SCIENTIFIC AND ENVIRONMENTAL DATA COLLECTION with AUTONOMOUS UNDERWATER VEHICLES

Sponsored by

MIT Sea Grant College Program's

Marine Industry Collegium and

C.S. Draper Laboratories

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Scientific and Environmental Data Collection with Autonomous Underwater Vehicles

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Introduction

Although the ocean covers more than 70 percent of the earth's total surface area, our understanding of the physical, chemical, geophysical and biological processes that take place in the ocean is limited. This limited understanding is due in part to the "harshness" of this environment, which limits our access to it. Presently, access to the ocean and its secrets is accomplished through the use of stationary, moored instrumentation; research vessels; manned underwater vehicles; satellites (remote sensing); and remotely operated vehicles. These instruments, while providing a wealth of information, do not meet all the needs of today's researchers.

The purpose of this workshop is to explore the potential for autonomous underwater vehicles (AUVs) to contribute to scientific and environmental data collection. The speakers at this workshop are primarily scientists and engineers with specific data acquisition needs. By bringing these investigators together with members of the AUV community, it is hoped that previously untapped synergies can be identified for future collaboration.

From the perspective of the potential user community, AUVs represent a new and largely unproven technology. While there is general interest in their potential for dramatically reducing the cost of scientific exploration in the ocean, there is also a concern that the technologies required are advanced and remain developmental. Therefore, a process is needed is to promote the transfer of AUV technology from the laboratory to the field. To reach that desirable goal, the group assembled for this workshop must answer two important questions. They are:

1) What are significant scientific and environmental data needs for which current AUV technology represents either the only or the most cost effective solution?
2) What are the key technologies that will enable these new missions?

Answers to these two questions will provide valuable information for vehicle development groups to plan AUV development programs that are truly relevant to the needs of the science community.

Since the mid-seventies, the MIT Sea Grant College Program has supported underwater vehicle research. In conjunction with this research support, MIT Sea Grant has provided a forum for the transfer of research findings to the marine community through its Marine Industry Collegium Program. A complete listing of Collegium workshops and conferences in underwater vehicle technology is provided on the following page.

MIT Sea Grant is committed to the continued support of underwater-vehicle technology developments and their broad applications within the marine community. We encourage your active participation during this workshop to define future missions for this technology, and hope that you will have the opportunity to join us again, either through our research program or at a future Collegium workshop.

James C. Bellingham
Research Engineer
MIT Sea Grant Underwater Vehicles Laboratory

John Moore Jr.
Manager
MIT Sea Grant Marine Industry Collegium

MIT Sea Grant Marine Industry Collegium Workshops and Symposiums in Underwater Vehicle Technology

Workshop Title	Date Held
Telemanipulators for Undersea Tasks	2/19/76
Untethered Robot Submersible Instrumentation Systems	6/14/76
Teleoperators Under the Sea	10/24/78
Some Federally Sponsored Research Programs for Unmanned Underwater Vehicles	11/1-2/79
Advances in Telemanipulators for Undersea Tasks	12/2/80
MIT Underwater Vehicle Research: Recent Advances and Future Programs	12/5-6/83
MIT Underwater Technology Research: Telemanipulator Developments	3/7/85
Undersea Teleoperators and Autonomous Underwater Vehicles (Sea Grant Lecture)	10/22-23/86
Some Technologies for Autonomous Underwater Vehicle Systems	11/17/89
Power Systems for Small Underwater Vehicles	10/5-6/88
Small Underwater Vehicle Design: Motors and Propulsors	9/4-5/89
Sensor and Navigational Issues for Unmanned Underwater Vehicles	1/9-10/91
Scientific and Environmental Data Collection with Autonomous Underwater Vehicles	3/3-4/92

Scientific and Environmental Data Collection with Autonomous Underwater Vehicles

MARCH 3rd

8:00-8:45	REGISTRATION
8:45-9:00	Welcome *John Moore Jr., MIT Sea Grant* *Jim G. Bellingham, MIT Sea Grant*
9:00-9:45	Keynote Speaker *Sylvia Earle, formerly NOAA Chief Scientist*
9:45-10:30	Capabilities of Autonomous Underwater Vehicles *Jim G. Bellingham, Workshop Chairman, MIT Sea Grant*
10:30-10:50	BREAK
10:50-11:35	Capabilities and Limitations of Bio-Optical Moorings *John Marra, Lamont Doherty Geological Observatory*
11:35-12:20	Use of AUVs for Long-Term Ecosystem Studies *J. Frederick Grassle, Rutgers University*
12:20-1:00	LUNCH (provided)
1:00-1:45	Large-Scale Circulation Studies with Multiple AUVs *Michael Triantafyllou, MIT, Dept. of Ocean Engineering*
1:45-2:30	Physics of Hydrothermal Vents *Terrence M. Joyce, Woods Hole Oceanographic Institute*
2:30-3:50	BREAK
3:50-4:35	The Role of AUVs and Video for Studies of Benthic Megafuana *Peter Auster, National Undersea Research Program*
4:35-5:10	Near-Term Applications of AUVs *Open Discussion by all Participants*
5:30-7:00	RECEPTION *MIT Faculty Club*

MARCH 4th

8:00-8:30 LATE REGISTRATION

8:30-9:15 Recent Developments and Trends in Fiber-Optic Chemical Sensors
David Walt, Tufts University, Dept. of Chemistry

9:15-10:00 In-situ Chemical Detectors for Potential Use on AUVs
Hans W. Jannasch, Monterey Bay Aquarium Research Institute

10:00-10:15 BREAK

10:15-11:00 Applications of AUVs to the Offshore and Gas Industry
J. Robert Fricke, MIT, Dept. of Ocean Engineering

11:00-11:45 Micro-Magnetic Field Measurements Near the Ocean Floor
Maurice A. Tivey, Woods Hole Oceanographic Institute

11:45-1:15 LUNCH (on your own)

1:15-2:00 Adaptation of an AUV for Geophysical Exploration Beneath the Antarctic Shelf Ice
Marcia McNutt, MIT, Dept. of Earth, Atmospheric and Planetary Sciences

2:00-2:45 Large Sea-Ice Mechanics
Henrik Schmidt, MIT, Dept. of Ocean Engineering

2:45-3:00 BREAK

3:00-3:45 Techniques of Basic Marine Geological Research: Application to Environmental Management
Herman Karl, U.S. Geological Survey

3:45-4:30 Data Needs for Harbor and Bay Monitoring
Michael Mickelson, Massachusetts Water Resources Authority

4:30-5:00 Next Steps for the Successful Application of AUVs for Civilian Uses?
Open Discussion by all Participants

Capabilities of Autonomous Underwater Vehicles

Dr. James G. Bellingham
MIT, Sea Grant College Program

The summary contained here is a condensed version of a longer report: "Review of Autonomous Underwater Vehicles."

OVERVIEW: AUVS

The acronym AUV is typically applied to any unmanned, untethered underwater vehicle. Autonomous underwater vehicles, as discussed here, are mobile instrumentation platforms that have actuators, sensors, and on-board intelligence to successfully complete survey and sampling types of tasks with little or no human supervision. They are tools for obtaining spatially distributed data at a cost low compared to other technologies. Thus, a motivation for employing AUVs for science and monitoring is to obtain measurements in the ocean economically .

A class of vehicles is emerging that is capable of completely autonomous operation based on abstract goals specified prior to a mission by a human operator. However, many untethered vehicles are better categorized as remotely piloted rather than autonomous. Others are capable of executing pre-programmed flight paths autonomously, but are not capable of responding to sensor data to achieve higher-level goals, for example avoiding obstacles. A range of naval vehicles has been produced that might be classified as autonomous, the primary example being the torpedo. Such devices are not considered AUVs for the purposes of the following discussion because such unmanned military vehicles are not intended as reusable platforms.

The first AUV was built in 1963 at the Applied Physics Laboratory of University of Washington. Since that time, a variety of vehicles have been built for the purposes of hydrodynamic testing and as proof of concept for various types of missions. There is a great deal of activity in the military sphere, most of which is highly classified and therefore not accessible to most of the oceanographic community. However, it is safe to generalize that the military vehicles are very large (the Draper DARPA vehicle has a dry weight of 6,800 kg) and employ large and expensive sensor suites. Consequently, it is not clear that the military work will be adaptable to commercial or scientific applications where economic considerations are paramount. Military vehicle work represents the the bulk of research in the U.S., while other countries have chosen to focus on either commercial or oceanographic types of vehicles. There are some exceptions, for example the research program at MIT Sea Grant has chosen to focus on small, yet intelligent, vehicles for scientific and commercial applications.

Notable programs outside the U.S. include the ambitious Japanese effort to develop the next-generation industrial work vehicle. The Advanced Marine Robot has been constructed by a consortium of several Japanese companies under the auspices of MITI, and incorporates a variety of exciting technologies. The SPIRIT consortium in Canada has pooled the resources of a variety of institutions for achieving similar objectives. The EUREKA program in Europe, which involves several countries, focuses on developing both advanced work and survey types of vehicles.

To summarize the general status of AUV technology with respect to nonmilitary utilization: there are specific science missions for which AUVs are the most attractive technology, however AUVs have not yet reached the point of commercial viability. However, when they do, they will revolutionize the way in which we work in the ocean. It is important to note that AUVs are in their infancy, and consequently their real strengths have probably yet to be discovered. AUVs are not likely to replace manned submersibles or unmanned tethered vehicles in the near future, rather they will make possible whole new realms of activity.

Example: Abyssal Operations
The economic benefits of tetherless operations at abyssal depths has been well established. The Naval Ocean Systems Center in San Diego (Walton, 1991) estimates a three-to four-fold increase in search rates of their AUV as compared to deep-towed systems. This is because typical deep-tow towing speeds are on the order of one knot, which is easily exceeded by an untethered vehicle. Soviet operations with the MT-88 demonstrated that even with equal speeds, a four kilometer square area at 5,000 meters can be surveyed two to three time more rapidly with an AUV than with a towed system. The problem faced by the towed system is that it requires 3.5 kilometers to execute a turn for additional passes at the survey area (Ageev, 1990).

Table I: Deep Ocean Capable AUVs

Vehicle	Weight (Kilograms)	Depth Rating (Meters)	Range at Speed (km @ km hr^{-1})
AUSS	1300	6000	130 @ 13
Epaulard	2900	6000	22 @ 3.6
MT-88	1000	6000	22 @ 3.6
ABE	450	6000	30 @ 1.8
Odyssey	165	6000	1000 @ 5

Operational vehicles which have depth ratings of 6,000 m include the Naval Ocean Systems Center Advanced Underwater Search System, AUSS (Mackelburg, 1981; Walton, 1991), the French vehicle, Epaulard (Grandvaux and Michel, 1979; Michel, 1981), and the Soviet MT-88 (Ageev, 1990). Two vehicles designed for science missions at abyssal depth, currently under construction, are Odyssey (Bellingham et. al, submitted) intended for survey operations, and the Autonomous Benthic Explorer (Yoeger et. al., 1991) which is intended for long duration (up to 1 year) deployment. Table I compares some critical parameters.

AUV TECHNOLOGIES OVERVIEW

Intelligent Control:
The software responsible for the intelligent control of an AUV remains one of the outstanding research areas. Any successful approach must be firmly anchored in the real-world problems of limited computational resources, poor sensor data, unreliable subsystems, and the high cost of program development time. The objective is to develop vehicles that are robust, capable of complex missions, and easy to use. The AUV should be capable of pursuing relatively abstract goals (e.g. find and follow a chemical gradient) while at the same time preserving vehicle integrity. Also, it should be possible to reconfigure the vehicle for a range of missions. When additional sensors are added to the vehicle, or a different capability is desired from existing sensors, it should be possible to augment the existing software in a relatively straightforward fashion.

Examples of specific "intelligent" capabilities:

- survey
- gradient following
- obstacle avoidance
- rendezvous & docking
- robust adaptive control (especially for sampling vehicles)
- sediment sampling techniques
- terrain following
- failure detection & recovery

Note that while failure detection and recovery is listed last, it is in many respects the most difficult problem. Failure of some vehicle component, for example a thruster, could cause loss of a vehicle unless software is sufficiently robust to system failure, or there is explicit incorporation of algorithms for managing the vehicle with reduced capabilities. Clearly, docking an injured vehicle to secure it for recovery must be the highest priority. However, not only must failures of subsystems be detected and surmounted, but failures of a more global nature must be handled as well. For example, rendezvous and docking of the vehicle with the moored station will not always succeed the first time. Consequently, methods to detect and recover from failed docking attempts must be integral parts of the overall rendezvous and docking strategy.

Navigation

A variety of navigation technologies have been examined for use with underwater vehicles. Radio navigation techniques cannot be used due to the lack of penetration of electromagnetic radiation into sea water. Following is a brief review of other navigation schemes.

The most obvious and longest established navigation technique is to integrate the vehicle velocity in time to obtain new position estimates. Measurement of the velocity components of the vehicle is usually accomplished with an accurate compass and speed log. Speed is typically measured relative to the water. The principal problem is that a current will add a velocity component to the vehicle that is not detected by the speed log. Since AUV speeds are typically low, current-induced error is usually unacceptable.

Velocity relative to an acoustically reflecting surface, usually the bottom, can be measured with at least two acoustic systems: the Doppler and the correlation log. Vehicle mounted Doppler sonar has promise for many AUV applications involving operations in the near-bottom environment. Doppler sonar navigation schemes use a multiple-beam arrangement to measure the vehicle velocity components relative to the scattering surface, typically the ocean bottom. Assuming an accurate compass, position errors (relative to the initial position) are less than 1 percent of distance travelled.

Correlation logs are an alternative to Doppler logs for acoustically measuring speed (Dickey, 1978). Correlation logs typically operate at low frequencies compared to Doppler navigation systems, and consequently are capable of operation at larger distances from the acoustic scattering surface. For example, operation at separations of 5,000 meters has been demonstrated (Bookheimer, 1984). Accuracies comparable to Doppler logs can be obtained.

Inertial navigation systems (INS) integrate the accelerations of the vehicle twice in time to derive an updated position. Extensively used for aircraft, inertial navigation is not frequently used on unmanned underwater vehicles. There are a variety of potential sources of error for such systems (Johnstone, 1988). Position drift rates for high-quality commercial-grade inertial navigation systems are on the order of several kilometers per hour. For slow-moving underwater vehicles, the drift rate might exceed the vehicle velocity. One other drawback of inertial navigation is that available systems are expensive, on the order of $100,000 for high quality systems. However, prices are expected to drop and accuracies to increase in the future.

A promising AUV navigation technology compares a map of some geophysical parameter with actual vehicle measurements to derive position (Geyer, 1987). Examples of quantities which might be measured include bottom topography, magnetic field strength, and gravity. Problems with this technique include the requirement of accurate maps prior to the vehicle mission and potential ambiguity of measured position.

A wide variety of acoustic navigation systems have been developed for underwater vehicle use. They are typically divided into long, short, and ultrashort baseline systems (LBL, SBL, and USBL). These represent technologies for which commercial products are available.

Long-baseline tracking systems typically use a widely separated (on the order of 0.1 to 10 kilometers) array of transponders or synchronized pingers that are interrogated or detected by the vehicle (Abbott, 1978; Baron, 1987; Bellingham, 1991). Position accuracy on the order of a meter is achievable (a 2 centemeters accuracy is claimed for the SHARPS system over a range of 100 meters). One important requirement of long-baseline implementations is that the positions of the elements of the array must be known to an accuracy better than the desired accuracy of the system.

Both SBL and USBL systems are used to measure the direction of propagation and the time of arrival of acoustic signals. Short-baseline systems achieve this by measuring the time of arrival of a pulse at hydrophones separated by a meter or more. Ultrashort baseline systems measure the phase difference of the acoustic wave at hydrophones separated by distances on the order of centimeters. USBL systems have typically been developed to be mounted on a ship and used for tracking an underwater vehicle (Jacobsen, 1985; Elliot, 1984). Typical accuracies for commercial systems are on the order of a meter in range and a degree in relative bearing.

While all of the above systems have weaknesses, more capable navigation schemes can be obtained by combining technologies into a single system. For example, drift in an inertial navigation system can be minimized by updating the INS with a Doppler or correlation log velocity measurement (Hutchisen, 1991).

Through-Water Communication

While acoustic communication is attractive for the prospect of long range communication, the time lag introduced by the speed of sound in water complicates real-time control of vehicles. A vehicle at a distance of 10 kilometers requires 8.8 seconds for round-trip communication. Thus even with high data rates, the vehicle software should be sufficiently intelligent that only relatively high level commands are necessary. Low level functions, such as avoiding obstacles, should be handled by the vehicle. Table II, taken from (Dunbar et. al., 1990) outlines existing underwater communications technologies.

Table II: Underwater Communication Technologies (from Dunbar et. al., 1990)

Method	50 m Range	1 km Range	10 km Range
Acoustics	300 k bit/s	20 k bit/s	3 k bit/s
Optics	10 M bit/s	-	-
Electromagnetic	300 bit/s	3 bit/s	-

Efficent Propulsion
Propulsion typically consumes a large fraction of the power required to operate an AUV. Thus efficient propulsion is an enabling technology for long endurance vehicles. Building a low-drag fairing is one step towards an efficient vehicle. A high performance propellor matched to the drag of the vehicle is also necessary. Typical submersible propulsion systems lose efficiency to the following processes: electric motor losses, gearbox inefficiency, shaft seal friction, viscous losses, and hydrodynamic inefficiency of the propellor. For deep operation, thrusters are operated immersed in oil for pressure compensation, leading to increased viscous losses. Efficiency in excess of 60 percent, as measured by (hull drag x velocity)/(power to propulsion system), would be considered excellent performance by today's standards. A thruster for a small electric ROV might typically have a peak performance of 20 percent.

Energy Storage
For energy storage, a large number of battery technologies are available. Lead acid cells are the lowest energy density (≈34 W-hr/kg), but are cheap, rechargeable, and very well understood. A table of some commercially available systems is given in below:

Table III: Commercially Available Batteries

Chemistry	Manufacturer	Battery	Energy Dens. W-hr/kg
Lithium-Thionyl Chloride (p)	BEI	33-127(DD)	395
Alkaline-Manganese Dioxide (p)	Duracell	MN1300	129
Silver-Zinc (s)	Whittaker	LR-12	112
Nickel-Cadmium (s)	Sanyo	KR-20000M	44
Lead-Acid (s)	Yuasa	NP 65-12	34

A number of other energy storage systems might also be candidates, although more complex systems like fuel cells might not be appropriate for small, inexpensive AUVs. The ability to operate and recharge various systems at ambient abyssal pressure is attractive.

Low Power Subsystems
Hotel load is used here to describe power used by the vehicle for functions other than propulsion. Great benefit is obtained by minimizing the hotel load, thus significant research and development effort should be deployed to minimize power use by vehicle subsystems (Bradley, private communication). Computers, obstacle sonar, altimeter sonar, payload sensors, and fin actuators are all systems that would contribute to hotel load.

TETHERED VERSUS UNTETHERED VEHICLES
General arguments for untethered versus tethered, unmanned vehicles include:

1) tethered vehicles require considerable manpower for operation
2) tethered vehicles require constant attendance of crew & support vessel
3) tether management can be complex and expensive
4) tethered vehicles require ships with sea-keeping capability
5) tethers can easily become tangled
6) long tether dominates drag of vehicle (especially a problem in high current or deep water operations)
7) tethers limit scope of action of vehicle (think of it as a leash)
8) operation in bad sea conditions precluded by tether management considerations

Advantages of tethers are:

1) high bandwidth available for video & command signals
2) power need not be carried by vehicle
3) human operator can make high-level decisions (or all decisions)

Eliminating the requirement of a tether from unmanned vehicles has been recognized as a highly attractive objective almost since the advent of ROVs. One means by which this can be accomplished, while still maintaining human control, is to provide a communication path through the water between the vehicle and the operator. Of course, the vehicle would have to carry its own power source. Since electromagnetic radiation is strongly attenuated by sea water, such a communications link is typically provided acoustically (see previous section).

REFERENCES

Abbott, R. C., "Submersible Acoustic Navigation for Precision Underwater Surveys," I.E.E.E./M.T.S., Proceedings Oceans '78, pp 462-465, 1979.

Ageev, M. D., "The Use of Autonomous Unmanned Vehicles for Deep-water Search Operations," Subnotes, September/October, p 10, 1990.

Baron, G., "An Autonomous Acoustic Positioning System for Divers," I.E.E.E./M.T.S., Proceedings Oceans '87, pp 1212-1217, 1987.

Bellingham, J. G., Goudey, C., Consi, T. R., and Chyssostomidis, C., "A Long Range, Deep Ocean Survey Vehicle," Submitted to the International Society of Offshore and Polar Engineers, 1992.

Dickey, F. R., and Edward, J. A., "Velocity Measurement using Correlation Sonar," Position Location and Navigation Symposium, I.E.E.E. Aerospace and Electronics Systems Society, p 255, 1978.

Dunbar, R. M., Klevebrant, H., Lexander, J., Svenson, S., Tennant, A. W., "Autonomous Underwater Vehicle Communications," Marine Technology Society, Proceedings ROV '90, p 270, 1990.

Elliot, S., and Olson, R., "Vehicle Tracking Using Advanced Acoustic Technology in an Ultra-short Baseline System,"" Marine Technology Society, Proceedings ROV '84, pp 42-44, 1984.

Geyer, E. M., Creamer, P. M., D'Appolito, J. A., and Rains, R. G, "Characteristics and Capabilities of Navigation Systems for Unmanned Untethered Submersibles," Proceedings of the Fifth International Symposium on Unmanned Untethered Submersible Technology, p 320, 1987.

Grandvaux, B. F., and Michel, J. L., "Epaulard—An Acoustically Remote Controlled Vehicle for Deep Ocean Survey," Proceeding Marine Technology Conference, p 357, 1979.

Hutchisen, B. L., Presentation at Workshop for Sensor and Navigation Issues for Unmanned Underwater Vehicles, Cambridge, MA, 1991.

Jacobsen, H. P., Klepaker, R. A., Knudsen, F. T., and Vestgård, K., "A Combined Underwater Acoustic Navigation and Control System," Marine Technology Society, Proceedings ROV '85, pp 52-56, 1985.

Johnstone, R. S., and Fries, D. W., "Simulation of a Submerged Autonomous Vehicle with Inertial Navigation," Presented at DARPA/CSDL Symposium on Modeling and Simulation, June 15-17, 1988.

Mackelburg, J., "AUSS (Advanced Unmanned Search System)," Proceedings 2nd International Symposium on Unmanned Untethered Submersible Technology, pp 5-13, 1981.

Michel, J. L., le Roux, H., "Epaulard: Deep Bottom Surveys Now with Acoustic Remote Controlled Vehicle, First Operational Experience," Proceeding Oceans '81, pp 99-103, 1981.

Tyler, M. C., "Lightweight Doppler Sonar for Submersible Applications," Marine Technology Society, Proceedings ROV '87, p 308, 1987.

Walton, J. M., "Advanced Unmanned Search System," Proceeding Oceans 91, p 1392, 1991.

Yoeger, D. R., Bradley, A. M., and Walden, B. B., "The Autonomous Benthic Explorer," Unmanned Systems, Spring, p 17, 1991.

TABLE IV: List of AUVs

VEHICLE	Country	Type	Weight	Depth	Status	Ref.
Advanced Marine Robot (MITI)	Japan	RP/A?	5600		90	s
ARCS (I.S.E.)	Canada	A	1360	300	84/>89	p
AROV (SUTEC)	Sweden				91/na	s
ARUS (Technomare, Ferranti, (Eureka))	Italy&U.K.	A		6000	cncpt(88)	p
AUSS (NOSC)	USA	RP	1300	6096	83/?	p
Autonomous Benthic Explorer (WHOI)	USA	A	450	6000	92/na	p
AUTOSUB/DOGGIE (NERC)	U.K.	A		6000	cncpt(88)	p
AUTOSUB/DOLPHIN (NERC)	U.K.	A		6000	cncpt(88)	p
B-1 (NUSC)	USA	PP	420	90	82/?	s
CSTV (NCSC)	USA	A	4082		80/?	p
EAVE-East (UNH)	USA	A	312	150	79/<89?	p
EAVE III (UNH)	USA	A	455	150	88/>89	p
EAVE-West (NOSC)	USA	A	204	610	79/?	p
ELIT (IFREMER & COMEX)	France			1000	86/--	s
Epaulard (IFREMER)	France	PP/RP	2910	6000	83/--	p
FLIPPER (Tokia University)	Japan	A	~155		cncpt(89)	p
LSV (NCSC)	USA				87/--	s
MK 88 (Acad. Sci.)	USSR	RP/A	1000	6000	89/>89	p
MUST (Martin Marrieta)	USA	A	~1500	610	88/>89	p
Multi-mission AUV (Sippican)	USA	PP/A?	11.5	308	cncpt(89)	p
No name (SIMRAD)	Norway	RP	240		86/--	p
NPS Model 2 AUV	USA	A	160	10	90/-	p
NSRV (ARE)	U.K.					s
Ocean Explorer (FAU/Perry)	USA	A	1221	154	92?/	s
Odyssey (MIT Sea Grant)	USA	A	100	6000	92/	p
PINGUIN (MBB GmbH)	W.Germ.	RP		200	80/?	s
PLA 2 (CEA & IFREMER)	France	PP/A?	14,500	6000	cncpt(85)	s
PTEROA 150	Japan	A	220	2000	90/-	p

PTEROA 250	Japan	A	1000	6000	cncpt(90)	p
Robot (MIT)	USA	PP	110	61	76/<81	p
Robot II (MIT)	USA	A	66	91	82/<87	p
ROVER 01 (Heriot-Watt)	U.K.	RP	120	100	cncpt(81)	p
RUMIC (NCSC)	USA				const(87)	s
SEASHUTTLE (APL, U.Wash)	USA	PP	9	250	88/-	p
Sea Squirt (Sea Grant)	USA	A	33	200	89/-	p
SKAT (Inst. of Oceanology)	USSR				proto(87)	s
SPAT (Westinghouse Oceanics)	USA	PP		240	80/?	s
SPURV I (APL, U. Wash.)	USA	PP/A	420	3659	63/?	p
SPURV II (APL, U. Wash.)	USA	PP/A		1500	73/?	p
Telemine (Teksea)	Switz	RP		150	83/?	s
TM 308 (Tecnomare, S.p.A.)	Italy			400	83/?	s
UARS (APL, U. Wash.)	USA	PP/A		457	72/?	p
UFSS (NRL)	USA	PP	~3600	357	79/>84	p
UUV (DARPA/Draper, 2 made)	USA	A	6800	450	89/-	p
WIR (Technomare, Ferranti, (Eureka))	Italy&U.K.	RP			cncpt(88)	p
XP-21 (ART)	USA	A	454	615	88/>89	p

Explanation of headings & abbreviations
Type: PP=preprogrammed, RP=remotely piloted, A=Autonomous
Weight: Dry weight, in kg.
Depth: In meters.
Status: Format XX/YY where XX is year vehicle first operated, YY is year last operated. const(XX) means vehicle under construction in year XX. cncpt(XX) means vehicle concept first described year XX (used only when vehicle not launched yet).
Ref.: p=primary reference, wom=word of mouth, s=secondary.

Capabilities and Limitations of Bio-Optical Moorings

Professor John Marra
Lamont-Doherty Geological Observatory

THE USE OF MOORINGS IN OCEANOGRAPHY

Historically, studying the ocean has relied on sampling from ships. The cruises aboard these ships are usually one to a few weeks duration at a given location and could never adequately sample longer-term changes in the environment. Longer-term changes could be observed using moored instrumentation, however these were generally deployed in the deeper parts of the water column, away from surface motions and atmospheric disturbances. Drifting arrays could carry instrumentation similar to moorings, however, given wind and vertical shears, drifters move in unpredictable fashion. Thus for a period of time, long-term changes in the upper ocean were neglected. It wasn't until 1977 that the first successful ocean surface-to-bottom mooring experiments were performed (see Halpern et al., 1981).

Success at placing instruments in the upper ocean for long periods (Briscoe and Weller, 1984) opened the way for the use of moorings with other kinds of sensors, such as to measure optical properties and biological variables. However, it was only recently that sensors for these met the requirements for moored operation. One of the early attempts at mooring biological and optical sensors was a program at Scripps, which for a time maintained a semi-permanent installation in near-shore waters (Warner et al., 1983). In the deep ocean, transmissometers had been attached to Anderaa current meters, as well as being moored by themselves (Gardner,1989). A group at Brookhaven National Laboratories developed a fluorometer to use in moorings in coastal waters (Whitledge and Wirick, 1986; Falkowski et al., 1988).

Probably the first comprehensive mooring experiment in the open ocean was the Biowatt Mooring Experiment in the Sargasso Sea in 1987. The Biowatt program which designed the experiment (Marra and Hartwig, 1984; Dickey et al., 1986) benefited greatly from the above-mentioned attempts, and also from three instrument developments. First was a new dissolved oxygen sensor that was sensitive and stable enough for use on oceanic moorings (Langdon,1986). Second was a new *in situ* fluorometer, developed by SeaTech Corp. (Corvallis OR), for the estimation of chlorophyll a, that was more compact, calibration-stable, and less power-hungry than its predecessors (Marra et al., 1992). Third were two new kinds of moored optical sensors, a moored spectroradiometer (Smith and Booth, 1988) and a moored bioluminescence sensor (Booth and Swift, 1988). All of these sensors are designed to collect data at frequencies of 5-30 per hour for periods extending to several months.

EXAMPLES OF MOORED SENSOR DATA

There are two fundamental time scales in biological oceanography, the diurnal and the seasonal (Marra and Hartwig, 1984). The general belief is that diurnal signals are mostly accessible from shipboard observations. However, evaluation of seasonal cycles requires observations for a long period of time, but with sufficiently high sampling density to account for shorter period phenomena such as weather (Marra and Hartwig, 1984; Dickey et al., 1986). These shorter period changes are particularly important to biological and optical sampling because so much of the dynamics is driven by the day-night cycles and the synoptic weather. When planning a seasonal sampling program in the open ocean, it becomes clear that moored observations are favored.

Diurnal Variability.

The enhanced time resolution in moored observations allows a better look at short-term variability. For example, in Biowatt large diurnal changes in fluorescence, beam attenuation coefficient (c(660) or "beam-c"), and dissolved oxygen were observed in large portions of the record. Changes in dissolved oxygen from the daily cycles of photosynthesis and respiration were expected because the new electrodes were sensitive enough (Langdon, 1986). A diurnal signal in beam-c also had precedent and can be interpreted in terms of particle growth (Siegel et al., 1989). Variability in fluorescence also was not unexpected but could have arisen from a number of sources. In other words, a diurnal signal could come about from changes in chlorophyll itself (i.e, growth), changes in fluorescence yield per unit chlorophyll, or changes in chlorophyll per phytoplankton carbon. If there were a mid-day depression in fluorescence yield, any changes in chlorophyll biomass might be masked.

An example of the diurnal variability observed in the mooring during a 5-day period in late winter, (mid-March), at a depth of 20 m is given in figure 1. The raw unfiltered data have been averaged over one hour (i.e., an average of 12 records per hour). Clear diurnal signals can be discerned in chlorophyll, and beam-c and dissolved oxygen. The source of these signals are biological in origin, and not due to advection of water masses with different biological properties past the mooring. These durinal signals are a common feature throughout the nine-month Biowatt Mooring Experiment, and occur at all depths where mooring data was obtained. For this time period at least, the signals do not correlate with inertial currents. Variance spectra show them to occur at the daily frequency, and phase spectra to lag the solar irradiance by 900. In other words, maxima occur at sunset, which is to be expected for biological growth. Interestingly, there are large decreases in the signal overnight (losses due to respiration).

By fitting the logistic equation to the data, we calculate particle growth rates of 0.1-0.5 d^{-1}. For these data, the fluorescence signal tracks the turbidity change and not the solar cycle. Thus, the chlorophyll fluorescence appears to give a good indication of biomass change. Langdon et al. (1988) have derived daily net production rates for the diurnal oxygen signals, and these are supported from other shipboard data. Biological oceanographers have argued for years about the growth rate of phytoplankton in the ocean. The mooring contains data to verify these claims directly.

Seasonal Variability

A composite realization, contoured by computer, of the chlorophyll and temperature data for the entire length of the mooring from March until the end of November is shown in figure 2. Because of the poorly resolved depths of sampling, we regard this as one possible view. Nevertheless, there are features in this diagram that attest to its veracity. There is a chlorophyll maximum near the surface during the time when a spring bloom can be expected to occur. Observations at this site in previous years agree with this pattern (Marra et al., 1992). Later, this chlorophyll maximum appears to "sink", although in this data, it looks as if a different population of phytoplankton appears at this depth range. Still later in the growing season, we can see the formation and maintenance of the deep chlorophyll maximum (with variations in its intensity at 10-20 d intervals). The subsurface maximum is attenuated late in the summer and early fall, until it goes below the resolution of our contouring scheme.

LIMITATIONS OF MOORED SAMPLING

It is fairly obvious from the foregoing examples that the primary attraction to this means of sampling the ocean is the highly resolved variability. The data shown in Figs. 1 and 2 could not have been obtained by other sampling platforms. The variability has never before been seen in biological properties in the ocean. It is also obvious, however, that there are substantial limitations to moored sampling.

First, the mooring samples the dynamics of the ocean at one geographic point. It is best therefore, for the sampling not to be contaminated, that the mooring be placed in a region of the ocean not characterized by fronts, eddies, and other sources of lateral variability. Such locations are difficult to find. As a corollary, moorings by themselves cannot be used in studies of fronts. One solution to this dilemma would be a spatial array of moorings, however, the spacing of the array is critical, and not enough is known about horizontal variability to provide guidance. If the spacing is too large, the individual sites become uncorrelated with each other. If too small, the array could be entirely within the spatial scale of the phenomenon of interest.

Second, moorings are eulerian. The water that is sampled is that which is advected by the sensors from someplace else. If there are time lags in a dynamic process, what is observed at the mooring may result from processes occurring upstream, or (in the case of vertical advection) from deeper in the water column. Usually the assumption is made that for some area surrounding the mooring location, the processes causing variability are statistically stationary. Related to this is that single moorings only detect the PRESENCE of events. For many oceanographic problems, we need to understand how populations change with time, requiring a lagrangian experiment.

Third, a practical matter, is that the vertical resolution of moored sensors is only 5-10 m. For many phenomena of interest, such as internal waves, the attenuation of irradiance near the surface, and vertical mixing, this is inadequate.

SUMMARY AND THE FUTURE

There are primarily three ways in which the ocean can be sampled. First, depth profiles of water properties can be collected. The sampling resolution for depth profiles can be very high, and time resolution can be optimized under limited circumstances. But since relatively few stations can be completed, geographic coverage is generally poor. Time resolution can be greatly improved by placing instruments in the ocean on moorings or drifters. While depth resolution is only moderately good (typically, 10's of meters), and spatial data non-existent, this method has the advantage, unobtainable with the other modes, of high resolution in time.

Finally, variability in space can be optimized if data can be collected while the ship is underway. In this second sampling mode, water is pumped aboard for sampling, or else sensing instruments are towed behind the ship. This method vastly improves sampling horizontal variability, however depth resolution is often compromised, and measurements cannot be ordered in time. This sampling mode has not been exploited as much as the previous two, perhaps because of the limitation of tethering the sensors to the ship. This constrains the spatial structures that can be sampled to the handling characteristics of the ship, and also limits depth resolution.

The advent of autonomous underwater vehicles (AUV's) can solve these sampling problems, but offer other kinds of opportunities as well. For example, the spatial scale of biological properties near fronts has only been crudely characterized, limited by the the speed of the ship and over-the-side operations. Many plankton populations are not sampled adequately if at all using standard shipboard techniques. For example, euphausiid populations have been observed by submersibles to inhabit a zone just above the bottom on continental shelves. "Natural" occurrences of bioluminnescence, the so-called passive bioluminescence, in the ocean are virtually unknown, and most sampling methods confound its observation. Even moored sensors, because they are subject to the vibrations of the mooring line, will create enough disturbance such that the measurement of passive bioluminescence may be compromised.

Many of the sensors developed for moored operation can be directly applied for use on autonomous underwater vehicles (AUVs). AUVs offer a promising solution to many of the sampling problems faced by oceanographers today.

REFERENCES

Booth, C.R. and Smith, R.C. 1988. Moorable spectro-radiometers in the Biowatt experiment. Proc. SPIE, Ocean Optics IX, 925, 176-188.

Briscoe, M.G. and R.A. Weller. 1984. Preliminary results from the long-term upper-ocean study (LOTUS). Dyn. Atmos. Oceans 8, 243-265.

Deser, C., R.A. Weller, M.G. Briscoe. 1983. Long term upper ocean study (LOTUS) at 340N, 700W: meteorological sensors, data, and heat fluxes for May to October 1982 (LOTUS-3 and LOTUS-4). WHOI Tech. Rept. 83-32, pp. 67.

Dickey, T. E.O. Hartwig, J. Marra. 1986. The Biowatt bio-optical and physical moored measurement program EOS 67, 650-651

Falkowski, P.G., C.N. Flagg, G.T. Rowe, S.L. Smith, T.E. Whitledge and C.D. Wirick. 1988. The fate of the spring phytoplankton bloom: export or oxidation. Cont. Shelf Res. 8, 457-484.

Gardner, W.D., 1989. Periodic resuspension in Baltimore Canyon by focusing of internal waves. J. Geophys. Res. 94, 185-18,194.

Halpern, D., R.A. Weller, M.G. Briscoe, R.E. Davis and J. R. McCullough. 1981. Intercomparison tests of moored current measurements in the upper ocean. J. Geophys. Res. 86, 419-428.

Langdon, C. 1986. Dissolved oxygen monitoring system using a pulsed electrode: design, performance, and evaluation. Deep-Sea Res. 31, 1357-1367.

Langdon, C., J. Marra and T. Dickey. 1988. Seasonal oxygen changes and net community production in the surface waters of the Sargasso Sea. EOS 68, 1759.

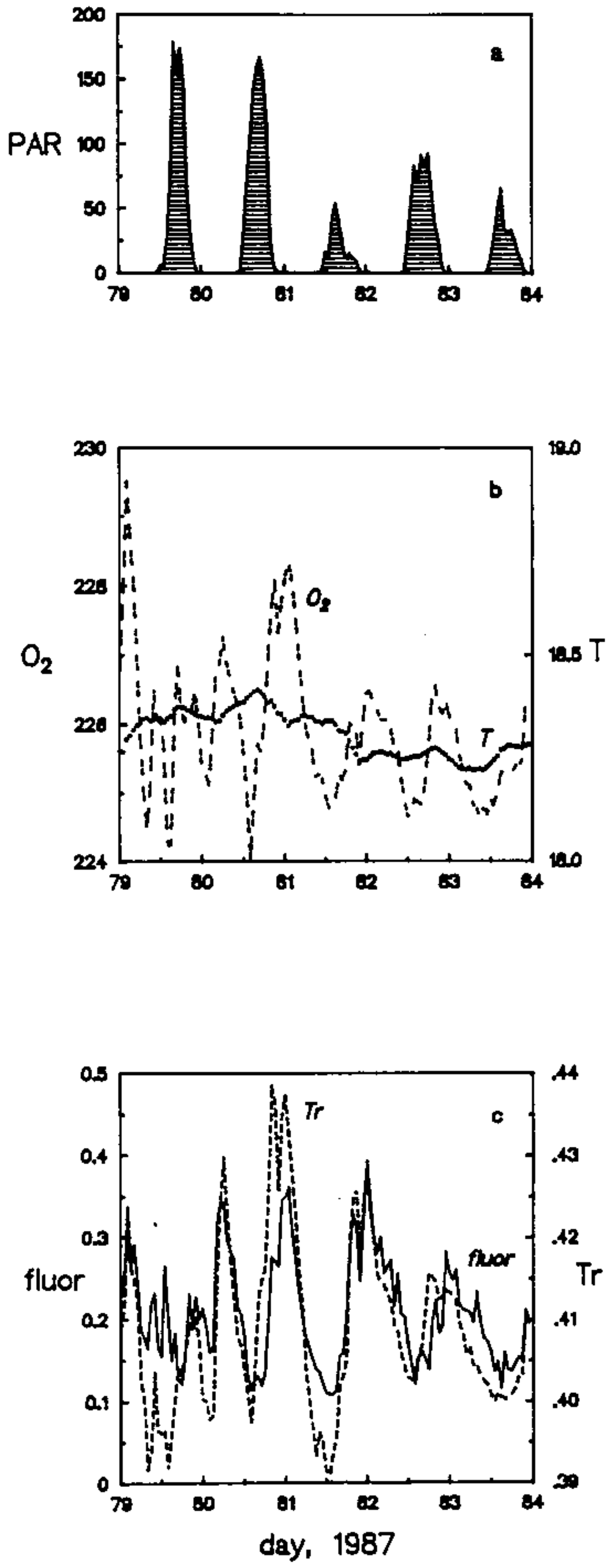
Marra, J. and E.O. Hartwig. 1984. Biowatt: a study of bioluminescence and optical variability in the sea. EOS 65, 732-733.

Swift, E. and C.R. Booth. 1988. Bioluminescence moored systems. Proc. SPIE, Ocean Optics IX, 925, 76-86.

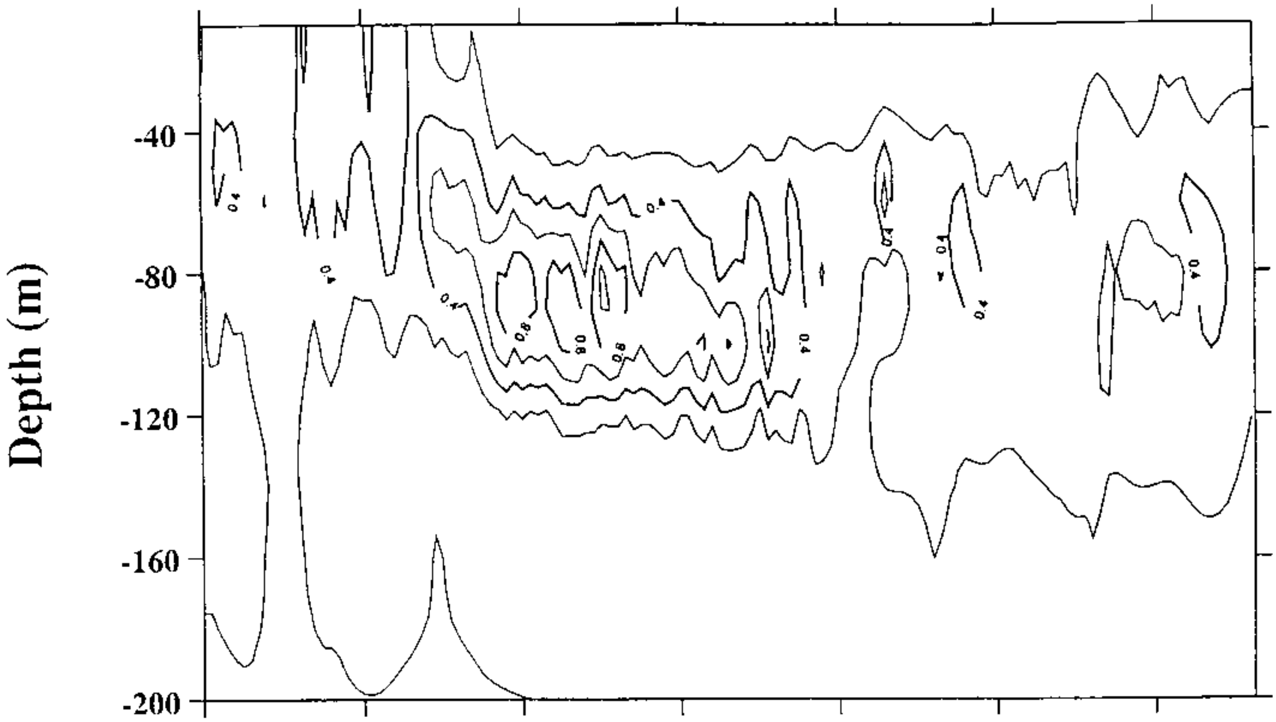
Warner, J.A., R.W. Austin, D. Bailey, G. Huszar, R.R. McConnaughey, K. Nealson, E.A. Stephan. 1983. Scripps canyon sea structure: a design and deployment for the study of oceanic bioluminescence. Mar. Tech. Soc. J. 17, 40-47.

Whitledge, T.E. and C.D. Wirick. 1986. Development of a moored in situ fluorometer for phytoplankton studies, pp. 449-462. In: Tidal mixing and plankton dynamics, M. Bowman, C. Yentsch, and W.T. Peterson, eds., Springer-Verlag, Berlin.

Figure 1. Moored sensor data for the period 20-25 March, 1987 (days 79-84) for the MVMS unit at 23m. These are hourly averages of (a) Photosynthetic Active Radiation (PAR) in µEinsteins $m^{-2} s^{-1}$; (b) dissolved oxygen (µM) and temperature (deg. C); and (c) beam attenuation coefficient (Tr)f and fluorescence of chlorophyll a ('fluor' but represented as µg chl l^{-1}).



Chlorophyll a (mg m^{-3})



Temperature

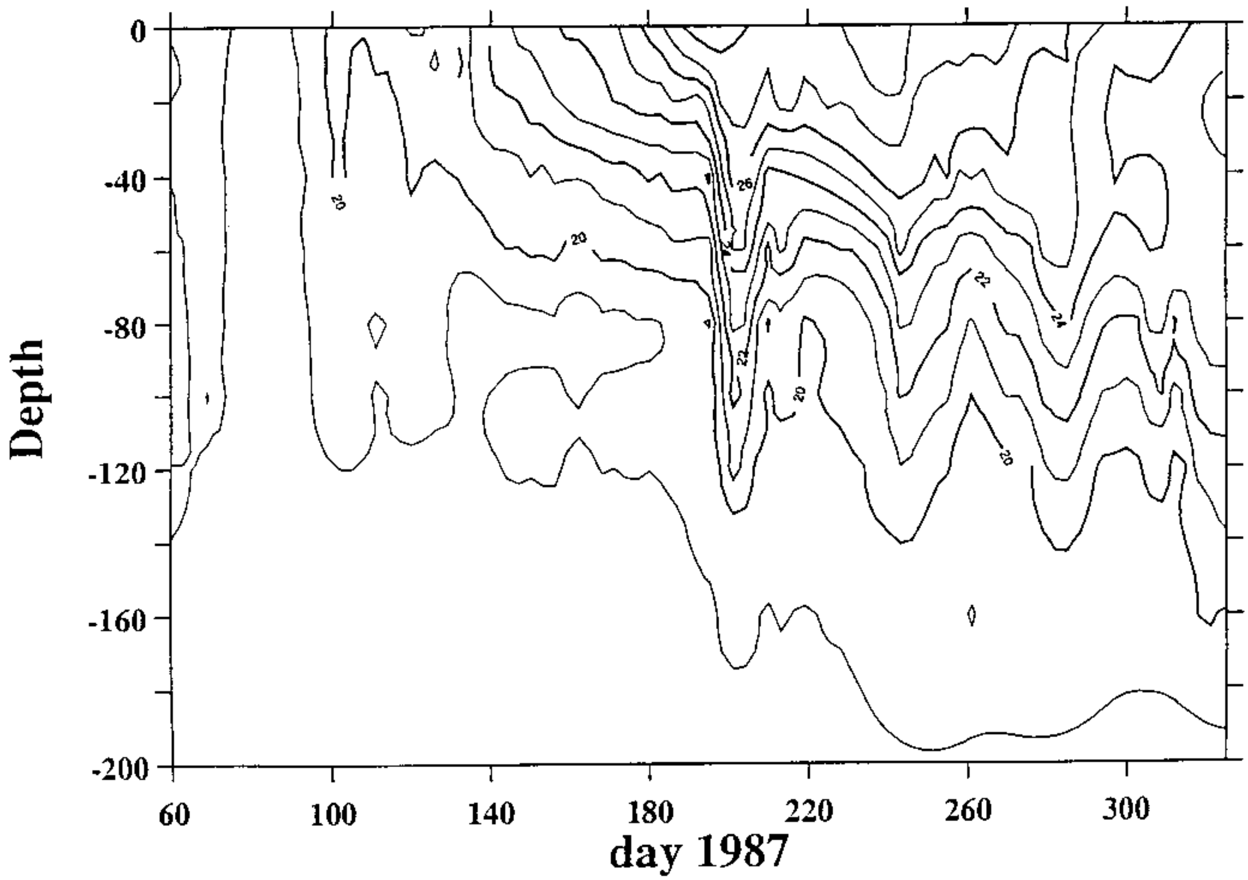


Figure 2. Contours of chlorophyll fluorescence represented a µg chlorophyll l^{-1} from all three deployments, that is from 1 March - 20 November, 1987 (days 60-320). These data are daily averages. The contour interval is 0.2 µg chlorophyll l^{-1}. The maximum seen in late March and early April is >0.8 µg chlorophyll l^{-1}. This is a computer generated contour plot and is one possible realization of the depth distribution of chlorophyll ove the growth season.

Use of Autonomous Underwater Vehicles for Long-Term Ecosystem Studies

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Autonomous underwater vehicles (AUVs) are inexpensive relative to ROVs and manned submersibles. For this reason, it is possible to consider use of several vehicles each dedicated to a single purpose. Examples of dedicated uses include: 1) repeat photographic surveys, 2) data transfer from networks of bottom instruments, 3) bottom sampling, and 4) recovery of apparatus used to conduct experiments. Manned submersibles have allowed us to return to precise locations on the sea floor and conduct controlled *in-situ* experiments. AUVs may be able to do the same work more efficiently with more than one kind of vehicle. Manned submersibles or ROVs will continue to be needed to provide observers a synoptic view of the environment, to establish long-term stations, and to operate in environments where tasks have not been adequately defined. ROVs at the end of fiber optic links from shore will be important to provide continuous observational capability over long periods and reduce the requirements for surface support vessels. The Autonomous Benthic Explorer (ABE) has been designed for the first set of tasks:

For repeat photographic surveys and data transfer from networks of bottom instruments, the basic requirement is continuous high-resolution close-up images over large areas. The height above the bottom and width of tracks would be predetermined and programmed into the vehicle. Height would be maintained by vertical thrusters and the tracks would be controlled by programming the vehicle to follow straight lines in a navigation net operated from transponders on the bottom. Rather than relying on the navigation or matching of edges of photographs the survey would be done from at least two distances above the bottom. The limitation on height above the bottom in the largest scale survey would be the light required for imaging with a very sensitive black and white video camera. Photographs would be organized according to SeaBeam or sidescan topography and navigation. Close-up photographs would be placed in a mosaic by matching features in the lower resolution photographs. An obstacle avoidance mechanism would be needed for the close-up survey.

Arrays of instruments collecting time series of data or images could download to a vehicle without having to retrieve and redeploy the instrument packages from a surface vessel. The instruments would be connected to a hitching post that the AUV would home toward and hook up for transmission of data. A manned submersible or ROV would be used to place the instruments with respect to a navigation net. The AUV would have its own probes for sensing the environment and could be programmed to remain at each hitching post to collect a short time series before moving on to the next site. Another possibility as the technology develops is to leave an AUV on the bottom for long periods to periodically conduct surveys and have it occasionally connect to a surface buoy for recharging and transmission of data to shore or satellites.

Another valuable kind of vehicle would be used to take bottom cores. This is presently done very successfully with manned submersibles such as ALVIN or the JOHNSON SEA LINK (JSL), however a relatively inexpensive autonomous vehicle might be more efficient. The requirements of a successful corer are:

1) Very slow rates of penetration so that the surface "fluff" layer remains undisturbed. Ideally the rate of penetration should be preprogrammed. This is presently accomplished by using very heavy coring devices such as the USNEL or Sandia box corer that are lowered very slowly into the bottom. Other approaches include use of hydraulically damped cores that allow a core to slowly descend in a frame sitting on the bottom.

2) Sufficient force to penetrate the most resistant sediments. Deployment from a heavy tractor vehicle such as RUM or a large submersible with considerable inertia and variable ballast such as ALVIN or JSL accomplishes this. Cores at the end of a long length of wire from a surface vessel must have to be very heavy to achieve slow penetration even in soft mud.

3) Large numbers of relatively small (3-10 cm diameter), long (up to one m) cores need to be taken on a single deployment.

4) Cores need to be vertical at all times.

5) Disturbance of the bottom should be minimal.

The inertia needed to slowly drive a core into a resistant bottom is unlikely to be achieved by an AUV even with a good variable ballast system. Thrusters could be used to overcome the resistance of the bottom but this might disturb the bottom over a sizable area. The best approach likely to be use of fixed posts pushed into the bottom as anchors to keep the vehicle from moving. This could be a set of spiral anchors that screw into the bottom like fence anchors or narrow shafts that are pushed in rapidly and have hydraulically operated flukes for anchoring.

The anchoring would create some resuspension of particles which could be desirable for sampling surface "fluff" particles. These could be captured with a pump sampler activated by a predetermined level of optical backscatter. Alternatively bottom disturbance could be made with a small thruster or vanes to resuspend fluff particles.

Once the vehicle is anchored then an articulated arm could reach out in radial directions to take cores in a circle away from the central disturbed area. If the whole vehicle were radially symmetrical then cores could be stored in a "cartridge belt" around the vehicle. The vehicle would need a variable ballast system to compensate for the weight of the sediment samples. A system for periodically transferring a set of samples to a passive free-vehicle "elevator" for retrieval by a surface ship is desirable.

Thrusters would be arranged for rapid ascent and descent and slow movement over the bottom. The coring arm would have a video camera that would photograph the bottom before, during and after the core was taken. The vehicle would have environmental sensors for water column characteristics and the anchors might be equipped with probes for determining sediment properties.

A third kind of vehicle might be used to seek out free vehicles, photograph their surroundings and release them. A single autonomous releasing vehicle would be cheaper than a large number of transponders and would provide photographic and other environmental information on each deployment site. This would work well for recolonization experiments used for studies of life histories of deep-sea animal populations.

Improvements in sound communications and signal processing are needed to allow transmission of even very low-resolution images or summaries of features in images from the AUV to a surface operator who could then make decisions based on the information.

Large Scale Circulation Studies with Multiple Autonomous Underwater Vehicles

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SUMMARY
A control scheme is developed specifically to control simultaneously many autonomous underwater vehicles (AUVs) mapping large scale patterns in the ocean. The scheme is robust, flexible and very simple to implement. The principal issues in developing this capability are: the design of the vehicles so they can be inexpensive for massive use; and the simultaneous control of these vehicles so that they can be used to map systematically a specific large-scale feature of the ocean.

INTRODUCTION
Developing unmanned underwater vehicles for performing underwater operations, and designing "smart" instruments, adopted to a specific ocean environment to measure sea properties and monitor a large area, are the major current challenges in marine exploration and utilization.

Given the immense size of ocean features and their continuous dynamic evolution, the classical method of observing the sea from oceanographic ships is clearly restricting seriously any attempt to obtain a global detailed understanding of these features.

The principal limitations of AUVs are the relatively small energy available from batteries, and the computationally intensive requirements for navigation and control. If one employs several vehicles, however, the explored area can be subdivided into much smaller areas each corresponding to a separate vehicle. Also, with the control scheme described herein, the problems of navigation and conrol can be solved by dedicating one (of the many) vehicles towards this task, while the good performance of the group of vehicles is guranteed.

INEXPENSIVE VEHICLE DESIGN
Presently, AUVs are still in a developmental phase and are not mass-produced. Also, most vehicles have been build as technological extensions of tethered, remotely operated vehicles (ROV). To replace an ROV, the AUV must have considerable capabilities for observation, computation and powering. If instead one sees the AUV as a sophisticated version of a self-powered sensor, the requirements are considerably reduced. To this effect the recently developed *Layered Control Theory* (Brooks 1986) is of substantial help, because it allows the development of autonomous control with very simple, even crude sensors; requires very limited computational capability and operates without the need of a "world map", i.e. neither requiring a detailed *a priori* description of the environment in which it will operate, nor building and storing such a map through observations on the site. One may compare the resulting low-level autonomous behaviour of such systems to the behaviour of insects, which although equipped with relatively primitive sensors and reasoning capability can still function very well in an unknown environment. We will not pursue the description of such algorithms herein, since they are given in

Brooks (1986), we note, however, that Sea Grant-sponsored research addresses specifically the development of vehicles equipped with layered control (Belingham et. al. 1989).

This low-level autonomous control equips the vehicles with a survival capability, as well as a primitive capability for decision making; the methodology, also, keeps the price of the vehicle low: neither expensive sensors for navigation, nor substantial computational capabilities are required. The vehicle itself has modest requirements; the designer can reserve most of the power and the computer and sensor capabilities for observing the ocean properties, and not simply to control and navigate the vehicle.

The remaining difficulty is in controlling these (possibly hundreds of) vehicles simultaneously, and gathering the obtained data in a central unit for transfer to an earth station. A solution for this control problem is through the use of effective chains of vehicles. The word *chain* is used here with the specific physical system in mind, since the control algorithm builds a virtual chain out of the vehicles, as explained in the sequel. Such a scheme has considerable advantages of simplicity of implementation, and inexpensive production; while it is best suited for the ocean environment, where communication is acoustical, because it requires a very short range transmission capability.

PROPOSED MULTI-VEHICLE SYSTEM: A VIRTUAL CHAIN

We will demonstrate the proposed concept through an example: Consider N vehicles, profiling an ocean eddy. The order of N is typically 30. The purpose is to keep the vehicles on a horizontal line, equidistant from each other, so as to provide a laboratory grid of observation. Hence each vehicle is at a distance h from the other, all moving at speed U (t) following a designated vehicle in the manner explained in the sequel. Several such profilers can provide a simultaneous global picture of the eddy.

The principal aim is to keep the navigation and control hardware on each component vehicle as simple as possible, including the acoustics hardware. For this reason, the listening capabilities of each vehicle are very limited in range (i.e. distance in the water from the source of the sound). We quantify this listening range as at least equal to 2 h, for reasons that will be obvious. Each vehicle is equipped with an equally limited emmission capability (since the range is limited, the frequency can be high, resulting in accurate positioning).

The control algorithm is based on the following concept: each vehicle responds only to errors in its positions with respect to the vehicles to its left and to its right. This is achieved through coding (in frequency) of the acoustical emmission of each vehicle. Since the range is small, coding can be repeatable, roughly every three vehicles, so there is no substantial complexity and book-keeping required. The control law is based on an equivalent finite-difference approximation of a chain hanging under constant tension, i.e. the nth vehicle having mass m, added mass m_a, drag coefficient c_d, projected area A_p, is governed by the following equation in one direction:

$$(m+m_a)\frac{d^2y_n}{dt^2}+\frac{1}{2}\rho A_p U_n|U_r| = T_n(t) \qquad (1)$$

where ρ is the water density, U_r is the relative velocity between the vehicle and the fluid, and the thrust T_n is given as:

$$T_n=\alpha(y_{n-1}-y_n)+\alpha(y_{n+1}-y_n) \qquad (2)$$

with α a control constant. The direct measurables are relative distances, i.e. $y_{n+1}-y_n$ and $y_{n-1}-y_n$, hence equation (2) can be implemented easily.

Similar equations are implemented for the other directions, except that one has to modify the drag equation to account for the coupling in drag; the essence of the control law, however, remains the same. Also, the control constant in the direction passing through the vehicles will invariably be larger than in the horizontal plane, in complete analogy with the properties of a chain.

Equations (1) and (2) are the essence of defining a *virtual chain*. These equations are exactly equivalent to the finite-difference approximation of the linearized transverse dynamics of a chain. If one adds the boundary conditions, i.e. that the end vehicles have on their free side a fictitious tensioning force (and should not expect any position signals), and that one of the vehicles, *the leader*, provides commands y_b to the chain, the scheme above is guaranteed to be stable, provided there is sufficient thrust in the vehicles to follow the commands. Also, there are natural frequencies given by the chain natural frequencies ω_n:

$$\omega_n = \frac{n\pi}{N} \frac{\sqrt{\alpha}}{m} \tag{3}$$

The drag-induced damping normally eliminates these natural frequencies in a chain. In this example this depends on the value of α, hence it may be necessary to add a velocity-dependent term to equation (2):

$$T_n = \alpha(y_{n-1} - y_n) + \alpha(y_{n+1} - y_n) + \beta\frac{dy_n}{dt}$$

where β is a control constant.

MEASUREMENT OF RELATIVE POSITION BETWEEN VEHICLES

We consider, for example, the case of a virtual chain of vehicles moving within a plane, in a nominally vertical configuration. Each vehicle is assumed to be capable of measuring at each instant of time:

1. the direction of the vertical
2. the relative distance from the vehicle above it (by interrogating)
3. the relative velocity from the vehicle above it (by interrogating)
4. the angle of the position vector of the vehicle above it with respect to the vertical
5. the angle of the projection of the position vector on the horizontal plane of the vehicle above it with respect to @math{x#}-axis of the vehicle
6. the relative distance from the vehicle below it (by interrogating)
7. the relative velocity from the vehicle above it (by interrogating)
8. the angle of the position vector of the vehicle above it with respect to the vertical
9. the angle of the projection of the position vector on the horizontal planeof the vehicle above it with respect to x-axis of the vehicle
10. the static pressure

The static pressure is an additional measurement, needed to establish that a vehicle is not too close to the free surface, or beyond the depth of operability. From the remaining measurements the vehicle can deduce the relative horizontal and vertical distances with respect to the vehicles above it and below it, which are esential for implementing the control of the virtual chain scheme.

It should be noted that all these measurements are possible through existing software, especially since the range is quite short.

SUMMARY

Multiple vehicles with coordinated behaviour to form a virtual chain offer a unique opportunity for efficient mapping and observation of large scale patterns in the ocean.

A significant element in the design of these multiple vehicles is that they must be viewed as sensors equipped with some low level intelligence and autonomy. The layered control theory is of significant help in building a simple robust control scheme for the vehicles, with minimal requirements in both initial cost and power for operation.

A central issue in the operation of such vehicles, then, is the simultaneous control of a large number of autonomous vehicles to achieve mapping of a specific ocean feature. The proposed control scheme of a virtual chain creates an equivalent passive system, hence guaranteeing stability with minimal requirements, good command following with minimal acoustic transducer requirements, and simplicity and adaptability of design.

REFERENCES

1. Bellingham J., Beaton R., Triantafyllou M. S., Shupe L., 1989, "An Autonomous Submersible Designed for Software Development", *Proceedings OCEANS* '89, Seattle, Washington.

2. Brooks R., 1986, "A Robust Layered Control System for a Mobile Robot", *IEEE Journal of Robotics and Automation*, Vol. RA-2.

3. M. S. Triantafyllou, 1988, "An Autonomous Underwater Vehicle to Study Large Vortical Patterns in the Ocean", *MIT Sea Grant Project*, July 1, 1988 - June 30, 1990.

Physics of Hydrothermal Vents

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Hydrothermal vents have been the focus of a great deal of oceanographic investigation in the past decade. In fact, much of the research effort of the deep sea submersible ALVIN, operated by WHOI for the oceanographic community, has dealt with geology, biology, and chemistry of hydrothermal vents. In order to better understand the physical processes active in the region of vents, in recent years studies have been undertaken to explore the energetics of vertical plumes which form over the very hot (temperatures in excess of 300 degrees Celsius) 'black smokers'. While the convectively-driven rise and mixing of these plumes has been documented in the field and studied in the laboratory, this is only the first step in a cascade of physical processes which occur near hydrothermal vents. Future studies are needed to identify and link together a hierarchy of larger-scale phenomena that are associated with these vent sites. In this shorter paper, I will discuss some of the important physical scales and processes that span the scales from small scale turbulence of individual plumes to the general circulation of the ocean!

CONVECTION AND VERTICAL MIXING OF RISING PLUMES

Localized sources of hot water with injection velocities of 10-50 cm/s quickly mix by entrainment of surrounding fluid so that temperature anomalies of 300° C are eroded to 1° C after tens of meters ascent into the water column. Because the ocean is vertically stratified and the rising plume is constantly mixing with denser fluid from below as it moves vertically upward into lighter fluid, its vertical ascent stops, typically a few hundred meters above the bottom. When the plume reaches a height above bottom where its density is equal to that of the surrounding fluid, the buoyancy force driving the upward motion vanishes. The plume's inertia causes its rise to continue for some distance: the convection is penetrative. These processes have been extensively modeled in the laboratory for some years, not surprisingly in view of the fact that there has been practical interest in the height of rising plumes (and their attendant pollutants) in the atmosphere. Laboratory determinations of the important 'entrainment parameter' and the relation of the maximum rise of the plume upon the heat flux at the source have been widely employed, but not critically tested, for vents. The initial area of the plume, which can be fractions of a square meter, can increase by several orders of magnitude at the equilibrium height where the density anomaly vanishes. Because mixing and buoyancy are so important in this early phase, the fact that the system is rotating is of secondary importance.

LATERAL SPREADING PHASE

When plumes reach the equilibrium level and fluid continues to arrive from below, they must spread laterally. This 'horizontal plume' is larger in extent and is more readily observed some hundreds of meters above the ocean bottom than the small-scale point sources. But what are the properties of this horizontal plume? Clearly, chemical properties injected into the water at the source and present in lower concentrations in the surrounding fluid, remain anomalous in the horizontal plume. These can be quantities such as particulates, methane, and helium. However the entrainment process described above can drastically alter properties of the horizontal plume due to the stratification in the ambient water. As an example, consider the case of temperature and salinity. In the deep Pacific Ocean north of its contact with Southern Ocean deep water, temperature increases and salinity decreases upward from the ocean bottom. Hot water with ambient salinity will mix with warmer, fresher water as it rises in the vertical plume. When it reaches its equilibrium depth, the water must necessarily have a salty anomaly due to entrainment of saltier water from below. Since the density anomaly is zero, the equation of state for seawater requires that the horizontal plume be slightly warmer than its environment. This seems reasonable and not contrary to what one might quickly predict. Consider now the deep Atlantic Ocean. In this ocean, both temperature and salinity increase upwards from the bottom. The rising plume is constantly entraining water with greater salinity. At the equilibrium height, it must be slightly lower in salinity than its surroundings making its temperature anomaly negative. Thus horizontal plumes spreading from hydrothermal vents in the Atlantic Ocean should actually be LOWER in temperature than their surroundings. Some limited observational evidence for this counter-intuitive result exists.

As I indicated above, the horizontal plume must spread, not only because there is constantly more fluid arriving from below, but because it is not in dynamic balance: horizontal pressure gradients exist that are unbalanced. As the slow spreading phase develops, fluids in the horizontal plume will move radially outward from over the source and begin to develop an anticyclonic rotation because angular momentum must be conserved. In the northern hemisphere the tendency is for the spreading fluid to be turned to the right, due to the rotation of the earth. Water below the spreading plume that is being entrained into the rising plume moves radially inward and develops a cyclonic motion (again turning to the right in the northern hemisphere). The net angular momentum of the pair of vortices thus generated is zero, but the vortex doublet consists of a pair of oppositely-rotating eddies: cyclonic near the bottom and anticyclonic in the horizontal plume. The horizontal circulation acts as a container for the water of the laterally-spreading plume.

VORTEX PHASE

Laboratory studies of vortices generated in rotating systems by buoyancy plumes indicate that a stage is eventually reached when the spreading vortex will either break up into small vortices or tilt relative to the deeper vortex. In either case, the anomalous fluid will propagate away from the source and the process will begin again. Vortex pairs of cyclonic/anticyclonic circulation can maintain their identity as they move substantial distances from the source-sort of a biological and chemical 'carrier' of information away from a particular site. Field evidence for this process near vents is very slim. Isolated anticyclonic eddies (mega-plumes) can be identified by their anomalous properties, but their cyclonic counterparts carry no readily-identifiable 'tag' except their circulation; and circulation is difficult to observe. Are mega-plumes the result of isolated explosive venting or could some of them be anticyclonic eddies generated as described above? One might make an analogy with the Mediterranean Water, initially a (negatively) buoyant plume which is observed to smoothly spread across the N. Atlantic at mid-depths. Upon closer observation, intense anticyclonic vortices (Meddies) have been observed carrying highly-undiluted amounts of source water.

OCEANIC-SCALE EFFECTS

The westward spread of helium from the East Pacific Rise indicates that hydrothermal vents can influence water properties on the scale of oceanic basins. As for the smaller-scale vortices, it appears that large-scale circulation may be generated by vent systems and even influence the spreading rates of fluid away from the vent systems. This problem has been studied mainly with theoretical models invoking planetary-scale (Rossby) waves as the agent for propagation of information. As above, the vorticity is layered in the vertical and must vanish when vertically integrated for conservation of total angular momentum. Since long planetary waves move westward there is an asymmetry in the solutions in the east-west direction. Planetary-scale plumes of temperature or density tend to move westward, even in the presence of an opposing current. If the background circulation is weak enough (slow compared with phase speed of planetary waves), the plumes spread westward and, in simple models, the deep cyclonic flow is offset by shallower anticyclonic flow and tracers can be advected zonally across an entire ocean basin by the self-generated flow. Background currents can limit this and, if strong enough, advect all of the tracers downstream. The tendency for westward influence is greatest near the equator where planetary waves have greater phase speeds than at high latitudes, all other things being equal.

SUMMARY

I hope this brief introduction to the physics of hydrothermal vents illuminates the variety of important phenomena associated with venting and broadens perspectives of important physics to be expected on a variety of physical scales. I think it fair to say that most interest has devolved on the two extremes in the above discussion, with little in the way of observations in the important middle ground.

The Role of AUV and Video Technology for Studies of Benthic Megafauna

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Much of our current understanding of the distribution and interactions of benthic megafauna (e.g., fishes, lobsters, crabs, scallops) in temperate and boreal waters, comes from studies using trawl sampling. Trawls have the inherent problem of averaging density and distribution variability over long distances. Visual techniques, such as still photography and video, overcome this problem and have been used to determine small-scale variability in density, distribution, habitat relationships, and the identification of potential intra- and inter-specific interactions based on the former factors. All previous studies have utilized either manned submersibles, ROVs, or camera sleds.

Historically, these types of small-scale studies have been limited to the use of still photographic techniques. A support platform with cameras traversed the bottom and photographs were taken at some set time interval. While this technique proved to be relatively productive, there are problems with using this type of data for understanding spatial relationships, due to spacing between successive photographs. Commercially available electronic flash units do not recycle rapidly enough to take sequential, non-overlapping (this is really a navigation problem) photographs at vehicle speeds that enhance stability in pitch, roll and altitude. Simply stated, you do not know what you missed. The use of continuous video recording alleviates this problem.

Video technology has evolved quite rapidly in the past ten years. The availability of compact, high resolution (>400 HTVL) cameras and recording systems has made their application in manned submersibles and ROV based surveys to be nearly universal. Post dive analysis is aided by the use of single frame advance VCRs and editing systems. Image analysis systems make the use of video for more rigorous measurement needs equally attractive.

Image resolution is one of the limiting factors when using any type of imaging system. Resolution of individual objects decreases with increasing altitude. For that reason oblique photography adds several benefits for quantitative imaging in general and video in particular. It is possible to maximize area of coverage at relatively low altitudes, increasing resolution in the nearfield portion of images. When using video, it is possible to scroll the video forward to identify individuals in the farfield when, using still images, this would be impossible and data quality would be sacrificed. Along this same line of reasoning, it is possible to identify individuals at much smaller sizes in the nearfield with oblique images. Forward looking imaging systems allow for assessment of vehicle avoidance by the species of interest. Depending upon horizontal visibility, it is possible to enumerate and compare species densities in the farfield and nearfield of a series of images. Also, imaging at oblique angles is optimal for recording identifying characteristics of many species and lighting can be optimized to highlight surficial characteristics of the substrate.

Many types of data can be collected from a series of recorded images, for example:

1. species composition
2. species abundance
3. spatial relationships of individual organisms
4. faunal-habitat relationships
5. size distribution of organisms
6. interspecific associations
7. scales of patchiness

and with additional sensor data:

8. the distribution of organisms in relation to specific oceanographic features
9. the activities of organisms in relation to light intensity, oxygen concentration, turbidity, current velocity, etc.

The following table summarizes the scientific needs and AUV system requirements to perform biological imaging missions related to megafaunal organisms:

DATA REQUIRED	HARDWARE REQUIRED	CONTROL NEEDS
Images to ascertain the distribution of organisms.	High resolution video camera, video recording system with capabilities to meet the dive profile (i.e., single or multiple VCRs for sufficient recording time), lighting.	Variable recording time from 1 sec. to capacity of tape system. Control system must also manage lights, sensor data acquisition and navigation data acquisition.
Time and position when images were recorded.	Time code generator, navigation system.	Position, altitude, pitch and role within predetermined parameters.
Environmental data such as CTD, fluorometer, oxygen, turbidity, light.	Suite of sensors with datalogger which are keyed to the time.	Sample acquisition timing keyed to video acquisition and available memory.

In order for an AUV to support the type of diving profile which we have used to collect megafaunal abundance and distribution data, the system should have the following capabilities in addition to those stated above:

1. maintain 0.5 m altitude (or less)
2. conduct transects at approximately 25 cm s (-1)
3. low mounted lights to highlight surface topography
4. obliquely mounted video camera to cover 1-2 m (2) per video frame
5. variable path trajectories (e.g., straight line, square wave) in order to accommodate different survey designs.

The current state-of-the-art in video technology makes the marriage of video and AUV systems, with supporting control architecture, attractive to the biologist. There is not always a need for real-time viewing of the survey area. AUVs could be used in conjunction with other systems such as manned submersibles or ROVs for wither pre-dive assessment of an area or post-dive surveys after initial reconnaissance. AUVs could be launched from surface standard oceanographic sampling (e.g., grabs, net tows). However, as we are finding with ROV technology, successful demonstrations of AUV capabilities will be the only way to convince the mainstream scientific community that AUVs are reliable systems for the collection of useful biological data.

References to Use as Examples of the Types of Imaging Tasks Similar to Those Described Using Manned Submersibles and ROVs

Auster, P.J., L.L. Stewart, and H. Sprunk. 1989. Scientific Imaging with ROVs: tools and techniques. Mar. Technol. Soc. J. 23(3): 16-20.

Auster, P.J., R.J. Malatesta, S.C. LaRosa, R.A. Cooper, and L.L. Stewart. 1991. Microhabitat Utilization by the Megafaunal Assemblage at a Low Relief Outer Continental Shelf Site-Middle Atlantic Bight, USA. J. Northw. Atl. Fish. Sci. 11:59-69.

Caddy, J.F. 1976. Practical Considerations for Quantitative Estimation of Benthos from a Submersible. p. 285-298. In: Drew, A., Lythgoe, J.N. and J.D. Woods (eds.). Underwater research. Academic Press, New York.

Grassle, J.F., H.L. Sanders, R.R. Hessler, G.T. Rowe, and T. McLellan. 1975. Pattern and Zonation: a Study of the Bathyal Megafauna Using the Research Submersible Alvin. Deep-Sea Res. 22:457-481.

Hecker, B. 1990. Variation in Megafaunal Assemblage on the Continental Margin South of New England. Deep-Sea Res. 37:37-57.

Holme, N.A. and R.L. Barrett. 1977. A Sledge with Television and Photographic Cameras for Quantitative Investigations of the Epifauna on the Continental Shelf. J. Mar. Biol. Assoc. U.K. 57:391-403.

Holme, N.A. and J.B. Wilson. 1985. Faunas Associated with Longitudinal Furrows and Sand Ribbons in a Tide-swept Area in the English Channel. J. Mar. Biol. Assoc. U.K. 65:1051-1072.

Kaufmann, R.S., W.W. Wakesfield, and A. Genin. 1989. Distribution of Epibenthic Megafauna and Lebensspuren on two central North Pacific Seamounts. Deep-Sea Res. 36:1863-1896.

Langton, R.W. and J. R. Uzmann. 1989. A Photographic Survey of the Megafauna of the Central and Eastern Gulf of Maine. Fish. Bull., U.S. 87:945-954.

Langton, R.W. and W.E. Robinson. 1990. Faunal Associations on Scallop Grounds in the Western Gulf of Maine. J. Exp. Mar. Biol. Ecol. 144:157-171.

Lough, R.G., P.C. Valentine, D.C. Potter, P.J. Auditore, G.R. Bolz, J.D. Neilson, and R.I. Perry. 1989. Ecology and Distribution of Juvenile Cod and Haddock in Relation to Sediment Type and Bottom Currents on Eastern Georges Bank. Mar. Ecol. Prog. Ser. 56:1-12.

Wakefield, W.W. and A. Genin. 1987. The Use of a Canadian (perspective) Grid in Deep-Sea Photography. Deep-Sea Res. 34:469-478.

Recent Developments and Trends in Fiber Optic Chemical Sensors

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The advent of optical fibers has initiated a revolution in telecommunications technology and is producing a subsequent and possibly equal impact on chemical sensor technology. The optical fiber functions as a conduit for light and can be used to monitor changes in absorbance, reflectance, chemiluminescence, and fluorescence. With fiberoptic chemical sensors, an optical signal change such as light intensity or color is monitored. Light of an appropriate wavelength is focused into the optical fiber through appropriate coupling opticals. Light travels efficiently to the end of the fiber, where it exits and interacts with an indicator layer. The indicator layer is designed to respond reversibly such that the light's color or the intensity changes in response to a change in the analyte concentration. In the absence of analyte, the indicator reverts to its original state. After modification by the indicating layer, the light returns through the same or a different fiber to a detector which correlates the degree of change with the analyte concentration of interest.

Since optical fibers can be many meters in length, are flexible, have diameters typically 125-1000 μm, and have low signal attenuation over many hundreds of meters, the potential for performing continuous spectroscopy in previously inaccessible or remote sites is now available. Fiber optic sensors offer advantages over electrochemical sensors. Their sturdy and simple construction permits placement in harsh environments. They are immune to electromagnetic interference, and require no reference electrode. The low cost of optical fibers permits the sensors to be disposable. Among the potential large-scale applications are *in-situ* monitoring of toxic waste sites, *in vivo* monitoring of blood gases, and *in situ* process control monitoring. The very significant potential for clinical diagnostic applications is also being pursued actively. Finally, they may be an extremely important tool for measurements in previously inaccessible locations.

Fiber optic sensors are classified as intrinsic or extrinsic sensors. With an intrinsic sensor the optical fiber itself acts as an optical component and is modulated directly by the change in a physical parameter, thus altering the transmitted light. Intrinsic sensors exist for the measurement of temperature, magnetic fields, acoustics, strain and electrical current as well as other physical parameters.

An extrinsic sensor is used in association with an optical transducer. The transducer must induce a optical signal change (absorption, fluorescence or reflectance) in response to the selective detection of an analyte in a complex mixture. A pH-dependent fluorescence intensity change is typical transduction mechanism. The indicating material can be in a sample that is viewed through a window *via* the optical fiber, such as in a flow injection analysis sensing scheme used for process control. Although such applications will be an important part of optical sensor technology, the more demanding approach is to prepare extrinsic sensors having the reagent phase attached directly to the fiber tip, a requirement for *in vivo* and *in situ* applications.

A variety of fabrication schemes for coupling the transducer to the fiber tip have been employed. Chemically-selective reagents have been contained within analyte-permeable membranes or tubing that cover the end of the fiber. Sensors have been prepared by attaching a glass bead on the tip of a fiber with the reagents adsorbed or bound to the bead. A variety of polymers and resins have been used with the sensor material adsorbed to their surface. The bare optical fiber is then placed in contact with the material and fixed by sealing with a membrane. Alternatively, indicator-containing polymer layers can be attached directly to the fiber tip.

The major thrust in sensor development today is directed to developing sensing layers which contain selective recognition elements. These may include indicators and ionophores (ion binding compounds), as well as a wide variety of selective polymeric materials. Chemistry, however, is not the only field from which selective recognition elements can be obtained. Recently, biological recognition elements including enzymes and antibodies, have been incorporated into sensors. Sensors employing biological recognition elements are referred to as biosensors. These sensors are used most frequently to detect organic materials including small organic molecules, proteins, nucleic acid based materials, and microorganisms. The most difficult aspect of developing a biosensor is to couple the selective catalysis of the enzyme or selective binding of the antibody to a transduction signal. In many cases, rather sophisticated combinations of enzymes, polymers, indicators, and electron transport mediators are employed to accomplish this coupling.

EQUILIBRIUM VS. STEADY STATE SENSORS

Sensors ideally should be constructed to operate continuously. Conventionally, this requires the use of reversible (i.e. equilibrium based) indicating chemistry. Despite the advantages of basing analytical measurements on continuous sensors employing reversible chemistry, the number of such systems is limited. There are only a few sensors that possess the proper selectivity, sensitivity in the concentration range of interest, dynamic range and reversibility to be used continuously. There is, however, an extensive body of well-established chemistry that can be employed in the conventional discrete sample approach. Many analytical measurements are performed by measuring precise amounts of sample and reagent and allowing a chemical reaction to occur. Usually this reaction generates a color change which can be monitored spectrophotometrically. The degree of color change then correlates to the concentration of analyte in the sample. These reactions are usually thermodynamically irreversible—they form extremely high binding constant complexes, generate gaseous by-products, or undergo a favorable chemical transformation. The net result is to generate a chemical adduct that cannot be returned to its original state, hence they are irreversible. In order to make a subsequent measurement, fresh reagents and sample must be mixed again.

Many of today's measurement needs require continuous monitoring to adequately follow the process or fluid stream being measured. Although frequent sampling can partially address this need, concentration spikes invariably occur and will be missed in a discrete sampling mode. For some applications, such as sea water analysis, frequent sampling may not be possible. In order to exploit irreversible chemistry in a continuous mode, fresh reagent must be brought into contact with fresh sample solution continuously.

A variety of approaches can be taken to deliver reagents including peristaltic pumps, osmotic pumps, and controlled release polymers. This approach greatly expands the utility of optical sensors to sea water measurement needs. It ultimately may enable recognition chemistry previously relegated to land based laboratories, such as immunoassays, to be used at sea.

FIBER OPTIOC SENSOR FOR $_pCO_2$ IN SEA WATER

Measurement of the partial pressure of CO_2 gas in sea water ($_pCO_2$) is a fundamental ocean chemical need, usually accomplished by gas chromatography or infrared spectrometry. Both of these techniques require large, complex and power demanding apparatus. We have explored the possibility of developing and using small, low-power instruments in conjunction with fiber optic sensors.

We have developed and tested a prototype pCO_2 sensor for sea water based upon the fluorescence of a dye combination encapsulated within a gas permeable silicone membrane at the tip of a single optical fiber. The optical module delivers 30 Hz chopped white light to a filter and is passed through a dichroic mirror. This light is then focused on to a 220 µm optical fiber. The fiber, approximately 2 m long, was terminated with a standard coupler equipped with a small silicone nipple. The internal volume of the sensor tip (about 10 µl) was filled with a combination of a fluorescent indicator and two absorbing dyes so as to achieve the required sensitivity. Illumination and fluorescent light was returned through the same fiber, reflected at 90 (degrees) by the dichroic mirror, passed through an interference filter and focused on to a sensitive silicon photodiode.

Experiments were carried out both in the laboratory on standard solutions, and at sea. Comparison at sea with gas chromatographic measurements of pCO_2 on recovered samples showed a precision of 3 percent in the range 400-500 ppm pCO_2. To our knowledge, this is the first demonstration of an optical pCO_2 sensor for detecting oceanic signals. This technology is complementary to optical detection of pH and points the way towards full characterization of the CO_2 system within this measurement framework.

WHAT ELSE CAN BE MEASURED?

To date chemical fiber optic sensors have been developed to measure a diverse array of analytes including pH, O_2, CO_2, Na^+, K^+, Ca^{+2}, Mg^{+2}, urea, glucose, penicillin, hydrocarbons, chlorinated hydrocarbons, antibodies, and various other ions and drugs. Each of these sensors is sensitive over a fairly narrow range of concentrations. Furthermore, the precision varies with the particular indicator chemistry employed. Sea water is unique as compared to samples encountered in medicine, chemical processes, and the environment. Consequently, sensors designed to measure analyte concentrations in sea water must be able to do so at high ionic strength, potentially high pressure, and in the presence of a complex milieu of possible interferents. Furthermore, the trace levels of many analytes may challenge the detection limits of the indicating chemistries.

THE FUTURE OF FIBER OPTIC SENSORS FOR SEA WATER MEASUREMENTS

Unlike sensors based on other transduction mechanisms, optical sensors can be constructed with an internal reference signal. Indicators with dual spectral peaks can be employed which allow for ratiometric, rather than signal intensity, measurements to be implemented. This feature enables calibration-free sensors to be prepared that do not drift after deployment—a significant advantage over other types of sensors.

Recent efforts have been made at developing multiplexed fiber systems. These systems possess either sensors with multiple chemistries for multiparameter analysis or arrays of identical sensors for spatial resolution of analyte concentration. The latter approach may ultimately be useful for looking at fine-scale dynamics in sea sediments.

Fiber optic sensor systems are comprised of three components—the sensor, coupling optics, and signal processing system. Sensors can be hundreds of meters or more in length without significant signal attenuation. The coupling optics and signal processing systems can be remote from the active sensor tip providing potential protection from fouling and corrosion problems with submerged instrumentation. The signal processing and data storage and transmission problems posed by multiplexed continuous sensors are daunting.

Assuming that problems of biofouling and corrosion can be addressed adequately, the challenge is to develop low power autonomous instruments coupled to optical fiber sensors with the appropriate selective indicating chemistry. These sensors could be towed at different depths or may be deployed on autonomous buoys for long time series measurements. Fiber optic sensors are only now coming into their own for solving measurement problems. Although much basic chemistry and engineering remains to provide autonomous, self-calibrating, continuous sensing systems, the advantages of using optical sensors for monitoring remote harsh environments are many. Consequently they should be used at an increasing pace for ocean measurement needs.

In-situ Chemical Detectors for Potential Use on Autonomous Underwater Vehicles

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Autonomous underwater vehicles (AUVs) serving as platforms for *in-situ* chemical detectors and samplers will allow oceanographers to acquire important data that is currently not obtainable from existing methods. Potential datasets include not only continuous profiles and time series data, but also data for the study of specific water masses, particles, and small-scale processes. Other examples include nutrient data collected during storm events and under-ice environments, which are nearly impossible to obtain from ships. Furthermore, intelligent AUVs can be programmed to "sniff out" locations such as hydrothermal vents and sewage outfalls (Blidberg and Sedor, 1991). Although AUVs can also be fitted with sample collectors, *in-situ* chemical detectors will likely offer the greatest benefits.

The main advantage of *in-situ* analyses is the ability to collect high resolution data with an affordable investment of time and money. Such high resolution information is required to resolve small-scale processes that could otherwise not be detected by conventional sampling methods (e.g. Coale et al., 1991). Similarly, high resolution long-term data sets will allow for a better understanding of temporal events (e.g., Dickey et al., 1991). *In-situ* detection also minimizes the probability of chemical changes in the sample due to reactions or contamination that can occur during transfer and storage of conventionally collected samples, which are well known for both trace elements and dissolved gases. Another advantage is that analyzers have an inherently rapid response time (ca. 10 sec. to 30 min.). Direct feedback, therefore, allows on-board decision making for more flexible and efficient research.

The most common type of sensors are electrochemical membrane sensors, including the glass pH and the Clark-type oxygen electrodes. Other membrane sensors use optical fibers and require a reversible, color-producing reaction in a closed volume separated from seawater by a semi-permeable membrane (e.g., CO_2: Walt, 1991 and this meeting; Goyet et al., 1991). Others use immobilized substrates with a very specific affinity for dissolved constituents, which are bonded to the ends of glass fibers (optrodes; Seitz, 1984; Wolfbeis et al., 1988) or piezo-electrical detectors (e.g., Ward and Buttry, 1990). Advanced sensors using semiconductor technology (ChemFETs) may prove useful in the future.

Another approach to *in-situ* chemical measurements involves the modification of conventional wet-chemical analyses to operate *in-situ*. These *analyzers* (vs. *sensors*) are based on the principles of flow injection analysis (Ruzicka and Hanson, 1988), where sample and reagents are pumped together to produce a chemical species which can be quantified in a flow-through detector. The difference between sensors and analyzers is that analyzers move the sample through the instrument (to allow the adding of reagents etc.) while sensors rely on diffusion of the substrate through a membrane or onto a surface. Although *in-situ* chemical analyzers require pumps and liquid reagents, they are not dependent on reversible chemistries and they are relatively immune to biofouling of membranes and binding surfaces.

Furthermore, such chemical analyzers can draw on decades of experience with well-proven reactions that are used extensively in the laboratory. Another important advantage is that these analyzers can be self-calibrated, which is desirable because of changing temperatures and pressures and instrumental drift over extended periods of time.

Submersible continuous flow systems using peristalic pumps have now been successfully deployed for profiling nutrients (e.g., Johnson et al., 1986; 1988; 1989) and trace elements (e.g., Coale et al., 1991). Peristalic pump analyzers have a $1/e$ response time of less than 10 seconds, which allows the instrument to resolve features as small as 5 m at a typical velocity of 40 m min^{-1}. High accuracy can be achieved with these systems because they can be easily recalibrated *in-situ* by switching between analyses of seawater and standard solutions. The detection limits obtained when analyses are performed *in-situ* are usually compared to, or better than, can be achieved in the laboratory. Peristalic pump analyzers, however, are not well suited for deployments longer than several days. The primary difficulty arises from the limited life of the flexible pump tubing.

For longer deployments, analyzers require mechanical simplicity to ensure reliability and minimum power requirements. For long-term use, therefore, either stop-flow technology or low flow-rate pumps must be used. We are now developing miniature continuous flow analyzers using osmotic pumps (Jannasch and Johnson, in press). Fluid flow in these pumps is driven by an osmotic pressure differential across a semipermeable membrane, and is typically 1 to 10 $\mu l\ hr^{-1}$. By maintaining solutions of different salinities across the membrane, the osmotic pressure will drive the pumps with no external power source. Flow rates are dependent only on the size and type of membrane, the osmotic pressure and temperature.

We have used these pumps to build several nitrite and nitrate analyzers which have run continuously for several months in the laboratory, and are now being tested in seawater. The basic nitrate analyzer, complete with a standard addition system but excluding the control electronics, measures approximately 8 x 16 x 16 cm. The present system is capable of measuring nitrate concentrations from 0.3 to 50 μM with a standard curve fit of r^2=0.997. The analyzer's response rate is approximately 20 to 30 min. and has a reproducibility within about 3% >10μM. To lengthen the duration of the commercially available osmotic pumps, we are also working on developing similar pumps with larger capacities. Two prototype 100 ml volume osmotic pumps have now been running continuously for over 14 months in the laboratory. Thus, there appears to be no significant mechanical impediments to building *in-situ* analyzers that operate for year-long time periods.

We are currently also adapting new chemistries for a wider variety of elements, including long-term PO_4, Mn and Fe analyzers. Although the colorimetric Mn and Fe method are not sensitive enough for open-ocean concentrations, their main purpose is for temporal studies of hydrothermal systems. We are also investigating new multi-wavelength detectors suitable for *in-situ* use for CO_2 and pH measurements.

In the future, stop-flow systems may also prove useful for AUV technology. These are batch-analysis systems that can be activated at any time while remaining dormant when not needed. A syringe pump system, being developed at MBARI for shipboard use, will be adapted to run *in-situ* in the future. This system is significantly more precise and accurate, can sample relatively quickly, but needs more power and space. Similarly, a gear-type micropump analyzer built by T. Whitledge (personal comm.) has been used for up to six weeks in coastal waters, and could be modified for AUVs.

The main differences among these various sensors and analyzers can be described by their inherent characteristics including response time, precision, duration, size, power requirements and cost. Table 1 shows an abbreviated summary of different chemical detectors and samplers currently available and under development, and some of their limitations.

As we are now reaching the limit of knowledge which can be gained by conventional methods, new types of analyzers and sensors, as well as platforms to deploy them, are needed to increase both the spatial and temporal resolutions of data. In any case, AUV-mounted *in-situ* instruments will likely become a common method for collecting data in the future.

REFERENCES

Blidberg, D.R. and G. Sedor. (1991). Workshop results from an interdisciplinary workshop to assess the scientific needs for a long-range autonomous underwater vehicle. Marine Systems Engineering Laboratory, University of New Hampshire.

Coale, K.H., C.S. Chin, G.J. Massoth, K.S. Johnson, and E.T. Baker. (1991). *In-situ* chemical mapping of dissolved iron and maganese in hydrothermal plumes. Nature.

Dickey, T., J. Marra, T. Granata, C. Langdon, M. Hamilton, J. Wiggert, D. Siegel and A. Bratkovich. (1991). Concurrent high resolution bio-optical and physical time series observations in the Sargasso Sea during the spring of 1987. J. Geophys. Res. 96, 8643-8663.

Goyet, C., D.R. Walt and P.G. Brewer. (submitted). Development of a fiber optic sensor for measurement of pCO_2 in seawater: Design criteria and sea trials.

Jannasch, H.W. and K.S. Johnson. (in press). *In-situ* instrumentation for dissovled nutriesnt and trace metal analyses in seawater. *Proceedings of the MARCILEM '91 Workshop on Marine Chemistry.* S.J. Martin, L.A. Codispoti and D.H. Johnson, eds., ONR report No. OCNR 12491-18.

Johnson, K.S., C.L. Beehler, and C.M. Sakamoto-Arnold. (1986). A submersible flow analysis system. Analytica Chim. Acta, 179, 245-257.

Johnson, K.S., J.J. Childress, R.R. Hessler, C.M. Sakamoto-Arnold, and C.L. Beehler. (1988). Chemical and biological interactions in the Rose Garden hydrothermal vent field, Galapagos Spreading Center. Deep-sea Research, 36, 1407-1413.

Ruzicka, J. and E.H. Hanson. (1988). *Flow Injection Analysis*. 2nd edition, Wiley-Interscience, New York, 498p.

Seitz, W.R. (1984). Chemical sensors based on fiber optics. Anal. Chem. 56, 16A-35A.

Walt, D.R., G. Gabor, C. Goyet, and P. Brewer. (1991). High resolution CO_2 seawater measurements using multiple indicator fiber optic sensors. (submitted).

Ward, M.D., and D.A. Buttry. (1990). *In-situ* interfacial mass detection with piezoelectric transducers. Science, 249, 1000-1007.

Wolfbeis, O.S., L.J. Weis, M.P. Leiner and W.E. Zeigler. (1988). Fiber optic fluorosensor for oxygen and carbon dioxide. Anal. Chem. 60, 2028.

Table 1: Samplers, chemical analyzers and sensors for potential use on AUV's

Samplers	Duration	Response time	Power req.	Size (liter)	Avail.	Reference
1 Syringe samplers	(2)	<1 min	low	1-10 l	Exist	Friederich and Codispoti
2 Bottle samplers	(2)	<1 min	low	large	Exist	General Oceanics
3 Peristaltic sampler	(2)	1 min	med	10 l	2 yrs	Codispoti and Friederich (in development)
4 Suspended matter samplers	(2)	mins-hrs	High	2-5 l	Exist	Many exist
5 Extraction samplers (Th)	(2)	mins-hrs	High	2-5 l	Exist	e.g., Buessler, Murray
Analyzers (3)						
1 With peristaltic pumps	1-2 days	<1 min	High	30 l	Exist	Johnson et al. (1986...)
2 With micro-pumps	2-6 weeks		High	30 l	Exist	Whitledge (unpublished)
3 With syringe pumps	~10K samples	1-10 min	medium	10 l	2 yrs	Friederich (in development)
4 With osmotic pumps	1-12 months	30 min	low	2 l	1 yr	Jannasch and Johnson (1991)
Sensors						
1 Salinity (by inductance)	months	fast	medium	1 l	Exist	Many in production
2 Salinity (by conductivity)	months	fast	low	1 l	Exist	Many in production
3 Clark oxygen electrodes	days (4)	fast	low	<1 l	Exist	Many in production
4 pH electrodes	days (4)	fast	low	<1 l	Exist	Many in production
5 Fiber optic CO_2 (pH dye)	1+ days	minutes	medium	<5 l	Exist	Brewer/Walt/Degrandpre
6 Chlorophyll (by fluourescence)	weeks	fast	medium	5 l	Exist	Several in production
7 Mn (fiber optical)	?	fast	low	5 l	?	Gary Klinkhammer
8 Organics (by scanning fluourescence)	?	minutes	medium	5 l	?	Kenneth Mopper
9 Organics (by decay of fluourescence)	?	minutes	medium	5 l	?	Steve Lieberman
10 Mass (piezo-electric detectors)	?	fast	low	1 l	?	Dan Buttry

(1) Size is in liters without controlling electronics.
(2) Samples may need to be preserved.
(3) NO_3, PO_4, Si, high levels of Fe and Mn
(4) Electrodes are generally not stable over periods >1 day.

Applications of Autonomous Underwater Vehicles to the Offshore and Gas Industry

Professor J. Robert Fricke
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The oil and gas industry is a large, diverse body of science and technology focused on the production of petroleum products for public use. Autonomous vehicles, marine and otherwise, may someday play a large role in many aspects of oil and gas production. The following three suggestions are but teasers and suggest a few of the vast number of autonomous vehicle applications. Two of the applications are truly marine and can rightfully be called Autonomous Underwater Vehicle (AUV) systems; these are a seismic acquisition crawler and a pipeline inspector. The third application, a storage tank inspector, is not truly marine but draws from a technology base common to AUV's. In all the cases presented here, there exists an evolutionary path leading from the present to the ultimate system design. This workshop, a blend of industry and academia, is a logical and important step along the way.

SEISMIC ACQUISITION VEHICLE

Detailed three-dimensional seismic mapping has become an accepted tool for reservoir development, production, and to some extent, monitoring of enhanced oil recovery. Due to the presence of production platforms, collecting such data in existing offshore fields is a major operational problem using conventional acquisition methods. The first application, then, is an autonomous seismic tow point.

The system design consists of a crawling autonomous vehicle to which a bottom seismic cable is tethered; deployment and operation proceed as follows. The crawler is deployed from a surface ship with its seismic cable attached. Upon reaching the bottom the crawler navigates itself into position using an acoustic network that has previously been deployed and calibrated. When a designated position is reached the crawler signals the mothership, which is also the seismic source ship, that it is in position and is prepared to collect data. The source ship commences a shooting program around the stationary cable while the crawler, which also contains the data acquisition instrumentation, collects and stores the seismic data. A relatively low data rate acoustic link permits the crawler to deliver quality control data to the source ship. This quality control feedback permits the source ship to adjust shooting parameters as necessary or to command the data acquisition system on the crawler to modify the acquisition parameters--all in an effort to optimize the data quality.

The benefits of such a system derive from the fact that the source ship is relatively unencumbered, with only a source array in tow. It can maneuver around the stationary cable, coming quite close to production platforms if necessary, and filling in a 3-D shooting schedule. Upon completion of the shooting schedule, the crawler moves the cable to a new position and the shooting continues, alternating shooting and cable moving until the full 3-D survey is complete. Other benefits offered by this system are extremely quiet hydrophones and the ability to shoot through the surf zone, another notoriously difficult mission for conventional seismic methods.

Some of the technology needed to realize such a system is already in place. Bottom seismic cables are currently used, though decoupling the tow-ship heave motion is problematic; autonomous crawlers are used for pipeline inspection; underwater acoustic modems have been developed for a variety of command and control applications; remote acquisition and storage is done routinely in radio telemetry seismic acquisition systems; and precise positioning is now routine, using long baseline acoustic networks.

PIPELINE INSPECTION VEHICLE

Transco Energy, a major gas pipeline company, alone has over 2700 km of pipeline in the Gulf of Mexico. Counting all the pipeline mileage, both oil and gas, there is on the order of 100,000 km in the Gulf. World-wide there may be many times more. The safety, environmental, and economic aspects of leaks from these pipelines is a major issue to the pipeline owners and to the offshore oil and gas industry as a whole.

The second application discussed here is an autonomous inspection vehicle that swims along offshore pipelines from platform to platform, navigating the web of pipes, monitoring the state of the pipeline as it goes. A sensor package, developed from existing technology, would be deployed on the vehicle permitting it to check for depth of burial, wash-outs, and leaks. Presently, depth of burial is determined by a magnetic gradiometer; wash-outs are detected by laser or sonar sector scanners; leaks are detected either by chemical analysis of the sea water, so-called sniffers, or by passive acoustic detection or both. At the end of an inspection run the vehicle would check in at a docking facilities on one of many designated platforms. It then refuels, transfers data from its inspection run, disengages, and proceeds to the next leg of the survey.

A system consisting of many such vehicles offers the benefit of quick leak detection, should any occur. This is especially important for small leaks, since large leaks are already detected by pressure and flow monitoring equipment; presently many small leaks go undetected for long periods of time. A system of autonomous inspectors would enable the pipeline companies to respond quickly and provide remediation at a precise location before the leak became a major problem. As an example of the system capability consider that a total of 15 vehicles operating at 5 knots could inspect 100,000 km of pipeline, approximately that in the Gulf of Mexico, in one month. The inspection process could operate continuously for maximum protection against leaks.

All the sensors mentioned above are presently used in support of pipeline inspection. In fact, an autonomous crawler is already used to determine depth of burial for pipelines in waters shallower than 20 feet. The crawler maintains its path by following the magnetic signature of the buried pipe. Currently available sniffer technology was developed for use on surface ships; the technology is based on gas chromatographic (GC) analysis and cannot be directly implemented on an AUV. Another chemical analysis method, which can be automated and operated at depth, must be developed to replace the GC analysis. Passive acoustic leak detection, however, is in common practice now and is deployed both via ROV's and by divers. It would be relatively easy to package the system for an AUV deployment. Navigation would be handled by a combination of magnetic tracking on the pipeline and bottom tracking with a doppler sonar to provide input for a dead reckoning system between platforms. Acoustic beacons at the platforms would provide geodesic benchmarks for updating the on-board navigation system.

STORAGE TANK INSPECTION VEHICLE

Above-ground tanks are used to store a variety of materials ranging from water to antifreeze to hydrocarbons. If a spill is to be prevented, these tanks must maintain their integrity. The fact that many tanks are part of a manufacturing or processing stream and are reluctantly pulled out of service complicates matters. The real problem is the tank bottoms; they are inaccessible, and they are in contact with the ground, which promotes corrosion. Currently, to inspect a storage tank requires taking it out of service, draining it, cleaning it, disposing of the sludge, and checking the bottom of the tank using ultrasonic thickness gauges and visual inspection. This is an expensive process.

The third application discussed here, that of an autonomous storage tank inspector, is not strictly an underwater application, but uses much of the same technology. The concept is to introduce a vehicle into the tank, have it navigate over the bottom, make ultrasonic thickness measurements, use passive acoustics to detect leaks, and if possible, take photographs for visual inspection. There are several issues involved in the logistics of such an operation: avoiding the internal superstructure of the tank, navigating in a closed reverberant field, dealing with the sludge on the bottom, and others. The advantage of such a system, however, is that the storage tank can remain in service during the operation, and this fact provides a strong incentive to develop an autonomous inspector.

The vehicle design would draw on many technologies that are already in use. The pipeline industry uses "pigs" that move through pipelines and do a variety of tasks including internal cleaning and maintenance. Some of these pigs are very sophisticated, with on-board computers to monitor and log the operation. The autonomous inspector is an extension of this technology to a free swimmer. Regarding the sensor package, ultrasonic inspection is already common in the industry as is passive acoustic detection. As discussed above, the ultrasonic inspection currently requires a drained tank, which is avoided by the vehicle approach. The current implementation of passive acoustic detection is based on a system of hydrophones place around the perimeter of the tank. The system listens for leak noises and tries to compute the location by correlation techniques. There is ambiguity in the process, both in terms of the ability to identify a sound as a leak and in the ability to localize the sound source. Again, a vehicle approach would overcome these problems. One remotely operated vehicle with some of the indicated capability is currently under development. A prototype has been used to inspect the bottom of a water tank, proving the concept in controlled circumstances. A natural evolution of this development is a completely autonomous vehicle.

SUMMARY

The systems discussed here are but a few of many possible applications in the oil and gas industry for AUV's. As seen by the suggestion of an autonomous storage tank inspector, the applications for this technology are not strictly limited to marine environments. While commercial autonomous vehicles are uncommon at this time, the sensor systems that they could carry are not. In developing autonomous systems, these sensors will be modified to allow for automatic data analysis, interpretation, and storage. The integration of vehicle systems and payload sensor systems is the challenge of AUV design, and though the road from initial concept to a production vehicle is uncertain, it is passable. Let us begin.

Micro-Magnetic Field Measurements Near the Ocean Floor

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BACKGROUND: MARINE MAGNETIC ANOMALIES

The study of marine magnetic anomalies has played a major role in the discovery and understanding of plate tectonics. In the early 1960's earth scientists (through dating and paleomagnetic studies of terrestrial lavas) discovered that the Earth's magnetic field had reversed polarity frequently in the past in a very regular manner. A crude timescale was pieced together using this reversal history [e.g. Cox, Doell & Dalrymple, 1964]. Meanwhile, marine scientists had noticed that the newly discovered midocean ridges were marked by significant magnetic anomalies that persist away from the ridge crests in a systematic pattern of "magnetic stripes". These two observations led Vine & Matthews [1963] to hypothesize that the ocean crust acts as a tape recorder of the Earth's magnetic field. As newly-formed ocean crust at a midocean ridge cools below the Curie temperature (150-580 degrees C), it becomes magnetized by the ambient magnetic field. This crust then moves out of the formation zone through the process of seafloor spreading to become part of the oceanic lithospheric plate. The positive magnetic stripes form during normal polarity periods and the negative stripes during reversed periods. This pivotal idea provided confirmation of the theory of plate tectonics and continental drift. Unlike on land, the marine magnetic anomalies provide a virtually continuous record of the Earth's magnetic field for the past 200 Myrs. The correlation of the terrestrial magnetic reversal timescale with the marine record produced the Geomagnetic Polarity Timescale. This timescale has allowed scientists not only to accurately date the ocean basins and unravel their tectonic history but also to obtain a detailed record of the Earth's magnetic field behavior.

Although marine magnetic anomalies have become an indispensable tool in marine geophysics, a number of important issues remain unresolved. The crustal source region of these anomalies remains a subject of continued controversy. Some models define the uppermost volcanic extrusive layer (ca. 500 to 1000 m thick) as the source layer, whereas other models suggest a significant contribution from the deeper intrusive dike and gabbro layers that compose the remainder of oceanic crust. Another fundamental question that remains to be answered is the source of the Earth's magnetic field itself. No convincing models of the geodynamo have yet been demonstrated that can satisfy all of the observations.

MEASUREMENT OF MARINE MAGNETIC ANOMALIES: SEA SURFACE MAGNETICS

Typically a sea surface magnetic survey involves a ship towing a proton precession magnetometer behind it at speeds of between 4 and 10 knots. The regional magnetic field (International Geomagnetic Reference Field) is removed from the data, which can then be either forward modelled with a block magnetization model or inverse modelled to compute magnetization. The final magnetization signal is compared to the Geomagnetic Polarity Timescale to identify the appropriate anomalies and to determine ages. The spatial resolution of the magnetic signal is approximately equal to the water depth, typically about 3 or 4 km. For seafloor created at a medium spreading rate of 30 km/Myr, a 3 km wavelength is equivalent to a time interval of about 0.1 Myr. The average reversal rate is approximately 0.3 Myrs of the Earth's magnetic polarity reversal history. Spectral topography contributes significantly to the magnetic field at wavelengths less than 2 km [Miller, 1977]. Thus, the sea surface data is relatively free from the effects of topography. It is clear, however, that short polarity events (on the order of 0.1 My or less) are severely filtered when measured at the sea surface. This missing signal is important to understanding the source of the geomagnetic field. The advantages of sea surface magnetic surveys are that they are fast, easy to accomplish, and provide an adequate signal both in terms of amplitude and resolution that is geologically meaningful. The main disadvantage is that sea surface data represent a filtered version of the geomagnetic signal with little or no contribution from short reversals.

NEAR-BOTTOM MAGNETICS

Near-bottom surveys provide an opportunity to improve the resolution of marine magnetic measurements by measuring the anomalies closer to their source. To date, this kind of measurement has been accomplished using either deep-towed vehicles or manned submersibles. There are a number of advantages to both of these methods, but also several logistical disadvantages. The advantage of getting closer to the magnetic source is that the spatial filtering effect is reduced to 100's of meters instead of 3 or 4 km (or several 1000's of years compared to 0.1 Myrs at a 30 km/Myr spreading rate). This finer resolution provides a more accurate record of the polarity reversal history than is possible with sea surface data. Closer to the source also means stronger amplitude signals, which is more important in equatorial regions where diurnal magnetic variations can be of the same magnitude as the crust signal. Although the magnetic signal is improved a greater percentage of this signal is "contaminated" with bathymetric and shallow crustal magnetic variations. Significant post-processing is required to analyze these near-bottom datasets and separate the various signals. Furthermore, the 2-dimensional assumptions used in analyzing the sea surface data must be used with caution in the near-bottom environment where topography becomes more 3-dimensional. Logistically, deep-towed surveys are complex operations. The long cable lengths, cable drag, slow tow speed (1 to 2 knots), depth control, navigation and difficult maneuvering around turns make deep-towed operations a challenge. Without a dynamically-positioned ship and tow-fish system, near-bottom surveys over rough topography or along scarp faces are virtually impossible to achieve. Manned submersible surveys offer the ability to negotiate such terrain but are very limited in their range and are very expensive to operate.

AUV TECHNOLOGY

Clearly, from a logistical point of view AUV (autonomous underwater vehicle) technology offers a great deal of promise in the collection of near-bottom geophysical data and in particular, near-bottom magnetic data. The operational problems of deep-tow surveys, including the speed limitations, depth control, and in turning maneuvers are easily overcome using untethered vehicles. Operation in rough topography and along scarp faces would also be possible provided that the AUV had obstacle avoidance capability. The role of the surface ship would be redefined. If the ship is not actively navigating the AUV then it would be free to pursue other tasks.

Assuming navigation data is also available the basic sensors required for a near-bottom magnetic survey are quite simple: a 3-axis fluxgate magnetometer sampled at between 1 and 10 second depth and altitude above the seafloor. In areas of sediment cover a sub-bottom profiler may be required. Other sensors that would also be useful but are not required include: pitch, roll and yaw of the vehicle. The light payload requirements of a fluxgate magnetic sensor might allow other sensors to also be included such as a CTD. More exotic sensors including video imagery, swath bathymetry, and side-scan would be useful but also require much more power which is perhaps the biggest factor in the design of a AUV. Other factors which must also be considered in the design of an AUV for near-bottom magnetic surveys are use of non-magnetic components, the distance vs speed tradeoff, the storage and telemetry of data as well as the navigation of the vehicle.

Although an infinite variety of experiments are possible there are two basic types of survey that are most often undertaken. These are : 1) a site-specific survey, typically consisting of a grid of lines over some small region of interest (< 10 km in size) and 2) a regional survey consisting of long survey lines parallel to each other (> 10 km). Some examples of a site specific survey would include mapping the magnetic field over a hydrothermal vent system, extinct ore deposit or midocean ridge neovolcanic zone. Regional geophysical surveys would be aimed at understanding the fine-scale magnetic structure of the ocean crust and ultimately the character and generation of the geomagnetic signal itself. To illustrate the possible application of AUV technology to the study of marine magnetic anomalies I present two case studies that engender the two types of surveys discussed above. The first study is a site-specific study that focuses on a hydrothermal vent system and its effect on the magnetic properties of ocean crust. The second is a regional deep-tow survey consisting of two 800 km long survey lines over 170 Myr-old ocean crust in an effort to understand the geomagnetic history of the earth during this period.

1) TAG Magnetic Anomaly

The deep ocean hydrothermal vent systems recently discovered on several midocean ridges around the world represent a significant source of mass and heat exchange between the oceanic crust and surrounding ocean. Many of the world's major metallic ore deposits appear to have formed in this kind of environment. The remnant magnetization of oceanic crust can be virtually destroyed by the thermal and chemical processes of such vent systems. It is has been suggested that such source-layer destruction may produce a magnetic anomaly signature that could be detected at the sea surface (Rona, 1978). The TAG hydrothermal vent system located on the Mid-Atlantic Ridge at 26 degrees 08'N represents the "type case" where a significant hydrothermal vent system appears to be coincident with a sea surface magnetic anomaly that has a clearly 3-dimensional morphology that is characteristic of a point-dipole type of source. The resolution limitations of the sea surface data can only restrict the source body to be smaller than a 4 x 4 km region. The central vent region consists of a 50 meter high mound, 200 meters in diameter at a depth of 3760 meters. The manned deep submersible ALVIN carried out a detailed near-bottom magnetic survey over the actively venting mound with a grid of lines spaced 40 m apart and 400 m long at an altitude of 20 meters. The magnetic results suggest that a zone of reduced magnetization exists beneath the mound itself, but that this is alone cannot produce the measured sea surface anomaly low. This implies that there are either more discrete lows nearby or a deeper, broader zone of low magnetization that was not sampled by the submersible survey. An intermediate scale survey (e.g. a 10x10 km survey box) would test these two different source model scenarios. The geophysical survey carried out by the manned submersible is not an efficient use of the capabilities of that vehicle. Such surveys are more ideally suited to AUV operations. The limited range of the submersible is also a drawback which could easily be overcome by in a AUV survey.

2) Jurassic Quiet Zone Deep-tow Magnetic Survey

This survey consisting of two parallel, 800 km long, near-bottom magnetic profiles was carried out in the western Pacific Ocean over the oldest ocean crust that exists on Earth. The sea surface magnetic data in this area is typically very low in amplitude (20 to 50 nT) and can be masked by diurnal variations making magnetic analysis difficult if not impossible. To overcome this problem a deep-towed magnetometer consisting of a 3-axis fluxgate magnetometer, pitch, roll, depth and altitude sensors was towed at depth of 5000 m (on a 8200 m cable) at approximately 2.5 kts for the entire 15 day survey with real-time data communication up the deep-sea cable. The near-bottom magnetic data shows a wealth of fine-scale structure and which is simply not apparent in the sea surface data. The importance of such 'missing' information to the understanding of the processes of seafloor evolution and geomagnetic field behavior is undeniable. The extension of such surveys to the entire seafloor magnetic record would be highly desirable. In terms of AUV operation, the endurance (in terms of power or distance) would again be of utmost importance. The method of data storage and transfer would also be a primary concern. This type of survey may be at the limit of current AUV technology but is certainly a realistic goal for future developments.

REFERENCES

Cox, A., R. R. Doell, G. B. Dalrymple, Reversals of the Earth's Magnetic Field, Science, 144, 1537-1543, 1964.

Miller, S. P., The validity of the geological interpretation of marine magnetic anomalies, Geophys. J. R. astron. Soc., 50, 1-22, 1977.

Rona, P.A., Magnetic signatures of hydrothermal alteration and volcanogenic mineral deposits in oceanic crust, J. Volc. Geoth. Res., 3, 219, 1978.

Vine, F.J. and Matthews, D.H., Magnetic anomalies over oceanic ridges, Nature, 199, 947-949, 1963.

Adaptation of an Autonomous Underwater Vehicle for Geophysical Exploration Beneath the Antarctic Shelf Ice

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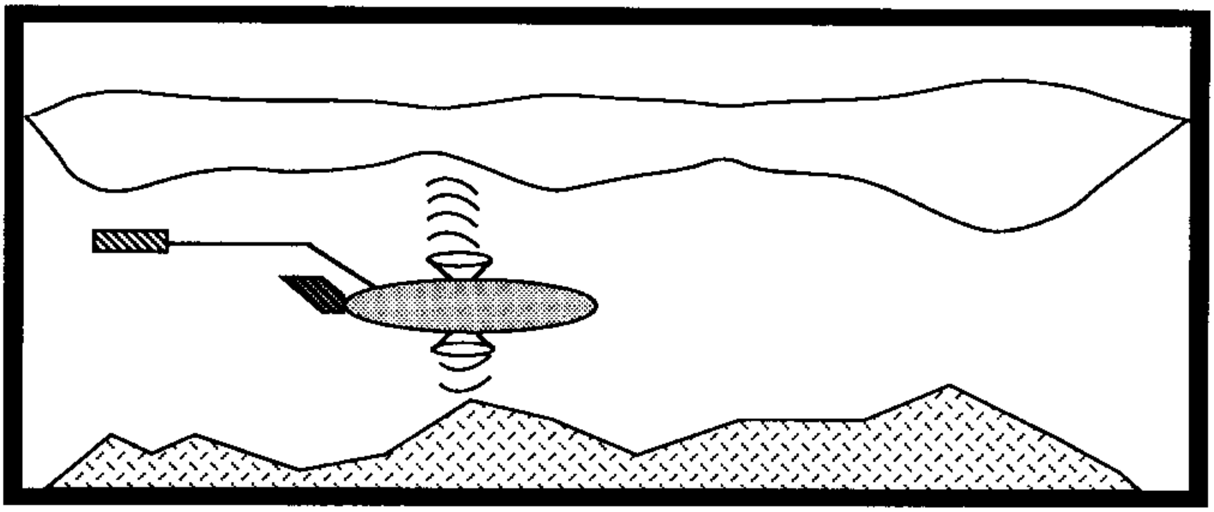

INTRODUCTION

Exploration of the sea floor beneath the polar ice caps is the last great frontier in marine geophysics. Surface ships are not capable of mapping bathymetry, sediment thickness, gravity, and magnetic fields in ice-covered areas adjacent to Antarctica or beneath the ice cap of the North Pole. Very expensive aeromagnetic and aerogravity surveys provide a partial solution to this problem for mapping the potential field variations, but submersibles—Autonomous Underwater Vehicles (AUV's), and Remotely Operated Vehicles (ROV's)—are the only viable means of acquiring sea floor bathymetry and sediment thickness.

The *Odyssey* AUV, currently under development at MIT, is a particularly attractive candidate for a low-cost survey tool capable of long distance (>100 km) geophysical exploration beneath ice-covered regions. Its small size (2.15 m long) and light weight (120-165 kg, dry) allow for convenient air freighting to vessels of opportunity and easy deployment from a conventional oceanographic research ship without special handling requirements. The low cost (<$50K excluding mission hardware) permits the possibility that a single ship could deploy a fleet of such vehicles to efficiently map a large region in a short amount of time.

SCIENTIFIC PROBLEMS TO BE ADDRESSED

We are currently planning a submarine geophysical survey beneath the Antarctic ice cover using the *Odyssey* AUV, perhaps as early as February of 1993. Dr. Robin Bell of Lamont-Doherty Geological Observatory of Columbia University has invited us to participate on an NSF-funded expedition of the *Polar Duke* to map marine magnetic lineations and bathymetry off Thurston Island and Marie Byrd Land. The data will be used to solve the most important remaining problem in Late Cretaceous-Early Tertiary plate reconstructions. Current models of the breakup of the supercontinent of Gondawna, as constrained by magnetic lineations and fracture zone trends in the southernmost Pacific, appear to require the presence of an extra plate, the "Bellingshausen Plate," prior to the time of anomaly 21 (50 Ma) (see Figure 1 below). Data from this expedition will be used to test for the presence of the Bellingshausen Plate by mapping the location of marine magnetic anomalies and fracture zones beneath the Bellingshausen Sea. If it exists, large Early Tertiary plate motions between East and West Antarctica or within New Zealand are no longer necessary when reconstructing the positions of the southern continents prior to the breakup of the supercontinent.

The *Odyssey* will extend to the south the area that can be surveyed with the ice-strengthened *Polar Duke*. If 1993 is a relatively ice-free year, the additional data from the AUV will extend the reconstructions back to the earliest phase of spreading along the Pacific-Antarctic ridge. If 1993 is a year with extensive sea ice, the additional data provided by surveys of the AUV under the ice could be absolutely essential to achieving the scientific goals of the expedition.

In the event that development of the *Odyssey* vehicle is not completed in time for this expedition, we are also proposing to NSF's Division of Polar Programs another geophysical survey of the Antarctic margin for February of 1994. The purpose of this mission will be to map the development of the large-offset fracture zones of the south Pacific during the early phases of spreading along the Pacific-Antarctic Ridge system. Such large-offset fracture zones are also well developed in the central Pacific, but because they formed earlier during the Cretaceous Magnetic Superchron, there are no reversals of the Earth's magnetic field to date their development and measure the increase in their age offset as a function of time. Data from this expedition would allow us to better understand what conditions lead to the development of large-offset fracture zones and how their thermo-mechanical evolution effects the state of stress within the plate. In the event that the *Odyssey* is ready in time for the *Polar Duke* survey, this project could be considered as a follow-on mission.

SURVEY REQUIREMENTS

Initially, we will try to achieve 100 km of penetration under the ice (200 km excursion round trip). Eventually, even greater range would be desirable. Positioning beneath the ice is difficult since it will not be possible to deploy a triangular grid of transponders. We intend to install a doppler sonar navigation sensor for the initial survey beneath the Antarctic ice. Eventually, we would like to run the AUV in a grid pattern.

INSTRUMENT REQUIREMENTS

Minimum:
Up and down-looking sonar system
Pressure gauge
Magnetometer
Desirable in the future:
Sub-bottom profiler (Power requirements may be a problem)
gravimeter (would require greater navigational accuracy than likely from the doppler sonar)

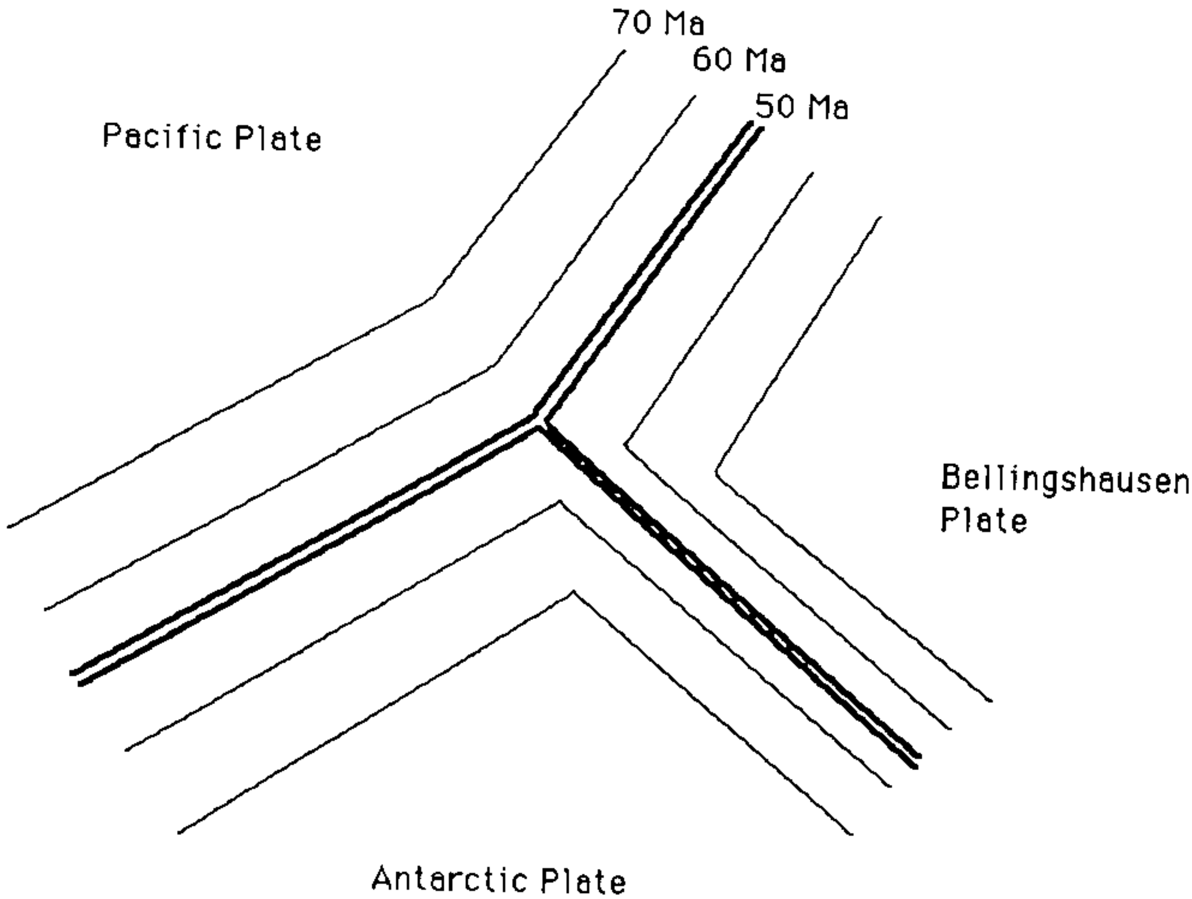

Figure 1a. Prior to 50 Ma, the geometry of plate motion in the southernmost Pacific may have looked something like this. The heavy double line marks the location of the spreading ridges, and the lighter lines show the locations of marine magnetic anomalies corresponding to 60 and 70 Ma isochrons.

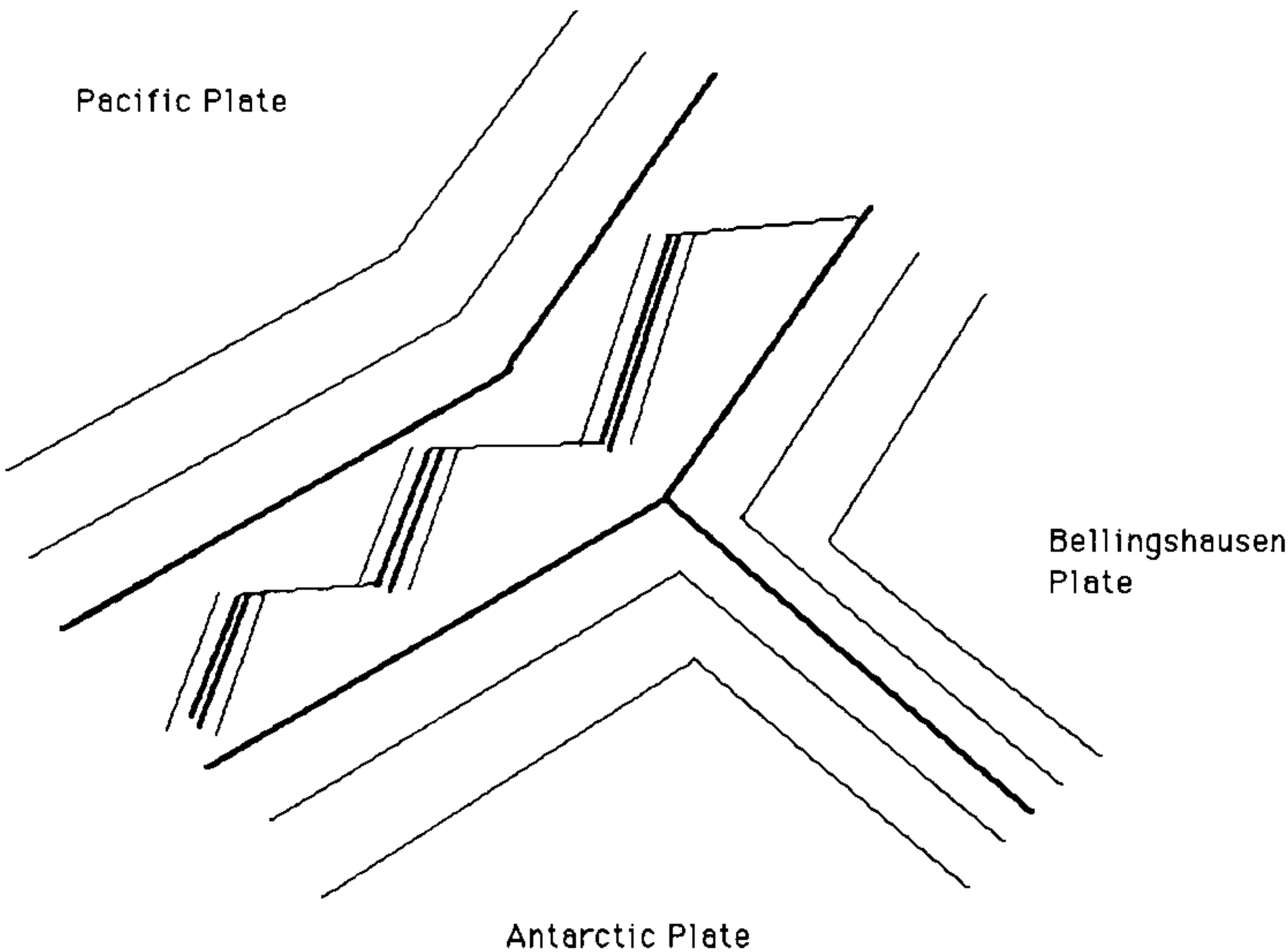

Figure 1b. After 50 Ma, the spreading system reorganized in the southernmost Pacific such that at later times only one midocean ridge system (offset by a number of fracture zones) existed, and the Bellingshausen and Antarctic plates fused into a single plate. The bathymetry and magnetic anomalies have not yet been mapped close enough to the Antarctic margin to directly test for the lineations demonstrating relative motion between the Antarctic and a third plate (Bellingshausen), but the slight "bite" or kink in the magnetic lineations on the Pacific plate in the northwest area of this map suggests that spreading between the Pacific and Antarctica involved a third plate.

Sea-Ice Mechanics

Professor Henrik Schmidt
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The Arctic ice cover is exposed to environmental forcing by atmospheric conditions such as wind and heat flux and oceanography in the form of currents, drift, sea surface tilt etc. This environmental forcing induces stresses in the ice cover with the result of deforming the ice in accordance with its constitutive laws. In places where the stress exceeds the local strength of the ice, fracture processes will be initiated. The fracture creates a micro-crack, providing a mechanism for the formation of high stress concentrations, which in turn will lead to the propagation of the crack tips until the crack becomes large enough to lower the stress intensity factors below the critical ones. Once a crack is formed, the macroscopic constitutive laws will obviously have changed, with the stress-strain distribution changing as well. With continued environmental forcing by the meteorology and oceanography such fractures and cracks will continue to form. Alternatively, the cracks may heal through refreezing. Depending upon the time scale of the environmental forcing, this process may lead to a dense distribution of cracks, significantly weakening the ice cover mechanically, with catastrophic or major macroscopic failures as a result. Such macroscopic failures in turn combine to create ice formations such as keels, ridges, rafts and leads.

The objective of the ONR ARI on Sea Ice Mechanics is to obtain a basic physical understanding of this highly non-linear process, i.e. the series of events leading from a particular environmental forcing scenario to the formation of the dramatic features characterizing the macroscopic Arctic ice. This obviously requires monitoring of the environmental forcing as well as the evolution of the macroscopic ice features. Although these phenomena are correlated, the non-linear nature of the relationship provides a basis for chaotic behavior with a wide spectrum of environmental scenarios leading to the same ice features and vice versa. The challenge of the Sea Ice Mechanics ARI is therefore the understanding of the series of events leading from environmental forcing through microscopic fractures to catastrophic failure, involving spatial scales ranging from mm to several km and temporal scales ranging from ms to hours and days.

There are several approaches to addressing this problem. The most obvious is the direct observation, visually or otherwise, of the fracture patterns existing in the area surrounding a major ice feature such as a ridge. However, such "post-mortem" observations do not provide information on the stress-strain distributions existing before the actual crack formation. Thus, it is virtually impossible, for example, to determine whether a particular crack was created by high concentration of tension or shear stresses. Since the stress-strain distribution controls the series of events leading to catastrophic failure, a thorough understanding of the ice mechanical behavior requires the spatial and temporal mapping of the stress and strain distribution, preferably down to microscopic scale.

Here, direct strain measurement is an important tool. High resolution strain measurements are possible locally. However, the small scale deformations will be concentrated in an area close to a point of fracture. Therefore, direct, small scale strain measurements require either rapid localization of an active crack or artificially induced cracks. Due to the very short time scale of crack formation, the first option is impossible. The artificially induced cracks provide an attractive option in terms of controlled conditions and instrumentation. However, the ice environment is extremely complex, with many preexisting cracks, and there is no guarantee that the present environmental forces will give rise to crack formation in the immediate vicinity of the instrumentation. Artificial loading may be used, but this option does not directly represent the environmental forcing, a connection which is one of the major objectives of this initiative.

The ideal method is one which determines the development of stress and strain distributions in space as well as time, providing coverage as well as resolution, and here acoustic, remote sensing of the fracture processes or (em acoustic emission) is an attractive and feasible option. This method is based on detection and analysis of the stress waves generated in the ice and the water column by fracture formation in the ice cover. When a crack is formed, the stresses are released over the crack surface, giving rise to stress waves radiated in a pattern characteristic for that particular fracture process. The parameters describing the fracture process can therefore be determined by inversion of the radiated stress wave field, in turn providing a spatial and temporal map of the ice fractures.

The resolution of fracture mapping by inversion of acoustic emission is dependent on the spatial sampling of the field. Further, the inversion is affected by the complexity of the acoustic environment involving significant scattering and reverberation from existing ice features and inhomogeneities, as well as the ambient noise. Therefore, high resolution mapping is feasible only over relatively small spatial scales, of the order of magnitude of 100 m. On the other hand coarse resolution (100 m) mapping is feasible over spatial scales of 10 km.

During an experiment planned for 1994, the stress-strain and fracture development leading from the environmental forcing to the creation of the dramatic ice features will be determined, covering length scales of 1 cm to 10 km and temporal scales of 1 ms to weeks, by performing an experiment involving the following major components:

- Extraction of environmental forcing from oceanographic and meteorologic measurements.
- Ice deformation measurement with sub-meter accuracy over a course grid covering a 100 km^2 area to determine the development of the "global"' deformation (strain).
- Low resolution (100 m) remote sensing of acoustic emission from initial fracture development in order to localize developing active zones.
- High resolution temporal and spatial mapping of crack development in an active zone by means of a rapidly deployed, combined geophone and hydrophone array for inversion of fracture parameters from the ice stress waves and the water acoustic waves.
- Use of ice morphology mapping in the active zone.
- Use of "post-mortem" observation of developed ice features such as keels, ridges, leads, rafted floes and crack patterns.

The basic strategy of the experiment is to continuously monitor the ice activity out to distances of 10 km from a wide aperture *'reconnaissance array'* of hydrophones near a base camp. Real-time focused beamforming will be used to localize regions of high activity. Once an active zone has been localized, an array of acoustic and seismic sensors will be deployed around the active zone within a time span of a few hours or half a day, together with equipment used by other research groups. The seismo-acoustic data will be recorded during the active period, typically 24-30 h, after which the sensor array would be recovered and applied in another active zone. The seismo-acoustic data will be inverted for ice fracture parameters such as crack type, location, orientation, fracture moment and rupture speed to provide a temporal and spatial map of the ice fracturing accompanying the ice mechanics of ridge building, shear deformation etc. In addition to serving as important input parameters to the understanding of sea ice mechanics and its relationship to environmental forcing, such fracture maps will provide a link between environmental forcing and the under-ice ambient noise, with the implication of supporting the development of more accurate predictive models for the Arctic ambient noise field.

The mapping of the ice morphology, both on the bottom and surface of the ice cover provides crucial inputs to the basic understanding of the ice mechanics as well as the seismo-acoustic propagation forming the basis of our fracture inversion procedures.

It is therefore important that ice morphology data are collected in tandem with the other experimental efforts. From the acoustics point of view, ice morphology data must be provided at meter resolution, and remapping should take place at intervals of no more than days to capture macroscopic changes.

Due to the fact that the ice activity in an active zone happens over a short time span of 30 hours or less, the rapid deployment of all instrumentation is a critical factor. Ice mounted instrumentation can be deployed in a few hours using helicopters and pre-assembled data acquisition systems. However, the deployment of under-ice instrumentation is clearly more time consuming. The important ice morphology can be determined acoustically using fixed arrays of sources and receivers. However, the deployment of such a system with sufficient coverage can at best be performed in a few days. An attractive alternative is to use an Autonomous Underwater Vehicle (AUV). MIT Sea Grant, is currently developing an under-ice AUV with a modular pay-load capability allowing for mounting of ice morphology instrumentation such as sector-scan and side-scan sonars, capable of performing ice morphology mapping. A critical issue for the use of such a capability in relation to the Sea Ice Mechanics experiment is the time factor. Thus, the vehicle must be deployed through a hydro-hole in base camp and navigate out to the active region to perform its mission. Critical issues are therefore speed and operational range. To be useful, the vehicle should be able to navigate to the active region up to 10 km away and locally perform under-ice mapping at sub-meter resolution and finally return to base camp for recovery and data unloading. Accurate navigation is therefore very critical, in particular during the measurement phase in and around the active zone.

Techniques of Basic Marine Geological Research: Application to Environmental Management

Dr. Herman A. Karl
U.S. Geological Survey

The U.S. Geological Survey is conducting systematic, environmentally focused, geologic investigations called Geologic Inventory projects on the continental shelf and slope within the U.S. Exclusive Economic Zone (EEZ). Areas that are offshore of major population centers have been and will continue to be most affected by human activities, and, therefore, the initial study sites are adjacent to large urban complexes. Eighteen areas in the coastal ocean (8 designated and 10 proposed) have been set aside as national marine sanctuaries. These pristine, unusual, rich and diverse ecosystems, particularly those adjacent to major urban areas, are also impacted and threatened by societal use of the oceans. The first of the Geologic Inventory projects, the Offshore Geology of the Farallones Region, was begun offshore of the San Fransisco Bay in 1989 where a national marine sanctuary is situated adjacent to a dense population center.

Each Geologic Inventory project is designed and conducted as a multidisciplinary research study. The basic research must be relevant to one or more specific social issues, and must also provide baseline information that can be used to design other environmental studies. Most importantly, the data derived from the project must be communicated in a timely way that is clearly understandable not only by professional scientists but also by the public and those charged with management decisions concerning multiple use of the offshore areas.

The continental margin offshore the San Fransisco Bay area was chosen as the site of the first Geologic Inventory project for six reasons:

1. The Gulf of the Farallones National Marine Sanctuary—a unique marine ecosystem—encompassesa large part of the Gulf of Farallones. The geology and oceanography of this area are poorly understood.

2. The Gulf of Farallones and adjacent waters are an important commercial and recreational fisheries area; fish products from the Gulf of Farallones are exported worldwide.

3. Selected areas of the ocean floor have been used and are being considered as disposal sites for material dredged from San Fransisco Bay. There is a great need to gather information about the geologic and oceanographic processes on the continental margin to understand the effects of these disposal sites on the environment.

4. More than 47,800 drums (55 gallon) and other containers of low-level radioactive waste were dumped on the continental margin between 1946 and 1970. These drums now litter a large area (1200

km^2) of the sea floor within the marine sanctuary. The exact location of the drums and the potential hazard the drums pose to the environment are unknown.

5. Many faults have been mapped in the Gulf of Farallones; for example, the San Andreas Fault crosses the Gulf near the Golden Gate. These faults are a potential seismic risk for the cities of the San Fransisco Bay area.

6. Study of the ocean environment complements ongoing USGS investigations of San Fransisco Bay and provides an opportunity to study an estuarine-shelf-slope system.

A wide variety of surveying and sampling techniques and technologies is required to sample and measure the many physical products and processes that characterize the continental shelf and slope environments. The Farallones Region project is multidisciplinary and consists of three basic elements of surveying and sampling techniques:

1. Framework geophysics and geology to investigate deep structure to assess seismic risk.

2. Use of high-resolution reflection profiling techniques to investigate near-surface structure and stratigraphy, sediment body geometries and surface morphologies. These studies will help evaluate seismic and slope stability hazards and areas of excessive sediment erosion and deposition.

3. Characterization of the sea floor with sidescan sonar, bottom photography, high-resolution subbottom profiling systems, acoustic profiling systems, and core samples. Sediment samples and cores are used for textural, geotechnical, mineralogical, geochemical, and paleontological studies.

The primary objectives of these activities are to construct a sonographic mosaic of the sea floor and a high-resolution bathymetric map as survey bases and to use the natural sediments as tracers for identifying pathways of sediment transport and ocean currents especially near the sea bed to measure and predict rates of sediment and pollutant transport.

The USGS mapped and sampled the continental shelf east of the Farallone Islands in 1989. In 1990 the project expanded in scope when the USGS conducted an investigation sponsored by the USGS and the U.S. Environmental Protection Agency, the U.S. Army Corps of Engineers, the U.S. Navy, and the National Oceanic and Atmospheric Administration (NOAA) to survey and sample the continental slope west of the Farallone Islands. This cooperative study by these federal agencies was designed to provide information on the location and distribution of the drums of low-level radioactive waste and geologic data on areas being considered as sites for disposal of dredge material from San Fransisco Bay.

Many surveying and sample techniques were used during both the shelf and slope investigations. These include but are not limited to geophysical surveys, sediment sampling, bottom photography, and measurements of ocean currents. One valuable surveying tool is sidescan sonar, which allows scientists to characterize the morphology of the sea floor by swath mapping. Sidescan sonar provides an acoustic image or sonograph of the sea floor that is similar to a satellite image of the Earth's land surface. Mapping with sidescan is commonly done in two modes or styles. In a reconnaissance mode track lines are widely spaced to cover an area quickly and swaths do not overlap. In a mosaicing mode, track lines are spaced closely together so that adjacent swaths overlap and a contiguous image is built of a given area of sea floor. Owing to the brevity of this summary, only some of the results obtained using sidescan surveying and bottom photography techniques are described in the following paragraph.

The low-level radioactive waste (LLRW) containers that were dumped in the Farallone Islands Radioactive Waste Dump (FIRWD) may or may not pose a risk to the environment. To evaluate the risk, samples of the sediment, biota, and water must be collected near the concentrations of barrels. However, the exact location of the barrels must be known prior to sampling. The USGS, in cooperation with NOAA, used sidescan sonar to map two areas within the FIRWD. Total sea floor coverage was obtained and computer-processed mosaics were constructed on board ship. Many small non-geologic targets were distributed throughout the survey areas that covered about 70 km^2 (20 square nautical miles) on the shelf and 125 km^2 (37 square nautical miles) on the slope. Analysis of the sidescan data suggests that the targets are 55 gallon drums. This interpretation was confirmed at one site with an underwater video and 35 mm camera system. Camera surveys are also necessary to assess the condition of the drums to determine whether they are breached and their contents exposed to the environment. maps of barrel distribution derived from the sonographs are being used to design sampling schemes to evaluate the risk that the levels of radioactivity may have on the biota and environment.

Data Needs for Massachusetts Water Resources Authority Harbor and Bay Monitoring

Dr. Michael J. Mickelson
MWRA, Environmental Quality Department

As part of its efforts to clean up Boston Harbor, the Massachusetts Water Resources Authority is required by state and federal regulatory agencies to conduct monitoring to provide a warning about any adverse environmental effects resulting from the proposed new outfall, 15 km offshore (fig. 1). The plan for monitoring has been developed by a task force representing environmental agencies, academic and scientific organizations, public interest groups, and the MWRA. The plan is structured around four general questions of public concern:

- is it safe to eat fish and shellfish?
- are natural/living resources protected?
- is it safe to swim?
- are aesthetics being maintained?

These concerns arise because the outfall will discharge nutrients and some quantities of toxic substances, pathogens, and visible material. The latter 3 will decline over the period 1994-1999 as the treatment plant is upgraded in stages to full secondary level.

Intensive monitoring will begin in February 1992 to establish baseline conditions before the outfall begins operation in 1995. It will not only focus on the vicinity of the new outfall site but reach into Massachusetts and Cape Cod Bays (e.g. Fig. 2 for the water column studies). The monitoring program consists of four main areas of investigation (A-D below) plus several special studies. The "special" studies are more experimental or shorter term than the four main areas. The asterisk (*) below denotes studies where an autonomous underwater vehicle (AUV) might be especially helpful.

A. Chemical analyses of the treated sewage effluent.
  - bacterial indicators; toxicity test; toxic contaminants; biological oxygen demand, total suspended solids, pH.

B.* Nutrient-related processes in the water column (Fig. 2).
  - hydrography stations; ammonia, nitrate, nitrite, phosphate, silicate; *in vivo* chlorophyll; irradiance; salinity, temperature, dissolved oxygen, light transmittance.
  - productivity stations: all the nearfield measurements plus dissolved and particulate carbon and nitrogen, total suspended solids, extracted chlorophyll, phytoplankton and zooplankton identification and enumeration, zooplankton biomass, primary productivity.

C.* Soft-bottom communities and sediment contamination with toxics.

• benthic species composition and abundance; PAHs, LABs, PCBs, pesticides, metals, total organic carbon, grain size, *Clostridium perfringens*; sediment profile imaging.

D. Fish and shellfish disease and body burden of toxics.

• mussel, flounder, and lobster PCB, PAH, and pesticides. In flounder and lobster; Ag, Cu, Cd, Hg, Pb, Zn, and incidence of disease.

E. Special studies:

1. water circulation and sediment transport
   • current velocity; sediment deposition, resuspension, and mixing.

2. detailed effluent characterization
   • sensitive methods will be used to estimate levels and variability of metals, PAHs, PCBs, pesticides, and sewage tracers (such as 15-N, Ag, LABs, and *Clostridium perfringens*).

3. sewage tracers in the environment
   • areal distribution of sewage tracers in surface sediments and in sediment cores.

4.* hard-bottom communities
   • video camera images of the rocky-bottom benthos to semiquantitatively determine percent cover and identify dominant species.

5. sediment/water exchange of nutrients and oxygen
   • rates of respiration, nutrient remineralization, and denitrification in sediment cores returned to the laboratory.

6.* tracking of the discharge plume
   • the freshwater effluent plume will be followed to see how quickly it is diluted by seawater. Concurrent measurements of toxics, bacteria, and suspended material will show whether water quality standards are violated and whether undesirable concentrations reach beaches or shellfish beds.

7. remote sensing
   • to provide temperature and chlorophyll data over a broad area.

Four studies above seem amenable to AUV involvement. The water column studies (Fig. 2) will determine whether any changes occur in ambient nutrients, dissolved oxygen, phytoplankton, or zooplankton. Sensors exist for dissolved oxygen, chlorophyll, salinity, temperature, light transmittance, and turbidity. Also new technology is emerging, such as strobed video identification of zooplankton. The length of the planned nearfield survey is close to the range limit of an AUV; the need for synoptic sampling, depth profiling, water samples for sensor calibration, and avoidance of obstacles are additional challenges. Immunity to adverse weather speaks in favor of AUVs, as does the potential for dedicated operation and therefore good temporal coverage by frequent repetition of cruises.

The soft-bottom studies will detect contamination and change in benthic communities in the muddy areas where particle-bound contaminants tend to accumulate. Conventional sampling and measurement methods are not suitable for an AUV as they involve equipment which presses into the mud with hundreds of pounds of weight. More delicate instruments are conceivable; tactile probes to assess and map softness of the bottom; redox probes which could determine the oxygen-status of the sediments (an indicator of eutrophication).

Video observation of hard-bottom (rock dwelling) benthos will detect gross changes in the communities. Because these communities are naturally highly variable in time, it is difficult to detect change which may be due to the outfall. Recognizing this, less effort has been allocated to this study. The frequent repeat coverage possible by dedicated operation of an AUV, however, may make this study more promising. In any case, position-fixing will be required.

The plume tracking studies will follow the effluent plume (after discharge begins in 1995) with turbidity and salinity measurements as it is diluted and transported in Massachusetts Bay. It may be possible to fully address the study objectives with a few conventional cruises. If the need for greater coverage is recognized, an AUV could act as an intelligent "sentinel," searching for undesirable excursions of the effluent plume beyond its allocated limits.

Figure 1. Location of proposed outfall

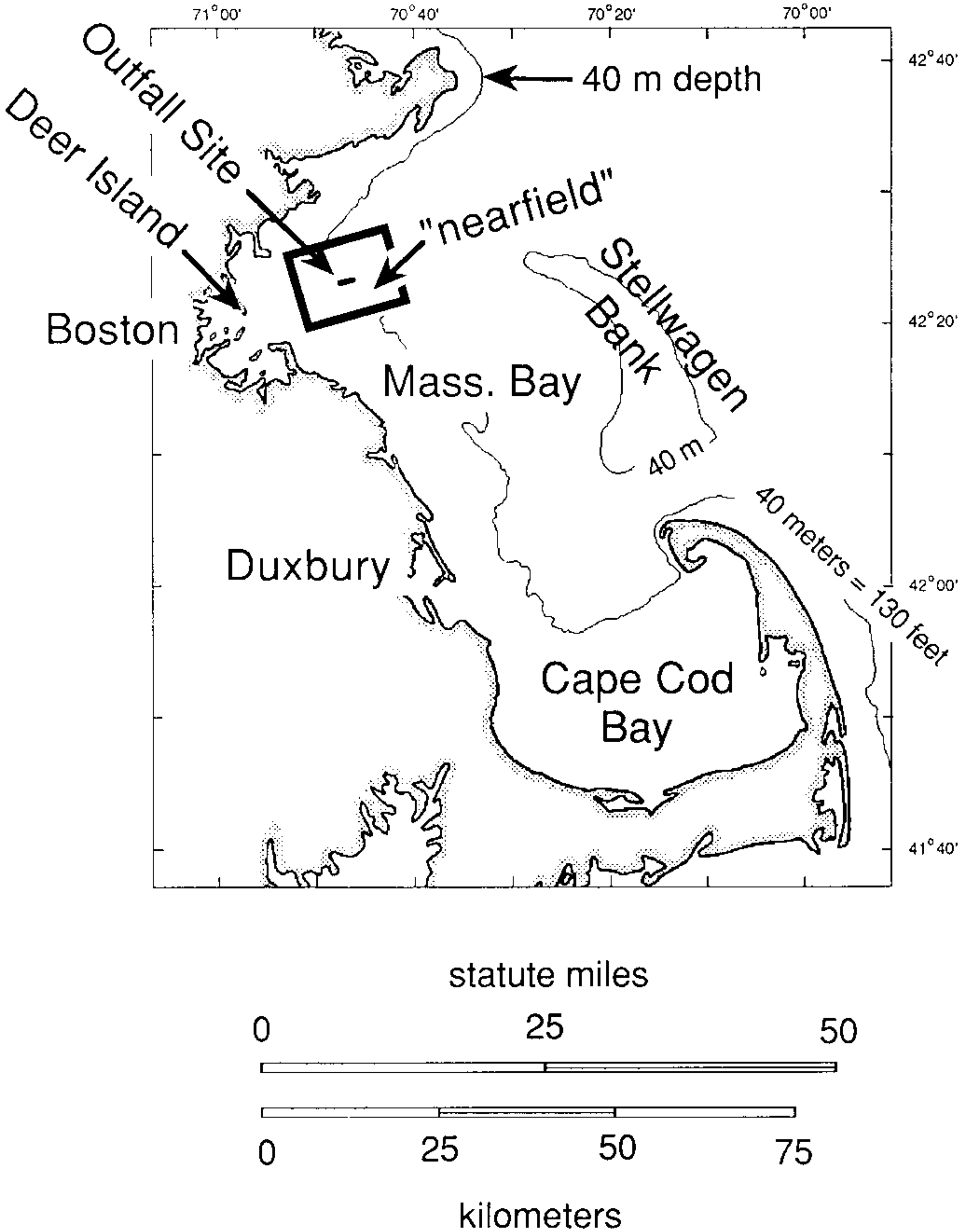
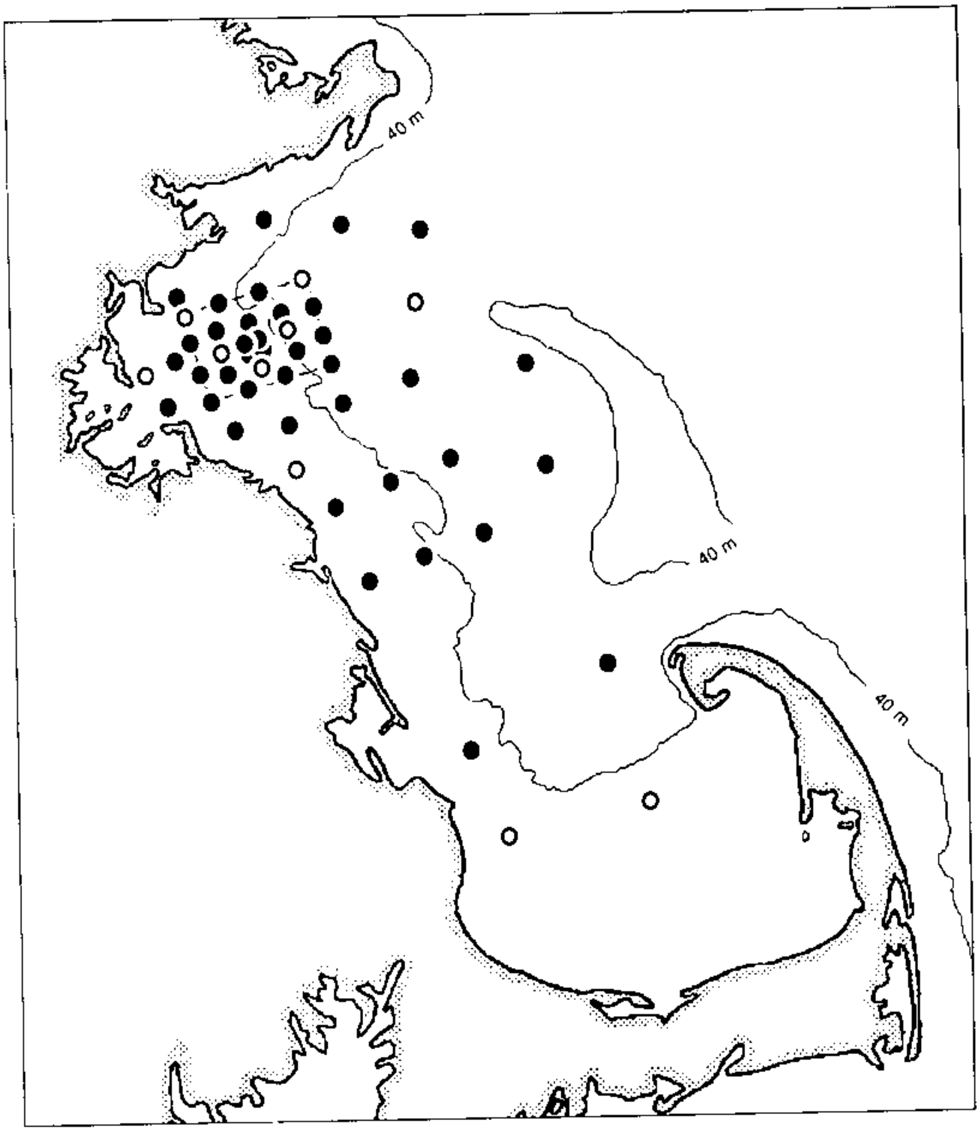


Fig. 2. Water column studies.



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EXTENDED ABSTRACT

The Abyssal Ocean Option for Future Waste Management: Monitoring Needs

Derek W. Spencer and Frederick L. Sayles

INTRODUCTION

The disposal of waste materials has become one of the most critical problems facing this nation and the world. The burgeoning world population and the associated increase in resource utilization has created a waste stream of enormous proportions and highly variable content. Current waste management practices are insufficient to handle present problems yet further growth in population is inevitable. The sheer volume of wastes together with threats to precious ground water supplies and problems with noise and odor pollution have combined to make landfill disposal sites a rapidly diminishing resource. Such sites now handle 80% of the waste stream of the U.S. There is an urgent requirement for innovative and effective schemes for dealing with wastes.

There is now wide recognition of the societal problems that the lack of adequate waste control and management has brought upon us. There is, further, no lack of concensus on the fact that current problems will be magnified greatly in the future unless some bold, and effective, new approaches are introduced. Many who have considered the issues advocate what is essentially a two-step approach:

1) Conservation: waste reduction by source reduction and recycling.

2) Multi-media disposal: to minimize risks.

The management of Municipal Solid Wastes, Sewage Sludge and Industrial Wastes poses large problems, and with the latter, in particular, there are some extremely hazardous products including highly toxic chemicals and radioactive materials. Efforts in source reduction and recycling can be accelerated, indeed they must be accelerated. However, such efforts will redress only part of the load. The EPA has set a national goal for the U.S. of 25% for reduction and recycling by 1992. Even if this can be met there will still be much more waste than can be accommodated with disposal systems now at hand or planned for the immediate future on land and thus: The options for this excess are limited; we can put it in the ocean or the air.

All waste disposal options pose similar environmental concerns. Risks to human health, loss of valuable resources, and environmental degradation are concerns common to all disposal alternatives, whether land-based, aquatic or atmospheric. The transport, fate and effects of wastes discharged to any environment are dependant on physical, chemical and biological processes that control contaminants within that environment.

THE 'OCEAN OPTION' FOR FUTURE WASTE MANAGEMENT

Optimal waste management programs must be designed to minimalize risks to human health and the environment. In the United States current legislation does not allow the implementation, or even consideration, of optimal practices. In particular, the "Ocean Option" has been almost discarded. This state of affairs has arisen largely out of public concern for a healthful coastal environment and a public lack of awareness of the major sources of chronic pollution in the coastal ocean as well as what the ocean, in its totality, is really like. Waste management strategies should consider all options and include safety, scientific information, available or needed technology and economic factors.

The ocean, particularly the coastal ocean, has been used for many years as a repository or dispersal medium for a wide variety of waste products. Despite considerable study, there are many instances where little or no effect of these practices has been observed. There are also many others where significant environmental change has occurred and strong suspicions of direct, and possible detrimental, feedback to human health exist or are forecast. There are few instances where human health has been clearly and directly adversely impacted by ocean disposal practices other than direct discharge of inadequately treated sewage with resulting food or water contamination by human pathogens.

Ocean environments are as varied as land. Of the total area of the earth about 29% is land, 1% coastal ocean and 70% deep ocean. Almost 50% of the world's surface, the abyssal plains and hills, lies under 4.5 kilometers or more of water and is effectively isolated from the upper ocean and land. Deep ocean circulation times are of the order of 1000 to 1500 years and there are no known processes that would allow the deep, abyssal ocean to communicate rapidly with the upper ocean.

There are large significant perturbations in the abyssal ocean as a result of hydrothermal vents and other natural phenomena associateed with an evolving earth. High levels of toxic metals, radioactivity and, in several places, abundant petroleum hydrocarbon products are currently vented at many ocean ridge sites. They have been in existence for millions of years yet evidence of vent activity is, at least for toxic substances, localized around the vent sites and certainly there is no impact on the ocean surface and coastal resources. The vent sites, due to chemosynthetic growth of bacteria, provide abundant sources of food in an otherwise impoverished abyssal ocean and organic productivity is significantly enhanced.

Ocean bottom boundaries have a number of attributes that establish effective scavenging processes for reactive chemicals many of which are removed from the ocean water on time scales of tens of years in contrast to the hundreds of years for that water to be returned to the surface.

We can now readily monitor events and perform experiments at the abyssal ocean floor. Further, new technology, in the form of tethered and free vehicles, is both in prototype application as well as development and is providing much more efficient and cost effective tools for remote observations. To support an extensive program of waste disposal in the abyssal ocean, further significant engineering developments are required.

The abyssal ocean has no resources that would conceivably be utilized by man and currently the only commercial use of the vast areas of 'real estate' present in the abyssal ocean is by cable layers.

Current understanding of the probability of impact to man from the use of ocean, particularly deep ocean, sites leads us to believe they may, in many instances, provide reduced risk and more optimal opportunities, when compared with terrestrial and atmospheric options, for future waste management schemes, particularly for high volume, relatively benign wastes such as sewage and incinerator ash.

However, despite the considerable increase in knowledge of the ocean environment that has occurred in the last twenty years there is need for further research to establish, in particular, the rates of change and recovery of bottom sites that may be perturbed with waste materials. The research required to assess the potential of the abyssal ocean will require experiments on a variety of spatial and temporal scales.

AN 'INDUSTRIAL SCALE' EXPERIMENT

In January 1991 a workshop was held at the Woods Hole Oceanographic Institution. The participants were charged to develop a research plan to assess the potential of the abyssal ocean for future waste management options. Important considerations included the types of data required and the frequency of the data needs in space and time. In order to provide a focus, as the total waste stream is vast and highly variable, the participants were asked to consider only such wastes as sewage sludge, incinerator ash and other relatively benign but high volume wastes which currently provide a significant and growing disposal problem. In addition, the participants were asked to address the potential benefits and problems of an "industrial scale" experiment extending over a period of 10 or so years. In this experiment, which would be a joint industry-academic venture, industry would seek a permit to operate a pilot program for a period of 10 years or so, with a contract, from one or more major municipalities or agencies, for the delivery of a million tons or so, per year of waste to the deep sea floor. It would, potentially, be a two-ship operation with an enclosed elevator system which would emplace the waste precisely at, or very close to, the ocean floor. Alongside this, a program of research and monitoring of the effects of the disposal would be conducted by academics with significant funding from the operating costs of the business.

Prior discussions had indicated that such a program could have a number of benefits and present some important opportunities for research related to some basic as well as applied oceanographic questions. For example, in the process of loading the sea bed with organic-rich substances, anoxic conditions would likely be produced, within the sediments, which would have a marked effect on the rates of redox cycling and mobility of chemical species and produce significant changes in the benthic fauna. It would be very difficult to project the aerial extent and larger scale rates of these processes by extrapolation from the small scale experiments normally conducted by scientists. However, a managed program, at the scale suggested, could provide us with substantial information on the rates of change of the ocean bottom in response to differing environmental, compositional and loading factors. Further, the participants were asked to consider the relative merits and appropriateness of contaminant and dispersal options for different classes of wastes. Clearly, such information would be critical to any future program for waste management in the abyssal ocean, particularly if the management scheme is to be expandable to global scales and at the same time be sustainable.

However, before such an experiment could be considered, we need to address any potential irreversible detrimental effects, particularly with impact back to humans. Also it is important to provide evidence and assurances that such a large scale experiment, if it did prove that major problems exist in the utilization of the deep ocean, would not, of itself, have significant undesirable impacts to human health and welfare. While, at present, we know of no processes that would affect concentration and rapid upward transport of materials from the abyssal ocean, the potential for such mechanisms needs to be assessed.

The activities of the workshop participants provided the background information and ideas to formulate a plan for the research that would be required to assess the potential of the abyssal ocean as an option for future waste management. At this time the plan must be considered preliminary in that information concerning the specific composition of the waste would be an essential prerequisite governing the studies needed. The acquisition of such information is the first step in the program. Nevertheless, there is sufficient known of the broad scale characteristics of high volume and relatively benign wastes that is possible to outline, in some detail, many of the issues that require study and these were thoroughly reviewed by the working groups. The workshop participants proposed studies falling into four main categories:

A) **Literature research** to assess the applicability of past research to the abyssal waste management problems and to narrow emplacement site selection choices.

B) **Laboratory, mesocosm and flume studies** to characterize the composition and physical properties of the proposed waste, to obtain preliminary information on the bioavailability of pollutants to deep sea organisms and to obtain preliminary information on waste-sediment-biota interactions affecting transport of materials across the sediment-water interface. Other laboratory studies would research appropriate tracer materials for plume dispersal experiments.

C) **Pre-Emplacement site studies** to determine the biological, geological and physical characteristics of proposed sites.

D) **Post-Emplacement and site monitoring studies** to determine the dispersion of the waste at and around the site and to follow the chemical and biological changes associated with waste impacts.

Some of the important workshop considerations are summarized in the following paragraphs.

Research over the past two decades has provided a general description of the reactions that occur and the processes that influence both the nature of reactions as well as reaction rates in what is generally termed diagenesis. This knowledge is probably adequate for the development of qualitative predictive models that describe the response of many environments to loadings inherent in waste disposal. The chemical environment of sediments is primarily governed by a sequence of biologically mediated oxidation-reduction reactions. This sequence is determined largely by the energy yield of the oxidation of carbon in organic matter by a variety of oxidants. The principle and most important of these in terms of the amount of carbon oxidized in O_2 which accounts for about 90% of the carbon oxidized in marine sediments. In the deep ocean pelagic and hemipelagic sediments up to 99% of the sedimenting carbon is oxidized by O_2. Other oxidants utilized, in order of consumption, are NO_3, MnO_2, Fe-oxides, and SO_4. Limited physical mixing in sediments results in a series of reaction zones with depth that approximates this sequence. Rates of reaction respond to carbon input with the result that the depth scale of the sequence is compressed (high input) or attenuated (low input). In areas of high rates of deposition the entire sequence can be encountered in the upper 10 cm whereas in environments of low deposition SO_4 reduction may not be encountered for tens of meters. In all cases, the sedimenting carbon is largely oxidized, with the result that less than 10%, often less than a few percent of the input, are preserved and buried. These reactions have implications on the behaviour of many species other than the direct reactants. They control the redox state of the sediments thereby affecting a variety of metals, both as a result of reduction with decreasing Eh and precipitation with reaction products, particularly sulfide. In addition, metabolic CO_2 causes the dissolution of substantial amounts of $CaCO_3$ well above the saturation horizon. Since only a small fraction of the carbon arriving at the sea floor is buried, rates of consumption of carbon and oxidants vary with carbon rain dates. This can be seen in the variations of O_2 consumption by sediments as a function of water depth off the East coast of the U.S. Sedimentation rates and carbon input are higher at shallower stations in proximity to the continent than at those at abyssal depths distant from land. O_2 consumption reflects this with measured rates falling from about 5×10^{-9} to 0.008×10^{-9} mol/cm^2/hr between 1700 and 5000 m. The depth to various redox horizons and to the occurrence of significant concentrations of $S^{=}$ inevitably varies in response to varying rates of consumption of oxidants. A variety of models have been developed to describe these chemical processes.

The concept of applying additives to the sewage waste was discussed. Certain inorganic elements are retained better as insoluble sulfides while other elements are adsorbed onto iron oxides. Similarly, iron oxides serve as good adsorbers of many classes of organic compounds. In hemipelagic marine sediments a thin layer rich in naturally occurring iron oxides at the sediment/water interface impedes the seaward transport of many pore water components. Adding sources of iron to the waste would act to both increase its density and also to decrease the mobility of many components transported in solution. If the engineering allowed, a better scheme would be to cover a load of waste on the seafloor with a load of iron oxide particles. This would lead to a deposit with both layers of anoxic and oxic horizons similar to naturally occurring turbidite deposits. Another possibility would be to substitute fly ash for iron oxides. This would serve two purposes; to act as an adsorber, as the ash is composed on various oxides, and dispose of a waste.

Transport processes also influence the observed distributions of species produced by biologically mediated reaction and the depth zonation of redox horizons. The activities of organisms have two important effects. Sediments are reworked by the biota and in the process, mixing of the solid phases occurs, carrying material to depths that would be reached through accumulation only after hundreds of years. When cast in terms of a diffusion coefficient, measurements of radionuclides indicate values of the order 10^{-8} cm^2/sec. Some organisms also circulate solution, a process often termed bio-irrigation. This type of process can enhance reaction in sediments through transport at rates far faster than diffusion and the introduction of oxidants at depths well below the depth to which they penetrate by diffusion.

The information available on the nature of benthic reactions, their relation to sedimentation, as well as the physical and biological processes that influence them, form a framework for predicting the fate of material and the impact of various waste disposal schemes that might be implemented in the deep ocean. The models derived from available data are adequate for qualitative predictions, but only rarely are they likely to lead to needed quantitative predictions or the level of certainty in the predictions that is essential for assessment of environmental impacts. They also indicate the gaps in our current knowledge, and lead to questions of some of the conventional idioms of ocean waste disposal.

The clearly established relationship between input rate, reaction rates, and redox conditions has obvious implications for the disposal of any solid material in the benthic environment. Delivery of significant amounts of material to the seafloor will have an inevitable impact upon the sedimentary environment. ***The sediments will move towards a more reduced state*** (barring the input of oxidants). If the material does not contain oxidizable substances, accumulation will still reduce O_2 fluxes below the interface, leading to more reduced conditions. If substantial amounts of oxidizable material are delivered, then reducing conditions will be enhanced all the more, the extent depending primarily on oxidation rate.

The simplified discussion of biogeochemical processes in the benthic environment above suggests several issues, or questions, that need resolution in the design of waste disposal schemes or in field programs designed to evaluate them.

The release and effects of harmful chemicals to any environment is one of the major concerns in any disposal scheme. In the simplest view, release may be considered a two step process. Readily soluble substances are released rapidly as material is mixed into the environment. Other releases occur as a result of reaction, usually much more slowly. For example, the oxidation of the organic matter matrix of sewage sludge will release occluded and bound material as the matrix is consumed. In the case of fly ash, release would be dominated by dissolution processes. Evaluation of the first is fairly straightforward while characterizing the second requires far more information, site specific as well as material specific.

Releases of material in the deep sea may be thought of as occurring in two relatively distinct environments: the water column and the sediments. In the waster column the amount released is a function of reaction rate (e.g. oxidation, dissolution, etc.) and settling rate. Both solubilized material and source move with the water mass for a period of time determined by settling rate. Material reaching the bottom reacts in a fixed location (in the absence of resuspension). Dissolved concentrations in the overlying water are determined by fluxes from the sediment and physical processes of advection and mixing. Concentrations in the water of released substances will likely be very different for these two scenarios. In reality of course, it is not likely to be an either/or case, but rather a balance between the two, a variable that can be adjusted through design.

Given that for many harmful substances, impact is related to concentration, as in the case of PCBs, DDT, etc., assessment of the consequences of these two scenarios is an important issue. The theoretical framework (models) to achieve this are by and large available. What is lacking is adequate data, in particular, the characteristics of the particulate material, reaction rates (sedimentary and water column), as well as site specific advective velocities and mixing parameters.

Sea-bed emplacement utilizes the remoteness of the deep abyssal ecosystems from existing and potential resources of the ocean (living; fishing, aquaculture and ranching; non-living; minerals, hydrocarbon, energy extraction, recreation, transportation, defense, safety at sea, and communications) for the isolation of the wastes. Previous research carries out in conjunction with the assessment of the safety of sea-bed disposal of high level radioactive waste, demonstrated the isolation of the deep ocean ecosystems and that potential pathways for contaminants are few and unlikely to be large enough to cause concern.

In a deep ocean regime, the responses of benthic communities to perturbations by wastes are not entirely predictable, but we would expect there will be marked changes in diversity in the near-field with species richness declining and dominance increasing sharply. These dominants will be opportunistic species which are rare outside regions of disturbance. The frequency of disturbance will determine whether or not populations are able to rapidly increase between disposal events. Beyond the initial zone of disposal, there is likely to be a great enhancement of species richness as a result of the organic compounds dispersing to the far-field. Changes can be expected in a range of characteristics of the communities such as size spectra and their composition in relation to feeding types. For example, the high suspended loads in the bottom water will favor the development of large populations of suspension feeders. Species with greatest tolerance to contaminants will flourish at the expense of those that are more susceptible. These responses will result in changes to the benthic community, with zones of impact gradually declining to undetectable levels.

The effective dispersion of materials in the open ocean is often cited as one of the primary beneficial characteristics of this environment. Large scale dilution lowers concentrations and in the case of solids minimizes accumulation on the bottom at any given point, a positive aspect in the framework of benthic reaction and response discussed above. However, on the down side, dispersion also guarantees maximum aerial distribution of the chemical load in the water mass. ***This may not be desirable in the case of persistent substances*** subject to accumulation in tissues and increases up the fool chain. Further, the detection of impacts and the causal relation to pollutants has proven very difficult to assess, a situation exacerbated by low concentrations and the complexity and natural variability of the system, with the result that we have insufficient knowledge of the significance of low levels of many substances.

An alternative is to localize waste materials, accepting the concept of "sacrifice" that is inherent in all land disposal. Whereas dispersal is most likely to result in maximum residence of all components of a given waste in the most active portions of the marine biosphere (the water column and bioturbated sediments), localization of disposal can be used to minimize the release of waste constituents to the ecosystem at large. Design characteristics and site specific environmental factors would govern the fraction of the total subject to release. A system designed to be strongly reducing would effectively immobilize many trace metals known to be harmful at elevated concentrations as well as isolating much of the waste material from direct contact with seawater and the reactions that occur therein. Further, a rather interesting possibility that could dramatically influence the mobility of virtually all waste components is the formation of methane clathrates. Deposition of carbon-rich waste could lead to the formation of substantial amounts of CH_4 if the reactivity of the organic carbon is high enough and the thickness of the waste accumulation sufficient to lead to the exhaustion of $SO_4^=$ and extensive production of CH_4 through fermentation. The formation of clathrates would solidify that portion of the deposit, immobilizing virtually everything at and below this horizon. The possibility of this eventuality as well as its consequences should be evaluated.

The two alternatives lead to contrasting exposures with dispersal resulting in maximum exposure at minimum levels and localization resulting in minimum exposures at maximum levels. The former is currently accepted for open ocean options, apparently without debate. This may not be the optimum strategy for the deep sea, as issue much in need of discussion and resolution. Is the risk, or "cost", in localized environmental degradation, for some waste types temporarily, greater than that inherent in the widespread distribution of persistent compounds that are harmful at poorly known "low" levels?

DATA NEEDS AND ENGINEERING SYSTEMS REQUIREMENTS

The following information needs, at a minimum, were identified.

Water Column Observations

1. From moored systems at and around the disposal site long term (2-5 years) observations of current velocity and direction, temperature, salinity, dissolved oxygen, and particle concentration. Measurements should be at a rate of a few times (~10) per day with capabilities of accelerated rates signaled by high energy events. Transmission of the data, by request, to the surface on a monthly to bi-monthly schedule would be required.

2. Plume dispersal monitoring using tracers intrinsic to the waste or deliberately released. Research is needed both for the development of suitable tracers and for the development of release and sensor systems.

3. Automated systems to collect water samples (~ 50ml), on a daily-weekly schedule, for delivery to the surface, on demand, six times per year.

4. Automated systems to monitor and count organism distributions both in the bottom water column and on the sediment surface. Pattern recognition systems to distinguish different shape classes are required.

Sediment Observations

1. Precise bathymetric and high resolution seismic reflection data, taken at least semi-annually, to determine the evolution of the geometry, thickness and gross textural characteristics of the waste deposit.

2. Monitoring of pore water chemical changes using sediment penetrating *in-situ* electrode systems. Microelectrodes are available for oxygen, and conventional electrodes for pH, NO_3^-, selected trace metals and sulfide. These systems would be deployed from free or tethered vehicles capable of precise positioning relative to the waste deposit. They would be deployed in a survey mode on at least a semi-annual basis.

3. Benthic chambers, emplaced at the sediment-water interface, to measure chemical fluxes across the boundary. Measurements would include oxygen, CO_2, nutrients, SO_4, Fe, Mn and some toxic compounds. The chambers would need to be precisely positioned relative to the waste deposit and would be deployed on a semi-annual basis.

4. Sediment coring systems to collect undisturbed samples of the upper 1 meter of sediment. These systems should be capable of precise positioning relative to the waste deposit and, ideally, be equipped with sediment surface imaging to allow operator control of the exact position.

5. Systems to precisely locate biological sampling systems, such as baited traps, bottom viewing cameras, etc. relative to the waste deposit.