is displaced as the tube is extended. By doing this, the position of the piston is held exactly at the level of the top of the core, thus accomplishing the same results as the fixed piston. The advantage of this floating piston is that after the sample is collected, the core tube can be retracted and stored back in the magazine. With this type of system, there is no practical limit to the amount of sediment cores that could be collected on a deployment.

With either type of system, the HPC uses hydraulic pressure created by a water/drill mud pump pumping fluid into the drill string to extend the core tube. The HPC creates a seal that prevents water/drill mud from exiting the drill string at the bit face. The piston is located at the top of the sample gathering tube and retained by shear pins. When the pump is started the internal pressure in the drill string rises and the water/drill mud pressure on the tube is increased until it exceeds the shear strength of the pins. Depending on the capacity of the hydraulic system, it is possible that an accumulator may be required to meet the momentary, high pressure/high flow requirements. At this point the sample tube with a beveled nose cone and a core retainer is forced into the formation. The sample tube will penetrate the formation until the total stroke length is obtained or may stop short of that distance if the resistance of the material is greater than the applied hydraulic force. The HPC is then recovered by tripping the drill string or by lowering an internal wireline cable and hoisting the HPC inner assembly to the vehicle and storing the core barrel with sample.

With either type of HPC, it should be possible to switch between rock and sediment coring while on the seafloor by selecting which type of core barrel to retrieve from the magazine.

GOAL: Sampling capability in all bottom types - bare basalt to very soft sediment. Operations on slopes up to 15° - discussion of trade-offs between height, width, leg style (vertical or "back hoe" type)

The stability of the drilling platform will determine how well the platform operates on a sloped surface, soft or rough bottoms and by its propensity for tip-over during landing and lift-off from the ocean bottom. We have assumed that the operational requirement for maximum slope is 15 degrees and the platform must operate on both soft sediments as well as hard rock. The stability requirements will be successfully met, if the platform does not slide, tilt or sink during normal drilling operations and the combination of weight and foot print design is sufficient to counter cable loads during lift-off as the ship maintains position within its required watch circle.

The platform stability is determined by the size of its footprint, footprint design, height of the platform lift point, platform weight and location of the center of gravity (c.g.). The stability is increased by:

--Increasing footprint
--Lowering lift point
--Lowering center of gravity
--Penetrating the ocean bottom by the foot structures
--Equally distributing the platform weight to all feet
--Decreasing surface pressure of foot structure on soft ocean sediments
--Using a three leg tripod foot pattern for rough ocean bottoms

The platform weight and height as well as footprint design and size are constrained by the requirement for deployment from an AGOR-23 size vessel, such as the R/V Thompson. The drilling platform must pass through the stern A-frame for deployment and recovery which limits both the footprint size and the platform height. The weight of the platform must be less than the dynamic weight limit for the A-frame as well as the operational load limit for the cable. An additional constraint is placed upon the footprint design by the requirement that the platform frame must be level while drilling on a slope. This requires that the legs to be extendable under command from the surface. Extension of the legs will affect the total platform height and may increase the platform footprint.

Two basic types of legs exist and have been used on seafloor drills. The first type is a vertically telescoping leg. The advantage of this leg type is that it provides stability in rough terrain. The disadvantage of this leg type is a small baseline, which reduces stability as well as an increased platform height if the legs fail to retract upon recovery. The second leg type is a hinged "backhoe" style that is lowered by rotating on a hinge pin. The advantage of this leg type is improved stability in soft sediments and a larger baseline. Its disadvantage is that it has poor stability on rough terrain, is harder to release if it becomes stuck and will also have a larger footprint area if it fails to retract during recovery. The BMS drill used telescoping legs and PROD drill used hinged legs. The solution that PROD used for the problem of stuck extended legs was to provide hydraulic fittings with quick disconnects at the top of the frame. During the recovery process, if the legs fail to retract due to power loss, the platform must be held at the edge of the fantail while a deck mounted HPU is connected to the platform and the leg retract cylinders are actuated. If the weather is rough, connection to the platform hydraulics may be difficult unless provisions are made for restraining the platform swing while it's hanging from the A-frame.

Assuming a ship such as the R/V Thompson, we can estimate the upper limits for the weight and size of the drilling platform as well as the requirement for the station keeping ability of the ship during platform handling operations. Information from the R/V Thompson indicates that the clearance between the A-frame members is 6.25 m, the height of the A-frame is 8.0 m and the load limit for operation of the A-frame is 13,600 kgf (30,000 lbs). Assuming that we have a drilling platform that is well within these constraints would give us a platform that weighs 7000 kgf (in-air), is 4.8 m wide and 5.5 m high. A 7000 kg platform, which is constructed from steel and aluminum, would weigh approximately 5800 kg pounds in water.

The total foot print area and foot design will be determined by the type of bottom upon which the drilling platform is to be placed. For a hard rock location, the foot contact area can be minimized and hard contact points are used to bite into the bottom surface and prevent slippage. In this case the coefficient of friction of the pad to bottom must be greater than the tangent of the slope. For a 15 degree slope, the coefficient of friction must be greater than 0.27. A quick check of coefficient of friction values shows a range of 0.28 to 0.50 for carbon steel upon emery or 0.29 for carbon steel upon sandstone. These numbers suggest that a 15-degree slope is the upper limit, if platform slippage is to be prevented by friction alone and that the footpad design must incorporate spikes that will readily bite into the base material.

For deployment in soft sediments, the footpad surface must have sufficient area to prevent sediment shear failure or plastic sediment flow that results in excessive platform settlement. In addition, the footpads should have a skirt that penetrates the sediment and is large enough to prevent lateral movement. For square or circular footpads, the sediment bearing capacity is approximately 5 times the sediment cohesive strength. A typical value for the cohesive strength of undisturbed ocean clay might be in the range of 50 gm/cm^2. If we apply a safety factor of 3 to the allowable contact pressure, we find that the allowable pad contact pressure is approximately 83 g/cm^2 (1.2 psi). For the case of a 5800 kg drilling platform that is supported by 3 pads, we see that each pad has a loading of 1900 kg and a surface area of 2.3 m^2. If the drilling platform is resting upon a 15 degree incline, a 0.7 reduction factor must be applied to the sediment cohesive strength, which means that the required pad surface area is increased to 3.3 m^2 (per pad). The resistance to lateral motion is based upon the cohesive strength of the sediment. A 5800 kg platform on a 15-degree slope will have 1500 kg of lateral force that must be resisted by the horizontal shear strength of the sediment. A single 3.3 m^2 pad with skirts will have sufficient sediment shear area to exceed the lateral gravity forces at 15 degrees of slope.

The height of the center of gravity above the footpad surface as well as the width of the drilling platform will determine the platform's resistance to tip over from excessive lateral cable loads during recovery. If we use the example of a 4.8 m wide triangular platform and assume that the center of gravity ranges between 0.5 and 1.5 m above the footpads, then we may solve for the maximum allowable scope of the ship for cable tensions, which are equal to the weight of the platform. In this case we find that the platform will remain vertical on a 15-degree slope if the ship remains within a watch circle radius that is 19% of the water depth. For a drilling operation in 1000 meters of water, this means that the ship must remain within a 190-meter watch circle or, for a ship the size of the R/V Thompson, about 2 ship lengths which is easily achievable.

In summary, the stability of a robotic drilling platform will be determined by the design, the drilling location and the ship station keeping capability. The stability is maximized by increasing platform width and keeping the center of gravity low. The pad design will be predicated upon the anticipated usage. A tripod design will provide the maximum stability for a variety of terrain. The bottom type will determine the required pad area. For hard rock locations, the area is small and the pads must bite into the bottom. The deployments slopes should not exceed 15 degrees for all cases but on hard rock, it is quite possible that 15 degrees is too much slope. For soft sediments, pad area must be sufficient to prevent sediment shear or flowing and skirts must be designed to prevent lateral movement.

2.4 Operational Platforms

GOAL: Deployable from current large US AGOR vessels (Thompson Class) without significant modifications – discussion of winch and cable options and weight and height trade-offs

One of the primary constraints on the system will be the weight and height limitations that are imposed by the A-frame or other deployment equipment.

In Table 2, Cable 3 is shown as being the best of the cables listed. The safe working load of this cable is 142 kN (31,900 lbs). This is conveniently close to the 134 kN (30,000 lbs) current safe working load of the A-frame on the R/V Thomas G. Thompson.

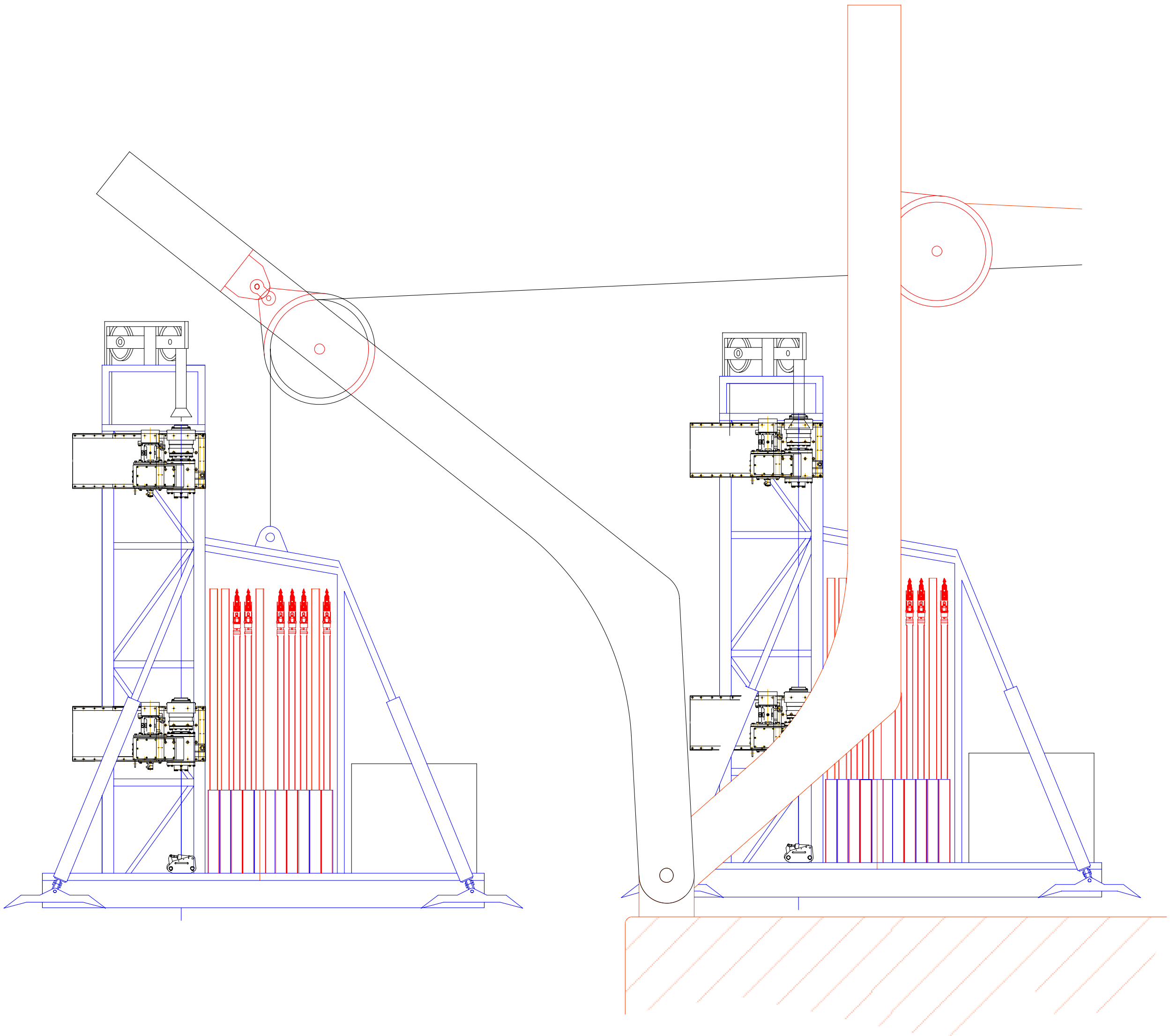

Figure 1 - Conceptual Design for a Robotic Wireline Coring System shown with the R/V Thompson A-Frame

The PROD system has been successfully operated on the R/V Thompson but the increased height of the wireline handling apparatus will add at least a meter to the height. Figure 1 shows a conceptual drawing of a wireline coring system on deck and being deployed on the R/V Thomas G. Thompson. It can be seen that the maximum height of the system may exceed the height of the A-frame/sheave but this can potentially be solved by positioning the system so that high side of the system is outboard of the A-frame. Additional work must be done in this area.

2.5 Drilling Equipment

GOAL: Industry standard tool sizes – specification table and discussion of standard tool sizes

Most of the downhole drilling tools will require little or no modifications. One problem that has been experienced with using standard drilling tools on robotic systems has been that the drill rod threads when threaded together can sometimes be difficult to unthread. With traditional terrestrial and shipboard drilling, it is possible for the operators to use hammers, wrenches, etc. to break threads that are too tight for the rotary motor, chuck, jaws and clamps but this is obviously not possible with remotely controlled systems. Several things have been used to improve the unthreading problem including better lubricants, spacers that prevent the threads from bottoming out, redesign of the thread geometry and plating of the thread surfaces with different metals. It is possible that some redesign of the threads and other parts of the tools may be required but the core barrels, bits and other tools may be used without modification.

This unthreading problem is reduced somewhat with wireline coring because there are fewer thread make/breaks and individual tools are generally only made/broken once. With conventional coring, the drill rods are used up to dozens of times which results in far more make/breaks which wears off any lubricants.

Another critical piece of drilling equipment is the drill head. Standard hydraulic drill heads have been used in water depths to 4000m with some simple modifications that primarily involve adding several ports that allow all cavities that would normally be filled with air to be filled with pressure compensated oil.

2.6 Environmental & Safety

GOAL: Elimination of all oil leaks, use of environment-friendly hydraulic oil

It is strongly recommended that all hydraulic fittings use an o-ring type seal such as Parker Seal-Lok. These are commonly used on ROVs and are much more resistant to vibration, shock and leakage than the more standard flare type fittings – particularly with stainless steel.

Commercial ROVs and shipboard hydraulic equipment are subject to the same strict rules regarding discharge of hydraulic oil and this has led to the development of several types of environment-friendly hydraulic oil that meet the minimum performance requirements for use with complex hydraulic systems. Three types of environmentally acceptable oils are:

1. Hydraulic fluids based on vegetable oils, Type HETG (TG = trigliceride, e.g. rape seed oil)
    a. very good viscocity/termperature characteristics
    b. good corrosion protection
    c. easily bio-degradeable
    d. poor aging characteristics

2. Synthetic hydraulic fluids based on polyglycol, Type HEPG (PG = polyglycol)
    a. very good viscocity/termperature
    b. good lubricity
    c. good corrosion protection
    d. easily soluble in water (need to keep water out of system)
    e. bio-degradeable
    f. good aging characteristics

3. Synthetic hydraulic fluids based on esters, Type HEE (E = ester)
    a. very good viscocity/termperature
    b. very good lubricity
    c. good corrosion protection
    d. easily bio-degradeable
    e. good aging characteristics

There are other hydraulic oils trade names that are advertised as environmentally friendly such as: Oceanwise, BioHydraulic, Naturelle, BioSafe, BioStar, EcoHyd, Envirosyn and others.

Almost any fluid that has acceptable performance for use in complex hydraulic systems will likely leave some sheen on calm water. The Type HEPG fluid advertises easy solubility in water which would minimize sheen but will require more frequent monitoring and possibly changing of the system fluid due to the fact that water is dissolves and not easily removed.

Other means that should be taken to minimize occurrence and impact of leakage of hydraulic oil into the environment are:

- determine the required level of environmental sensitivity of the area of operation with vessel operator, principle investigator, local officials, etc. and design an appropriate environmental mitigation plan
- understand all of the local regulations regarding oil spills
- provide for a containment system on deck that provides a means for capturing, storing, removing and disposing of leaked oil – including when the system is rinsed with fresh water, or if the motors require water spray for cooling
- provide for a system for dealing with accidental spills and have a plan for immediately contacting the appropriate authority and a local contractor for cleaning up a major spill
- clean the system of all oil residue with high pressure, steam and/or detergent prior to installation on the vessel

3.0 Rock Coring

3.1 Conventional Non-Wireline Coring

Conventional rotary rod rock coring uses a drill string that consists of a bit/core barrel and number of pieces of drill rod that are used to advance the bit/core barrel. For a robotic coring system to be a size that is manageable on UNOLS vessels, the overall length of the core barrels and rods will be approximately 3 m (actual core sample is approximately 2.2 m). The coring operation consists of lowering the drill string – consisting of the bit/core barrel and *N* pieces of drill rod – into the hole, collecting the core sample in the core barrel by rotating and lowering the bit/core barrel and advancing the hole depth. When the drill reaches the end of its stroke, the entire drill string is recovered, broken down and the barrels and rod stored in the drill magazine. The process is repeated by building another drill string consisting of a new bit/core barrel and *N+1* rods. This process is repeated until the desired hole depth is reached.

The main advantage of this type of coring is that each of the barrel and rod (collectively referred to as tools) handling actions is simple and easily automated, the results of the actions are easy to monitor and confirm and the whole process is relatively easy to accomplish by remote control. The disadvantage is that the number of tool handling actions involved with making and then breaking the entire drill string for every 2.2 m of advance/sample increases arithmetically – the first sample requires 0 make/breaks, the second sample requires 2, the third sample requires 4, etc. Table 1 below shows the incremental and total number of tool make/breaks for different depths. For example, for a hole depth of 25 m, 21 make/break actions would be required for the next sample (from 30 to 32.2 m) for a total number of 180 make/breaks to that point. At a depth of 75 m, 66 make and break actions would be required for the next sample for a total number of 1120 make/breaks to that point. The marginal time/cost of the samples at 75 m is three times that of the samples at 25 m. Another consideration is that with a remotely controlled drilling operation that involves many handling actions and coring in a non-homogeneous medium that contains voids, inclusions, fractures, etc., there is potential for a jammed drill string, unthreaded down-hole tool, stuck thread, mishandled tool or other effect from a rock discontinuity that will cause a failure of the drilling equipment or coring operation that could range from cessation of the coring operation, loss of the drill string in the hole, etc. As the hole depth advances and the number of tool handling operations increases, the "mean time between failures" will be approached and the likelihood of a failure increases – often with greater consequences, e.g. the loss of the drill string in a deep hole.

Conventional, non-wireline drilling for terrestrial drilling operations, due to the simplicity of the operations and equipment, are generally favored to hole depths of approximately 30 m. Beyond this depth, the law of diminishing returns applies and the sample retrieval per unit of time becomes less cost effective. If other techniques such as wireline coring are available, they would generally be favored. If a remote location or other logistical constraints exist, rod drilling techniques would still be successfully utilized, accepting the decreased efficiency. To date, the only coring techniques that have been applied on the seafloor by robotic systems are variations of conventional coring techniques.

Hole Depth	Rod Incremental Make/Breaks	Rod Total Make/Breaks	Wireline Total Make/Breaks
25	21	120	12
50	44	500	23
75	66	1120	34
100	89	2025	46

Table 3 - Comparison of Tool Handling Operations between Rod and Wireline Coring

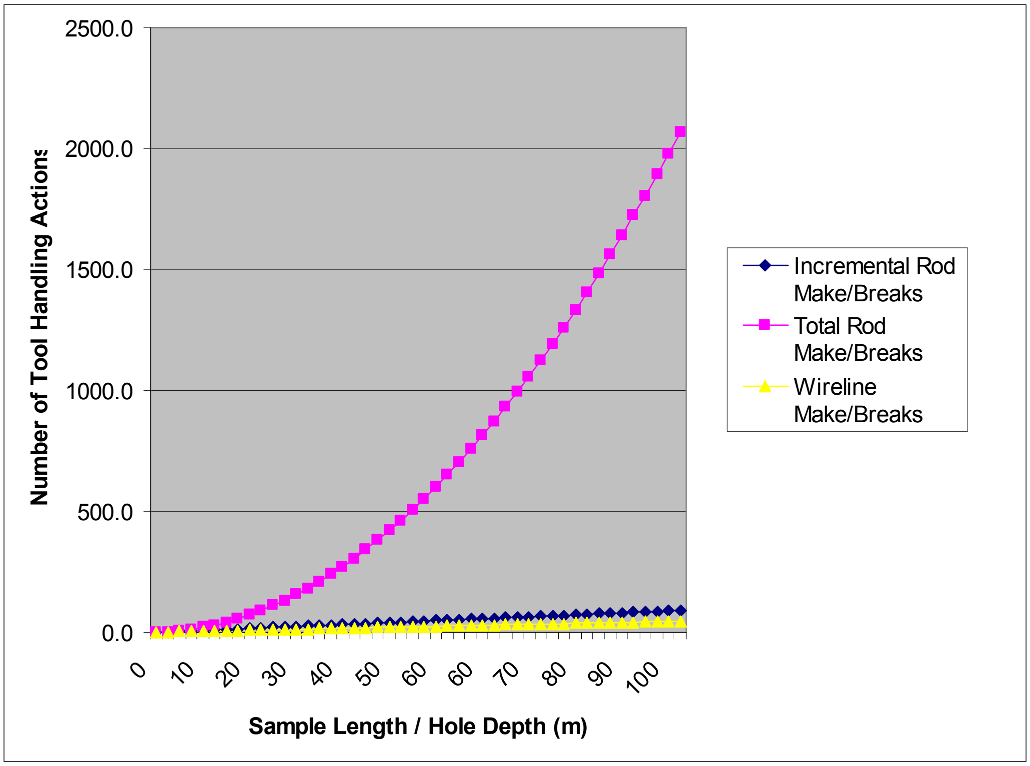

Figure 2 - Tool Handling Actions vs. Hole Depth

3.2 Wireline Coring

Wireline coring is different from rod coring in that the drill string is made up as the core hole is advanced and not broken until the coring operation is complete.

The way this is done as shown in Figure 3 and as follows:

1. A core barrel assembly (inner barrel latched into outer barrel with bit) is taken from the magazine by the tool arms. The drill head is then lowered and the chuck is closed on the top of the barrel.

2. The drill head rotary and flushing water pump are started, the drill head and core barrel are lowered and the first section of core sample is taken.

3. The drill string (consisting only of a single core barrel with sample at this point) is raised off the bottom of the hole, the foot clamp is closed and the drill head is moved out of the way.

4. The wireline sheave is moved into place over the drill string, the overshot is lowered, connected to the inner barrel (with sample) and the inner barrel is raised on the wireline and stored in the magazine.

5. A new inner barrel is removed from the magazine, loaded into the drill head jaws, lowered into the top of the drill string (outer barrel at first and drill rod subsequently) and released so it can drop to the bottom of the drill string.

6. A piece of drill rod is removed from the magazine and loaded into the drill head chuck, the drill rod is screwed into the top of the drill string, water is pumped into the drill string to "wash" the inner barrel to the bottom, the inner barrel latches into place causing a spike in the water pressure.

7. The foot clamp is opened, the drill head rotary and flushing water pump are started, the drill string (now consisting of a core barrel assembly and a drill rod) is lowered to the bottom of the hole, and the second section of core sample is taken.

8. Repeat from #3 to #8 until desired core depth is reached.

9. When the final inner barrel is recovered, the drill rods and outer barrel are recovered from the hole and stored in the magazine.

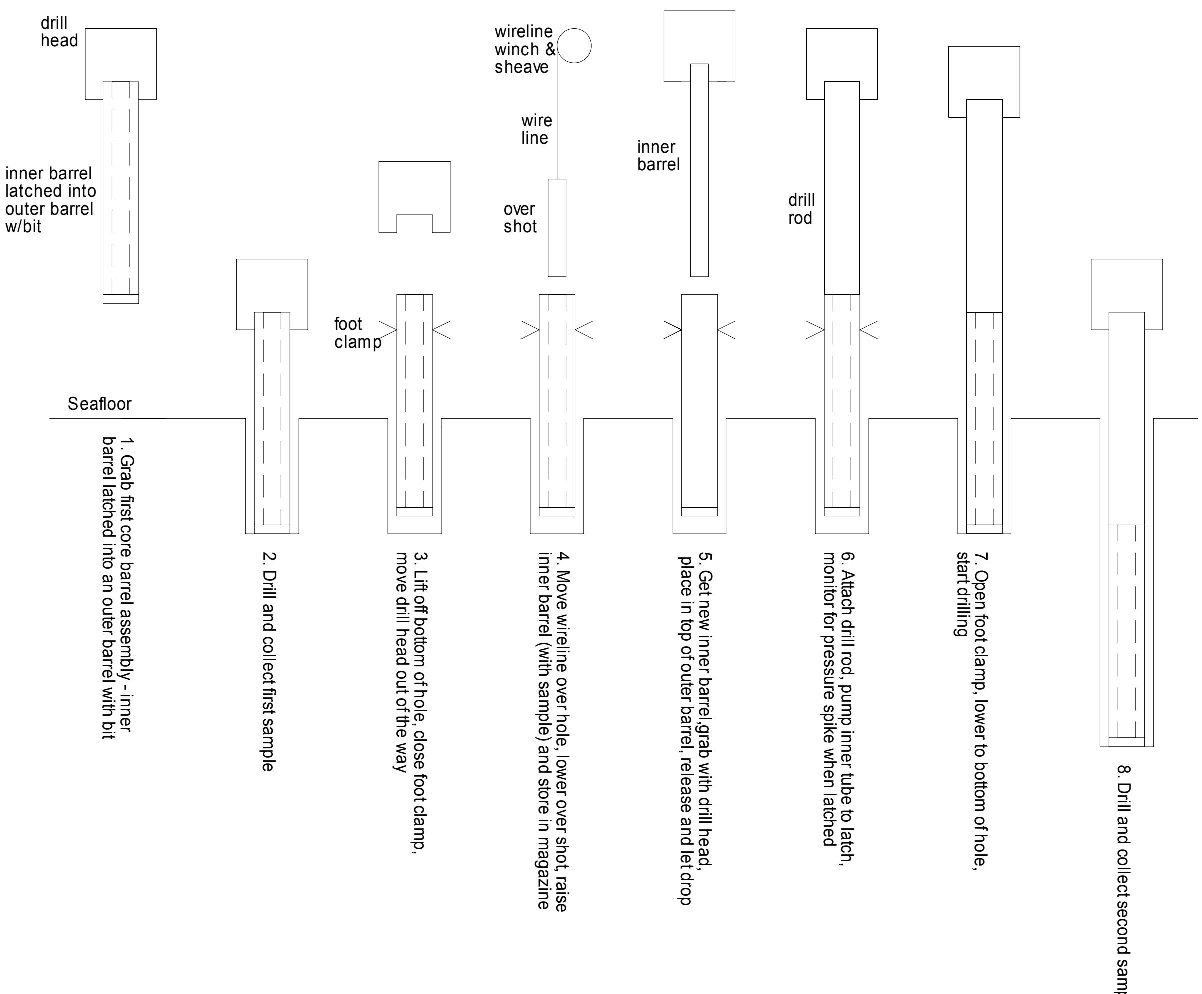

Figure 3 – Wireline Coring Sequence

The different down-hole tools are shown in Figures 4, 5 & 6 and described in detail below. The number in parentheses is the number of each item that would be included in a 100m coring system.

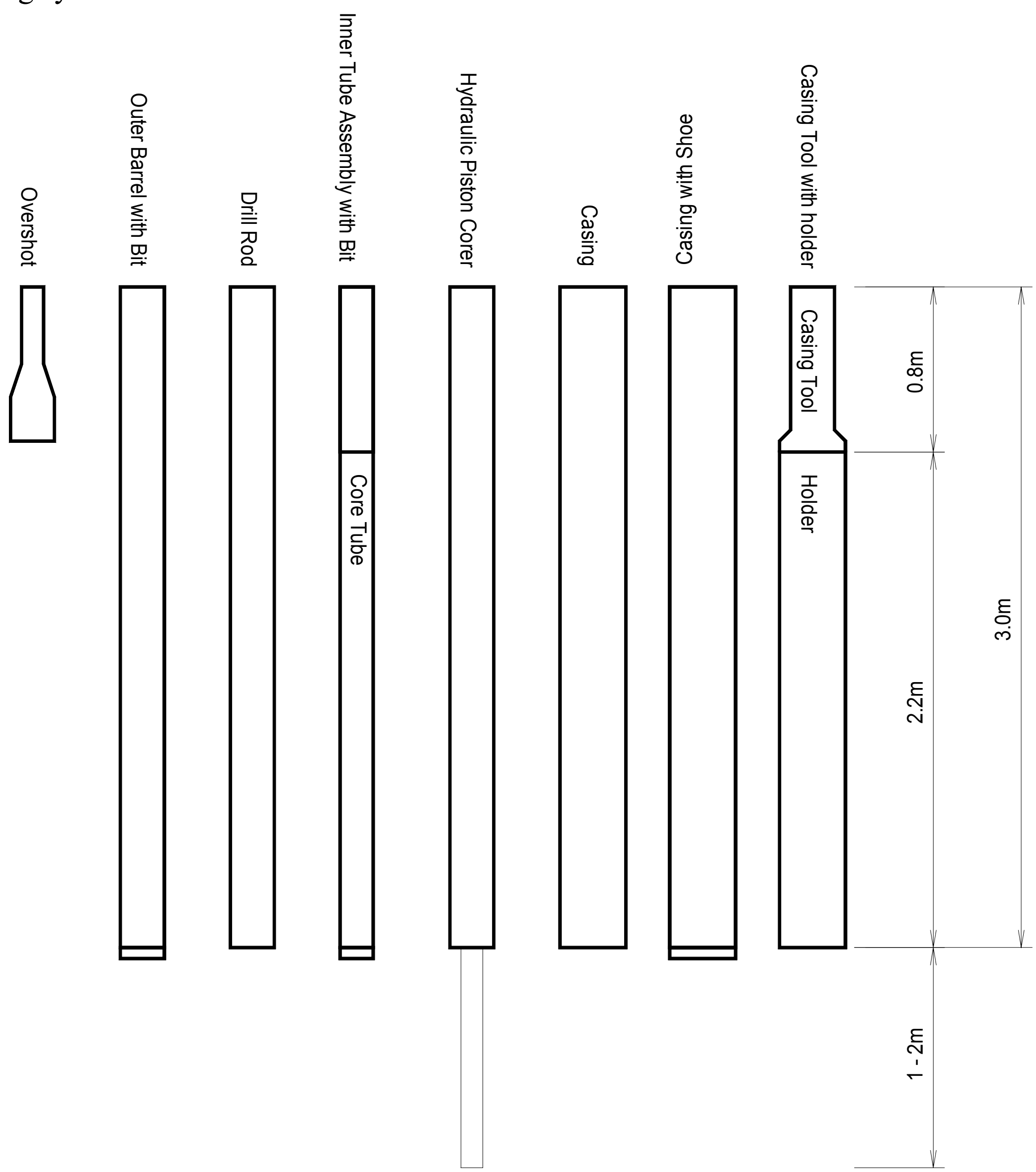

Figure 4 - Wireline Coring Tools

Overshot (1) – The overshot is attached to the end of the wire line and is used to raise and lower inner core barrels in the drill string. An overshot is shown in Figure 7. The lifting dogs (#19 in Fig. 5), hook onto the inner barrel spearhead (#1 in Fig. 7).

Casing Tool with Holder (1) – If drilling through unconsolidated or flowing materials such as sand or mud, it may be necessary to use casing to stabilize the top of the hole. One or more pieces of casing can be used for the portion of the hole that is above consolidated material. In the general case, 3 pieces of casing would be carried which would work with sediment cover to a depth of approximately 8-9 meters. Casing is generally one size larger drill rod that is used for coring – in the general case, HQ rod would be used as casing when coring with NQ rod. The first tool that would be used is the casing tool which is necessary to allow the HQ rod to be used with a NQ chuck. Once the tool casing tool with holder is picked up by the drill head, the holder would be unthreaded and restored in the magazine.

Casing with Shoe (1) – The first piece of casing would have a shoe, or bit. This would be rotated and lowered into the seafloor. When consolidated material is encountered, the shoe would allow cutting into this material to a multiple of 3 m so that whole pieces of casing can be used and lowered out of the way of the foot clamp.

Casing (2) – With the general tool payload, a total of 3 pieces of casing can be used.

Outer Barrel with Bit (1-2) – The outer barrel with bit is the "sharp" end of the drill string and will be continually advanced into the hole. In general only one outer barrel will be used but a second outer barrel may be carried in case of a problem or if a different bit may be required.

Drill Rod (30) – Drill rods are attached to the top of the outer barrel with bit to advance the bit and the hole and would have a nominal length of 3m.

Inner Tube Assembly (45) – The inner tube assembly are lowered empty with the overshot on the wireline through the drill rods (if any), are latched into the inside of the outer barrel with the bit, hold the sample as the coring takes place and are then raised with the overshot/wireline and stored with the sample in the carousel. A "Core Barrel Assembly" consists of an Outer Barrel with Bit and an Inner Barrel and is shown in detail in Figure 6.

Hydraulic Piston Corer (3) – HPCs would be used to collect samples in unconsolidated sediments and are discussed in Section 2.3.

A possible configuration for a tool magazine with 16 slots and sufficient N size wireline tools for coring to 100m depth is shown in Figure 8. The size of the magazine is very approximate – the mechanisms for spring loading and retaining the tools need to be included. The HPC tools are shown out of the magazine because, depending on the type of HPC used, their length after the sample is taken may be too long for storing in the main magazine and another storage rack would be required. If a different type were used, they could be stored in place of the rock core barrels.

The main advantage of wireline coring is the high efficiency of the operation as shown in Table 3 and Figure 2 above. For each section of sample recovered, the only action is adding a length of casing, advancing the casing bit by rotary drilling, removing the bit/barrel from the magazine, lowering the bit/barrel on the wireline, advancing the bit/barrel by rotary coring, recovering the bit/barrel/sample on the wireline and storing the bit/barrel/sample in the magazine. Except for the small additional time required to winch the additional length of wireline up and down, the time required for each section of sample is the same.

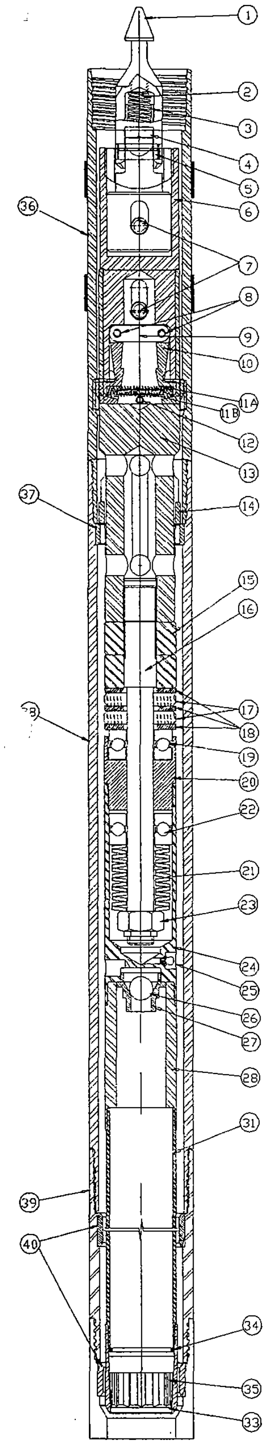

Figure 5 - Wireline Core Barrel

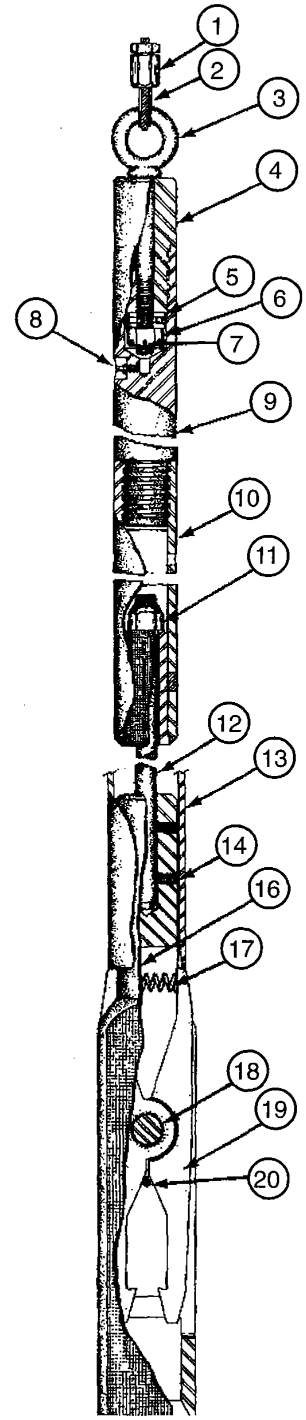

Figure 6 - Wireline Overshot Tool

Figures 7 & 8 below show conceptual views of a seafloor robotic wireline coring system.

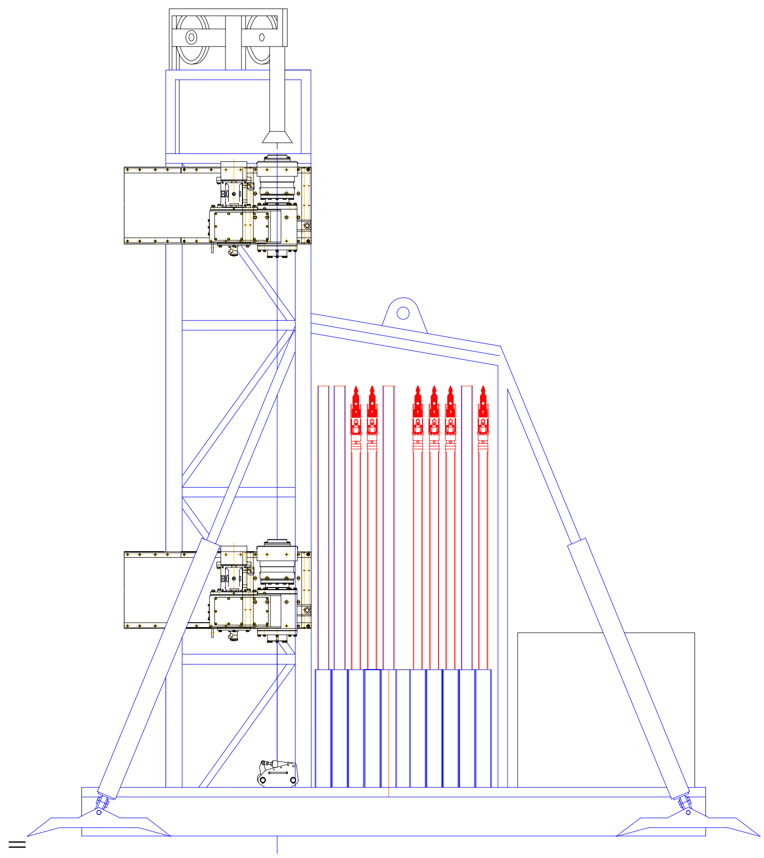

Figure 7 - Profile View of a Conceptual Design of a Robotic Wireline Coring System

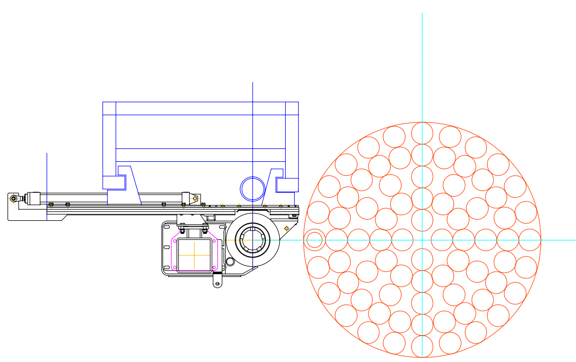

Figure 8 - Plan View of a Conceptual Design of a Robotic Wireline Coring System

Figure 9 below shows a conceptual view of a drill tool magazine layout and contents that would allow wireline sampling to a depth of 100 m with "N" size tools.

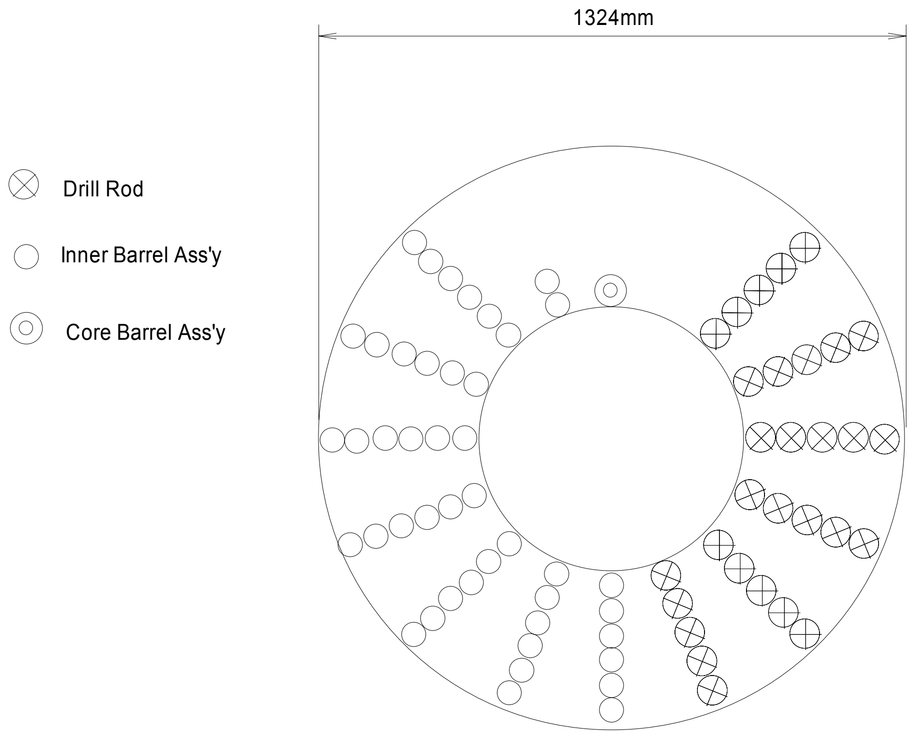

Figure 9 - Possible Magazine Configuration

3.2.1 Contingencies

Mislatch A mislatch is rare but can occur when the inner tube assembly fails to latch into the outer barrel. This could be caused by rubble in the outer tube due either to sampled material that falls out of the previous inner barrel or to surrounding material that is sucked in.

In terrestrial and shipboard coring operations, verification of successful latch-in can be done by listening for the latch sound or by feeling the wire for the latch. This is obviously not possible with a remotely controlled system. There have been attempts at detecting this acoustically but they have not been successful. The most reliable method of verifying latch-in is by using a system which generates a spike in the pump pressure as the inner barrel is pumped and eventually latched into position. This pressure spike can be detected (either manually or automatically) to confirm that latch in has occurred.

Stuck Tube A stuck tube is another rare occurrence that happens when a core barrel gets wedged into the inside of the outer barrel or rod by rubble or other material while lowering or raising. This generally means that the hole needs to be abandoned. Because the wireline is in the hole and unable to be disconnected from the core barrel, it is not possible to recover the drill rod and outer barrel that is in the hole. Even of the wire were cut, it would still prevent reliable disassembly of the drill string. It may be possible to recover the entire system by picking up the drill frame and all of the downhole tools still in the deployed position – depending on how far the string is in the seabed. This would present a difficult recovery on the surface that may require personnel manually removing rod and tools with the drill over-the-side or from a small boat.

Alternatively, a method for releasing the drill rods and cutting the wireline cable should be implemented so that the tools can be abandoned and the drill vehicle to be recovered.

Legs Stuck in Extended Position It is possible that the legs on the drill frame could get stuck in the extended position due to an electrical, hydraulic or mechanical failure which would make a normal recovery difficult or impossible. In this case, some method must be determined for either retracting the legs or recovering or securing the drill or retracting the legs manually. The PROD drill had quick disconnect fittings at the top of the frame that could be connected (in good weather) to an on-board hydraulic power unit (HPU) that would allow the leg cylinders to be powered and retracted by the HPU.

4.0 Specialty Coring, Sampling and Measuring

Gas hydrate – Gas hydrate coring would require the development of pressurized core barrels so that the sample can be preserved from sublimating. This has been researched and it appears to be possible to design a method of collecting and preserving cores with a diameter of 25-30mm. There is an existing tool that has been developed for sampling radioactive cores that may be easily adapted that can take a 430mm long sample. It has been determined that the gas hydrates are relatively stable if stored for moderate time periods at ambient pressure at a temperature of -5°C so a possible alternative to a pressurized core barrel would be a method of refrigerating the sample.

Water Sampling – There is significant interest in collecting water samples from core or drill holes. It would be possible to design passive or active sampling or measurement systems that could be left behind and recovered later.

X-Ray – There are existing downhole tools for doing X-ray sediment characterization that may be adaptable for a coring system.

General Purpose Data Logger – For many of the down hole measurements that are envisioned, it would be very difficult to have a direct wire connection to the drill electronics so it will be necessary to use a battery powered data logger in the measurement tools. One application of this is described in the Section 7.0, Oriented Cores.

Clean Sampling – If it is necessary to develop a method for clean coring, it will be difficult to work without any lubricants. Many commonly used lubricants contain metals such as copper, zinc or molybdenum and these could be replaced with special lubricants with more benign materials or materials that would be traceable in the sample and corrected for.

Other measurements include electrical resistivity for density/fluid content, cone penetrometer testing for soil shear strengths and pore pressure.

5.0 Handling

5.1 Vessel

The primary requirements for a vessel would be the ability to deploy and recover the system, and adequate deck space for the system components – winch, vans, etc. Other requirements include sea-keeping ability, lab space, berthing, etc.

Standard methods of handling over-the-side equipment such as a large coring system would generally either involve an A-frame or a crane. The R/V Thompson has an A-frame (shown with a concept coring system in Fig. 1) with a vertical clearance of 8.0 m when vertical and a safe working load of 30 tons. The R/V Knorr uses a deck crane, with a similar 30 ton capacity that can be used to deploy and recover the system. During operation, the crane rests in a support crutch to support the weight of the system.

5.2 Cable

A critical piece of handling equipment is the opto-electro-mechanical cable. The cable used will dictate the maximum system weight, electrical power budget and data capacity.

Parameter	Units	Steel									aramid				
Cable Diameter	mm	17.3	23.7	26.7	29.7	33.1	33.1	36.3	45.6	65.4	27.3	30.5	38.0	38.1	43.2
Cable Weight (in H_2O)	kg/m	0.905	1.75	1.91	2.6	2.28	3.39	2.84	4.39	8.37	0.276	0.598	0.438	0.746	1.01
Cable Breaking Strength	kN	205	325	320	560	413	640	449	645	1014	222	271	449	498	600
Cable Working Load	kN	62.3	75.6	78	142	102	151	112	161	254	31	40	62	71	85
Cable Working Load	kgf	6357	7714	7959	14490	10408	15408	11454	16454	25867	3163	4082	6327	7259	8673
Cable Safety Factor		3.3	4.3	4.1	3.9	4.0	4.2	*4.0*	*4.0*	*4.0*	7.2	6.8	7.2	*7.0*	7.1
Power Conductors		3	3	3	7	3	3	13	15	34	3	3	9	6	6
Signal Conductors		0	0	4	7	0	0	4	3	0	0	0	9	3	4
Single Mode Fibers		3	3	4	8	3	3	6	9	4	3	3	3	6	8

Table 4 - Parameters of existing commercial cables

5.2.1 System Weight

The cable working load will determine many of the operational capabilities and constraints on the system. The cable load will generally be greatest at the overboarding sheave and will be equal to the sum of the following:

Cable weight (function of water depth)
Drill Vehicle weight
Drill tool weight (function of tool size and sampling depth)
Sample weight (function of tool size and sampling depth)
Dynamic loading from ship heave
Pull out force (suction on drill base in sediment)

Some of these weights are fixed (vehicle weight) and some of these are a function of water or sampling depth (cable, sample and drill tool weight).

5.2.2 Power

The desired maximum operating depth will obviously determine the total length of the cable. The maximum length of the cable will also determine the maximum amount of power that can be transmitted to the drill in all water depths.

The copper conductors in the cable must be able to supply enough power to the drill to allow the voltage to be stable throughout a variety of load conditions. A long power transmission cable is subject to a voltage drop/loss that is equal to the resistance of the cable multiplied by the current in the cable (I x R). For example, if the resistance of a long cable is 25 ohms and the current through the cable is 20 A, the voltage drop would be 500 V. For this reason, it is important to keep the cable current as low as possible. For a given load power, the current decreases as the source voltage increases. For this reason, power transmission is optimized by operating at the highest practical voltage. Several standard cables, connectors and other components are designed for operation at 3000 V and this is a commonly used operating voltage for ROVs and similar equipment.

When analyzing the power load, it is important to anticipate all the possible load conditions – particularly the maximum, minimum and surge loads – so that the subsea voltage (equal to surface voltage minus the cable voltage drop) does not surge high enough to damage equipment or low enough that the motors will stall (approximately 60-75% of nominal voltage).

Number of Conductors – The number of conductors in the cable will need to be specified. The cables listed in Table 4 contain a variety of numbers of both power and signal conductors. Typically the power conductors are larger gauge with a voltage rating of 2000-3000V and the signal conductors are smaller with a voltage rating of 600-1200V. The number of conductors will determine the number of circuits in the cable and how many subsystems will be powered by each circuit.

With 3 power conductors, there will be a single 3 phase electrical circuit in the cable and it would be necessary to have motor starters in the vehicle electronics to allow the instrumentation to be powered at all times with control for the motors located in the vehicle. It would also be necessary to have the instrumentation power on the same circuit as the motors that would be subject to noise, wide ranges of voltage, etc. With 6 power conductors, it would be possible to have one or two high power 3 phase electrical circuits for the electric motor(s).

Smaller signal conductors could be used for lower power transmission for the instrumentation. With these smaller conductors, the instrumentation can be powered separately and the motors can have dedicated circuits with the starters on the surface, resulting in simpler vehicle electronics and isolated motor and instrumentation circuits.

Table 10 below shows the cable losses and power transmission capability of a cable with 6 power conductors, each with a resistance of 6.9 Ω/km and a 50 HP motor operating at 3000 VAC. During motor start, the nominal 3000 VAC drops to 2236 VAC which is the worst case condition.

	Units	Motor Start	10% Load	50% Load	Full Load	
Source	watts	230134	4676	23371	46202	Load+Cable Loss
V1 - Voltage Input	volts	480	480	480	480	
I1 - Current Input	amps	278.1	5.6	28.1	55.6	I2*step up ratio
Step Up Ratio		6.25	6.25	6.25	6.25	
V2 - Surface High Voltage	volts	3000	3000	3000	3000	V1 * Step Up Ratio
I2 - High Voltage Current	amps	44.5	0.9	4.5	8.9	I2=I3
L - Cable Length	km	5.0	5.0	5.0	5.0	
R - Resistance	Ω/km	6.9	6.9	6.9	6.9	
N - Conductors/leg		2	2	2	2	
RC - Cable Resistance	Ω	17.3	17.3	17.3	17.3	L * R / N
VD - Voltage Drop	volts	768	16	78	154	I3 * RC ohms
V3 - Subsurface High Voltage	volts	2232	2984	2922	2846	V2 - VD
I3 - High Voltage Current	amps	44.5	0.9	4.5	8.9	I4/step down ratio
Step Down Ratio		1.00	1.00	1.00	1.00	step down ratio
V4 - Voltage Output	volts	2232	2984	2922	2846	V3/step down ratio
I4 - Current Output	amps	44.5	0.9	4.5	8.9	
Load	watts	172063	4652	22778	43879	sqrt(3)*V*A
Load Efficiency	%	85%	85%	85%	85%	
Load Horsepower	HP	196	5	26	50	Load/Source
Cable Efficiency	%	75%	99%	97%	95%	Load/(Load+Cable Load)

Table 5 – Power Calculations for Seafloor Drilling System

5.2.3 Data

It is assumed that the cable will contain optical fibers for data and video telemetry. One single mode fiber will likely be sufficient for the data transmission requirements but the cost of adding additional fibers for spares or possible future use is minimal and recommended.

5.3 Winch

The winch that would be required for this system would be one of two basic types – single drum or traction.

A single drum winch is smaller, lighter, less expensive and easier to transport, install, etc. The major drawback is that the cable is stored on the winch drum under tension. This puts additional stress on the cable which can result in a shorter life expectancy.

A traction winch uses a traction assembly that consists of 6 or so large grooved wheels that provide the traction drive to maintain tension on the cable. In this way, the cable is stored on the winch drum with very low tension and low stress on the cable. The traction wheels need to be of a sufficient size that they do not put the cable under undue bending - especially since the cable will pass over these wheels 12 times during deployment and recovery. A traction winch has a cost of about 150% of a single drum winch and is much larger. It would still be possible for the winch to ship in standard containers but it might require 2 containers. If a cable with a synthetic strength member (kevlar or similar) the larger diameter of the cable will result in a significantly more expensive winch.

Heave compensation – An active heave compensation may be considered but to operate with a system of this size with the required umbilical cable it would be a large, complex and expensive system.

Slip Rings - The winch/cable system will require a set of electro-optical slip rings. The slip rings will need to have an electrical circuit for every independent conductor and one optical circuit for every fiber that is used.

5.4 Vans

There is the potential to have several types of vans for shipping and operating the drill. These would likely be converted 20 or 40 foot ISO shipping containers and include the following: control van, workshop van, sample processing van, and misc. storage and shipping van(s).

The control van would have insulated walls, heating/air-conditioning, power panel with power conditioning, work benches & desks, etc. The workshop van could include a power panel, work bench, lights and room for shipping and storage. The sample processing van would contain any special processing equipment that was required for the specific project. The storage and shipping vans would be included as necessary for shipping and storing the drill tools, spare parts, etc. If necessary a refrigerated van may be included for core storage.

6.0 System Design

6.1 System Capabilities

6.1.1 Instrumentation

Video and Data Telemetry Video and data telemetry systems have been developed for the ROV and other industries that have all the capabilities that are required by a robotic seafloor coring system. These systems are typically able to accommodate 8 or more video channels, stereo audio for each video channel (useable for acoustic or other analog signals), multiple data channels that include RS-232/RS-485, Ethernet, etc. and other status channels. These systems can easily transmit and receive over up to 10+ km on a single mode fiber using wave division multiplexing which sums both the uplink and downlink optical signals on a single fiber. This allows the use of a simpler and less expensive single channel fiber optic rotary joint in the slip ring assembly.

Control and Software Several different software systems have been used for the previous drilling systems including "C", LabView and high level industrial SCADA (supervisory control and data acquisition) systems. All of these systems have advantages and disadvantages. Considerations for selecting a software environment include performance (speed), flexibility, ease of modification by field personnel, availability of skilled programmers, compatibility with other systems maintained by the same personnel, etc.

The software should be designed in a way that shows all of the pertinent data in graphical and/or alpha-numeric format on multiple windows. Different data displays and controls will be needed during different phases of the coring operation and there should also be display windows for specific functions such as magazine set-up, camera control (camera power, pan & tilt and light control), landing (thruster, positioning, altimeter, etc.), etc.

There are a number of functions that would best be actuated or controlled by hardware switches, joysticks, buttons, etc. The same is true of several of the important data displays such as voltage current, etc.

Video A low light camera selected and located for good viewing of the seafloor will greatly assist the site selection and landing process. This camera would ideally have a viewing range of up to 10 m in clear water to allow for a wide area view with the vehicle well clear of the bottom in the presence of heave. A high powered arc light would improve the camera performance and allow good viewing at a higher altitude. If a positioning system (LBL or USBL) is available, the vehicle could be maneuvered around the sample site using the thrusters and the seafloor imagery could be stitched into a photo mosaic of the area surrounding the sample site.

Black & white cameras with simple incandescent lights would be placed that would allow viewing of the foot clamp, seafloor hole entry, wireline winch and mechanism and several other critical locations. There should also be 1-2 zoom color cameras with lights mounted on pan & tilt units that would allow viewing and inspection of different parts of the vehicle.

Sensors A number of analog and digital sensors will be required to monitor the position, status, etc. of several components on the drill vehicle.

Pressure Sensors – A number of absolute and differential pressure sensors will be provided that will allow calculation of important parameters. These include ambient pressure (depth), rotary pressure (torque), drill head drive (bit weight) and flushing water pressure (can indicate blockage or voids).

Proximity Sensors – A number of magnetic proximity sensors would be used to indicate the position and status of critical components. These include position of all hydraulic cylinders (indicates position of arms and whether jaws are open or closed), magazine position, etc.

Displacement Transducers – Linear displacement transducers indicate positions of components that have variable positions. These include the drill head height, hydraulic reservoir level, leg extension, etc.

Acoustic Transducer – In addition to the video and graphical and alpha-numeric data displays, it has been found that another valuable way of getting feedback from the coring process is with an acoustic transducer. With the transducer, it is possible to hear when pumps start, when cylinders reach end of stroke, when jaws open and close and whether the coring is running smoothly or not.

6.1.2 Navigation and Positioning

Positioning and Maneuvering – A standard acoustic transponder could be mounted on the vehicle to allow positioning by the surface vessel by long baseline (LBL) or ultra short baseline (USBL) acoustic positioning systems. If higher accuracy relative positioning were required – for performing a sonar, seismic, video or photo survey of the site – Doppler velocity and/or inertial positioning sensors could be added. Joystick (or computer) controlled thrusters should be included to allow maneuvering of the vehicle. Due to the large weight of the vehicle, the maneuvering speed and distance will be limited but will allow selection of a coring site that either is desirable scientifically or is appropriate with regard to slope, roughness, boulders, etc.

6.2 System Operation

Vessel Requirements – The primary vessel requirements are deck space and launch/recovery capability. The deck space requirements include space for the umbilical winch far enough forward to allow an acceptable fleet angle for the cable, space for several ISO containers for operations and storage and space for the vehicle storage, maintenance and servicing.

The launch and recovery requirements are likely to be the most critical. The two primary methods of launching and recovering similar vehicles is by A-frame and by crane.

Cable Catenary Management – Umbilical cables under tension can store a large amount of potential energy in the form of cable torque. When the tension is removed (as when the drill vehicle is set on the seafloor) this potential energy can be released suddenly and cause kinks or hockles in the cable which could damage the cable and result in lost time to repair the cable or possible loss of the vehicle. A technique that has been very successful in controlling this is shown in Figure 11. With this technique, a number of floats are attached to the cable 50-100 m above the vehicle. These floats will maintain some tension on the cable so that the hockles do not occur. A pinger on sliders can then be put on the cable so that the height of the lower loop of the cable can be monitored. The position of the vessel on the surface is then not as critical and the station keeping requirements are reduced. The pinger height can be controlled by paying cable in and out. For recovery, it is necessary that the vessel maintains position directly over the drill when lifting off the bottom so that it is not pulled over on its side.

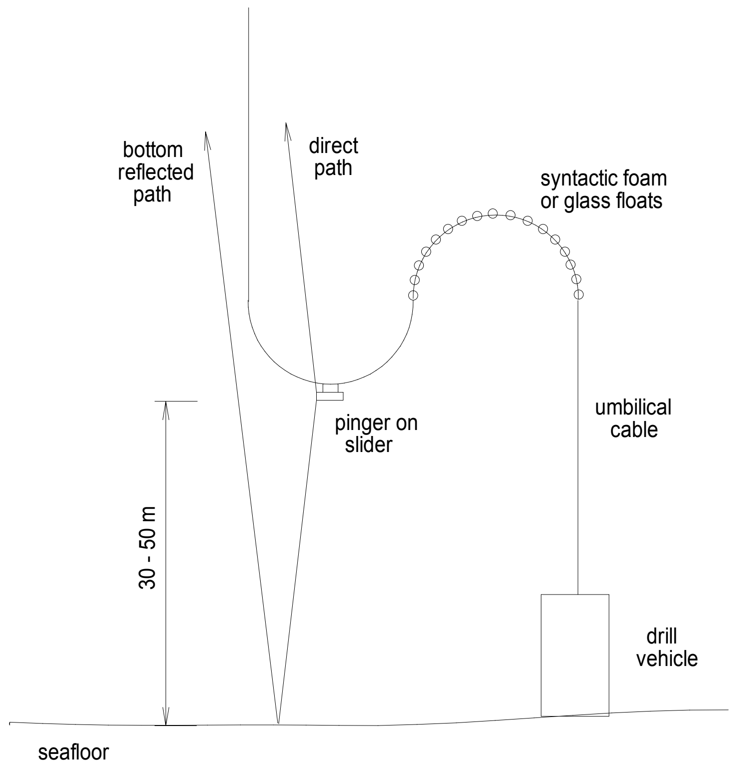

Figure 10 - Umbilical Catenary Management

Dynamic Positioning – If the cable catenary management system described above is used, dynamic positioning should not be required.

7.0 Advanced Features

Blowout prevention – Blowouts caused by drilling into sediments that contain pressurized gas is probably not much of a problem but is should be considered. Blowouts are a major concern with drill ship operations due to the safety considerations of the personnel on-board. With an unmanned, riserless seafloor mounted drill, the only risk is to the drill equipment.

Oriented Cores – There are several challenges with acquiring oriented cores.

The first requirement is to determine the absolute orientation of the drill frame relative to true north – the frame heading. Fluxgate compasses are available and relatively inexpensive ($1000) but are only accurate to a few degrees. The accuracy is degraded by the large mass of steel present in the drill frame, the moving steel parts which make calibration difficult, ferrous components in the electronics (transformers, etc.) and ferrous geological formations. For these reasons, a fluxgate compass is generally not adequate for orienting cores with an accuracy of better that 5-10°.

A more accurate way of measuring the drill frame orientation is with a north-seeking gyrocompass. These sensors are available but fairly expensive, approximately $80-100k. A less expensive alternative to the expensive north-seeking gyro compass that has been considered is the use of a fiber optic gyro that measures heading change and rate of change but not the absolute heading. It would be necessary to log the heading of the frame while it was on board the ship prior to deployment, monitor the relative heading difference while on the seafloor and then log the heading after the drill is recovered. If the drift is sufficiently small and can be corrected in post-processing, this technique could work.

The other requirement for oriented cores is to be able to orient the core to the drill frame. For short, single barrel cores, this can be done by fixing the core liner to the platform. This will insure that the orientation of the core is fixed relative to the platform. This could be done with either rotary diamond rock coring or push sediment coring.

For longer cores, where multiple rods or core barrels must be used, orienting cores is more difficult. One potential technique would be to install a data logger with a small gyro rate sensor in the core barrel. The gyro/data logger would record the rate of any rotation and store it as a function of time. There would be some drift but the drift would only be critical over the few minutes of the coring with that barrel because the drift during other times could be corrected by the frame compass – before and after the core was collected. Once coring starts, the inner barrel (and data logger/gyro) would be held by the sample and would not rotate but the core barrel would be rotated as it is lowered to the bottom of the hole so the gyro would need to be able to measure rate changes (to calculate the relative orientation) up to the expected rotation rate. There is at least one small, reasonably priced (a few $100) gyro that has acceptable accuracy up to a rotation of 573°/sec which translates to 95 rpm. Some care would need to be taken to make sure that this rotation rate was not exceeded.

Re-entry capability - For applications where hole re-entry is desired, it would be possible to mount a guide base to the underside of the drill vehicle. The base could be connected by latches that could be released by the hydraulic system and later reconnected for recovery of the base, if required. The drill feet would fit into the guide base and index and align the drill head to the base so that tools could be inserted into an existing hole, instruments retrieved, etc.

Downhole logging (i.e. temperature, pressure, electric, velocity etc.) – A small data logger housed in a pressure case and mounted in the upper section of the core barrel could have a general purpose I/O that would be capable of controlling, monitoring and logging a wide variety of devices and signals. Due to the difficulty of a direct wire connection between the logger and the vehicle electronics, the logger may need to be totally autonomous. It is possible that there could be an acoustic link to trigger, control or communicate with sensors.

8.0 Operation

A team of trained personnel will need to be involved with the drill system for operation in the field and for maintaining and enhancing the system and in the shop.

For offshore operations, it would be necessary to have hydraulic and electronic engineers/ technicians that are very familiar with all aspects of the system and able to troubleshoot and repair any field repairable problems that might occur. During the early operations, and possibly after that, it would be necessary to have a software engineer who is similarly familiar with the system and capable of modifying the software as required. It will also be necessary to have 2 shift leaders that are familiar with the specifics of the system operation as well as drilling/coring in general.

For around-the-clock operations a recommended crew would, at a minimum include a party chief and 2 watches of 3 persons for a total of 7. This crew size would allow 2 persons to operate the system and 1 person to fill in, work on samples, service drill tools from a previous deployment or prepare tools for the next. For sustained, around the clock operation, another 2 personnel would be recommended for servicing and preparing drill tools and simple sample processing. Additional crew would be required for more sophisticated sample processing.

9.0 Budget and Schedule

An estimated budget is shown in Appendix 1. The total budget – including design, construction and shop, shallow water barge and deep water trials is estimated at $2.8M. The estimated time for design, construction and testing estimated at 12 months.

10.0 Conclusions and Recommendations

The overall conclusion of this study is that a seafloor robotic wireline drill is technically feasible. The development of a drill of this type is evolutionary in many respects (basic coring, hydraulics, sensors, fiber optic telemetry, etc.) and revolutionary in others (remote wireline coring).

Construction of smaller, non-wireline robotic coring systems would have a low risk and could proceed with the existing technology.

Development of a robotic wireline coring system would benefit from using a staged approach where a non-submersible prototype wireline system would be built for testing and development by assembling only the components and sub-systems required to develop and test the wireline tools, handling techniques, software algorithms, etc. This test system could be used for shop testing and mounted on a truck for land testing to allow use of the system in a variety of formations at a relatively low cost. Remote operation could be simulated by the use of inexpensive video cameras and an appropriate suite of sensors and the necessary control and monitoring software.

The approximate cost of developing this prototype robotic wireline coring system is estimated to be $750k. It is estimated that approximately 75% of the labor, software and hardware developed in this effort would directly apply to (and reduce the eventual cost of) the development of the full deep water system.

It is recommended that design, construction and testing of this prototype robotic wireline coring system take place as a first phase of the development of the full seafloor robotic wireline coring capability.

11.0 References

1. Report from a Workshop: Requirements for a Robotic Underwater Drills in U.S. Marine Geologic Research, 3-4 Nov 2000, Texas A&M University.

2. Discussion with Dave Robinson of Boart Longyear in Salt Lake City, UT.

3. Feasibility Assessment of a Deep Ocean Rock Coring Drill, NSF SBIR Contract OCE-8361067, Williamson & Associates, Inc., 1983.

Appendix 1 - Estimated Design and Construction Budget

Description	Budget
	k$
Surface Support	
Control Van	25
Workshop Van	10
Storage Van	5
Surface System	50
Control Console	
Power System	
Handling Equipment	550
winch	
cable	
slip ring	
sheave	
cable floats	
cable termination	
pinger	
Drill Frame	45
frame	
magazine	
Drill Electric Motor	25
starters	
Hydraulics	130
pump	
manifolds	
reservoir	
hoses, fittings	
mud pump	
thrusters	
press compensators	
Electronics	90
Telemetry System	
Control System	
Software	
Video & Lights	
pan & tilt	
DC power	
Sensors	55
proximity	
hall effect	
altimeter	
core depth	
pressure	
atitude	

Description	Budget
	k$
Positioning	115
transponder	
gyro compass	
doppler velocity	
Housings	75
internal racks	
cables & connectors	
Sub-Surface Transformer	10
transformer	
housing	
Coring System	170
drill head	
feed mechanism	
wireline	
winch	
clamps, arms	
swivel	
misc	
Coring Tools	60
Casing	
Rods	
Core Barrels	
Bits	
overshot	
Hydraulic piston corer	50
Oriented Core Logger	50
Labor	1250
Design	
Assembly	
Shop Testing	
Shallow Water Testing	
Deep Water Testing	
Total	2765