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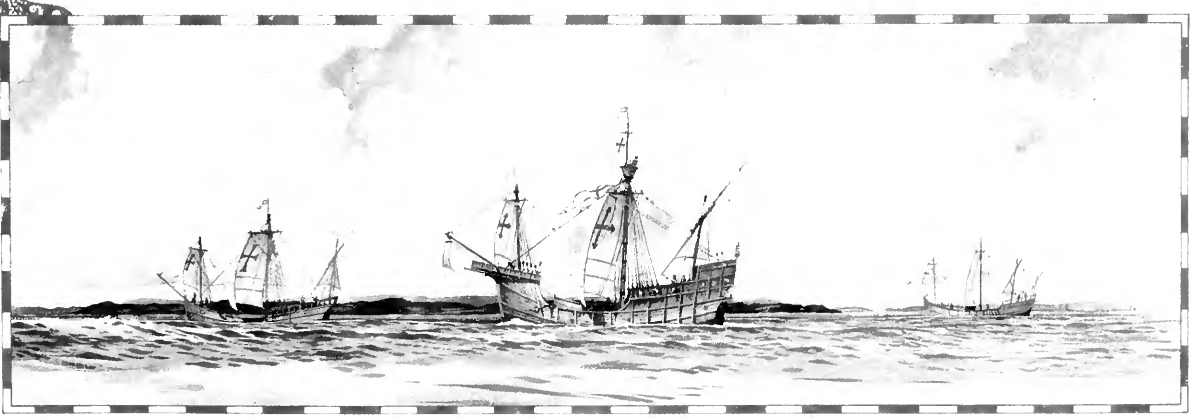
Columbus' Landfall Still a Mystery



New Calculations Point Again to San Salvador, Not Samana Cay

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92 letters

94 **Books Received**

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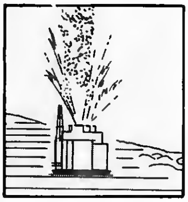

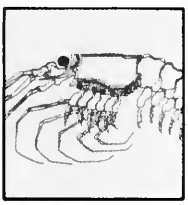

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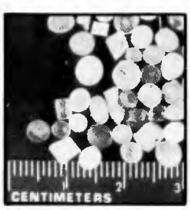

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The first known portrait of Columbus, from the Town Hall, Genoa, Italy. (The Bettmann Archive)

The Columbus Landfall: *Voyage Track Corrected for Winds and Currents*

—Where did Columbus first land in the New World? Two oceanographers from the Woods Hole Oceanographic Institution join the debate. Their calculations point to San Salvador Island.

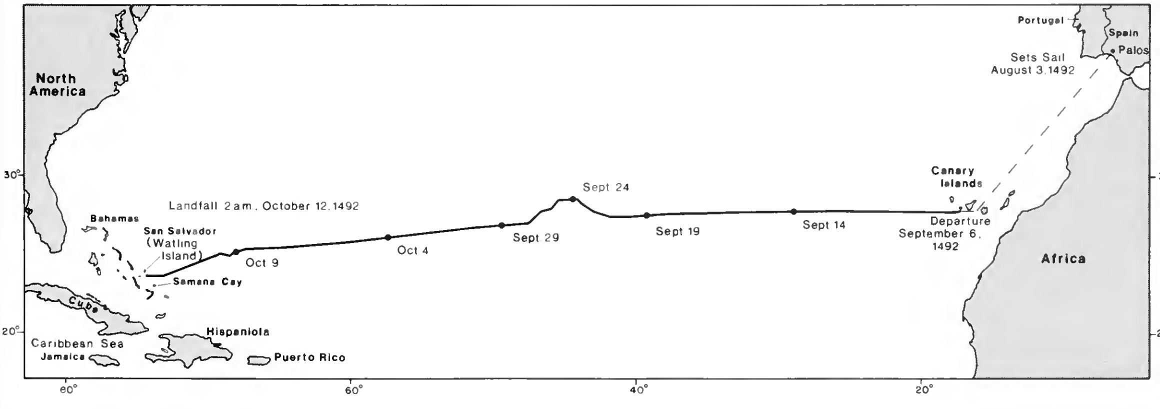
by Philip L. Richardson, and Roger A. Goldsmith

Wednesday, October 10, 1492: The 34th day at sea, sailing westward from the Canaries. The crew is complaining bitterly of the long voyage, urging their captain to head for home. Columbus promises that they will go another 44 leagues, no more.

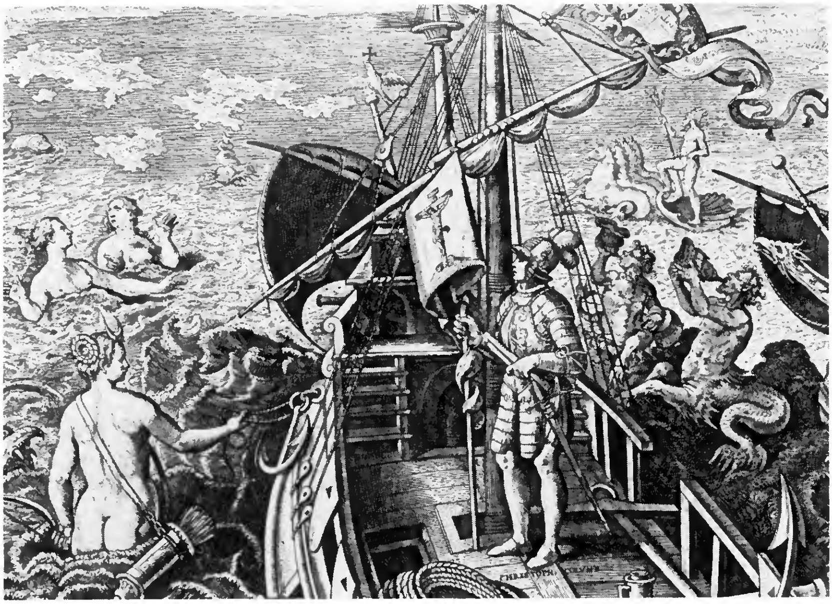
Thursday, October 11: Birds and floating sticks are sighted, hinting that land could be near. The lookouts keep an especially sharp watch that night.

2 A.M., Friday, October 12: A sailor, Rodrigo de Triana, first spies land at 2 leagues distance. The *Santa María*, *Niña*, and *Pinta* lay to waiting for daylight, and for Columbus to step ashore for the first time in the New World.

The island Columbus landed on was called Guanahani by the Indians. But just which island is it? Despite the historical significance of Columbus's first landfall, the identification of Guanahani has remained uncertain for nearly 500 years. The ambiguity of the written description of the island combined with the uncertainties of 15th century navigation has made it difficult to determine on which of the many possible Bahamian Islands Columbus landed.



With corrections for winds and currents, the computer-generated track of the 34-day voyage from the Canary Islands points to a landfall at San Salvador.



Christopher Columbus overcoming the terrors of the ocean. (Engraving by Johannes Stradanus, printed by Adrianus Collart about 1580. The Bettmann Archive)

The most recent addition to the controversy over the identity of Guanahani is a study reported by Luis Marden and Joseph Judge in the November 1986 *National Geographic* magazine. Using three main lines of reasoning, they argue persuasively that Columbus landed first on present-day Samana Cay. They claim that 1) Columbus's transatlantic voyage when corrected for wind and current ends at Samana Cay, 2) Columbus's description matches features of the island, and 3) Columbus's description of his subsequent voyage toward Cuba and among the West Indies matches real islands and sailing passages only when one starts at Samana Cay. However, many earlier geographers, including R. T. Gould, Samuel Eliot Morison, and John W. McElroy concluded that the first landfall was San Salvador (Watling Island). Others have argued that Columbus first landed as far southeast as Grand Turk Island, or as far northwest as Egg Island.

Luis Marden, however, was the first to quantitatively apply corrections for wind and current to Columbus's transatlantic voyage; this shifted the endpoint of the cruise from San Salvador to Samana Cay. There were, it seemed to us, two flaws in Marden's corrections. He applied wind corrections for the first part of the voyage in the Northeast Trades, but not for the latter part in the Southeast Trades. Second, he used speed and direction of currents given in the modern U.S. Pilot Charts. The velocity on these charts is rather schematic, but more importantly, the charted speeds are about three times larger than the appropriate values of average velocity (for explanation, see box on page 8)—the result of the charted speed being calculated using only those observations in the same general direction as the average velocity. These flaws suggested to us that Marden's result could be incorrect.

To test this idea, we assembled the best historical wind and current data available and applied corrections consistently along the whole track of the *Santa María*, Columbus's flag ship. These historical data sets were already in hand, and have been used for several years as part of our ongoing investigations into the currents and circulation of the world's oceans. All that was needed was to extract from previous compilations a detailed subset for the region to be studied.

The most significant finding is that, when winds and currents are accounted for, the end of the voyage falls within 25 kilometers of San Salvador Island. No adjustments were applied to decrease the cruise track length to match a possible first landfall as other investigators have done. The effect of the wind and current is rather small—wind shifts the cruise endpoint only 8 kilometers northwestward; current shifts it 135 kilometers westward.

Columbus's Log

To hit his expected landfall, Cipangu (Japan), and to later chart his cruise track and discoveries, Columbus paid very careful attention to his navigation; he maintained an accurate log of the steered magnetic courses of the *Santa María* and the estimated distance in leagues travelled through the water. Although the original log is lost, an abstract of a copy of it by Bartolomé de Las Casas, who was on the cruise, is extant. The navigation data was published and plotted by John McElroy in 1941, and more recently by Marden in 1986. We used Marden's value for a league, which is equal to 2.819 modern nautical miles, as well as his listed courses and distances. The departure point of the cruise was identified by McElroy as being located near 28 degrees North and 17 degrees West, southeast of the Canary Island of Gomera. For consistency with previous investigations, we used this point (as did Marden).

The landing of Columbus in the New World. (Painting by Vanderlyn, engraving by H. B. Hall. The Bettmann Archive)

Current, Wind, and Magnetic Variation

Even though at least some of the navigational information is on hand, reconstructing the ship's track, and landfall, depends heavily on external factors—the wind, currents, and magnetic variation (Figure 1). We assumed that winds and currents encountered by Columbus in September and October of 1492 did not differ appreciably from historical compilations for September and October taken during the last 50 years. Part of the justification for this is the consistency of the general climatological circulation patterns in this tradewind region of the North Atlantic. We did, however, adjust the dates of the voyage by 9 days to match the modern Gregorian calendar* used in the compilation of the modern wind and current values.

The current field was calculated using historical ship drift data obtained from the Naval Oceanographic Office.** Each ship-drift measurement of surface current velocity consists of the vector difference between the velocity of a ship determined from two position fixes and the average estimated velocity of the ship through the water during the same time interval, usually 12 to 24 hours. Because of their method of derivation, these measurements are especially appropriate for correcting the track of the *Santa María*. Vector averages were calculated from all velocity measurements in each 2-degree latitude by 5-degree longitude quadrat for September and October separately. Average velocity values were then interpolated to a 1-degree by 1-degree grid in order to have a uniform, closely spaced field for correcting the track.

* The original Julian calendar did not appropriately match the astronomical year. During the course of 1500 years, therefore, the calendar became out of step by about 10 days. The seasons were out of skew with the calendar, affecting, for example, the planting and harvesting of crops. Therefore, in 1582 Pope Gregory XIII decreed that the day following Thursday, October 4, 1582, should be Friday, October 15, 1582—along with other calendar reforms. Since Columbus sailed 90 years before the decree, we advanced the date of the voyage by 9 days, instead of the full 10.

** Under direction of Matthew Fontaine Maury, the U.S. Naval Oceanographic Office began compiling wind and current measurements in the mid 1800s. Maury studied ship's logs and developed charts and sailing directions that were issued as a series of publications—including the first Pilot Charts. He was instrumental in systematically collecting logs from U.S. Naval ships as well as domestic and foreign merchant vessels. Free copies of the charts were given to each vessel furnishing Maury with an abstract log. The pilot charts issued today are based on the entire suite of data collected since the time of Maury.

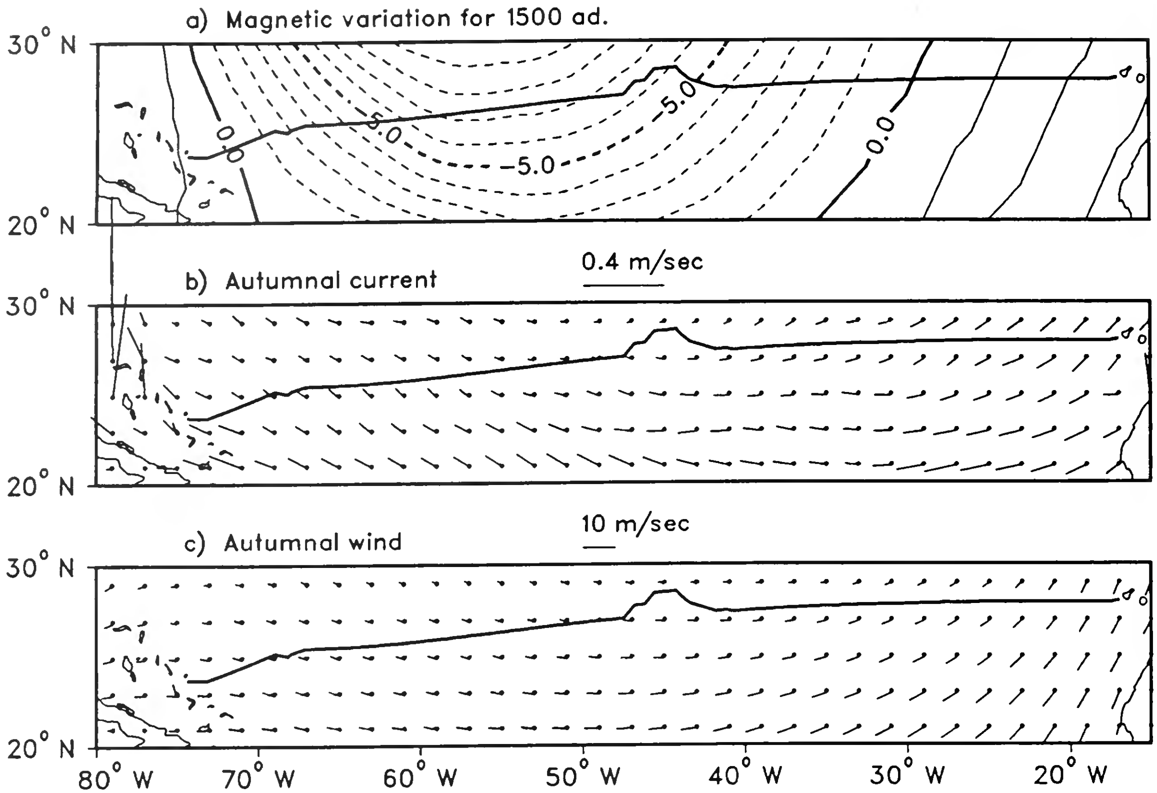


Figure 1. Corrected track of Columbus's flag ship Santa María *superimposed on maps showing a) magnetic variation for the year 1500 as charted by Van Bemmelen in 1899, b) the autumnal current field, and c) the autumnal wind field. Negative values of magnetic variation correspond to westward variations. The historical current and wind fields were vector averaged for the combined months of September and October. Wind and current measurements were obtained from ship's logs.*

Historical winds for the North Atlantic have been compiled at the Woods Hole Oceanographic Institution by Andrew F. Bunker and author Roger Goldsmith. The data were obtained from the National Climatic Center, a branch of the National Oceanic and Atmospheric Administration, which acts as collection agency for the many observations made by ships of opportunity and the merchant marine. The results of that study were further processed by Hans J. Isemer, at the University of Kiel, West Germany, to produce the data set on the 1-degree by 1-degree grid used in this study. The winds were computed using the vector averaging method for each month, September and October, separately.

The effect of the wind blowing on the *Santa María* is leeway, the sideways drift of the hull through the water. The leeway is a complicated function of the wind velocity, sea-surface condition, and the characteristics of the vessel. Today, 495 years after the voyage, the exact leeway is unknown. We therefore estimated leeway by calculating the component of wind at right angles to the steered course and by multiplying this component by an empirical factor of 0.014.* This correction for leeway is similar to Marden's during the first part of the cruise; however, we applied leeway consistently throughout the whole voyage. Even though our exact numerical value of leeway could be in error, the approximate magnitude and direction are correct. Further, subsequent tests, discussed later, show that the cruise endpoint is not very sensitive to the leeway factor. Lastly, the component of wind parallel to the course was ignored since it would vary the speed of the *Santa María*, but not the leeway, and the speed was already included in Columbus's log.

Magnetic variation, the difference between true North and magnetic North, was different in 1492 than it is today. To correct Columbus's logged magnetic courses, we used the magnetic variation for the year 1500 compiled by Van Bemmelen in 1899, and as used by both McElroy and Marden.

*Leeway can be expressed either as a sideways drift velocity or as the angular difference between a steered course and a course through the water. Our leeway factor value of 0.014 for sideways drift was calculated to be equivalent to Marden's 1.5 degree angular course difference in the northeast tradewinds off the Canary Islands.

Track of the *Santa María* and First Landfall

We calculated the track by starting near the Canary Islands at 28 degrees North and 17 degrees West on September 8, 1492 (old calendar), and advanced the *Santa María* in half-hour steps following the logged headings and distances. Every half hour, magnetic variation, wind, and current were interpolated to *Santa María's* position and corrections were applied to the next half hour of the cruise. The small time steps are necessary to reduce errors that could be introduced in interpolating wind, current, and magnetic variation over daily intervals.

At two hours after midnight, on October 12, 1492, land was sighted 2 leagues (about 10 kilometers) ahead. For that time, our best replotted position (point d on Figure 2) places *Santa María* about 24 kilometers southeast of the present island of San Salvador. Another possible island, Rum Cay, has been excluded from consideration because it does not match Columbus's written description; most previous researchers agree that Rum Cay is not the first landfall.

This result is exciting, and merits emphasis—when the *Santa María's* voyage is corrected for wind and current, it ends very close to San Salvador. All earlier attempts to replot the voyage resorted, by necessity, to adjusting *Santa María's* speed to make the end point come out right. Usually the endpoint was much too far (about 500 kilometers) to the west, and the cruise had to be artificially shortened to make the end match a possible landing site. Marden's overrun of 10 percent of the total distance was due primarily to the inflated current speeds that he used. McElroy's overrun was apparently the result of his using an incorrect length of a league. In our reconstruction, the cruise length matches almost perfectly with San Salvador. By perfectly, we mean within several kilometers out of a total cruise length of about 5,500 kilometers. It is difficult to know if this match is the result of chance, or due to Columbus's very accurate log coupled with modern corrections. Considering Columbus's careful attention to navigation, we favor the latter.

The effect of wind and current on the latitude of the endpoint is rather small. This is because the track cuts across the southern half of the North Atlantic gyre, and northward and southward deflections of the *Santa María* by wind and current nearly compensate for each other. Wind and current velocities are directed toward the Southwest during the first part of the voyage, but they swing around through West and are toward Northwest during the second part (Figure 1). Leeway alone shifts the end of the cruise 8 kilometers toward the Northwest (Figure 3). Current alone shifts the end 135 kilometers westward. Overall, the combined wind and current shifts it westward 140 kilometers, but northward only 16 kilometers.

The small deflections as the result of wind and current are in agreement with the conclusions of McElroy, but in disagreement with Marden. Marden found a much larger, 52 kilometer, southward shift. We attribute this to misuse of the pilot charts as a basis for wind and current corrections, and omission of leeway corrections west of 40 degrees West.

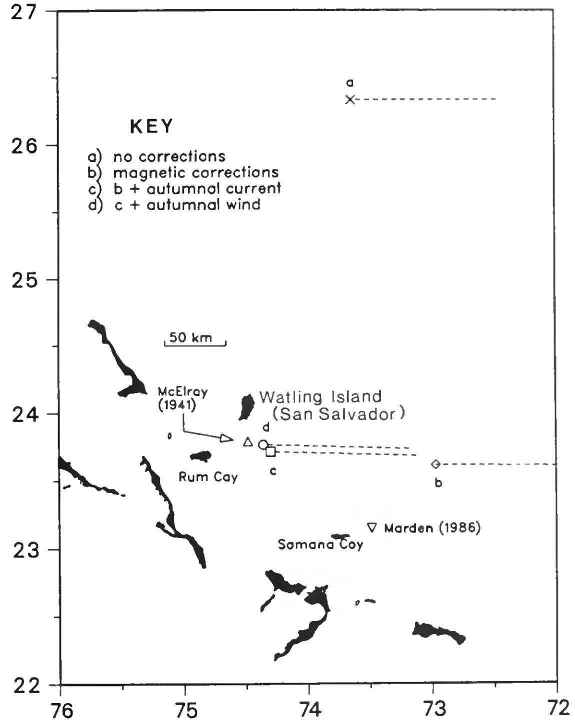


Figure 2. Endpoints of Columbus's transatlantic track showing the effect of successively adding corrections for magnetic variation, current, and leeway. Also shown are endpoints plotted by McElroy, who used no corrections for leeway or current, and Marden, who corrected for current along the whole cruise, but corrected for leeway only for the first portion of the cruise. Both McElroy and Marden resorted to backtracking the endpoint about 500 kilometers to make it match a possible landfall. Vertical axis is latitude in degrees North, horizontal axis is longitude in degrees West.

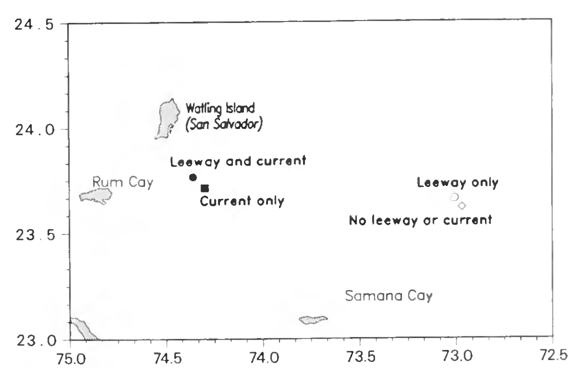


Figure 3. Expanded scale plot of cruise endpoints showing the effects of currents and leeway. Magnetic correction was applied for all cases. Vector average wind and current fields for the combined months of September and October (autumnal) were used to correct the track.

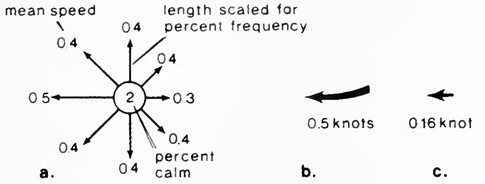
Current Calculations

Two terms—"prevailing current" and "vector average current"—can be used to describe ocean currents. In practice, the numerical values of these are calculated differently. The resulting values can also be very different.

Pilot Charts show prevailing currents, which indicate the most likely direction in which a current will flow, and the average speed of current in that direction. The prevailing current direction is the direction of the largest number of velocity observations in a certain region. The speed of a prevailing current is an average of only those observations lying within a 45-degree sector containing this direction. On the other hand, the average current is a vector average of all velocity observations in a certain region without regard for their direction.

Consider a hypothetical example, which is representative of currents in the mid-Atlantic portion of Columbus's track. In this example, the prevailing current is 0.5 knots westward, several times larger than the vector average velocity, which is 0.16 knots.

To correct a trackline for average conditions, the vector average velocity is the appropriate quantity to use. This is especially true where variations in velocity are large. Variation in velocity is a combination of real ocean fluctuations, or eddies, plus measurement errors. Random errors, which can be large in ship drift measurements, tend to cancel out in vector averages of velocity, but may not cancel in averages of speeds. Thus, part of the difference between the speed of prevailing currents and that of vector averages could be due to measurement errors.



Current depiction: a) "Current rose" representative of the mid-Atlantic portion of Columbus's track. The variability of currents in this region is shown by displaying the percentage of current velocities lying in each of the 8 principal directions, and the average speed in each direction. This information can be summarized in two additional ways: by b) a prevailing current, as shown on the Pilot Charts, which is the direction in which the largest percentage of velocity observations lie and the average speed in this direction—0.5 knots westward in the present example; and c) a vector average velocity of all velocity observations in a certain region—0.16 knots westward in this example.

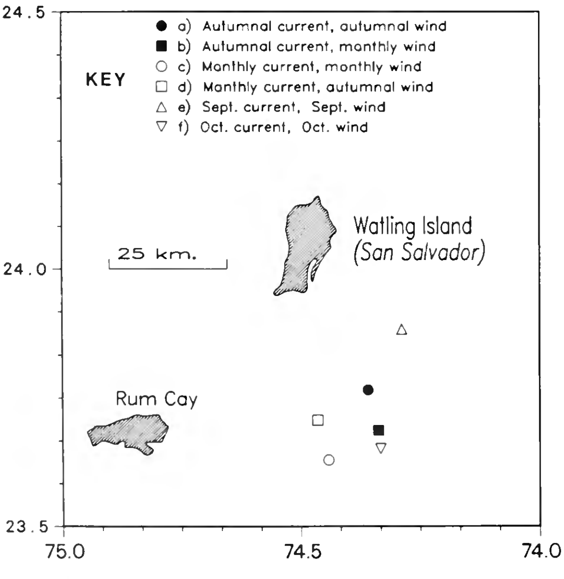


Figure 4. Cruise endpoints determined by using different wind and current fields. Autumnal is used to signify averages over September and October. Monthly means that September fields were used for the September portion of the cruise, October fields for the October portion. A leeway factor of 0.014 was used for all cases.

Examining the Results

With our first computer-generated track in hand, and the tentative conclusion that San Salvador was indeed the landfall, we next sought to critically examine what we had done. In generating our first track, a number of decisions were made about the variables involved, and "best estimates" were made for some of the unknowns. Would different choices change the outcome?

We think that the most representative wind and current fields for the Columbus voyage are given by averages of the combined months of September and October, called autumnal here (Figures 1 and 2). This is because the cruise overlapped both months. To study how the seasonally varying winds and currents would affect the track, we recalculated it using various combinations of different months (Figure 4). All values of the cruise endpoint fall within a circle 16 kilometers in radius, the center of which lies virtually on top of the autumnal endpoint adopted as our best case. A remarkable result is that there really is not much variation in position attributable to different wind and current fields. All tracks favor San Salvador; none of the endpoints lie close to Samana Cay.

The relative importance of the numerical value of the leeway factor was studied by recalculating the track with various values ranging from zero to 0.020 (Figure 5). Increasing the leeway

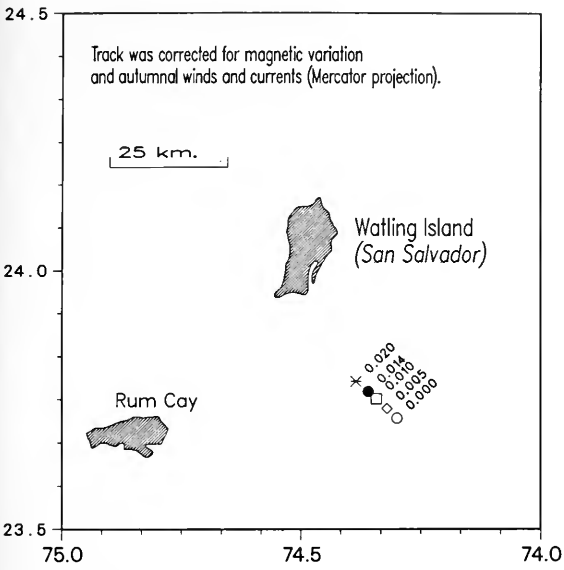


Figure 5. Cruise endpoints showing the effect of varying the leeway factor. The cruise track was corrected for magnetic variation and autumnal (September and October) wind and current.

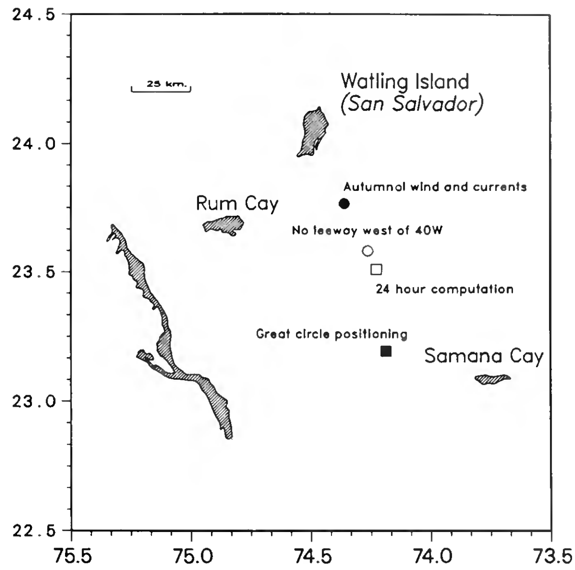


Figure 6. Cruise endpoints showing the effects of Marden's calculations; the progressive effects of removing leeway west of 40 degrees West, using a one day computation interval, and using a great circle positioning. Magnetic corrections and a leeway factor of 0.014 were used in all cases.

factor shifts the endpoint northwestward toward San Salvador, but the shift is rather small, 12 kilometers for the full range considered here. Thus, if we have underestimated the leeway factor, the error is probably small, and would tend to make the endpoint lie even closer to San Salvador. The northwestward shift with increasing leeway factor clearly shows the influence of the Southeast trade winds in the western Atlantic, which would set the *Santa María* northwestward. Thus, one cannot assume, as did Marden, that no leeway occurs west of 40 degrees West.

When we included the leeway correction only east of 40 degrees West to simulate Marden's calculation, the endpoint is shifted about 23 kilometers toward Samana Cay. What then causes the remainder of the distance toward Samana Cay that Marden shows? The difference could be accounted for in part by the daily computation intervals that he used. It is also important that rhumbline positioning* and not great circle positioning be used when computing positions for time intervals of this magnitude. When we recalculated the track using Marden's 1) leeway only east of 40 degrees West, 2) great circle positioning, 3) daily time steps, *but* 4) our vector-averaged currents, the endpoint is shifted southward 65 kilometers (from our endpoint), to lie 39 kilometers west-northwest of Samana Cay (Figure 6). This is almost due west of Marden's endpoint, which he shifted eastward to match a first possible landfall.

While several factors have a rather small role, the cruise track depends heavily on the magnetic variation. For example, when the track is recalculated with a zero magnetic variation, instead of the Van Bemmelen field for 1500 A.D., the cruise ends 300 kilometers northward, implying an eventual landfall on Great Abaco Island (Figure 2). If this had been the real track, presumably the 44 leagues Columbus promised his men would have been exceeded before reaching land, and his mutinous crew would have forced him to turn East toward Spain. Viewed from the Canary Islands the angle between the two islands San Salvador and Samana Cay is only about 1 degree. This means that to accurately pick one of these as the landfall based on the track of the *Santa María*, her average course and the average magnetic variation need to be known to better than ±1 degree. We suspect that neither the course nor magnetic variation for 1492 are that accurate, which implies that there remains a large uncertainty in our conclusion that San Salvador was Columbus's first landfall.

To further demonstrate the key role of magnetic variation, we retracked the cruise with modern values of magnetic variation which are about 15 degrees West. The track is shifted far to the south, and passes between the islands of Antigua and Guadaloupe in the Antilles (Figure 7). In fact, Columbus was aiming for Cipangu (Japan), which he

* Rhumbline positioning approximates the track of a vessel following a constant course on a spherical surface—the ship's track crosses all meridians at the same angle. A vessel sailing due West will remain at the same latitude at which it started. Great circle positioning results in a track along which the course will vary—sailing along the arc of a great circle is often the shorter route. A vessel starting out with a course due West along a great circle track would soon find itself on a course south of West (in the Northern Hemisphere) and south of the latitude at which it started. For small distances, such as those covered in a half-hour sail, the rhumbline and the great circle track are nearly the same. For a 24-hour period, however, the endpoints may be several kilometers different.

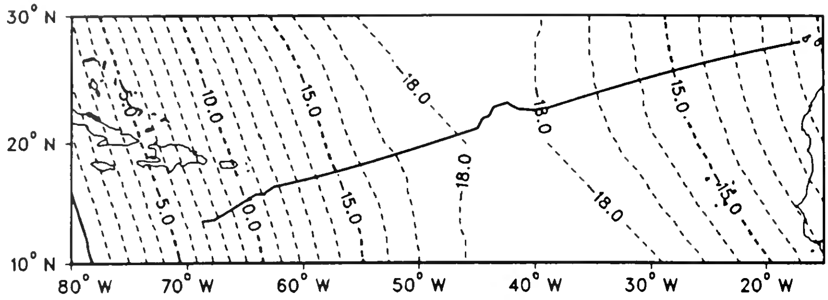


Figure 7. Hypothetical track using 1980 magnetic variation field, demonstrating the key role of magnetic variation in determining the cruise track. Negative values indicate westerly variation. Wind and leeway corrections were not included. The cruise track cuts between Antigua and Guadaloupe in the Antilles, the first possible landfalls.

thought was due West of the Canaries. Had the magnetic variation been as large as today's values, he might have compensated by steering north of magnetic West. Whether or not he tried to compensate for the smaller 3 degree West real variation on his voyage is not entirely clear.

Summary

We think that our corrections to Columbus's first voyage have helped improve our knowledge of his real track and first landfall. Our cruise endpoint matches very closely with San Salvador, suggesting that this island was his first landing in the New World. The differences between our endpoint and Marden's near Samana Cay were explored and explained as being due to Marden's partial leeway corrections, his daily time steps, and his inflated current speeds. We found the track depends critically on magnetic variation, which is rather poorly known for 1492. Further work validating Van Bemmelen's magnetic variation map could lead to a better track. A real improvement in the reconstructed track and a final resolution of the landfall question may have to wait until Columbus's original log is discovered. The original log would help clear up inconsistencies and gaps in the Las Casas version.

The analysis presented here considered only the transoceanic portion of the voyage. Marden and Judge also match Columbus's description of Guanahani with Samana Cay and his subsequent voyage to other Bahama Islands. The complete suite of information needs to be considered before the first landfall can be identified unequivocably.

Philip L. Richardson is an Associate Scientist in the Department of Physical Oceanography, Woods Hole Oceanographic Institution. Roger A. Goldsmith is a Research Specialist in the Department of Ocean Engineering at WHOI.

Acknowledgments

Funding was provided by National Science Foundation Grant OCE85-14885. Contribution 6561 from the Woods Hole Oceanographic Institution. The Judge and Marden provocative articles stimulated our interest in the Columbus voyage. Colleen Hurter helped find early studies of the first landfall, Terry McKee calculated the ship-drift current vectors, and Mary Ann Lucas typed the manuscript.

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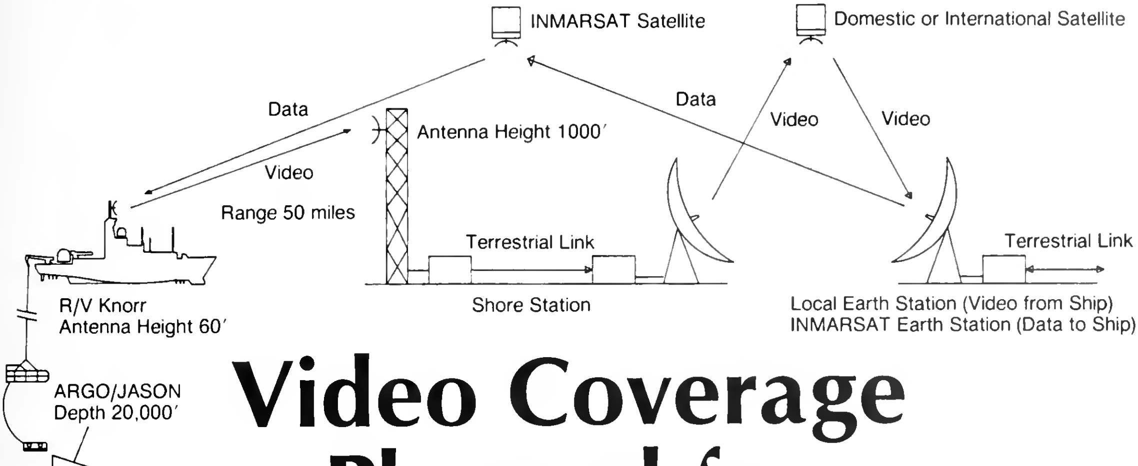
Live Deep-Sea Expedition



Above, Figure 1. Near-shore microwave video link with satellite video distribution and return data link.

Video Coverage Planned for Scientists Ashore, Educational Institutions

by Robert D. Ballard, Christopher von Alt, and William J. Hersey III

The exciting possibility of exploring the ocean with those who must remain on land is rapidly becoming a reality. A satellite communication system, being developed by the newly created Center for Marine Exploration at the Woods Hole Oceanographic Institution (WHOI), will permit members of research and educational institutions to participate in blue water benthic expeditions while remaining on shore. The system will transmit live video images, as seen through the eyes of advanced robots such as Argo/Jason, directly from the sea floor to participating institutions throughout the world. The compressed video and data will be transmitted via the International Maritime Satellite (INMARSAT). Inquiring minds may ask questions or transmit data back to the research vessel in real time over the same satellite link. In essence, the system will permit a video conference to be held between scientists and others ashore and shipboard personnel, while exploring the bottom of the deep ocean.

Previous expeditions, which include the finding and exploration of the *Titanic* by the senior author and others, have clearly demonstrated that high-quality video images may be collected from the sea floor and transmitted to a surface ship. To date, however, the importance of the information collected could not be shared with those on land until the ship returned to port. It is hoped that by allowing public research and educational institutions to experience the excitement of ongoing oceanographic research, greater public awareness of the need for this type of research will be generated and, as a result, greater economic support for this type of work will be forthcoming. In addition, Ballard hopes that young people who are exposed to these adventures will be stimulated and seek technical careers, a resource vital to our nation's future.

Satellite communications for use in maritime applications is a well-established business. The INMARSAT (International Maritime Satellite) system provides worldwide communications capability to the marine industry. This system allows voice communications similar to the standard telephone as well as narrowband data communication between ship and shore. Up to now, technical concerns, such as shipboard antenna size, transmitter power, and satellite bandwidth have made video transmission

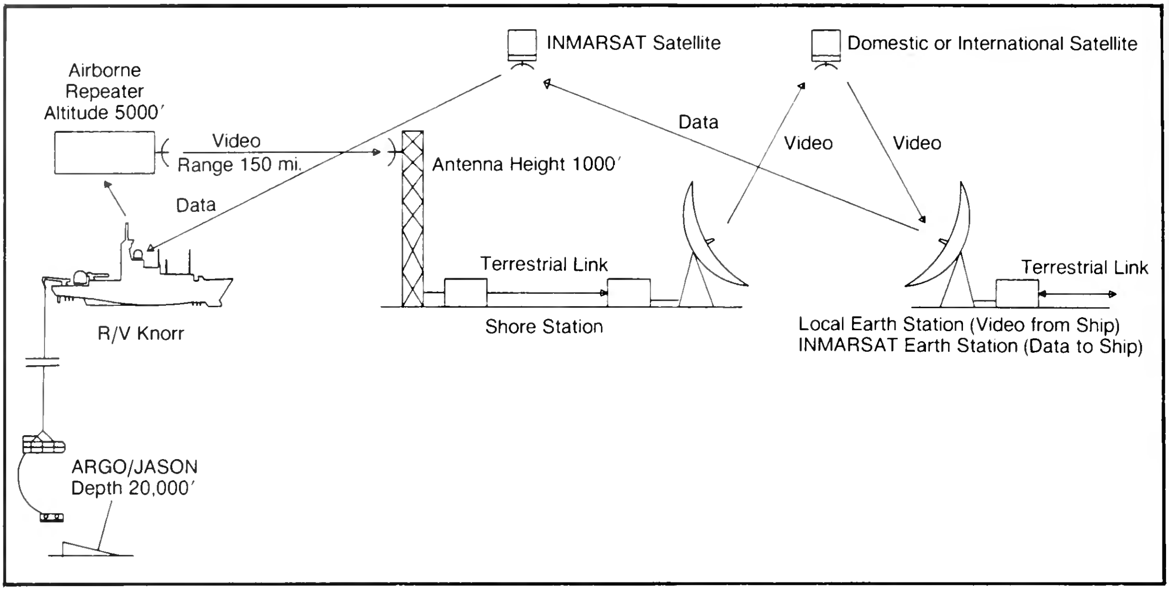


Figure 2. Extended-range microwave video link with satellite video distribution and return data link.

via the INMARSAT system using standard techniques impossible. While ships cruising close to the United States coast can receive video from domestic satellites for entertainment purposes, the antenna signal pattern of domestic or international satellites other than INMARSAT does not cover most of the oceans of the world. The INMARSAT system is thus the only choice for satellite reception.

The increased demand for terrestrial video teleconferencing using limited bandwidth transmission systems, such as the telephone network, has pushed for the commercial development of video bandwidth compression systems. These compression systems enable a high-quality video signal to be sent over a restricted bandwidth transmission system. The system under development at WHOI will take advantage of the availability of these compression systems to provide ship-to-shore video service.

Technical Concerns

The compression of video using commercially available equipment while providing a high-quality image has its drawbacks. To provide a high-quality picture with reduced bandwidth, only necessary video information is transmitted on a frame-to-frame basis. As long as motion in the video signal is limited, no disruption of the received picture is noticeable. However, if significant motion is present, the information required to update the picture on the receiving end exceeds the capability of the system. This causes degradation of the picture until the extreme motion ceases and the system catches up.

Ideally, it would be desirable to have full motion, broadcast-quality video capability from oceanographic research vessels at sea. Indeed, this is possible with certain restrictions. For near-shore exploration, the location of the search area close to shore would allow for such a system. Here, several techniques would be available.

The simplest technique would require a microwave link from the ship to the nearby coast. As long as a line-of-sight path could be maintained, transmission of the video signal would create minimal technical difficulties. This would require that the transmitting antenna on the ship be placed so that it could be pointed directly at the receiving antenna on the shore. The receiving antenna must track ship movement, and would have to be placed at a suitable elevation to assure that the curvature of the Earth would not interrupt the line-of-sight path. This type of system is shown in Figure 1. Once the signal is received on shore, it could be sent by terrestrial links to a domestic or international satellite Earth station as required for distribution or transmission back to the United States. By placing the shipboard transmitting antenna on the ship superstructure at an elevation of about 60 feet above the waterline, and the receiving antenna on shore at an elevation of 1,000 feet, a range of about 50 miles would be possible. This range is marginally adequate for the various expeditions now being planned.

A second technique requires addition of an airborne microwave repeater to the first system. By elevating the transmitting antenna, the range of the system can be improved. Figure 2 shows such a system. Here, a helicopter or balloon carries a stabilized antenna that is always pointed at the receiving antenna on shore. The ship then transmits its signal to the airborne repeater for transmission to shore. By elevating the transmitting antenna to 5,000 feet, the allowable range increases to about 120 miles.

A third technique uses a system similar to that used by ships receiving domestic video transmissions. A domestic or international satellite would be used to send video to a shore station as in Figure 3. This system would provide better range than either of the previous two systems, but it too has its technical problems. Because of restrictions on

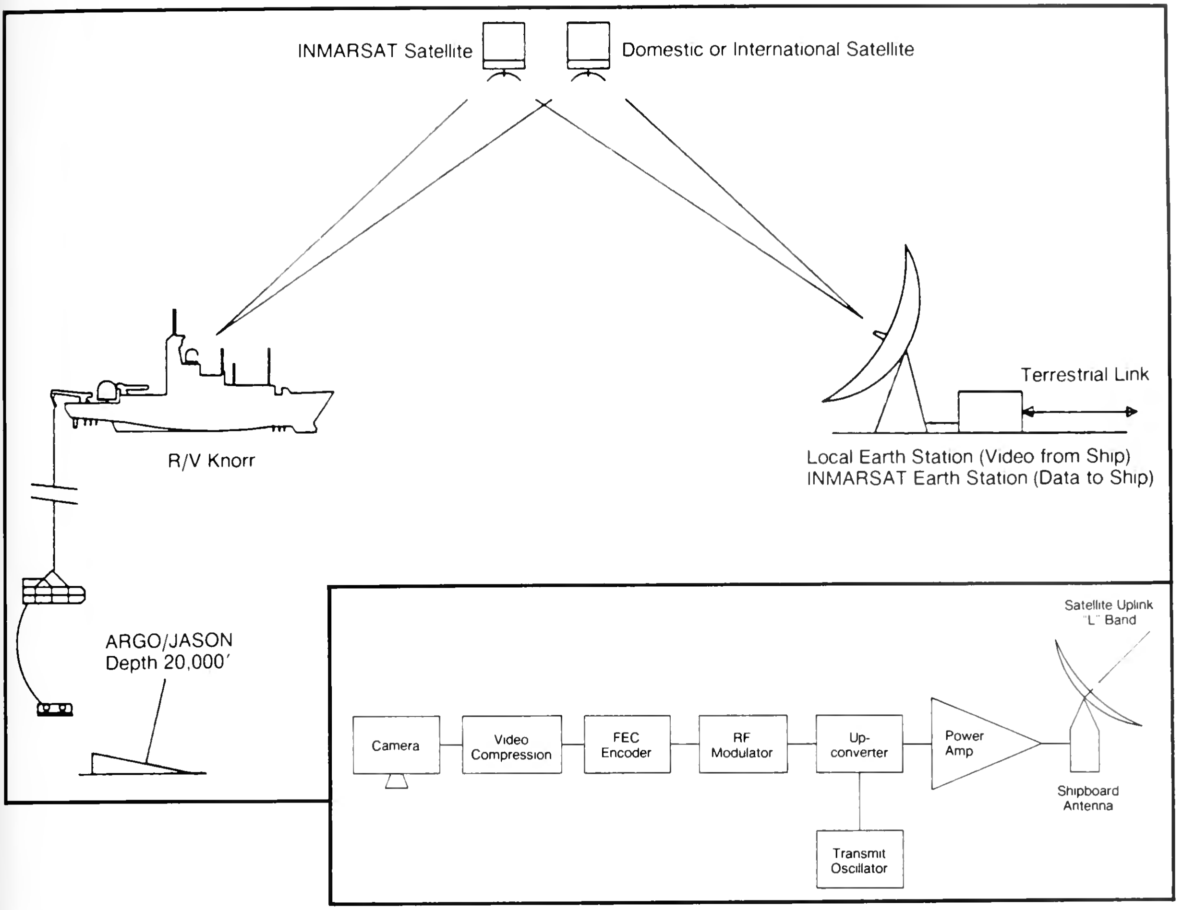


Figure 3. Full-bandwidth coastal satellite video link with return data link. Inset shows shipboard video transmission equipment for satellite uplink.

shipboard antenna size and transmitter power limitations, use of special, highly directional satellite based antennas (called spot-beam antennas) would be required to assure that enough signal power was available for a good quality picture. In fact, limitations on signal transmitter power might require compression of the video signal as well. This system also appears to violate the international treaty under which INMARSAT was established, which requires that all satellite transmission from a ship at sea be conducted using the INMARSAT system.

All three techniques, while providing full bandwidth and broadcast quality video, have one major drawback. They all restrict operational range of the oceanographic vessel. The first two by the necessity of a land-based receiver, and the last by the requirement of satellite spot-beam antenna coverage. As many of the areas where oceanographic research is being conducted would be beyond the range of any of these three systems, even though they would be adequate for near-shore projects, it was decided that for overall oceanographic use, the range available with the compressed video INMARSAT system outweighed the motion-caused video degradation. Since most underwater imaging has only moderate motion, it is felt that this degradation will be minimal.

Satellite System Design

The satellite system under development is to be installed on the *R/V Knorr*, operated by WHOI. This system is by no means limited to operation on the *Knorr*, as it has only minimal requirements from the ship, such as power, a suitable location for antenna placement, and navigation information used for satellite tracking. These are required for any INMARSAT satellite terminal installation.

The shipboard system consists of several major units as shown in Figure 3 inset. The first unit is the compression unit already mentioned. This unit modifies the video from the camera source to fit in the restricted bandwidth of the system. This signal is encoded with forward error correction (FEC) and modulated using another commercially available unit. The FEC coding improves system performance by maximizing the effective power in the satellite link. Next, the signal is converted to the desired transmitter frequency and amplified to the level required for transmission. The most visible unit is, of course, the antenna. An antenna designed for

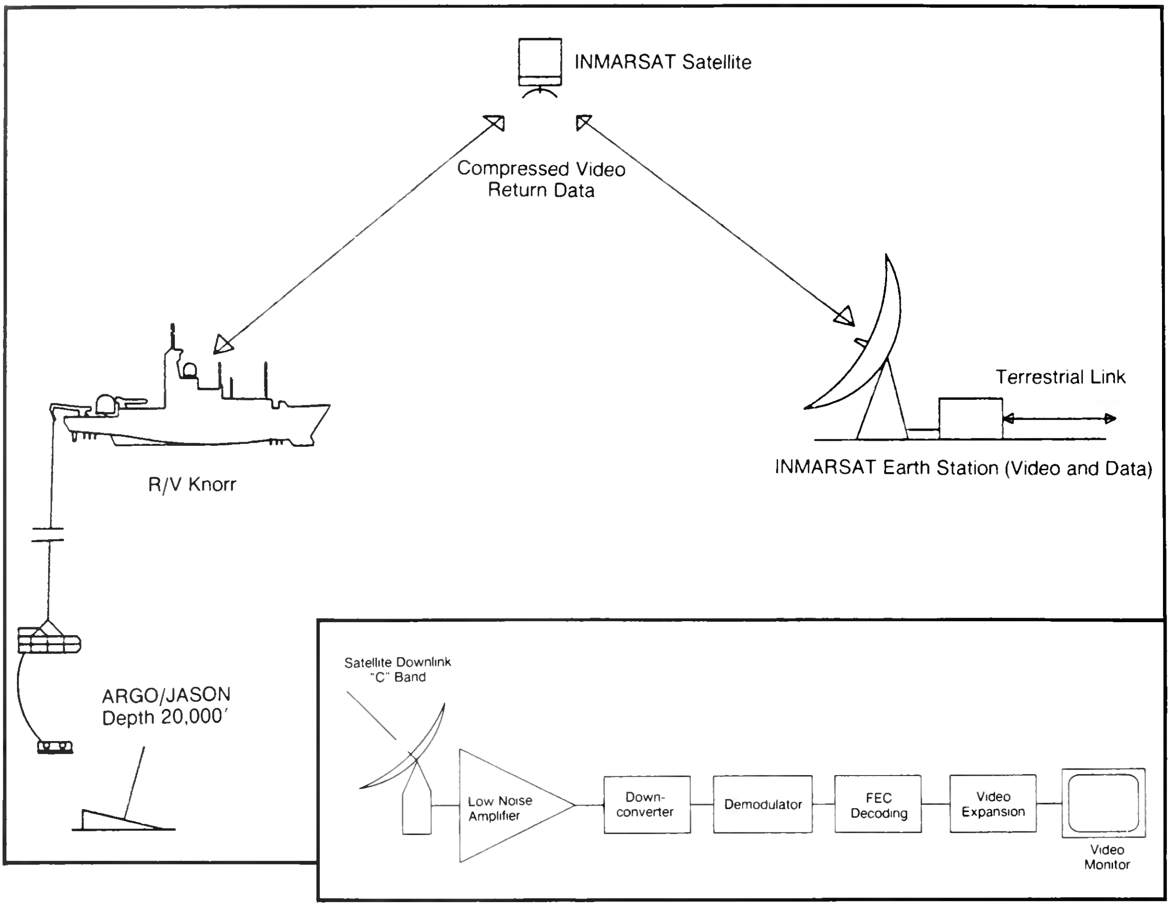


Figure 4. Full ocean coverage satellite video link with return data link. Inset shows shorebased video reception equipment for satellite downlink.

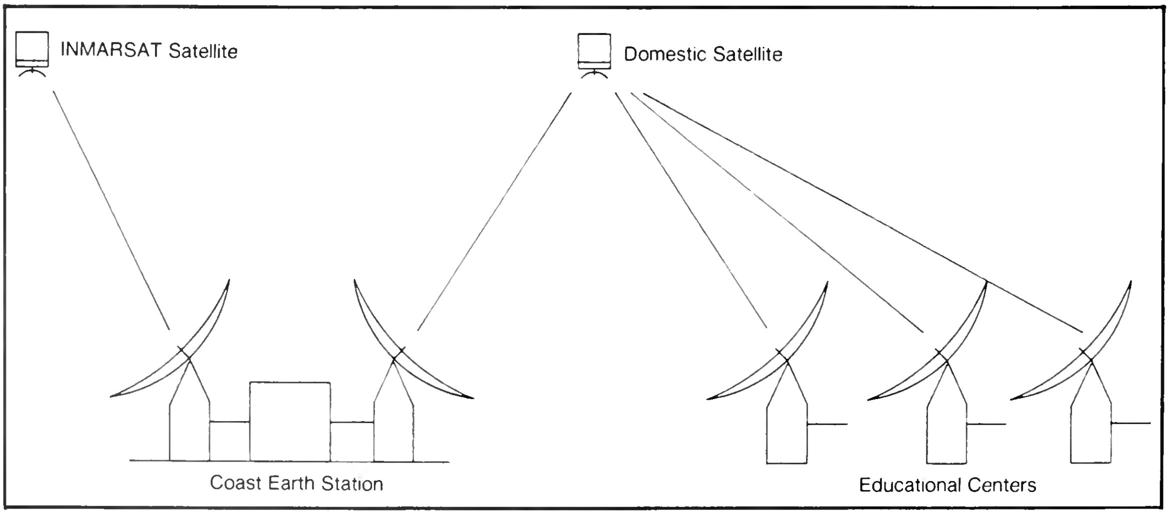
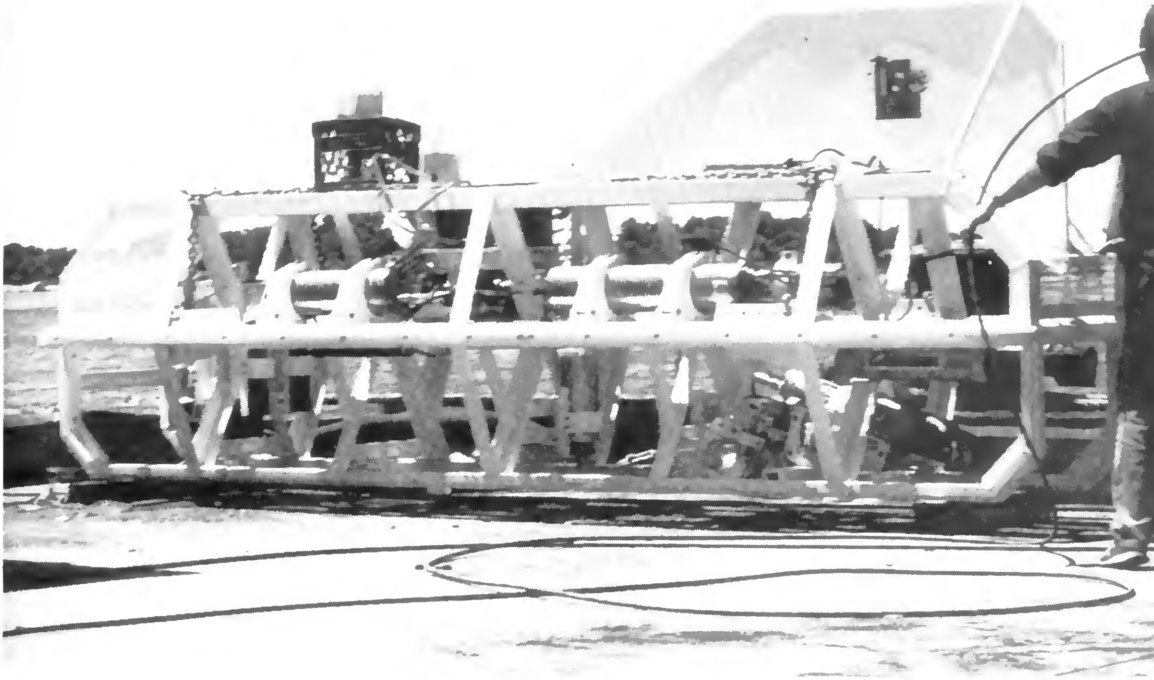


Figure 5. Distribution network for multiple end-user system.



The Argo camera sled. A new model now under development will serve as a base for the tethered ROV, Jason. The completed Argo/Jason unit is visualized as the remote eyes, or "telepresence" of scientists aboard ships, or ashore. (Photo courtesy of WHOI)

shipboard reception of entertainment programing is available for use as a transmitting antenna. This antenna already qualifies as a stabilized platform necessary for shipboard use. Additionally, a previous video experiment has been conducted by COMSAT (Communications Satellite Corporation) Laboratories using this antenna with the INMARSAT system to receive video on the *Queen Elizabeth II*. The last piece of equipment is a modified INMARSAT terminal. This terminal provides satellite tracking information to the antenna platform.

The signal is transmitted to the INMARSAT satellite and sent to a coast station in the United States as seen in Figure 4. Here the reverse process from that of the shipboard equipment takes place. Figure 4 inset shows the flow at the receiving station. A low noise amplifier (LNA) boosts the signal received by the antenna from the satellite. This signal is then converted and demodulated. The FEC decoding then removes some of the errors introduced during transmission. The signal is now ready to have the compressed information transformed back into a video signal. At this point, any television monitor can be used to view the video sent from the ship.

Terrestrial Distribution

Once the video has been reconstructed at the coast station, it can be distributed to interested users. Several methods are available for this task. If only a single destination is necessary, the video expansion operation can be done at the final destination. This will allow use of a T-1 telephone link* for transmission of the video signal. If multiple destinations are desired, it might be desirable to send the received video via domestic satellite link to the final destinations. This can be readily accomplished as shown in Figure 5 using standard commercial equipment. Other variations of these methods also can be implemented. The final choice has yet to be determined. This decision will be based on the number and location of educational centers and other viewers interested in the various underwater expeditions.

Robert D. Ballard is Head of the Deep Submergence Laboratory (DSL) within the Ocean Engineering Department of the Woods Hole Oceanographic Institution. He also is Head of the Center for Marine Exploration. Christopher von Alt and William J. Hersey are DSL research engineers.

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This is Contribution 6574 from the Woods Hole Oceanographic Institution.

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* Terrestrial data link using high-grade telephone line operating at 1.544 megabits per second data rate.

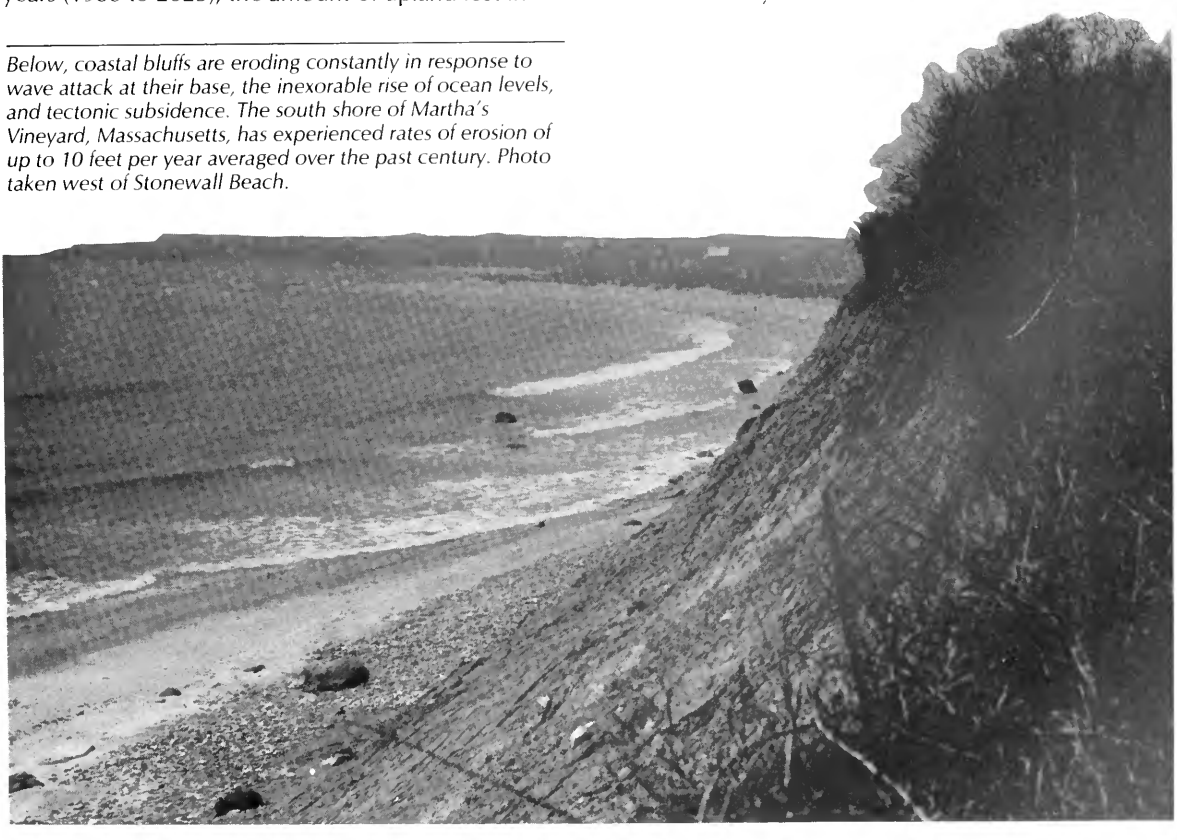
Truro, Cape Cod, Massachusetts. A combination of wave action and gradual sea-level rise combines to erode the oute shoreline of Cape Cod approximately 3 feet per year, providing approximately 600,000 cubic yards of sediment to the oceans. This rate of erosion and submergence would increase markedly if projections of increases in rates of sea-level rise are correct.

Losing Coastal Upland to Relative Sea-Level Rise: *3 Scenarios for Massachusetts*

by Graham S. Giese, and David G. Aubrey

Coastal shoreline retreat is a major environmental and societal problem in the United States and in many other parts of the world. Recent predictions of increased rates of sea-level rise for the 21st Century add to the urgency of the problem. A recent study by the authors and colleagues indicate that in 45 years (1980 to 2025), the amount of upland lost in Massachusetts as the result of relative sea-level rise will range anywhere from 3,000 to 10,000 acres. If ocean-front property is worth a nominal $1 million per acre, the total loss will be between $3 billion and $10 billion. This loss will affect private homes, transportation, and commerce. Similar losses could be sustained by other states and nations.

Below, coastal bluffs are eroding constantly in response to wave attack at their base, the inexorable rise of ocean levels, and tectonic subsidence. The south shore of Martha's Vineyard, Massachusetts, has experienced rates of erosion of up to 10 feet per year averaged over the past century. Photo taken west of Stonewall Beach.



The term "upland" refers to terrain landward of wetland that has not been altered appreciably by coastal processes—waves and tides, for example. "Wetland" refers to coastal terrain that has been reworked or eroded by coastal processes. Examples are coastal bluffs and dunes, beaches, and marshes. We have found it useful in our studies to separate the retreat of uplands from that of wetlands because of the differences in the processes involved.

When land area is lost, the effects on uplands and wetlands may be different. Upland retreat always results in the loss of upland area, whether the retreat is caused by erosion, or encroachment by wetlands. Wetland retreat, on the other hand, may or may not result in a reduction of wetland area. For example, coastal dunes and barrier beaches frequently migrate landward without sacrificing total area. It is true that upland loss is usually accompanied by wetland gain. But, since wetland use is highly regulated, the area available for most societal uses, such as for farming or home building, is reduced by the amount of upland lost.

Coastal upland retreat takes two forms: active, wave-produced erosion; and passive loss resulting from relative sea-level rise. The eroding sea cliffs of outer Cape Cod are, for many of us, a familiar example of upland lost to ocean wave action. Although a rise in relative sea level contributes to active wave-produced erosion, it is not possible at present to isolate the cause of rise in sea level from the many other factors that contribute to the erosion process.

We can, however, estimate with reasonable accuracy the upland recession (or "inundation") of a passive shoreline (one that is not being altered actively by wave or current action) as relative sea level rises. By "relative sea-level rise" we mean a rise in the level of the sea with respect to the level of the land. This definition does not specify the amount contributed by global changes in the level of the sea surface versus local changes in the level of the land surface (subsidence or uplift). Relative sea-level changes at a specific coastal location are determined from analyses of tide gauge records.

As relative sea level rises, the mean high-water level, the mean spring high-water level, and all other tidal reference levels associated with sea level, rise also. Therefore, as shown in Figure 1, the level of the boundary separating upland from wetland (which is sometimes referred to as "shorelevel") rises at the same rate as relative sea level, regardless of the local elevation of that boundary, which varies considerably from place-to-place due to varying exposure to waves and tides.

The rate of passive upland retreat at any one point on the shoreline depends on both the upland slope and the rate of relative sea-level rise, which, as we have seen, depends on both the local rate of land subsidence/uplift and the rate of global sea-level change. In Massachusetts, relative sea level has been rising at a mean annual rate of about 3 millimeters during the last 40 years. Approximately 2 millimeters per year can be attributed to land subsidence, so the contribution as the result of global sea-level rise is about 1 millimeter per year.

If the present rates of submergence continue

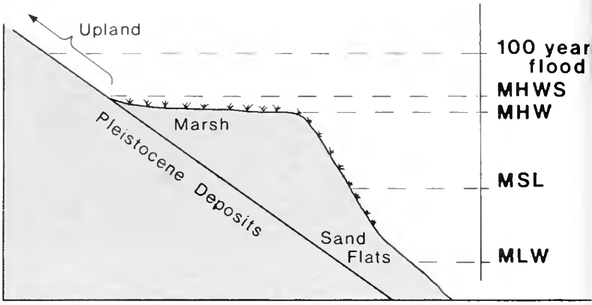


Figure 1. Deposits typically found in Cape Cod coastal embayments. Pleistocene (glacial) deposits are covered by fringing contemporary salt marsh deposits in the intertidal zone. Several commonly used tidal datum planes are illustrated: Mean Low Water (MLW), Mean Sea Level (MSL), Mean High Water (MHW), Mean Spring High Water (MSHW), and the expected level of the highest high water for the next 100 years. All reference levels, as well as the wetland-upland boundary, rise at the same rate as relative mean sea level.

unchanged, by the year 2100 relative sea level in Massachusetts will be 36 centimeters above its 1980 level. However, it is accepted widely that the global rate of sea-level rise in the 21st Century will exceed that of the 20th Century. Most likely, according to a recent Environmental Protection Agency (EPA) report, the increase between 1980 and 2100 will range between 144 and 217 centimeters (4.7 to more than 7 feet). Using these estimates (without necessarily accepting them as correct), and adding local land subsidence, Massachusetts will experience a relative sea-level rise ranging between 168 and 241 centimeters (5.5 to just under 8 feet) by the end of the next century.

Past studies of coastal upland retreat have concentrated on shore erosion and have neglected passive submergence, probably because such losses have been considered to be relatively small. Such is not the case, however, even at present rates of relative sea-level rise (as the results of our study show). In addition, when we consider the possibility of large increases in the rate of sea-level rise, the importance of measuring this loss due to relative sea-level rise becomes obvious. Thus, we set out to quantify the passive retreat of upland within the coastal communities of Massachusetts.

Hypsometric Curves

Measuring the passive retreat of coastal upland presents special problems. The linear retreat rate at any point is simply the product of the inverse of the local upland slope and the rate of relative sea-level, or shorelevel, rise. But using this method to calculate the rate at which upland is lost by an entire community would require a voluminous, and presently unavailable, collection of coastal topographic data.

We have found a shortcut to the calculation of community upland retreat rates in the use of "hypsometric curves." A hypsometric curve (from the Greek roots, "hypsos," height and "metron," measure) presents the distribution of the area of a given land (or sea-floor) surface area with respect to elevation. As an example, the hypsometric curve for the Town of Falmouth on Cape Cod, Massachusetts, is shown in Figure 2. At a glance, we can tell from the curve that almost all of Falmouth upland is less than 60 meters in elevation, and that about 50 percent of the town is less than 15 meters high.

Similar hypsometric curves were drawn for each of 72 Massachusetts coastal towns, several of which are shown in Figure 3. There is a striking variation between communities in the shape of their hypsometric curves, reflecting the variation in the geological processes that formed them. For example, communities on glacial outwash plains, such as Yarmouth, have curves with flatter slopes at low elevations as compared to those, such as Brewster, that lie on glacial moraines. Certain well-known local topographic features, such as the "Wellfleet Plains," also show up clearly on the figures. The elevation information needed to create these curves was obtained from U.S. Geological Survey digital data tapes, which provide one elevation data point for each approximately 1½ acres of upland area. All wetland areas—including inland features such as lakes and swamps, and coastal features, such as marshes, beaches, and dunes—were excluded from the data base. Altogether, more than half a million individual elevation data points were used.

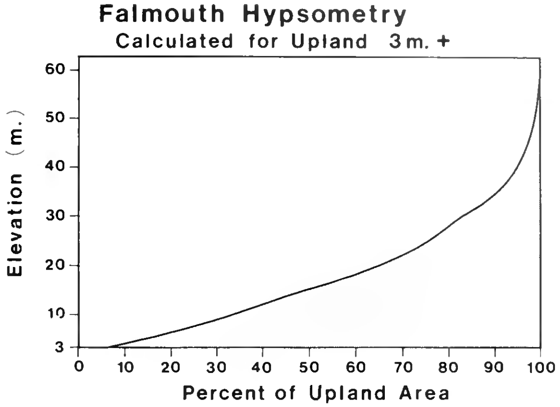


Figure 2. Hypsometric curve for the Town of Falmouth on Cape Cod, Massachusetts. From the curve, we can read the percentage of upland area of the town that lies below any given elevation. Almost all Falmouth upland is less than 60 meters high, and about 50 percent of the town is less than 15 meters high.

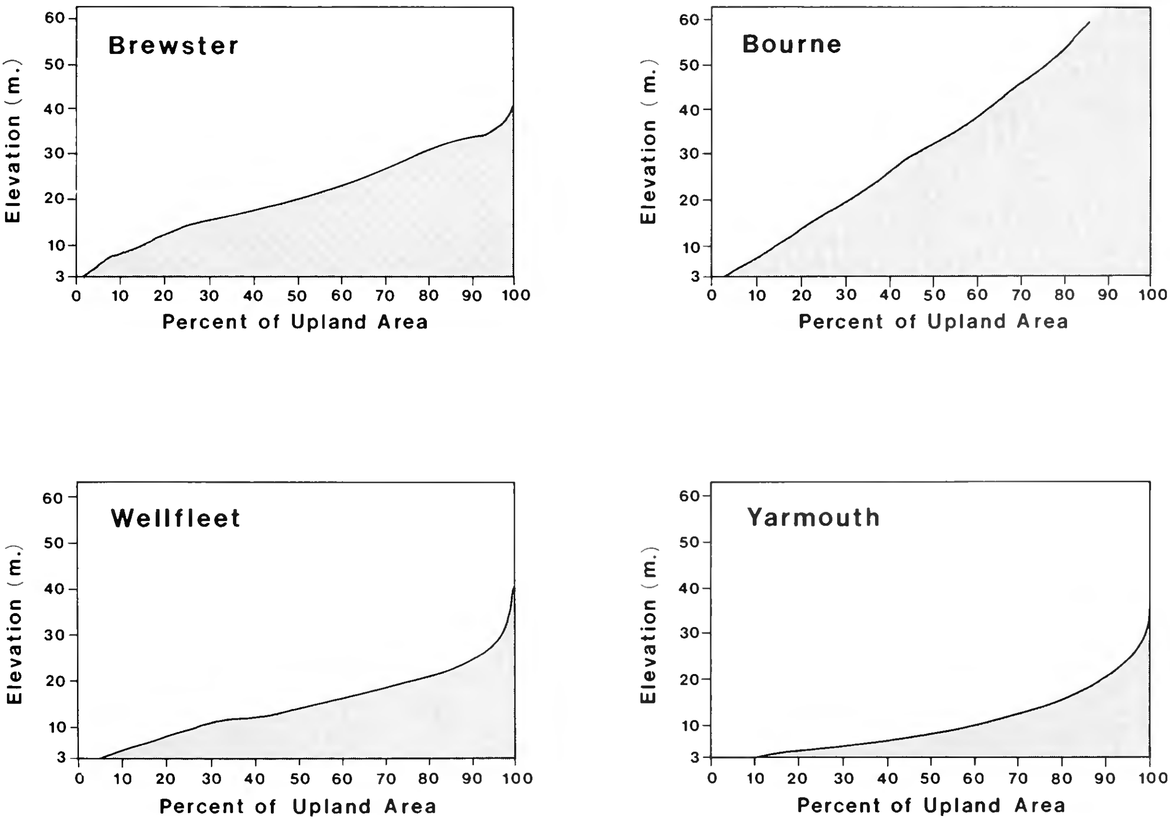


Figure 3. Hypsometric curves for representative towns on Cape Cod. The variations between the curves indicate variations in topographic form between the towns, which in turn reflect variations in the geological processes that formed Cape Cod.

The hypsometric curves of Figures 2 and 3 begin at an elevation of 3 meters above mean sea level rather than at sea level. Because the source data did not always permit separation of salt marsh areas from upland at 1- and 2-meter elevations, we excluded data for those elevations from the analysis. However, from studying many such curves, we know that their changes in slope tend to be gradual, and conclude that the percentage of upland per meter of elevation at 3 meters may be taken as representative of the upland distribution at low elevations. Therefore, the assumption was made that the percentage of upland at 1 meter and at 2 meters of elevation was equal to that at 3 meters. However, no assumption was made about the elevation of the wetland-upland boundary within a community, other than that these boundaries, whatever their elevations, rise at the same rate as relative sea level.

Upland Loss Rates

Once we obtained the hypsometric curve for the upland in each coastal town, we calculated the upland area that each community would lose, given particular scenarios for changes in relative sea level. The results of these calculations for selected towns in Massachusetts are presented in Table 1. Of particular interest are the last three pairs of columns, which give the amount of retreat, first in percentage of total upland area and then in acres, that will occur between 1980 and 2025, given three different sea-level rise scenarios. The first scenario, Case 1, calls for a continuation of the historical mean annual relative sea-level rise rate of 0.01 feet per year, yielding a total rise of 0.45 feet over the 45-year period. Case 2 assumes that global sea level will rise 0.86 feet during the 45-year period (as given by EPA's "mid-range low" scenario) and that the local coastal subsidence rate will remain at 0.006 feet per year, giving a total relative rise of 1.14 feet by 2025. Case 3 is based on the same assumption about local subsidence, but uses EPA's "mid-range high" global sea-level rise estimate of 1.29 feet by 2025, yielding a total relative rise of 1.57 feet.

The total Massachusetts upland loss at the historical relative sea-level rise rate is 65 acres per year. Averaged among the 72 communities, this is equivalent to 0.9 acres a year per community. However, the variation between communities is great: Nantucket loses 6.2 acres per year, while Winthrop loses only 0.1 acres. Communities other than Nantucket having large annual losses are: Wareham, 4.7 acres; Falmouth, 3.8 acres; Barnstable, 3.7 acres; and Yarmouth, 3.2 acres. The communities most affected are: Marion, which loses 0.031 percent upland per year, Nantucket, which loses 0.027 percent per year, and Hull and Yarmouth, which lose 0.026 percent per year.

Looking forward to the year 2025, if the historical rate of relative sea-level rise were to remain unchanged (Case 1), the total Massachusetts upland loss would be 2,950 acres. A relative sea-level rise of 1.14 feet (Case 2), would be accompanied by an upland loss of 7,460 acres, and a rise of 1.57 feet (Case 3) would cost the Commonwealth 10,270 acres of upland.

Table 1. Calculated upland retreat for Massachusetts coastal communities (areas are in acres, % represents percent of upland lost).

Town	Upland Area	Historical Annual Retreat: 0.01 ft/yr rise		Total Retreat: 1980–2025 Case 1: 0.45 ft. rise		Case 2: 1.14 ft. rise		Case 3: 1.57 ft. rise	
	Acres	%	*Area*	%	*Area*	%	*Area*	%	*Area*
Barnstable	30,710	0.012	3.7	0.54	167	1.38	424	1.90	583
Bourne	23,940	0.006	1.5	0.29	69	0.73	175	1.00	241
Brewster	14,110	0.005	0.7	0.23	34	0.58	82	0.80	113
Chatham	5,250	0.020	1.0	0.89	47	2.26	119	3.11	163
Dennis	10,620	0.024	2.5	1.06	113	2.69	286	3.71	394
Eastham	6,630	0.014	0.9	0.62	41	1.57	104	2.17	144
Falmouth	24,340	0.016	3.8	0.71	172	1.79	436	2.46	600
Harwich	11,830	0.016	1.9	0.73	86	1.85	218	2.54	301
Mashpee	13,390	0.010	1.4	0.45	61	1.15	154	1.59	212
Orleans	6,210	0.017	1.1	0.78	48	1.97	123	2.72	169
Provincetown	1,170	0.018	0.2	0.81	10	2.05	24	2.83	33
Sandwich	24,470	0.005	1.2	0.22	54	0.56	137	0.77	188
Truro	10,730	0.006	0.6	0.25	28	0.65	70	0.89	96
Wellfleet	9,130	0.011	1.0	0.50	46	1.27	116	1.74	159
Yarmouth	12,560	0.026	3.2	1.15	145	2.92	366	4.02	505
Boston	24,260	0.009	2.2	0.40	97	1.01	246	1.40	339
Hull	620	0.026	0.2	1.18	7	3.00	19	4.13	26
Marion	6,880	0.031	2.1	1.39	96	3.53	243	4.87	335
Nahant	470	0.019	0.1	0.83	4	2.11	10	2.90	14
Nantucket	23,230	0.027	6.2	1.19	277	3.02	702	4.16	966
Seekonk	11,430	0.001	0.1	0.04	4	0.09	10	0.13	14
Wareham	19,820	0.024	4.7	1.07	211	2.70	537	3.72	738
Weymouth	9,940	0.001	0.1	0.06	6	0.16	16	0.22	22
Winthrop	300	0.021	0.1	0.94	3	2.37	7	3.27	10
Other Mass. Coastal Communities	502,210		25		1,120		2,840		3,910
TOTALS	804,250		65		2,950		7,460		10,270

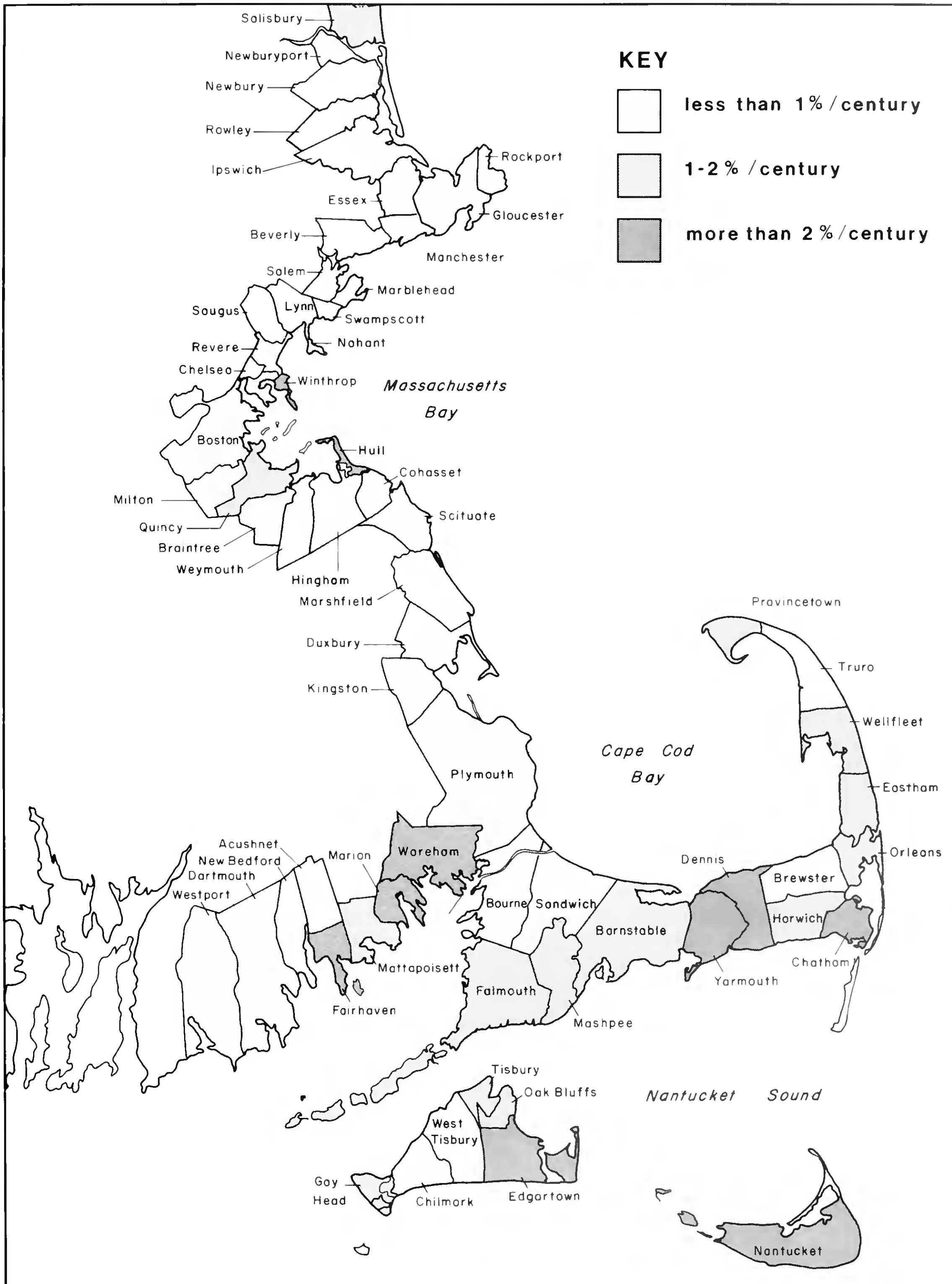


Figure 4. The upland retreat rates among the coastal communities of Massachusetts, coded according to the percentage of total upland lost per century at the present rate of relative sea-level rise. Note that several barrier beaches and sand spits are not shaded, and are not included in the calculations of upland lost by their respective towns.

When considering these figures, it is important to realize that they do not include the upland losses that would result from the response of groundwater levels to sea-level rise. In those communities where bedrock is absent, and the terrain consists of unconsolidated sediments, the water-table level over geological time periods is controlled by relative sea level. As sea level rises, the water-table level rises with it, increasing the size of existing streams, ponds, and bogs, and creating new ones. This secondary effect has not been included in the hypsometric analysis.

The upland retreat rates are based on the assumption that the coastal uplands have a natural form and are not protected by engineering structures. Particularly in urban coastal areas where seawalls, riprap, and fill are prevalent, the actual losses will be less than those predicted here. However, when large values of sea-level rise are considered, these structures may be overwhelmed.

The presently existing rate of passive upland retreat as the result of relative sea-level rise is much greater than the upland retreat rate caused by active, wave-produced erosion. This may be illustrated by considering the Cape Cod coast, well-known as a rapidly-eroding region. Although detailed estimates for cliff retreat do not exist for the entire region, the rate of erosion of the outer coast is known, and reasonable estimates can be made for the remaining and more slowly retreating cliff areas. Using existing information, and reasonable estimates where data are lacking, the annual upland loss experienced by Cape Cod as a result of active wave-produced erosion is about 9 acres a year. On the other hand, the annual loss as the result of the passive effects of relative sea-level rise, calculated from the figures for each Cape Cod town listed in Table 1, is about 24 acres a year. Thus, even considering a region of rapid erosion and excluding the effects of groundwater-table rise, passive retreat accounts for 73 percent of coastal upland loss under present conditions.

Conclusions

The major conclusions of the study are:

- *Relative sea-level rise is the major process responsible for upland loss in Massachusetts. Neglecting coastal erosion and groundwater-table changes, Massachusetts presently loses about 65 acres of upland each year as the result of passive submergence.*
- *The rate of upland loss due to passive submergence varies widely from town to town, and depends on the geology of the region in which the town lies.*
- *The hypsometric curves of each town provide important basic information that permits the calculation of the upland areas that those towns will lose to passive submergence as the result of any given increase in relative sea level.*
- *The total land loss by the year 2025 has been calculated for several relative sea-level rise scenarios. At the present rate of rise, Massachusetts will have lost about 3,000 acres of upland between 1980 and 2025. This is the same upland loss that occurred between 1935 and 1980, an equal length of time. For a rise of 1.14 feet, about 7,500 acres would be lost; and for a rise of 1.57 feet, the maximum likely, more than 10,000 acres would be lost. Given a nominal value of ocean-front property of $1 million per acre, the economic impact of this retreat is substantial.*
- *Although the present study has shown that passive retreat is an important element of the shoreline response to anticipated global climate change, this inundation is certainly not the sole impact. Future research is mandated for other climate impacts on the coast of Massachusetts, including but not limited to:*
  - *Effects of relative sea-level rise on groundwater resources.*
  - *Effects of relative sea-level rise on marshes and other biotopes.*
  - *Possible global climate-change impact on storm climatology of Massachusetts waters (a potentially devastating effect).*
  - *Improved estimates of future rates of sea-level change to improve the scientific basis for management.*

Graham S. Giese is a Visiting Investigator in the Geology and Geophysics Department of the Woods Hole Oceanographic Institution. He is visiting from the State University of New York, Stonybrook. David G. Aubrey is an Associate Scientist in the same department at WHOI, and Director of the Institution's Coastal Research Center.

Acknowledgments

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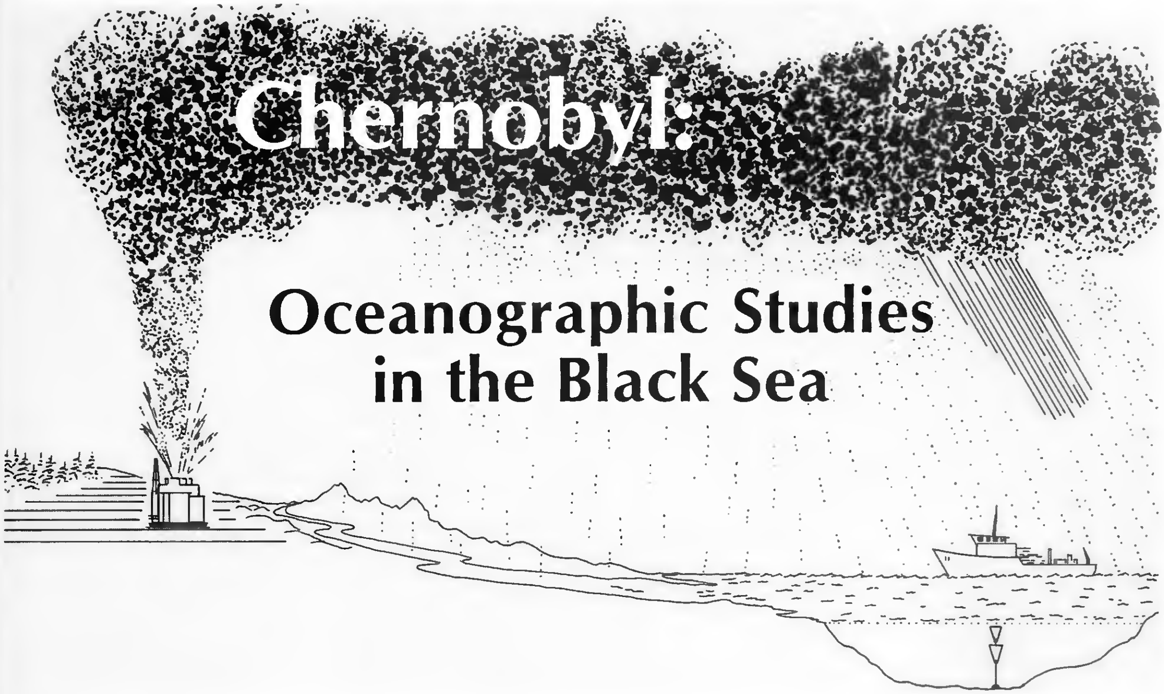
Chernobyl:

Oceanographic Studies in the Black Sea



—Studies on the radioactive fallout from Chernobyl provide information about the fates of nuclear discharges to the environment, and about the circulation of the nearest body of salt water—the Black Sea.

by Ken O. Buesseler

During the early morning hours of April 26, 1986, the Unit 4 reactor at the Chernobyl nuclear power station in the Soviet Union became the source of the largest release of radioactive material to the atmosphere from an industrial accident. Now, more than a year later, many of the questions concerning how the accident occurred, and the nature of some of the immediate and long-term environmental consequences can be answered.

For marine scientists, the Chernobyl accident resulted in the deposition to the oceans of a unique mixture of fallout radionuclides.* These radionuclides can be used to trace a variety of geochemical processes, such as water circulation and ventilation** processes, and the chemical scavenging process† in surface waters.

The Black Sea is the closest body of salt water to the reactor site (Figure 1). It received considerable direct atmospheric fallout from Chernobyl. Additional Chernobyl radionuclides were and are being carried to the Black Sea by the Danube and Dnepr rivers—their drainage basins include many of the high fallout areas of Eastern Europe and the accident site itself.

Aside from its proximity to the accident site, the Black Sea has several unique characteristics. For example, its deep waters are completely devoid of oxygen, and as such, the geochemical processes characteristic of this basin are quite unusual, and not well understood. The research team now studying the Black Sea includes the author and colleagues from the Woods Hole Oceanographic Institution (WHOI), along with West German and Turkish scientists.

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* Radionuclides—for the atoms of a given element, there may be several forms. The atoms have the same atomic number (the same chemical element), but have different atomic weights (different characteristics). These various forms are termed isotopes. A radionuclide is an unstable, radioactivity-emitting isotope.

** Ventilation—the transport of oxygen to the deep ocean as surface water sinks. In the absence of such a process, as in the Black Sea, the deep water becomes anoxic.

† Chemical scavenging—the transport of elements to the deep waters, with subsequent removal from the surface layers, through attachment to sinking particles.

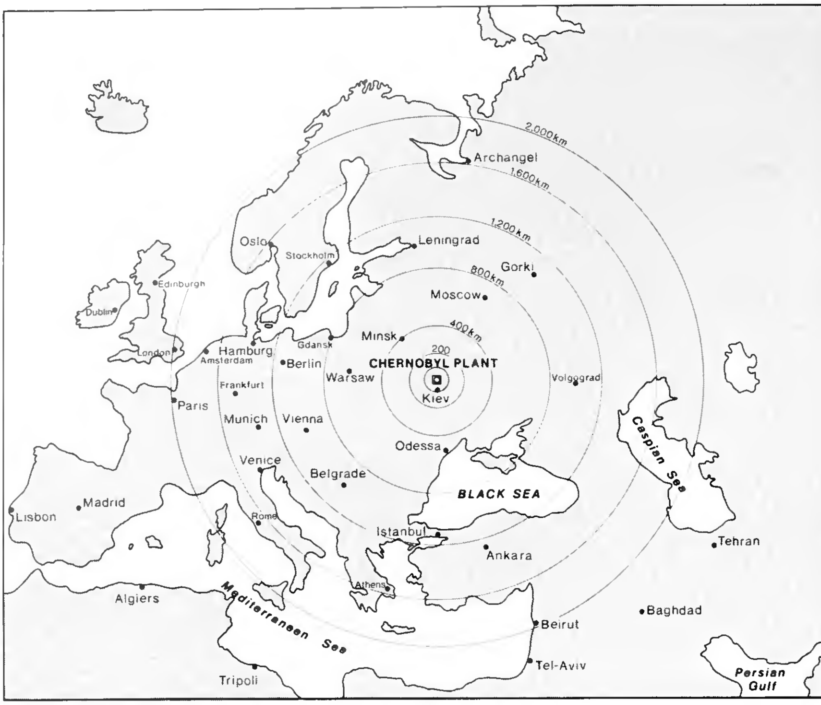

Figure 1. Chernobyl, with major cities and bodies of water.

The Accident

There now appears to be little disagreement that the Chernobyl accident was caused by a series of operator errors that occurred during the 24-hour period prior to the accident. Electrical engineers (not nuclear reactor specialists) at the site were given approval to conduct a test of the turbogenerators.

The Chernobyl test needed to be conducted at low reactor power, and a variety of automatic and emergency controls were disabled to allow the reactor to run at far below its regular operating power. At this low power level, the Chernobyl-type reactor becomes difficult to maintain at constant energy levels, and there is the possibility of rapid power excursions.

The operators mistakenly reduced reactor power too low during their tests, when, in order to increase reactor power, in the early hours of April 26 they attempted to rectify their error by removing most of the control and safety rods from the reactor core. As the result of this and other oversights, when the power began to increase, it did so with a tremendous surge.

Within 4 seconds, the reactor power peaked at approximately 100 times its nominal power rating, resulting in an explosive release of energy equivalent to many tons of TNT. This energy caused some of the fuel rods to rupture, allowing hot fuel particles to contact the cooling water directly, resulting in a massive steam-explosion. The reactor containment structure was breached, and large pieces of flaming debris were ejected from the destroyed reactor building. Exposed to air, the reactor's graphite core caught fire, further vaporizing the more volatile radionuclides in the core, and providing the major pathway for uncontrolled radionuclide releases.

Emergency measures were undertaken, including a heroic effort to contain the fires to Unit 4. Starting on April 28, more than 5,000 tons of boron, dolomite, sand, clay, and lead were dropped on the site from helicopters to quell the graphite fire in the reactor core, and to adsorb and filter some of the aerosol* particles. The aerial measures were successful in slowing down the fire and radionuclide releases, but, despite these efforts, the reactor burned out of control for 9 days until May 6.

Somewhat unexpectedly, the heated smoke plume from the fire carried the largest amounts of radioactivity up to higher altitudes, where it was carried away from the accident site by the prevailing winds. Thus, in the vicinity of the accident, radioactive fallout deposition was much lower than earlier models had predicted. Radioactivity levels at sites further away, however, were surprisingly high. Even with this widespread dispersion of fallout radioactivity, more than 100,000 people living in the surrounding areas were evacuated by bus. This evacuation started on April 27, some 36 hours after the explosion. Because of the extensive radiation contamination of the soils and waters around the vicinity of the reactor, these residents may never return to their homes.

Radionuclide Releases

A fact unrecognized by many is the complexity and variability in both the composition and quantity of this type of radioactive release. This was indeed true

* Aerosol—the suspension of fine solid or liquid particles in a gas (smoke, fog, mist).

for the Chernobyl accident. By the end of the accident, the radioactivity releases totaled more than 50 million curies*, or 3 to 5 percent of the total radionuclide inventory in the reactor core. This release of aerosol particles and gases was made up of more than 30 different radionuclides characteristic of reactor operations, many of which are potentially hazardous to man.

It was both the quantity and the characteristic composition of the fallout radionuclides that alerted the Swedes on April 28, some 2 days after the fire began, that a nuclear reactor accident had occurred. It is these same characteristics that enable oceanographers to use the fallout from this type of incident as a "label" or "tag" for ocean dynamics and circulation studies.

The major pathway for release of radioactivity was through volatilization during the fire. In general, those radionuclides with lower boiling points, such as the isotopes of radioactive iodine (iodine-131) and cesium (cesium-137 and cesium-134), escaped preferentially from the reactor core. Since the intensity and temperature of the fire varied considerably from day to day, the relative ratios among the different radionuclides released also varied. This has important implications for environmental studies, since many areas received a different mix of fallout radionuclides, depending on when the particular source cloud for that region was emitted.

A second mechanism for radionuclide release was through mechanical processes, such as during the initial explosion when many small particles were generated from the reactor core material. Many of these tiny, micron-sized particles (a millionth of a meter in diameter) were carried, along with the gaseous releases, by the smoke plume into the environment.

One way to think of this complex release of radioactivity is by analogy to what I call "Chernobyl soup." If each radionuclide were an ingredient in a soup, every day the amount of that ingredient in the recipe would be changing. In this instance, volatility and mechanical release mechanisms were continually changing the flavor of the "soup" (Figure 2).

Additionally, the composition of the Chernobyl fallout has changed quite rapidly since its release as the result of radioactive decay.** Using the soup analogy, as soup ages, it tastes differently from day to day; radioactive decay similarly produces striking differences over time in the relative abundances of the Chernobyl radionuclides in the fallout. For example, of major immediate health concern were releases of iodine-131, and cesium-137. Iodine-131 is a highly toxic substance that is easily volatilized. Iodine-131 has an 8-day half-life,† so that after one month, the original iodine-131 activity had decreased, as a result of radioactive decay, by more than a factor of 10. Today, more than a year later, essentially no iodine-131 remains. The radionuclide cesium-137, on the other hand, is also easily volatilized, and of similar concern. Because it has a much longer 30-year half-life, most of the Chernobyl cesium-137 remains with us. Even after 100 years, 10 percent of the cesium-137

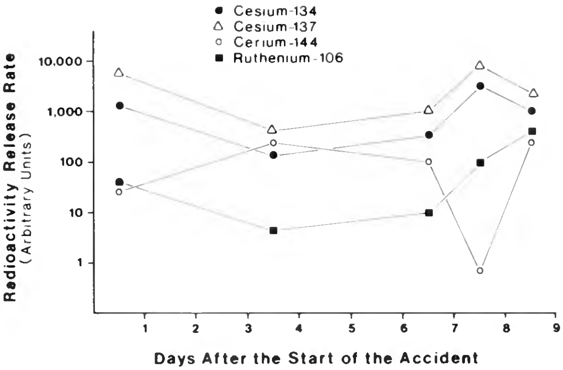

Figure 2. Isotopic release rates for Chernobyl releases versus the day of release. Note that the mixture of escaping radionuclides changed dramatically from day to day.

released by Chernobyl accident will still be present in the environment. Of the major Chernobyl radionuclides of concern, their half-lives range from a few days to many thousands of years.

Two other variables in determining the final impact of Chernobyl at any given site were the winds that carried the radioactive debris, and the rains that were primarily responsible for depositing the fallout on land. Since the radioactive fallout was carried by prevailing winds, variability in the wind patterns resulted in the eventual spread of Chernobyl radioactivity in a variety of directions. Although the fallout plume was initially carried north towards Scandanavia, by April 30, the winds had completely shifted towards the south (Figure 3). In fact, the fallout originating at the accident site after May 1 is the most important component of the Chernobyl releases for our Black Sea studies.

Within any given fallout plume, the actual deposition of Chernobyl aerosol particles and gases occurred predominantly during rain storms, which are often highly localized in nature. Thus, even within a distance of a few 10s of kilometers, the relative levels of radioactivity at ground level varied by a factor of 10 to 100, depending on local wind and rain patterns. Environmental scientists are finding that, with limited sampling, this patchiness in radionuclide deposition levels and radionuclide composition makes it very difficult to predict fallout levels and characteristics over large areas.

To put the Chernobyl releases in perspective, some 10 percent of the total inventory of the volatile cesium-137 in the reactor core escaped. This represents some 1 million curies of cesium-137. This total is significantly smaller than the 36 million curies

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* Curie—a relatively large unit describing the rate of release of radioactivity, defined as 37 billion disintegrations per second.

** Radioactive decay—as unstable atoms emit energy or particles, they lose radioactivity in the transformation to different, more stable, elements.

† Half-life—the rate at which unstable atoms disintegrate or decay, expressed in the time required for half of the atoms to decay to another form. This may range from seconds to billions of years, depending on the isotope.

of cesium-137 released during all of the atmospheric nuclear weapons-testing programs in the 1950s and 1960s. However, in many places in Europe, the cesium-137 inventories from Chernobyl are greater than the preexisting weapons-testing inventories, because of the patchiness in the Chernobyl deposition pattern discussed earlier. Also for comparison, the total release of cesium-137 from the Three-Mile Island incident in the United States in 1979 was only 10 curies. In the Black Sea, we estimate that the Chernobyl cesium-137 fallout input was roughly twice as large as the cesium-137 inventory deposited to this basin from weapons testing fallout.

Black Sea Studies

In general, we, along with many other scientists, are learning about the fates of radioactive discharge to the environment. In particular, we have focused our attention on the Black Sea.

The Black Sea (Figure 4) is quite an interesting basin for chemical oceanographers because of a variety of unusual features. The surface waters are brackish (a salinity of 16 to 18 parts per thousand) because of the strong influence of the major river discharges into the basin. The surface waters also are biologically very productive. In sharp contrast, the Black Sea deep waters are completely devoid of oxygen, and hence most life forms are absent at depth. These deeper waters are more saline (21 to 23 parts per thousand) than the surface waters, and represent about 90 percent of the basin by volume. Being saltier, the deep waters are significantly denser than the surface layer, and hence a strong density gradient occurs somewhere between 50 to 200 meters, depending on the location and season.

In essence, the surface waters are "floating" on top of the deeper waters like "oil and vinegar." Any mixing between the layers is severely limited. It is this lack of mixing that produces the depletion of oxygen at depth, occurring as the organic matter produced in the surface waters sinks and decomposes in the deep waters. A limited source of fresh oxygenated (and highly saline) water to the deep Black Sea is an undercurrent of Mediterranean water that flows into the Black Sea through the narrow and shallow Bosporus Straits. The total water balance is maintained by the surface outflow of less saline surface waters, and by evaporation in the basin.

Because of this unique set of conditions, the Black Sea can be used as a natural laboratory to study a variety of geochemical processes. For instance, in the Black Sea, we can examine to what extent any downward mixing of surface waters occurs, despite the strong density gradient between the surface and deep layers. Many of the so-called particle-reactive elements, attached to sinking particles, are likely to cross this oxic/anoxic

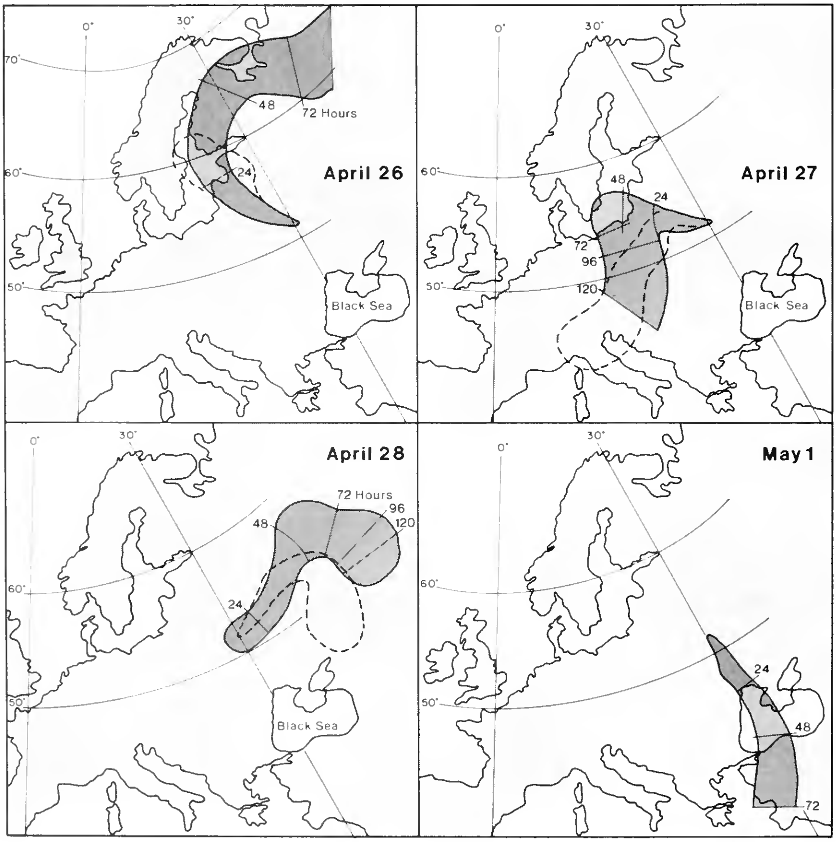


Figure 3. The atmospheric pathway of radioactive fallout from Chernobyl at 750 meters (dashed line) and 1,500 meters (shaded plume) originating from the accident site on different days.

boundary. Also, at the boundary between the oxygenated surface waters and deep anoxic region, a variety of chemical transformations are thought to occur.

Given the known Chernobyl fallout releases, it was important to sample these waters as soon as possible after the accident. Our plan was to determine the fallout levels and range of radionuclides present, and then to use these Chernobyl radionuclides as tracers of water or particle-related processes. In general, this work is similar in nature to studies that use fallout from the atmospheric nuclear weapons testing programs in the 1950s and 1960s to trace oceanic processes. Of course, many of the short-lived radionuclides from weapons testing fallout have decayed away, while the more recent Chernobyl fallout still included the shorter-lived radionuclides.

With rapid planning and cooperation from our European colleagues, we were able to participate in two cruises aboard the Turkish research vessel, *K. Piri Reis*, to the Black Sea in June and September of 1986. The cruises involved international participation, including German scientists from the University of Hamburg, Turkish scientists and crew from the University of Izmir, and WHOI chemists and geologists. Overcoming Turkish, German, and English language barriers, we were successful in obtaining the first set of samples from the Black Sea surface waters on June 17, just under 2 months after the Chernobyl releases.

Back at WHOI, it was only a matter of minutes before the samples revealed an indication of the levels of Chernobyl fallout. Using highly sensitive radiation detection techniques, cesium-134 and cesium-137 signals from Chernobyl were detected in the surface water samples. Within 24 hours, 8 additional Chernobyl radionuclides were identified:

K. Piri Reis, *the Turkish research vessel used for Black Sea studies.*

cerium-144, cerium-141, ruthenium-106, ruthenium-103, lanthanum-140, barium-140, niobium-95, and tellurium-129. With further radiochemical analyses, the isotopes of plutonium, americium, and curium were also detected.

While these radionuclide activities were not high relative to radiation exposure safety guidelines, they were certainly elevated compared to any preexisting activities. For example, the cesium-137 activity in the Black Sea surface waters was found to be elevated over its previous activity levels by a factor of 10 to 20. The Chernobyl signal appeared across the entire southern Black Sea (our sampling efforts were confined to Turkish territorial waters). Some of the patchiness seen in the fallout levels on land appeared in the surface water data as well.

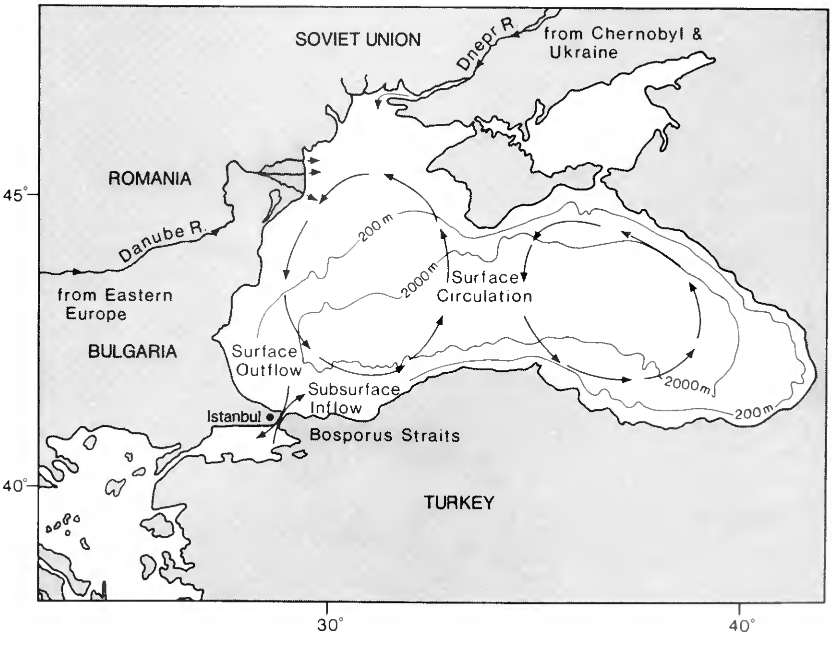


Figure 4. Circulation of the Black Sea, with river inputs.

Cleaning the streets of Kiev, the nearest large city to Chernobyl, on June 3, 1986, shortly after the accident. (Sygma Photo News)

Results to Date

Based on their chemistries, the Chernobyl fallout radionuclides can be broadly grouped into two categories. The highly soluble elements, such as the cesium isotopes, are used to trace water movement and mixing processes. The more particle-reactive elements, such as cerium, ruthenium, plutonium, americium, and curium, are used to trace the rapid scavenging and removal of an element from the surface waters—due to their strong affinity for particle surfaces, and their potential rapid transport to depth.

Cesium-137 is a good example of a highly soluble radionuclide whose marine chemistry has been well characterized—because of its relatively long half-life and previous studies on this major component of atmospheric nuclear weapons testing fallout. Because the Chernobyl fallout contains in abundance the shorter lived cesium-134 isotope in addition to the cesium-137 (about half as much cesium-134), it is possible to easily separate the pre- and post-Chernobyl cesium signals. We found in the Black Sea that surface water cesium-137 levels had jumped from 15 to 340 becquerels* per cubic meter in the surface waters near the mouth of the Bosporus. By September 1986, the Chernobyl cesium signal had penetrated down to the base of the summer thermocline,** and with future samplings, we should be able to see the progression of this signal deeper into the water column. With time, this Chernobyl cesium signal may penetrate into the deeper waters, if some limited mixing exists between the surface and deeper layers. It is precisely this progression of the cesium signal over time that will quantify the rate at which the surface waters are being mixed to depth.

For several other elements, movement through the water column may be somewhat more complex. While cesium-134 and cesium-137 primarily trace water movement, because of their chemistries, many of the Chernobyl radionuclides are considered highly particle reactive. Such particle-reactive tracers are rather "sticky," and their oceanic behavior is often determined by the particles to which they are attached. Therefore, the fate of these particle-reactive tracers is determined not only by the water mixing processes, but also by their partitioning onto the large and small particles in the water column. The removal of particle-reactive elements to the deep waters and underlying sediment is termed "scavenging." The rate of scavenging of particle-reactive elements is a topic of major concern in oceanographic studies, because the balance between the supply of an element to the ocean, and its ultimate removal from the ocean is largely determined by this scavenging removal rate. The scavenging rates of Chernobyl radionuclides also will be of value to local authorities interested in how long the radioactivity will remain in the Black Sea surface waters.

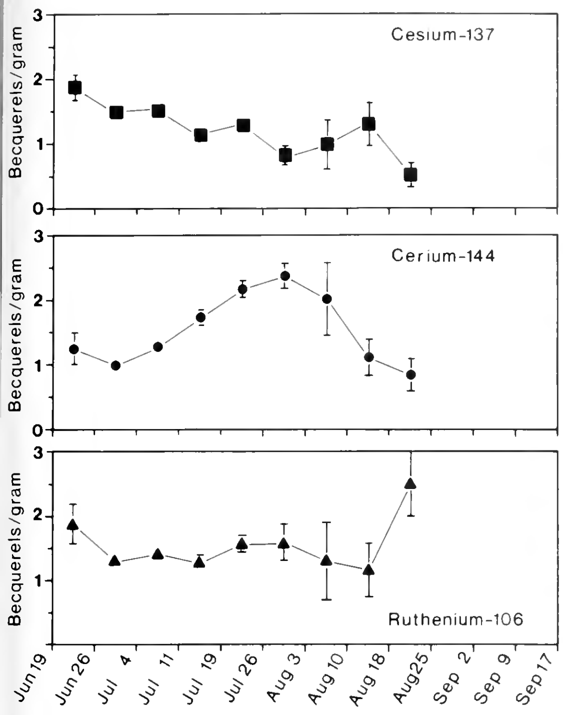
Recently, much attention has been focused on large biogenic (produced by living organisms) particle aggregates, which are formed in surface waters, and their role in transporting a variety of particle-reactive elements to depth. A variety of organisms, either through their feeding or defecation processes, act to aggregate smaller particles into larger ones. This increases the rate of particle settling, perhaps up to hundreds of meters per day. As such, these sinking particles can form the major removal pathway for a variety of elements from the surface oceans.

A great deal of data on particle activity in the oceans have been collected from sediment traps deployed by Susumu Honjo, Senior Scientist in WHOI's Geology and Geophysics Department. One sediment trap (Figure 5) was moored at 1,071 meters in the southwestern region of the Black Sea from June to September, 1986. This has provided a set of preliminary data on Chernobyl radionuclides.

Sediment traps are essentially large, cone-shaped funnels that collect settling particles as they fall through the water column. With an electronic switching device, it is possible to obtain a time series of sediment trap samples from a single trap deployment, by rotating new sample collection cups into position at the base of the funnel. In this case, a

* Becquerel—an international unit of radioactivity equal to 1 nuclear disintegration per second. A curie equals 37 billion becquerels.

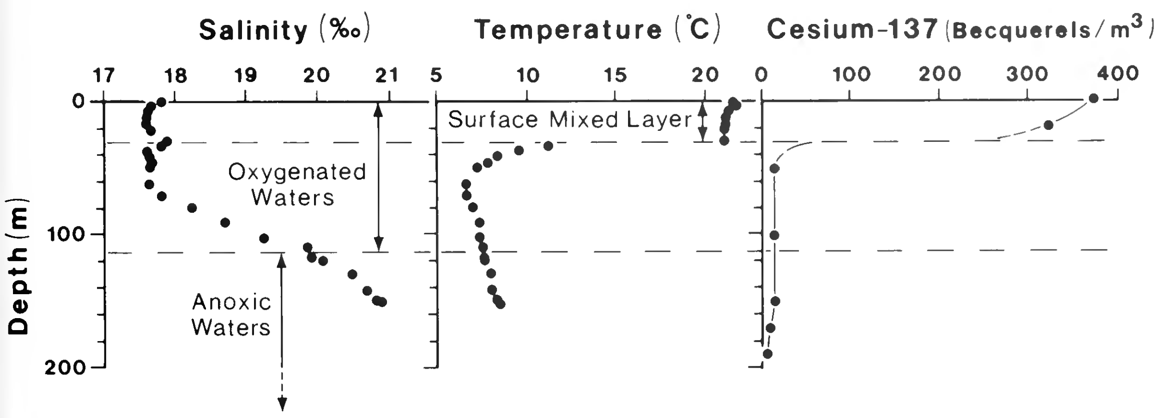
** Thermocline—A zone where the water temperature decreases more rapidly than the water above or below it. When the gradient is steep, mixing of the surface and deep waters is impeded.



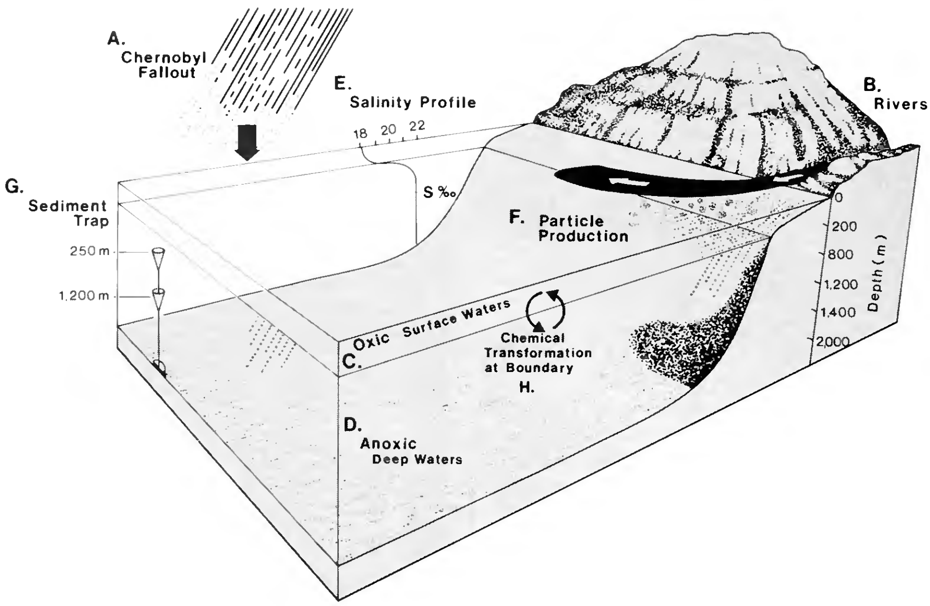
Collection of Chernobyl radionuclides by Black Sea sediment trap. The dates correspond to sediment trap sampling intervals. The error bars on several data points are statistical uncertainties relating to radioactive counting techniques. Note that the cesium-137 activity is decreasing, ruthenium-106 is fairly constant, and the cerium-144 appears to peak around the end of July. The reason for the cerium-144 peak is presently unknown.

Figure 5. The Black Sea sediment trap on the stern of the research vessel.

weekly time interval was used. Researchers have shown that, on a seasonal basis, the large particle fluxes can vary quite substantially. This variability in particle flux is often due to local productivity levels in the overlying waters, but in the Black Sea the fluxes also vary due to physical processes that transport particles from the shelf regions into the interior of the Black Sea.



The September 1986 cesium-137 activity profile (right-hand graph) from a site north of the Bosporus Strait as compared to the depths of the surface mixed layer (middle graph) and the salinity gradient (left-hand graph). Note that the very high surface-water cesium-137 signal, which had been labelled by Chernobyl fallout, had only penetrated to about 35 meters, or the depth of the summer thermocline. Cesium-137 activities below this depth represent background cesium-137 remaining from nuclear weapons testing fallout. The progression of this surface water cesium-137 with time will be of major interest. (From Livingston and others, 1987)



Black Sea Processes

Key:

A. Atmospheric deposition of Chernobyl fallout to the Black Sea was the major initial source of new radionuclides to this basin.
B. The Danube and Dnepr rivers will become important for the delivery of dissolved and particulate Chernobyl radionuclides from run-off in their watersheds. These rivers also help maintain the low salinity in the surface waters.
C. Surface waters. Because of density differences, they are almost completely sealed off from the deep waters. While the surface waters are highly productive, the deep waters (D) are devoid of most life.
E. Because of the strong salinity gradient, the surface oxygenated waters remain isolated from the anoxic deep waters.
F. Large particles produced in the surface waters can sink rapidly to depth at speeds of 50 to 100 meters per day. We sample this settling particulate matter with sediment traps (G), which are moored at fixed depths in the water column.
H. The boundary between the oxygenated surface waters and the anoxic deep waters is a site for chemical transformations of some elements. For instance, the geochemistry of many trace elements can be directly or indirectly tied to chemical transitions at this boundary, which can strongly affect the scavenging (attachment to sinking particles) rate of the element, and its transport across this boundary.

Our data show that at least some of the same Chernobyl radionuclides we had detected in the surface waters had been very rapidly removed to the trap at 1,071 meters—within less than 2 months of the initial fallout deposition at the surface. As expected by their differing chemistries, the removal rates for a more soluble element like cesium are much slower than that of the more particle-reactive cerium-144 and ruthenium-106. If the fluxes we measured continue (we have in place a program to monitor these trap samples for the next two years), the Chernobyl cesium-137 signal would take 100 to 200 years to be scavenged from the surface waters, while the cerium-144 and ruthenium-106 signals will be removed in only a matter of years.

Long-term Studies

In the future, the Chernobyl signal will be used as a tool to study the geochemistry of the Black Sea. With the spring run-off in 1987, the input of Chernobyl radionuclides from the rivers should be seen. We hope to use this riverine signal to trace surface circulation rates as the river waters travel from the Northern Black Sea region to the south, and to some extent out of the Black Sea, and through the Bosporus Straits.

Studies of Chernobyl fallout at other oceanic sites are underway, and comparisons between the behavior of the Chernobyl radionuclides in different settings will be possible. Future Chernobyls must be avoided, and cannot be excused for any reason, but we must act responsibly to learn as much as we can from this tragic accident.

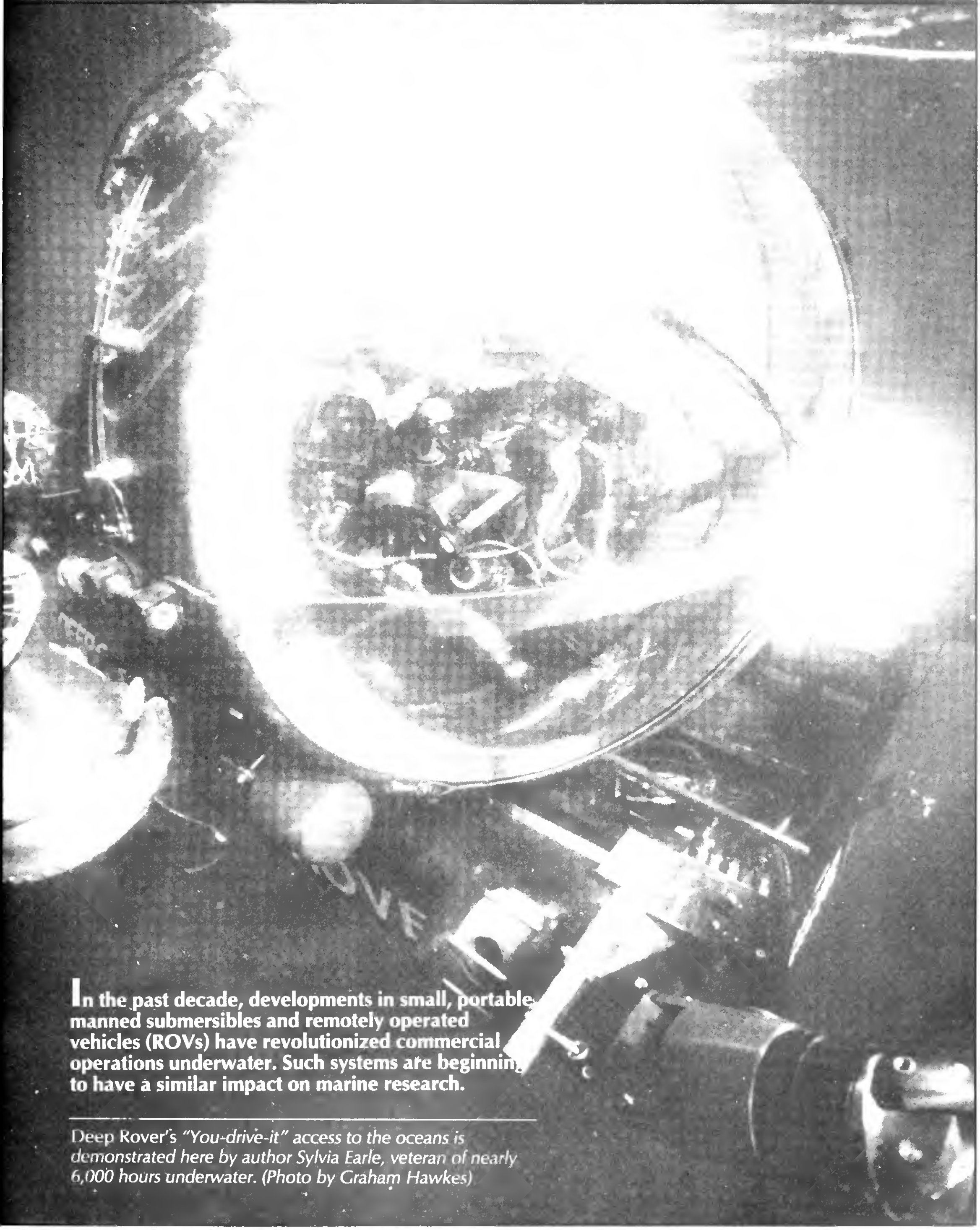
Ken O. Buesseler is a Visiting Investigator in the Chemistry Department, Woods Hole Oceanographic Institution.

Acknowledgment

Scientists participating in this study other than the author were: H. D. Livingston, S. Honjo, B. J. Hay, and S. J. Manganini, WHOI; E. Degens, and V. Ittekkot, Institute of Geology and Paleontology, University of Hamburg, West Germany; and E. Izdar and T. Konuk, Dokuz Eylul University, Turkey.

Submersibles for Scientists

by Lynne Carter Hanson, and Sylvia A. Earle



In the past decade, developments in small, portable manned submersibles and remotely operated vehicles (ROVs) have revolutionized commercial operations underwater. Such systems are beginning to have a similar impact on marine research.

Deep Rover's "You-drive-it" access to the oceans is demonstrated here by author Sylvia Earle, veteran of nearly 6,000 hours underwater. (Photo by Graham Hawkes)

In industry, trends are continuing toward "deeper and cheaper," using systems that can be effectively deployed from relatively small vessels. Low cost, transportability, versatility, and ease of operation have caused these new systems to displace large submersibles, saturation diving, and large robotic vehicles for many "traditional" underwater tasks. They also have been applied in situations where the larger and heavier equipment could not be used. Recently, these new systems have been used for scientific research with results so rewarding that programs are now being planned to take advantage of their special features. For science as well as industry, these new vehicles are revolutionizing working capability and overall access to the sea.

In April 1986, the National Oceanic and Atmospheric Administration (NOAA) convened a panel chaired by Feenan D. Jennings, Texas A&M University, to examine new directions for undersea research. The resulting report includes the following observations:

- *In many important respects, we have reached the limits of what we can learn from traditional methods. We need new kinds of data before significant advances can be made. . . . Technological progress in the last 10 years has made it possible to obtain these kinds of data, but necessary tools tend to be expensive, and have not been generally available within the oceanographic community.*

- *The prospects for filling the principal gaps in our understanding are coupled to two emerging disciplines: 1) remote sensing, which incorporates satellite technology; and 2) in situ research, which involves both manned and unmanned undersea systems. Each of these new disciplines provides an entirely new scientific perspective on resource dynamics, and each is coupled to an expensive technology. The biggest challenge . . . facing federal sponsors of ocean research is how to improve these new tools and get them into the hands of the research community.*

Several meetings of scientists, engineers, and representatives from government and industry have been convened in the last year to discuss the research applications of these new technologies, and to identify future requirements. The most intensive effort was held at the University of Rhode Island (URI), Kingston, Rhode Island, in October, 1986. There were 80 participants; support was from the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration/National Undersea Research Program (NOAA/NURP), and the Office of Naval Research (ONR).

At the meeting, the need to equip researchers with new tools was repeatedly emphasized, and an analogy was drawn that likened the plight of ocean scientists today to terrestrial counterparts being given the task of exploring for the first time all of North and South America—with three or four jeeps and a few gallons of gasoline.

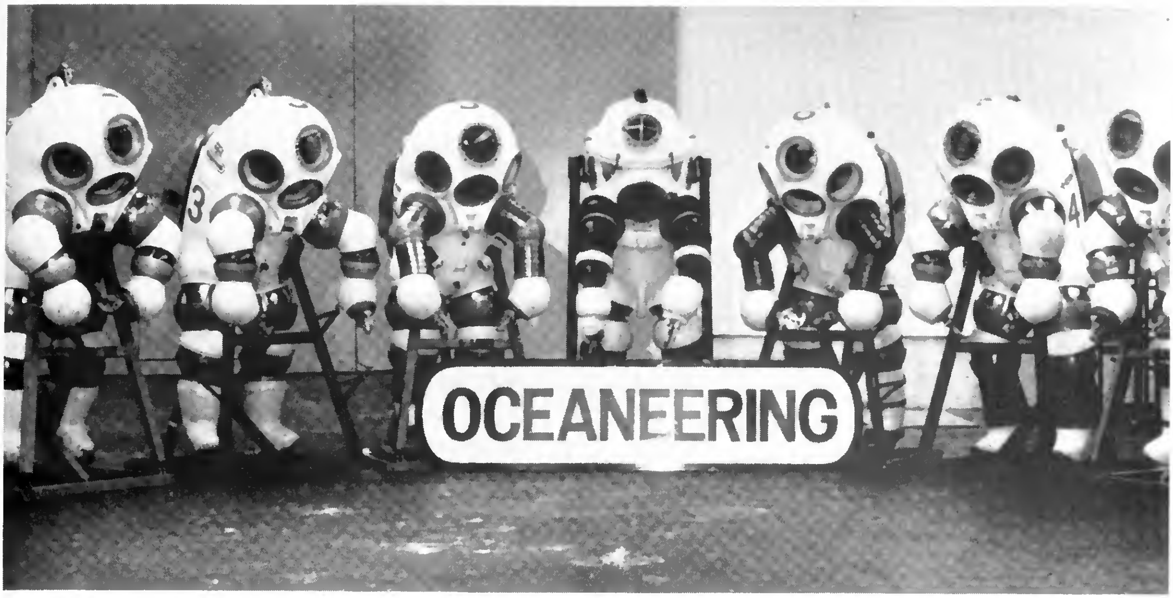
Manned Submersibles

Manned submersibles encompass everything from large nuclear-powered craft, to small, battery-operated "wet subs" that transport SCUBA (self-contained underwater breathing apparatus) divers. Here, we define a manned submersible as a tethered or autonomous vehicle that can accommodate one or more persons, and can maintain an internal "cabin pressure" at 1 atmosphere (normal surface pressure).

The best known scientific manned submersible is the Woods Hole Oceanographic Institution's (WHOI's), *Alvin*, famous as the vehicle that transported scientists to survey and document the mid-Atlantic Ridge, hydrothermal vents, giant tube worms, and other benthic life, and, with the ROV, Jason Jr., to explore the wreck of the *RMS Titanic* (see *Oceanus* Vol. 29, No. 3, pp. 2–15). Launched in 1964, *Alvin* has undergone continuous upgrading and therefore remains a modern vehicle. Many of the more than 50 other manned submersibles built for research and industrial applications in the 1960s and early 1970s have been retired. Aside from WHOI, however, there are presently a number of other submersible operators.

The University of Hawaii operates two submersibles built during this era and renovated for current operation. One, the two-man *Makali'i*, (formerly *Star II*), is small enough to be deployed from various support platforms—including a towed submersible launching system. The lack of a required dedicated vessel is an advantage, and can greatly reduce the daily support-vessel costs. A second submersible, the *Pisces V*, has recently been acquired for operation in depths to 2,000 meters. Typically deployed from a dedicated support ship, the *Pisces V* also has been provided with a towed launching system.

Harbor Branch Oceanographic Institution's two submersibles, *Johnson Sea-Link I* and *Johnson Sea-Link II*, were designed in the late 1960s primarily to transport and lock-out (exiting from and returning to the submerged vehicle) divers. A pilot and a passenger-observer occupy a clear, acrylic forward sphere, and two additional passengers may observe through small viewing ports in the aft diving chamber. Harbor Branch has made many significant contributions through the use of the Johnson Sea-Link submersibles. They have been involved with the exploration of the *U.S.S. Monitor* for the marine sanctuary established by NOAA; they recently discovered the deepest-known living marine algae, off the Bahamas; and searched for marine drugs in the Galápagos (see *Oceanus* Vol. 30, No. 2, pp. 69–71). Perhaps their most well-known contribution was for the search and recovery of the *Challenger* space shuttle debris. Harbor Branch also has developed a number of tools for use on their submersibles, and their large ROVs—the CORD and the Hysub 40.



A fleet of 15 Jim suits have been built for operation worldwide, mostly in support of offshore oil operations. The operator supplies muscle power, but Jim relies on a tether for communication and deployment. (Photo by Graham Hawkes)

The Japanese also have an active research submersible program. Operated by the Japan Marine Science and Technology Center (JAMSTEC), the *Shinkai 2,000* has made about 70 dives a year around the Japanese Islands since 1983. A new submersible, the *Shinkai 6,500*, scheduled for launch in 1989 (see *Oceanus* Vol. 30, No. 1, pp. 29–32), will be one of the world's deepest-diving submersibles.

The French also operate several submersibles, among them the *Nautile*. The *Nautile* has a 6,000-meter depth capability, and this past summer made a series of dives on the *Titanic* to recover artifacts.

Technology represented by *Alvin*, the *Johnson Sea-Links*, *Pisces V*, and other submersibles, while proven effective for scientific studies and exploration, is expensive. Use of these systems is therefore somewhat limited. There are also characteristics inherent in each of these relatively large systems that make them impractical for certain applications. This has led to a new class of lighter, smaller, and less expensive submersibles—for shallow- and mid-depth research.

New Capabilities

Three categories of small, readily transportable systems have been used for scientific research in the past decade. They include:

- Two-person, autonomous
- One-person, tethered
- One-person, autonomous

Two-person autonomous vehicles. The first category includes the *Makali'i* (mentioned previously), as well as the two-person Nekton/*Delta* submersible. With support from NOAA/NURP for research in the eastern United States coastal areas, and in the Bahama Islands, the Nekton/*Delta*-type vehicles have become scientific "workhorses" for benthic work to depths of 1,000 feet. Particularly useful for relatively low-cost operation from various vessels in New England waters, the Nekton/*Delta* has been used by scientists for benthic studies on lobster habitats, "ghost" gill nets, fisheries dynamics (particularly herring spawning) and canyon environments, to name a few.

One-person Tethered Vehicles. The history of one-person tethered systems began more than half a century ago. Best known is *Jim*, essentially an armored, articulated diving unit, named after Jim Jarrett, the first person willing to try it on for testing. After successful use for salvage in the 1930s, the *Jim* was put aside until the early 1970s when North Sea offshore oil development generated new interest in "atmospheric diving." Fifteen of these one-man "personal submersibles" have been built and commercially operated worldwide in depths to 500 meters.

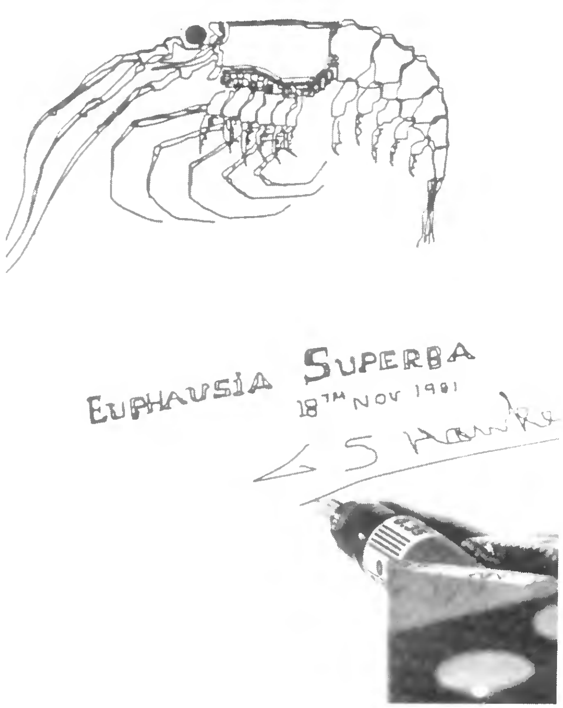
Wasp, a more advanced one-man anthropomorphic (having a human form) vehicle that is self-propelled and capable of working throughout the water column, was developed in 1976. Since then, 18 *Wasps* and 30 related one-man submersibles, called *Mantis*, have been used worldwide for industrial applications ranging from oil-rig inspection and maintenance, to recovering bits of downed aircraft. In less than a decade, these vehicles transformed deep-water commercial diving—by lowering costs, increasing operational depth, and improving overall working capabilities.

The first scientific use of *Wasp* was pioneered by Bruce Robison of the University of California, Santa Barbara, with support from NSF. Robison and a

Table 1. Vehicle information.*

Name	Launch date	Number of People	Operating depth (m)	Certification/ Classification	Cruise/ Speed max. hts.	Weight in Air	Owner/Operator
Alvin	1964	3	4,000	U.S. Navy	1/1.5	18 T	U.S. Navy/WHOI
Johnson-Sea Link (I & II)	1971, 1975	4	915	American Bureau of Shipping (ABS)	.75/1.25	9,700–10,400 kg.	Harbor Branch Oceanographic Institution, Fort Pierce, FL
Makali'i	1966	2	366	(ABS)	1/3	4.5 T	Univ. of Hawaii
Pisces V	1973	3	2,000	(ABS)	1/2	10.8 T	Univ. of Hawaii
Delta	1982	2	305	(ABS)	2/3.5	2,222 kg.	Marfab, Torrence California
Jim (type II–IV)	1973	1	305/610	Lloyd's Register of Shipping (LRS)	NA	245–354 kg.	Oceaneering Int'l Houston, Texas
Wasp	1977	1	610	(LRS)	1	405 kg.	Oceaneering Int'l Houston, Texas
Mantis	1978	1	700	(LRS)	2/2	1,179 kg.	Many
Deep Rover	1984	1	1,000	(LRS)	2/3.2	3,085 kg.	Can-Dive Services No. Vancouver, BC Canada
Nautile	1985	3	6,000	Society Standards (Bureau Veritas)	1/2.5	18.5 T	Infremere, Paris France
Shinkai 2,000	1981	3	2,000	Japanese Government	1/3	23 T	Japan Marine Science and Tech. Center, Yokosuka Japan

* All information on this chart is from Busby's *Undersea Vehicle Directory*, 1985 and 1987. Refer to this directory for more complete information.



Dexterity is an important characteristic for manipulators in order to perform delicate underwater work tasks. The exceptional control on Deep Rover's *arms is illustrated here, with accuracy possible to within ±.01 millimeter. The shrimp shown in the illustration was drawn by an operator controlling a 6-foot-long arm capable of lifting 200 pounds. (Photo by Graham Hawkes)*

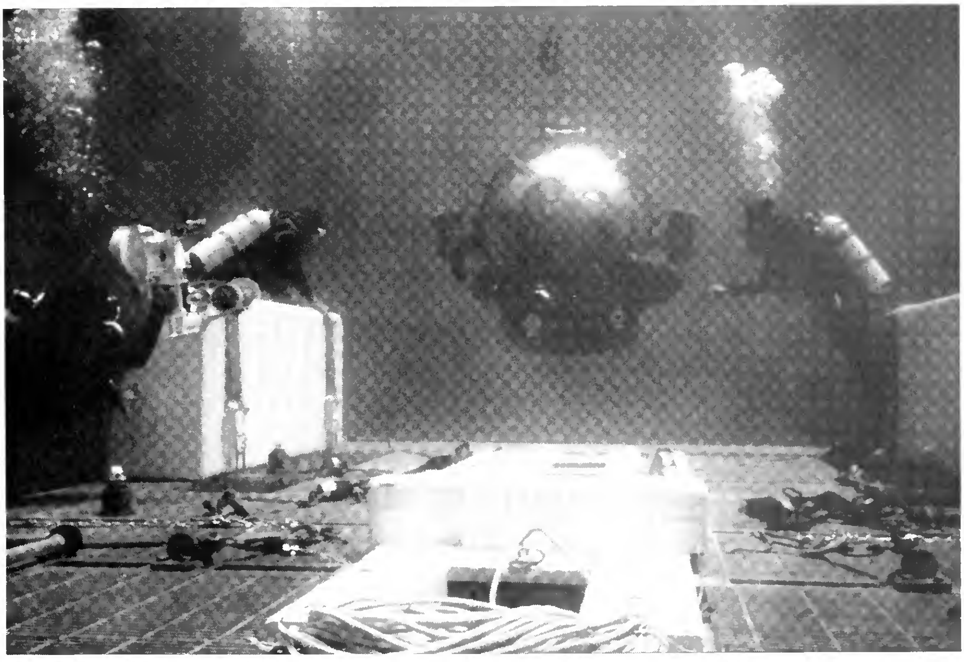
team of five other scientists went through a standard, one-week commercial-diving course to learn to operate *Wasp* before making repeated midwater excursions to depths of 1,700 feet. Using *Wasp*, dozens of new observations were made, including the discovery of clouds of copepods (small, shrimp-like animals) in deep water that had eluded conventional surface-deployed sampling techniques.

Wasp was remarkable not only because of the quality of observations that could be made using the vehicle, but also because the scientist and the pilot were one, a factor that contributed significantly to the success of *Wasp* as a scientific tool. Within a week, individuals who were accustomed to the limits of SCUBA diving were spending several hours in their armored diving suit in depths beyond 1,000 feet—with no decompression.

Results gained by Robison and his colleagues during two summers of observations in 1983 and 1984 dramatically changed concepts concerning the ecology, distribution, and behavior of organisms in the three-dimensional realm of the water column and stimulated interest in the use of other one-man systems for research. Further stimulus came about through the successful use of *Wasp* for archaeological exploration of the sunken vessel, *Breadalbane*, under the Canadian arctic ice in 1982.

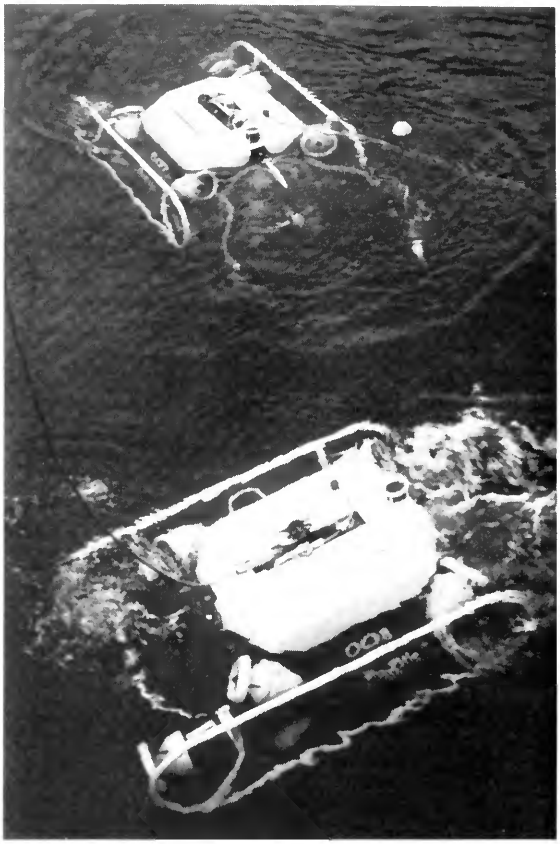
One-person Autonomous Vehicle. The development of a unique one-man microsubmersible, the *Deep Rover*, in 1984, by Deep Ocean Engineering, was greeted with enthusiasm by scientists who had used the other one-man systems, *Jim* and *Wasp*. This system, however, was unique in that it was not anthropomorphic in shape, but was basically a large acrylic sphere with thrusters. It is autonomous (untethered), lightweight, small, portable, low-cost, highly maneuverable, and retains the "user friendly" characteristics of the other one-person units.

The LRT, with the submersibles Jim *and* Star II *aboard, submerged at a dive site off Hawaii. The completely submersible launch-and-retrieval platform, or LRT, operated by the University of Hawaii avoids difficulties sometimes encountered when using conventional techniques in less-than-optimum weather and wave conditions. (Photo by Sylvia Earle)*



Coming in for an underwater landing, Deep Rover *here uses the submersible towed "LRT" platform normally used to deploy the 2-man sub,* Makali'i, *in Hawaii.* Deep Rover *differs from most larger submersibles in that it does not require a dedicated support ship. More than a dozen launch platforms have been used successfully to deploy the little submersible. (Photo by Terry Kersy)*

In September, 1986, author Sylvia Earle organized a 30-day project for use of Deep Rover *at the Caribbean Marine Research Center, Bahamas, that resulted in use of the system by 46 people who made 66 dives in depths as great as 3,000 feet. Most of the pilots were first-time submersible-users. New scientific observations include the surprising discovery of huge sand dunes in depths from 1,000 to 2,500 feet, the documentation of plant life in depths to 800 feet, and numerous observations concerning the day/night behavior of midwater and bottom-living fish and invertebrates. (Photo by Sylvia Earle)*



Like divers, one-man submersibles, such as the Mantis *systems shown here, can be deployed as "buddy diving" pairs. A novice operator can be accompanied by an experienced partner for safety, if desired. The two subs can also cooperate for tasks where "four manipulators are better than two." (Photo by Sylvia Earle)*

In 1985, Robison organized a program, using *Deep Rover* for research on midwater ecology in the Monterey Submarine Canyon, off California. With support from NSF, 50 dives, averaging 4 hours were made during 30 days of operation in depths to 2,000 feet. As with *Wasp*, scientists were trained in a few days to operate the system safely, abiding by the same guidelines as commercial submersible pilots. The advantages of having the research scientist at the controls of the submersible has proven to be effective and efficient.

Since the Monterey project, *Deep Rover* has established a track record of research operation in depths to 3,000 feet during dives conducted in San Diego, California, and in the Bahamas. More than 100 individuals, including G. Richard Harbison of Harbor Branch Oceanographic Institution and Larry P. Madin, Associate Scientist in the WHOI Biology Department, have used the system from 12 different launch platforms, including a barge with a moonpool (central equipment-handling well), and from ships using A-frame deployment and various cranes.

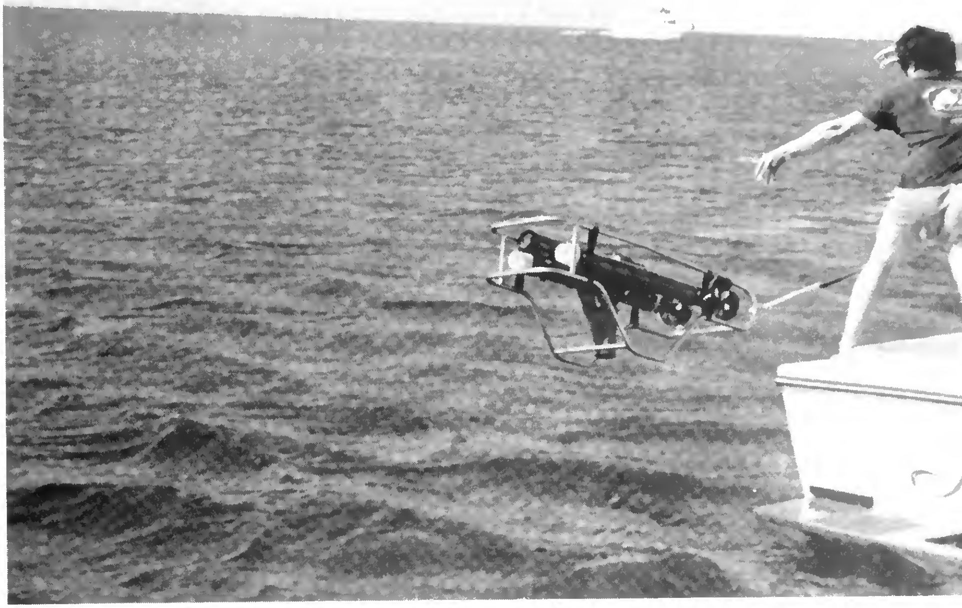
Future Developments in Manned Submersibles

Anticipated new developments include greater availability for portable manned submersibles for scientific applications. This will fulfill needs expressed at the URI meeting by Edith Widder: "The major problem is not that the state of the technology is inadequate, it is just that there are not enough vehicles available." Other needed developments are tools for specific tasks, and refinement of accessories for existing systems.

Entirely new systems for search and survey, as well as site-specific tasks, also will be developed—ultimately for operation in the oceans' greatest depths. One example for mid-depths, presently under construction, is a one-man 1,500 meter vehicle, *Deep Flight*, described in the December 1986 issue of *Sea Technology* magazine.

Remotely Operated Vehicles

The history of scientific application of ROV technology has not been as long and varied as that of manned submersibles. However, the industrial development of early (large and expensive) ROVs by



Easy to deploy, Phantom vehicles and other small, portable ROVs can readily be handled by one or two people working from a small boat. (Photo by Sylvia Earle)

An HD Phantom is used by scientists from the Bermuda Biological Station to explore submarine caves. A Phantom 500 was used to pioneer ROV operations in Antarctica during a 1986–87 project sponsored by the National Science Foundation. (Photo by Tom Iliffe)

Hydro Products, Inc., San Diego, California, and their contemporaries, as well as application developments by Taylor Diving, Belle Chasse, Louisiana, and others, were important historical steps. ROVs have generally been used more in the industrial and military sectors, but ROV technology is making the transition to science.

Deployment of the small, Jason Jr. ROV from *Alvin* to explore the *Titanic*'s intricate interior in 12,000 feet of water demonstrated an effective marriage of manned and ROV systems for research in the deep sea. A small Phantom ROV for use from *Deep Rover* has been developed to enable the pilot to observe and document events up to 100 feet away from the sub.

When low-cost, portable ROVs were introduced in 1984, the first applications were primarily commercial. Deep Sea Systems' MiniRover was the first ROV developed in this class. More than 60 small vehicles have been produced by Deep Sea Systems, Falmouth, Massachusetts, including MiniRovers, and the deeper-diving, more robust, Sea Rover vehicles. Four variations on the small-vehicle theme have been produced by Deep Ocean Engineering, Inc., San Leandro, California, ranging from the Phantom 300, for use in depths to 300 feet, to the Super Phantom, rated for use to 1,000 feet. More than a dozen kinds of portable systems are now available, and applications for scientific research are limited only by the number of vehicles and the imagination of scientists.

Some recent scientific applications of ROVs include:

- Under-the-ice observation and documentation in the Antarctic of benthic life and the behavior of fish, penguins, seals, and whales, supported by NSF.
- Monitoring the behavior of fishing nets and other gear, as well as the behavior of fish by fisheries biologists, through NOAA/NMFS (National Marine Fisheries Service).
- Exploration of fish behavior and the deep reefs offshore from Lee Stocking Island, Bahamas, by scientists associated with the Caribbean Marine Research Center.
- Observations of marine crabs by scientists from Hopkins Marine Station and the Monterey Bay Aquarium.
- Documentation of the reactions of marine organisms to a baited system by researchers from the Hubbs Marine Research Institute, San Diego.

Future Developments in ROVs

The next major developments for research application of small ROVs are likely to emphasize accessories for specific tasks. Small Conductivity-Temperature-Depth (CTD) units for continuous monitoring of hydrographic characteristics, and other data, and specimen-gathering equipment are now being developed.

While it is unlikely that small, portable ROVs will replace present methods of obtaining data underwater, such systems will provide researchers with powerful new tools that will lower the cost of obtaining certain kinds of information, prolong observation time, and make it possible to observe, gather data, and provide documentation well beyond diver depth, and in inhospitable environments.

A New Era

Considering the current emphasis on issues relating to global change and global processes, one might ask where these technologies fit into today's science. It appears that they are most appropriate for the study of small- and micro-scale phenomena, and process-oriented research. Understanding these small-scale phenomenon makes it possible to more quantitatively assess and accurately model large- and global-scale occurrences. In some ways, new submersible technologies will provide the ground truth for remotely gathered data.

The NOAA report said that: "These new technologies must be the basic tools of the next generation of oceanographers; and the only way for this to occur is for the present generation to begin using them now." The issue of availability, or lack thereof, led to two areas of consensus at the URI meeting:

- *Availability of the technology (through funded national programs) will follow the needs of science; and*
- *the coalescing of scientific interest in ROVs and submersibles with major, mainstream science programs is essential.*

The demand, the enthusiasm, and the funding for these new technologies are all dependent on the new scientific questions that can be both asked of, and answered by, the use of these special capabilities. The scientific interest is building. A new era of exploration and understanding of the deep sea has just begun.

Lynne Carter Hanson is the Executive Director of the Center for Ocean Management Studies at the University of Rhode Island. Sylvia A. Earle is a Research Biologist at the California Academy of Sciences, and Vice President of Deep Ocean Engineering, Inc., San Leandro, California.

Suggested Readings

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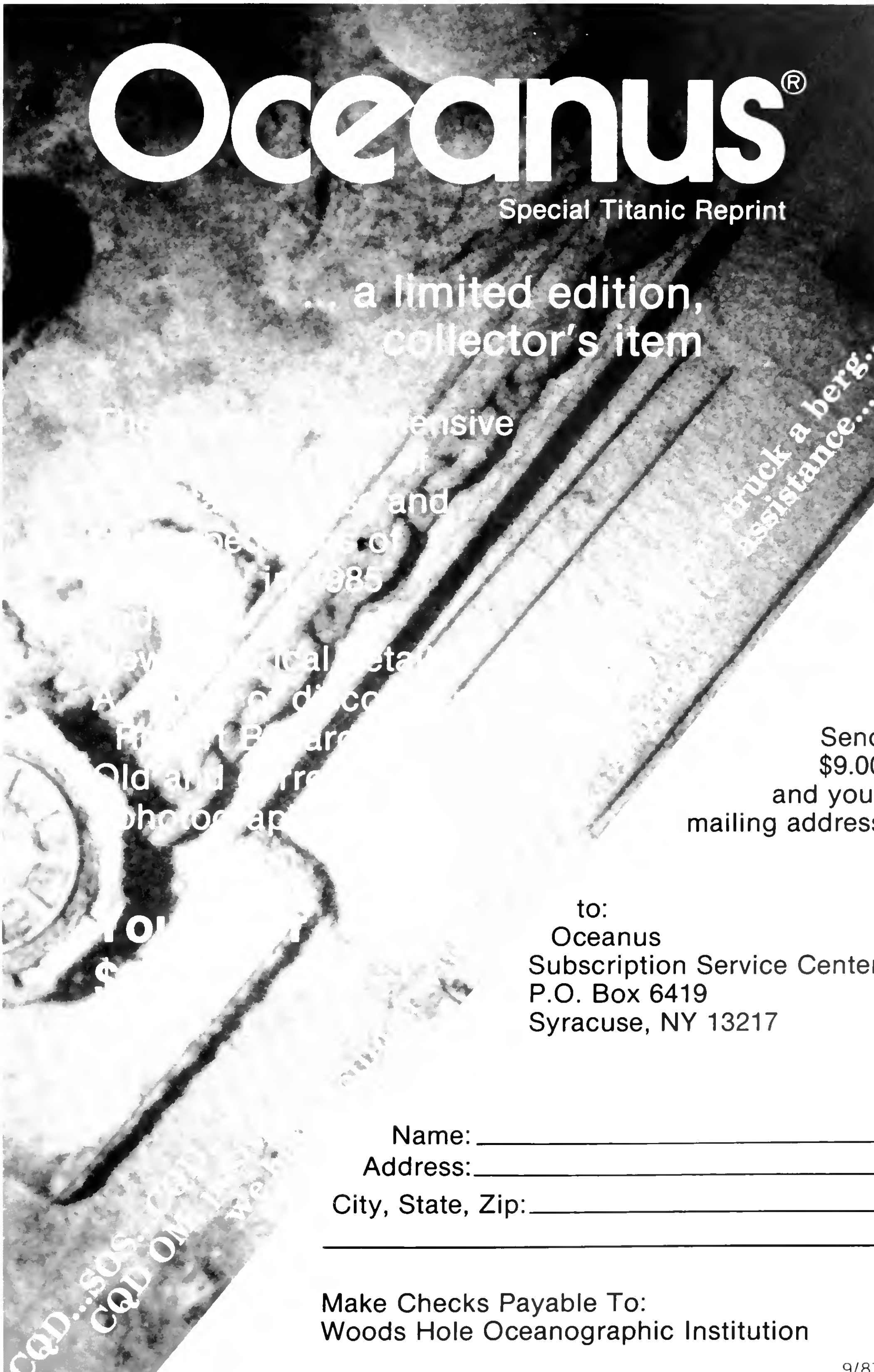
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Mass Extinctions:
Volcanic, or Extraterrestrial Causes, or Both?

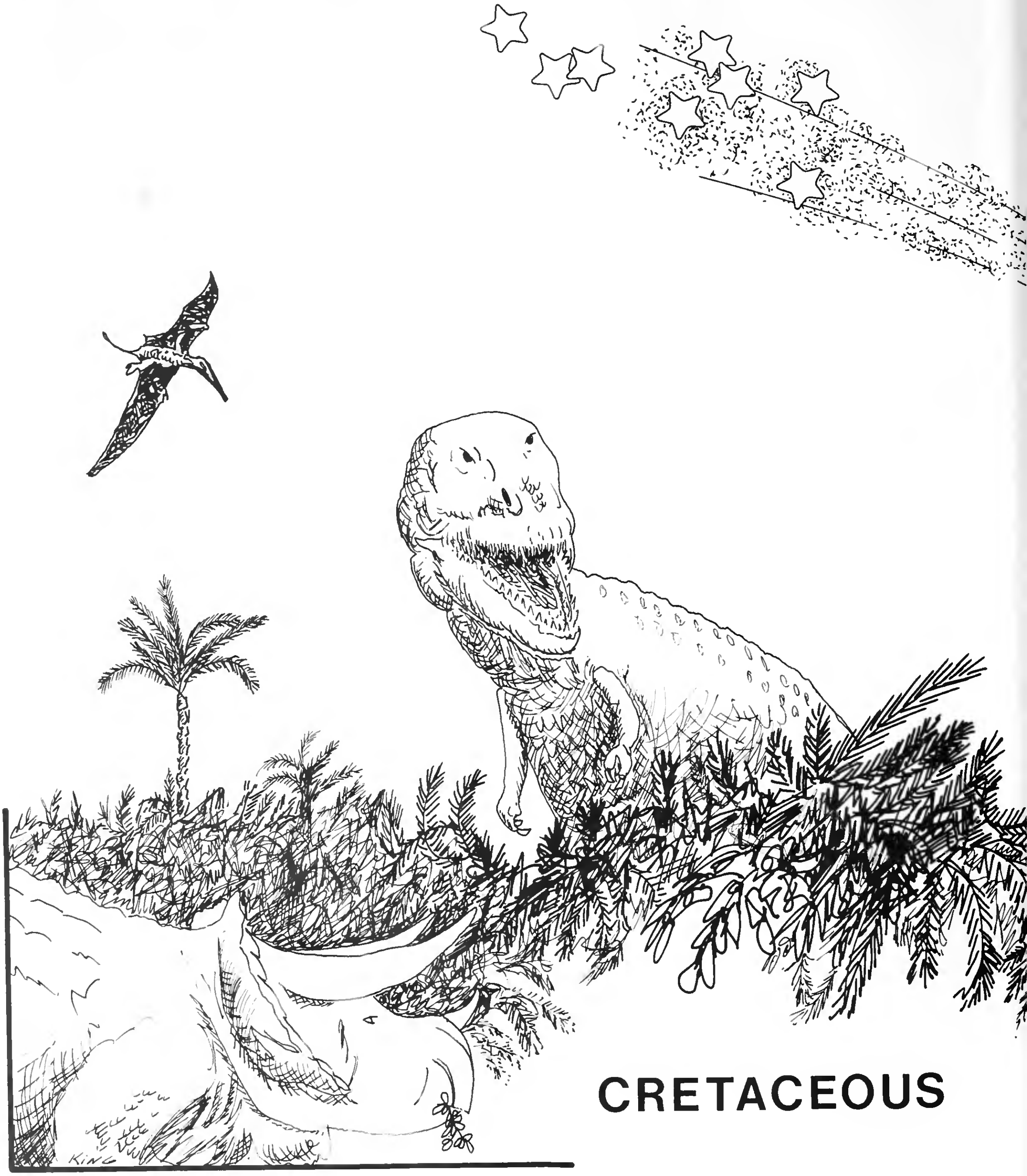
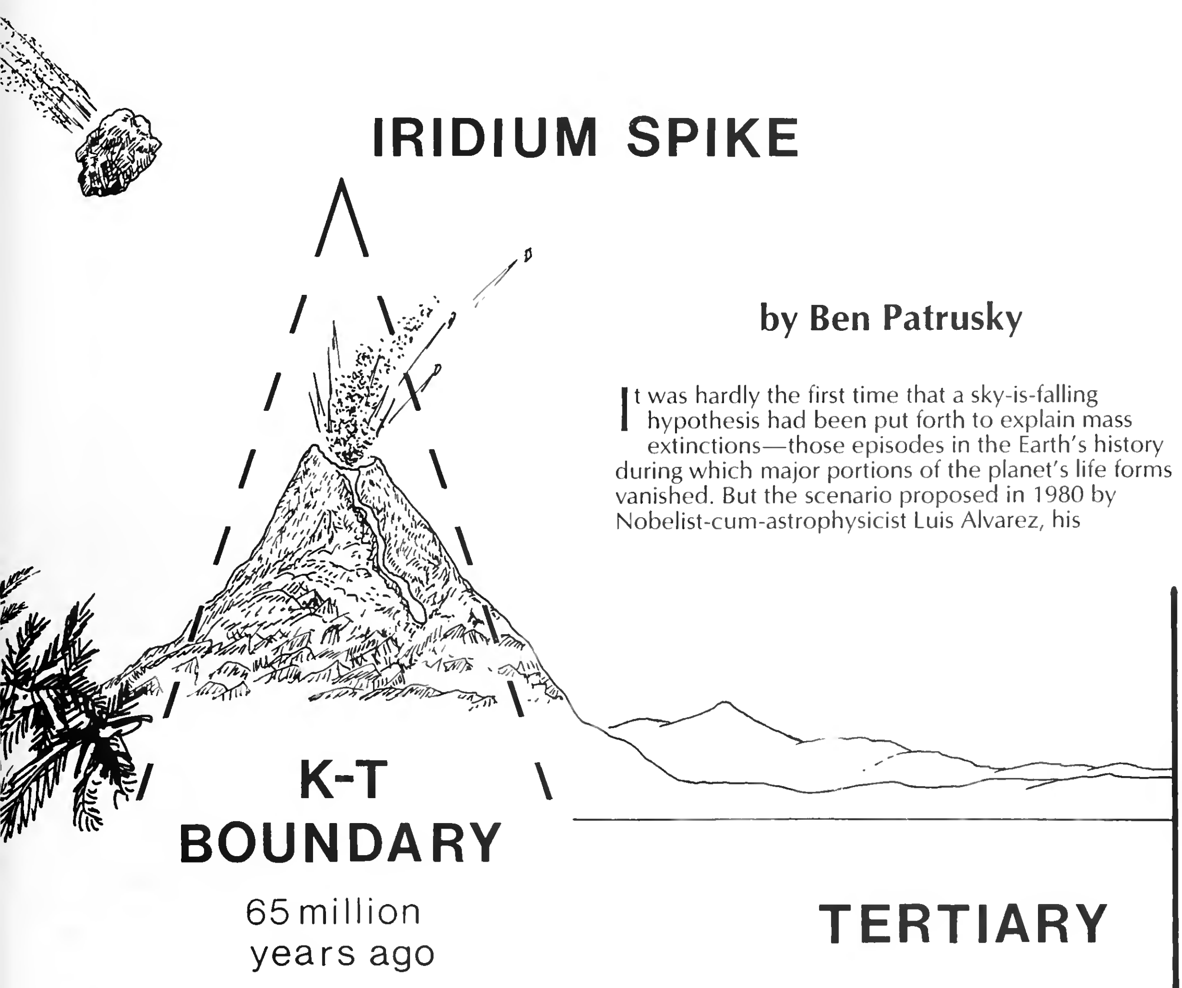


Illustration by E. Kevin King

EDITOR'S NOTE: A pair of Canadian geologists reported in June of this year in the British magazine *Nature* that they had identified a large crater caused by a meteorite on the North Atlantic continental shelf some 200 kilometers southeast of Nova Scotia, Canada. Although meteorite craters have been studied extensively on land, the Canadians—Georgia Pe-Piper of St. Mary's University in Halifax and Lubomir F. Jansa of the Bedford Institute of Oceanography in Dartmouth, Nova Scotia—maintained their identification from geochemical and seismic evidence was the first of an impact crater at sea, although there have been several other proposed sites. The crater is 45 kilometers in diameter and sits in 113 meters of water. The crater itself is 2,800 meters deep. In recent years, a controversy has been raging among geologists and paleontologists over whether a large impact, or a series of impacts, by meteorites could possibly have initiated a round of mass extinctions 65 million years ago during the transition from the Cretaceous to the Tertiary periods when dinosaurs roamed the land. In contrast to the meteorite theory, many scientists argue that the extinctions were the result of large-scale volcanic activity on Earth. And one researcher recently has proposed in a letter to *Nature* (Michael R. Rampino, a scientist at *NASA*'s Goddard Institute for Space Studies, 11 June 1987) that the extinctions may have been triggered by an extraterrestrial event which in turn caused large-scale volcanic activity with resultant clouds of ashes that blocked out the sun and brought on the Ice Ages. The following article, reprinted in part from the Winter 1986/87 issue of *Mosaic*, the journal of the National Science Foundation, documents the controversy and points out the role that marine science plays in this heated debate.



by Ben Patrusky

It was hardly the first time that a sky-is-falling hypothesis had been put forth to explain mass extinctions—those episodes in the Earth's history during which major portions of the planet's life forms vanished. But the scenario proposed in 1980 by Nobelist-cum-astrophysicist Luis Alvarez, his geologist son Walter, and co-workers at the University of California at Berkeley was different. It came with evidence: an iridium spike—an above-normal concentration of the platinumlike metal—discovered in a 65-million-year-old layer of clay demarking the boundary between two geological periods, the Cretaceous and the Tertiary.

To the Alvarez team, the spike, or anomaly, suggested a collision of the earth with a giant asteroid. The catastrophe, they argued, led to the almost instantaneous annihilation of much of the then-extant biota, including, most dramatically, the last of the dinosaurs. The detection in 1982 of a similar anomaly elsewhere in the geological record quickly led the team to ascribe yet another major extinction—the so-called terminal Eocene or Eocene–Oligocene event, dated at 37 million years before the present—to catastrophic impact with a bolide, or extraterrestrial body.

So artfully delineated was the hypothesis, and so forcefully presented, that it quickly received worldwide publicity and widespread acceptance. But endorsement was hardly universal. Not insignificantly, among those who greeted this proposition most skeptically were the scientists most intimately involved in writing the obituaries of the earth's long-departed denizens. Extinction is, after all, first and foremost a biological story, and the paleontologists and paleobiologists who interpret that story as limned in the fossil record were disinclined to endorse a catastrophy theory.

To a large degree, theirs was the resistance of gradualists, adherents to the idea that extinction is an element in the saga of Darwinian evolution and, like it, one of the protracted, ecological, earth-bound processes rather than a consequence of abrupt, catastrophic phenomena. And from what they knew of ground-truth as embodied in the fossil record, paleontologists certainly felt justified in their conviction.

The paleontological community is not by nature a vociferous or confrontational group, however. For the most part, at least initially, the community elected to ignore the Alvarez hypothesis, which it thought would disappear as have all prior extinction models involving extraterrestrial influences. That assumption proved to be erroneous.

Finally, pressed by the persistence of the bolide idea, paleontologists were obliged to take some action. They turned to the extinction data base, the fossil record, and began to comb it in fine-toothed detail. By collecting evidence at hitherto unheard-of levels of resolution, they sought to test the predictions generated by the Alvarez hypothesis against what actually happened biologically. The quest is still continuing, but the almost feverish work of the last few years has already had important theoretical impact. It has uncovered complex patterns of extinction that clearly cannot be explained by the single-impact hypothesis, neither at the Cretaceous–Tertiary (K-T) nor the Eocene–Oligocene (E-O) boundaries or, for that matter, at any of the other major extinction boundaries. These discoveries, in turn, have forced proponents of the extinction-by-bolide theory to work on major revisions.

What they have begun to promulgate recently is a far more drawn-out extinction scenario—a hybrid of catastrophism and gradualism—involving bombardment not by a single killer asteroid but rather by cometary showers that rained down upon the earth over a period lasting, say, a few million years. But many paleontologists remain firmly committed to the belief that there is no need to invoke extraterrestrial causes; they say the newly uncovered biological data are readily explicable by terrestrial extinction processes. These would be changes in climate (especially temperature) induced, for example, by protracted and excessive volcanism, a global reduction in sea level, or a shifting of tectonic plates. If it achieves nothing else, in fact, the asteroid hypothesis will have served science by galvanizing paleobiologists, geochemists, geologists, and scientists from a host of other disciplines into a new round of fact finding. This heightened activity is a major plus, even though the new facts may spell the demise of the original Alvarez proposal.

Coincidence or Proof?

One of the first to challenge the asteroid hypothesis was Berkeley scientist William A. Clemens, whose specialty is vertebrate paleontology. Clemens has for many years been working on terrestrial extinctions and species origination across the K-T boundary. His primary research arena is the badlands of northeastern Montana, part of the Western Interior of North America lying east of the Rocky Mountains and extending from southern Canada to the southwestern states.

During the late Cretaceous period, this stretch was the coastline for a large epicontinental sea that covered the central United States. Coexisting at the sea's western edge was a large assembly of mammals and lower vertebrates, including dinosaurs. With its many exposures of rock from the late Cretaceous and early Tertiary, the badlands, particularly a place called Hell Creek, have yielded what may well be the most complete record of change in the terrestrial biota across the boundary. Clemens and his colleagues also have done extensive collecting in similarly fossil-rich sites in Wyoming and Alberta, Canada.

Clemens took early issue with the Alvarez hypothesis on a number of accounts. One had to do with the fact that the iridium anomaly was first discovered in three marine sections—in Gubbio, Italy; Stevns Klint, Denmark; and Caravaca, Spain—all of which showed a sudden decline in marine invertebrate taxa. By what justification, Clemens wondered, did Alvarez and his colleagues (his son Walter, Frank Asaro, and Helen Michels) link these marine-based findings to the demise of dinosaurs and other terrestrial creatures?

Since then, the iridium anomaly and other evidence of impact, including the presence of microtektites (glassy rock) and so-called shocked quartz, have been identified at dozens of K-T boundary sites, both marine and terrestrial. But even so, says Clemens, there is still very good reason to question whether extraterrestrial objects had anything at all to do with terrestrial extinctions. In his own studies, for instance, he has found the last fossil traces of dinosaur as far as 3 meters below the K-T boundary, suggesting that they became extinct well before the presumptive impact that produced the iridium spike. Moreover, Clemens has traced dinosaur diversity patterns through late Cretaceous rock formations and observed a significant reduction in the number of species and overall population size during the 10 million years leading up to the K-T boundary. To Clemens, this clearly suggests that dinosaurs were not in full flower but were, in fact, already well on their way out long before the putative asteroid event 65 million years ago.

Last year, Robert E. Sloan of the University of Minnesota and his coworkers—J. Keith Rigby, University of Notre Dame; Leigh M. Van Valen, University of Chicago; and Diane Gabriel, Milwaukee Public Museum—reported finding fossils of "the last dinosaurs known" in the Hell Creek section of eastern Montana. The fossils were found in sediments containing pollen and mammalian teeth from the post-Cretaceous period. The sediments were said to be more than four feet above the clay layer containing the clues that argue for the asteroid-impact hypothesis. Other paleontologists have expressed reservations about this new report, contending that the relation to an iridium-rich clay deposit is inferred, and that the fossils and sediments have been so mixed up by stream erosion that they may in fact be of Cretaceous origin. If the new discovery proves to be post-Cretaceous, however, this new finding would serve to further refute the Alvarez hypothesis. As Clemens explains, "I heard Luis [Alvarez] say, 'Bill, if you find one dinosaur bone above the iridium level, you've got me.'"

Another major objection of Clemens' concerns the premise on which the Alvarez hypothesis was implicitly based: that contemporaneity equals proof; that existence of presumptive evidence of impact at the K-T boundary meant, of necessity, that this impact caused extinction. "I have no hang-up with the notion of extraterrestrial objects periodically colliding with the earth," he says. "What I have trouble with is the assumptions having to do with how these impacts impinged on biology, if in fact they did." In his original argument, Alvarez proposed a mechanism of extinction akin to nuclear winter. His thesis was that an iridium-rich, ten-kilometer asteroid, upon colliding with the earth, threw up a dust cloud that suppressed photosynthesis and caused a temporary collapse in the food chain. To Clemens' way of thinking, very little could have survived such a formidable catastrophe. But the terrestrial record of vertebrate fauna says otherwise.

Luis, left, and Walter Alvarez believe that the iridium layer is evidence of extinctions. (Photo courtesy of University of California, Berkeley)

Too Few Victims

The only taxa that did not make it across the K-T boundary at all, says Clemens, were the dinosaurs, the pterosaurs (flying reptiles), and one family of freshwater fish. Two orders of animals showed a high rate of extinction: marsupials (which lost 75 percent of late Cretaceous genera and 65 percent of families) and freshwater sharks and rays (which lost three of five Cretaceous genera). Turtles, by contrast, sailed through the boundary almost unscathed, according to recent studies by William Clemens' Berkeley colleague, J. Howard Hutchison, and former student David Archibald, now at the University of California at San Diego. They detected a loss of only three of nineteen turtle genera—representing an extinction rate of merely 16 percent. Unlike marsupials, the other orders of mammals, multituberculates (rodentlike animals) and placentals, fared pretty well. Among the former, four of eleven genera and two of eight families became extinct during the transition from the Cretaceous period to the Tertiary period. Among placental animals, only one of nine genera and one of four families died out at the end of the period.

Of the entire spectrum of fossil faunas unearthed in the Western Interior, only 43 percent of the 117 known latest Cretaceous terrestrial genera (including freshwater fishes) and 35 percent of the 65 recognized families lack Tertiary decendants. "The record [from the northern Western Interior] clearly shows that extinction of dinosaurs and pterosaurs was not accompanied by extraordinary decimation of most contemporary groups of terrestrial vertebrates," says Clemens. In his view, the complex, highly selective pattern of extinction seen in the fossil record hardly meshes with the severe, haphazard pattern that would have been expected from a catastrophe of the magnitude of an earth-asteroid collision.

Evidence garnered by marine paleontologists also has served to undermine the original Alvarez hypothesis. Here, too, the fossil record tends to refute a primary assumption of the collision thesis: that all late Cretaceous organisms that went extinct did so at the K-T boundary. Working in Zumaya, Spain, on an outcrop that had lain beneath the sea 65 million years ago—a section bearing perhaps the most complete, continuous, land-based marine fossil record of the Cretaceous and Tertiary periods—Peter Ward of the University of Washington in Seattle scrupulously tracked, layer by layer, the history of the ammonites, the once-populous marine invertebrates.

He found that the ammonites—which bore a strong resemblance to today's chambered mollusk, the sea nautilus—had begun to go into serious decline six million to seven million years before the end of the Cretaceous period, and had all but disappeared 300,000 years before the K-T boundary. Ward turned up shells of at least eight to ten species of ammonites 100 meters below the K-T boundary, but he found no traces in the highest 12 meters of the Cretaceous section. From his studies, Ward concluded that the final extinction for another group of invertebrates, large bivalves known as inoceramids, had come earlier. Hence, the demise of these ammonites and inoceramids could hardly be ascribed to a one-shot impact at the still-to-come iridium-rich K-T boundary. It had rather to be ascribed to sweeping and protracted deleterious changes in the late Cretaceous ecosystem.

Stepwise Extinctions

Closer analysis of the ammonite data brought yet another critical observation to light. It seems that these species died out not one by one in a series of gradual, continuous disappearances but rather in what amounted to three or four rather abrupt steps. First a few species went out at one level, then a few more disappeared perhaps hundreds of thousands or a million years later, and so on. Still-viable species remained stable during the intervening sequences, though no new species of ammonites sprang to life. Ward readily acknowledges that the extinction record from the Zumaya outcrop may represent only a local happening and cautions about using these findings to draw more generalized conclusions. But studies reported in 1985 by Gerta Keller of Princeton University suggest that this stepwise extinction pattern occurred globally.

Keller has centered her paleontological research on the fossilized remains of planktonic foraminifera—microscopic, single-celled organisms that lived as marine floaters. When they died, their calcareous (calcium carbonate) shells slipped to the bottom of the sea, each species depositing its own distinctive brand of shell. In microfossil samples from different deep-sea sites as well as a once-submerged site in El Kef, Tunisia, Keller found what appeared to be four discrete intervals of foram species extinction or rapid faunal turnover. These occurred over a 4-million-year period prior to the K-T boundary. At least three of these steps appear to coincide with those observed by Ward in his Zumayan ammonites.

In foram extinction, the K-T boundary represented still another step, clearly the most dramatic, in the decline. But not all species disappeared; Keller has found that at least five—not one as had been argued previously—made it through the K-T boundary. Before the extinctions, 35 or more species had existed at one time or another during the late Cretaceous period.

Marine Macrofossils

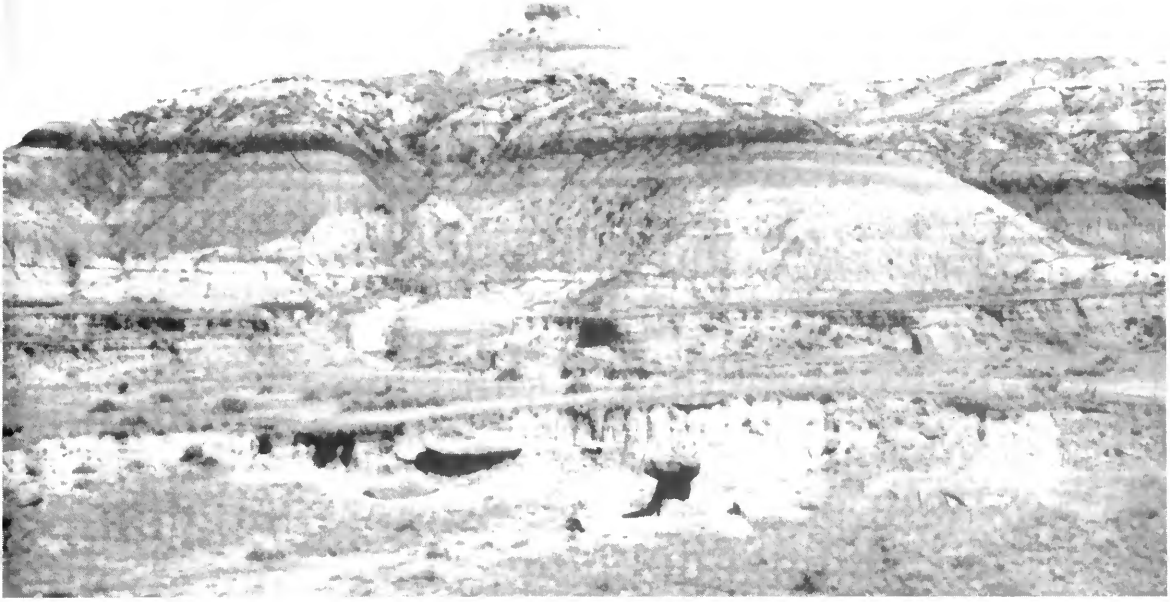
Perhaps the first scientist to take notice of stepping as a characteristic of K-T extinction and other mass extinctions was Erle G. Kauffman of the University of Colorado at Boulder. A marine paleontologist, Kauffman has for more than two decades concentrated largely on studies at the K-T boundary of molluscan macrofossils. His particular interest is mollusks, including Cretaceous, reef-forming rudists. Those bivalves underwent a tremendous, global expansion in mid-Cretaceous times, displacing corals, by way of competitive superiority, as the major reef-building organisms. Kauffman investigated extinction among bivalves at various sites in the Western Interior, on the Atlantic Coast of North America, on continental sections of Western Europe, and in the Caribbean Sea and Central America.

Through an extensive analysis of all available evidence for extinction patterns of marine macrofossils across the K-T boundary, Kauffman concluded in a report published in 1984 that the mass extinction was a protracted event spanning a period of about three million to four million years. In his reading of the data base, Kauffman sees the disappearances beginning about two million years before the K-T boundary and proceeding in a series of five discrete steps across the boundary into the early Tertiary period. He finds that the most dramatic extinction event occurred at the boundary itself. Each step, he explains, represents a short episode of highly accelerated extinctions. Those first affected were the most ecologically sensitive organisms (that is, tropical creatures presumably able to withstand only the narrowest swings in temperature or oceanic chemistry), with progressively more tolerant groups succumbing in the later stages.

Kauffman has observed much the same pattern at yet another marine-extinction boundary on which he has lavished considerable research attention and which fell in the mid-Cretaceous period, 93.3 million years ago. This event, recorded in and around the Cenomanian–Turnonian (C-T) boundary, was not in the same league as the K-T extinction boundary. It was still of major consequence, however, wiping out 50 to 75 percent of species in various major groups of the marine biota over a period of 2.5 million years. The C-T extinction was clearly stepwise in nature, says Kauffman. It showed six brief intervals of accelerated extinction separated by longer recovery intervals characterized by low-level background extinction rates that characterize the evolution of species.

Comets

Recognition of these stepwise patterns, made possible through highly refined stratigraphic analysis of abundant marine fossil records, led advocates of



Above, a typical badland area in northeastern Montana. The black line across the bluffs is the so-called boundary coal. Dinosaurian remains occur below this level; none have been found above it. Below, a researcher collects a limb bone of a "duck-billed" or hadrosaurian dinosour in the badlands. (Photos by Christa J. Sadler, courtesy of W. A. Clemens) the impact hypothesis to revise the original Alvarez theory. They stopped far short, however, of abandoning the notion that extraterrestrial agents were involved in these extinction events. They came up instead with an alternative catastrophe model to account for these and possibly a number of the other major extinctions recorded in the planet's fossil history. The new hypothesis, as propounded by Piet Hut, an astrophysicist at the Institute for Advanced Study in Princeton, replaces the idea of a single asteroid impact with a cometary-shower theory. It proposes as a possible extinction mechanism a passing star that disturbed a comet cloud and scattered comets into space. The notion is that several of the comets would have struck the earth over a period of a few million years and these could account for the stepwise extinctions.

This idea of cometary fleets has begun to acquire a measure of support from several marine paleontologists who had opposed the original Alvarez proposal, among them Kauffman, a onetime out-and-out gradualist. "I used to think you don't need impact with extraterrestrial bodies to explain what happened," says Kauffman. "My belief was that earthbound events, such as regression of the seas as occurred prior to the K-T boundary, were enough to account for the changes in climate and temperature that are taken to be the immediate cause of extinctions. But I've changed my mind."

His conversion stems from the discovery of what he calls "very unusual signals" from the stable isotopes found in the fossil-shell record. When organisms, such as calcareous plankton for example, make their calcium carbonate shells, the ratios of carbon-12 to carbon-13 and oxygen-16 to oxygen-18 incorporated in the construction has much to do with the ambient temperature and chemistry. When the organism dies, those ratios are frozen in the shell. As a result, a great deal can be inferred from a shell about the contemporary marine environment. What the records show, says Kauffman, is a variety of large-scale and rapid changes in the stable isotope signals indicative of rapid and bizarre perturbations in the ocean environment. These changes were significant enough to cause extinctions.

Kauffman thinks that collision with comets might be just the vehicle to trigger these shifts. A comet crashing into the sea, he says, could certainly serve as enough of a stirring rod to bring about a major turnover in the chemical and temperature regimes. Land impact would also have an effect on marine life through establishment of a light-filtering dust cloud and possibly by its fallout and the production of acid rain. He points out, too, that the impacts may well have come before the actual extinctions; it is the resultant oceanic and climatic perturbations that finally cause extinction. "Final extinction simply occurred when already stressed organisms couldn't hang on any longer as the perturbations kept building on top of each other," he suggests.

For the most part, paleontologists have spent their time looking for clues to extinction at or near the boundary layers that define these extinctions. Now, given the revised hypothesis, there seems to be good reason to look at levels below the actual extinction events for evidence of impact. And that is what scientists have begun to do.

Multiple Impacts

For the present, the only really strong signs of impact related to K-T extinctions are those seen at the boundary itself: heavy concentrations of iridium, the presence of microtektites, shocked quartz, and feldspar. But in 1985 two new, tantalizing pieces of evidence were turned up that pointed to the possibility of multiple impacts near the K-T boundary. One comes from Gerhart Graup and his associates at the Max Planck Institute for Chemistry in Mainz, Germany. It involves the detection of three iridium spikes in a section of the Bavarian Alps: one at the K-T boundary, another in the clay-rich layer about 30 centimeters above the boundary, and a third, one meter below the boundary and associated with the presence of microtektites. The last, says paleontologist Keller, is the first hint of an impact event occurring prior to the K-T boundary. "Taken together," she says, "the three iridium anomalies suggest multiple impacts near the K-T boundary. Although Graup and his associates suggest that they represent tectonic disturbance of a single event, this explanation appears very doubtful considering that the iridium anomaly and microtektites 1 meter below the K-T boundary are associated with late Cretaceous fauna and the iridium anomaly above the boundary is associated with early Tertiary fauna."

New Evidence

The second piece of evidence was turned up by the Alvarez group. They reported finding multiple iridium anomalies—one major peak at the K-T boundary and three smaller peaks preceding the boundary—in a deep-sea core sample from the North Pacific. According to Keller, there is a possibility that the lowest iridium peak represents the same event as the microtektite layer and iridium anomaly discovered by the Graup group 1 meter below the boundary. She also cites a study involving analysis of samples from the same core by paleontologist Robert Thunnel of the University of South Carolina and former graduate student Jennifer Gerstel. Gerstel (now at the South Carolina Department of Health and Environmental Control) and Thunnel reported a rapid decline in larger species of planktonic forams less than 1 meter below the K-T boundary, suggesting a relationship between the lowest iridium anomaly and the faunal change. Keller and her graduate student Steve D'Hondt have subsequently embarked on a study of selected deep-sea and onshore marine sections, including the area in the Bavarian Alps where Graup made his initial discovery. Keller hopes to determine the timing and nature of these late Cretaceous and early Tertiary stepwise extinctions, or faunal turnovers, and locate further evidence of impact events. "We expect the study to show whether stepwise K-T mass extinctions are related to impact events and what type of environmental changes are associated with them."

Needless to say, the cometary-shower hypothesis has met with a fair amount of skepticism. The critics continue to insist that extraterrestrial influences are not needed to account for the K-T mass extinctions. They contend that an excess of volcanic activity could well have been at the root of these extinctions. Several studies conclusively show that the earth experienced a major, extended peak of volcanism from the late Cretaceous to the early Tertiary period.

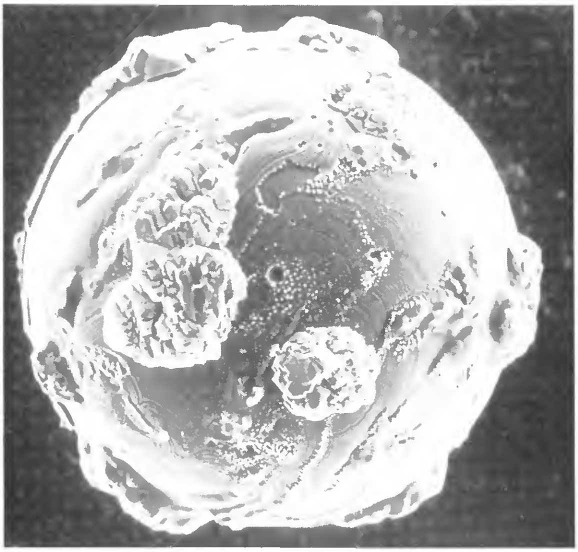
In 1985, geologists Charles B. Officer and Charles L. Drake of Dartmouth College conducted a detailed analysis of all pertinent research bearing on volcanic activity and extinctions during this transition period. They argue that the volatile emissions caused by these eruptions would probably have led to intense acid rain and a concomitant change in ocean chemistry, as well as global ozone-layer depletion with a consequent increase in ultraviolet radiation. These factors, they say, in conjunction with sea-level regression known to be going on at the time, would have produced the extinction patterns observed in the geologic record. Moreover, they contend, the ostensible signatures of extraterrestrial impact—deposition of an excess of iridium, microtektites, and shocked quartz—might just as readily have been products of this massive and extended volcanic activity.

Terrestrial or extraterrestrial? Cometary showers or vulcanism? "That's a tough one," says Donald Prothero, a paleontologist at Occidental College in Los Angeles. "The irony is that the predictions devolving from the vulcanism model are almost indistinguishable from those arising out of the comet scenario. Both fit the spaced, stepped extinctions seen in the record. The largest general conclusion to come out of looking at extinctions patterns among late Cretaceous animals, both vertebrate and invertebrate, is that the animals don't follow any single, simple model. I've yet to hear anyone come up with a good explanation for why, for example, dinosaurs went out and crocodiles and turtles did not. You can't use size or warm- or cold-bloodedness as differentiating criteria. Right now there's just not enough difference between survivors and nonsurvivors to make any simple model explain everything."

Back to Earth

In 1982, on the heels of discovery of an iridium spike following microtektite detection high up in a deep-sea core, Alvarez and his colleagues extended their single-bolide theory to another major extinction event—this one at the Eocene–Oligocene boundary, dated at 36.5 million years ago. The assumption again was that the extinctions associated with this epoch boundary all happened suddenly and simultaneously right at the end of the Eocene period. An intensified search of the fossil record, by marine and terrestrial paleobiologists, showed that an instant-extinction hypothesis was incorrect in this instance as well. In response, the bolide advocates again advanced the cometary-shower hypothesis, but there seems to be far more reason to believe that earth-derived, tectonic-driven processes were principally responsible.

From the marine side, the argument against catastrophe stems in part from the work first reported in 1983 by Princeton's Keller. She had



Microtektites found in deep-sea cores. (SEM ×300. Courtesy of Princeton University, Gerta Keller)

spent several years studying the Eocene–Oligocene microfossil record in deep-sea cores from various parts of the globe. The cores were continuous (that is, without geological gaps), enabling her to observe changes with resolution of just a few thousand years. The story the fossils told was that of stepped extinctions extending over a period of 3.4 million years, between 40 million and 36.6 million years ago. Close examination indicated that each of the four successive and rather sharply defined steps was marked by extinction of three to five species. The steps were separated by relatively stable or quiescent periods and included the accelerated origination of new species. The species that became extinct at each step event represented fewer than 15 percent of the number present, but the sum total of the late Eocene stepwise extinctions resulted in a near complete faunal turnover. Collectively, it was a mass wipeout.

At each step, it was the warm-water surface forams that successively became extinct, with the vacated waters occupied in turn by expanding colonies of species that rose from cooler depths to occupy the vacant niches. These observations, together with oxygen-isotope data, suggested that a protracted cooling trend was in progress. Curiously, the least devastating of the steps (in terms of the total foram population) came at the E-O dividing line itself. This further dispelled the notion of a catastrophic event. Similar findings were made by Western Washington University's Thor Hansen, who examined the late Eocene history of mollusks in the Gulf Coast and found stepwise extinction of bivalves and gastropods amounting to a collective loss of 79 percent of species present. Moreover, the steps coincided in time with those of foram extinctions, in which successive warm-water groups suffered higher extinction rates than cool-water groups.

What lent credence to the theory of some contribution by a cometary shower was Keller's discovery, in the deep-sea cores, of microtektites at three stratigraphic levels closely associated with two of the later steps of foram extinction. There is no evidence of impact associated with the preceding two steps, says Keller, nor for another recorded later, at 32.5 million years ago, in what is called the mid-Oligocene event. To Keller, the evidence strongly suggests that the extinctions were due to a long-term climatic cooling trend that started before these impacts occurred and was driven by earthbound phenomena. "We don't need impact," says Keller of the extinctions, "but the fact is we have impact, and that coincidence cannot be ignored." Her tentative conclusion: "Populations already in decline and teetering on the brink of extinction because of climatic pressures may be pushed over the edge into oblivion by a minor perturbation—a collision with a comet, for example."

The Psychrosphere

The overriding cause of these extinctions is thought to be protracted terrestrial cooling. The cooling would derive from the origination—during the Eocene-Oligocene transition—of the so-called psychrosphere, the cold layer of bottom water in oceans. Its appearance resulted from the submergence and global circulation of dense, refrigerated waters. Prior to this, the world's oceans are presumed to have been of a piece, with essentially the same temperature from top to bottom. This psychrosphere idea was first advanced in 1977 by Richard Benson of the Smithsonian Institution. He deduced its formation from changes noted in the composition of deep-sea ostracods, small, bivalved crustaceans. In 1977 James P. Kennett of the University of Rhode Island proposed a model, based on plate tectonics, to explain how the psychrosphere came into existence.

His hypothesis has since gained considerable scientific support. It takes as its starting point the separation of Australia and South America from Antarctica, which opened the way for ocean waters to circulate around the isolated continent perched atop the South Pole. The water grew colder, sank to great depths, and spread toward the equator. The process continued as water from higher latitudes became trapped in this cooling engine. Meanwhile, as the Antarctic region grew more and more thermally isolated, ice began to accumulate on its surface. That accretion was further enhanced by the albedo effect, in which light is reflected by the ice, causing accelerated cooling, an increase in glaciation, and a reduction in sea level around the world. Cool temperatures that began to pervade the earth were transmitted by frigid winds and ocean currents as they traversed the lower latitudes.

To terrestrial paleontologist Prothero, who has probably studied Eocene-Oligocene mammalian extinctions in greater detail than anyone else, there is little reason to believe that impact with extraterrestrial bodies had any significant impact on land fauna. "Even if you had things coming in from outer space, be it an asteroid or comets," says Prothero, "the land animals were already so stressed by sea-level drops, glaciation, climate changes, and consequent changes in habitats that I don't think they would have noticed."

What Prothero sees from his work and that of others on the North American fossil record is a drastic but gradual change in species diversity, spread out over as much as 10 million years from the late Eocene to the mid-Oligocene period. During this time archaic forms, most already in decline, go extinct and better-adapted forms emerge.

The majority of archaic forms, remnants of taxa long past their prime, were gone 42 million years ago, says Prothero. This was well before the Eocene-Oligocene boundary, which further refutes the notion of an abrupt E-O transition. Prothero thinks the forms found at the North American E-O boundary were, in part, migrants from Asia that had come by way of a land bridge across the Bering Strait connecting Siberia and Alaska during a time of glaciation and reduced sea level, or by way of Greenland, which still linked the old and new worlds.

Another Boundary Event

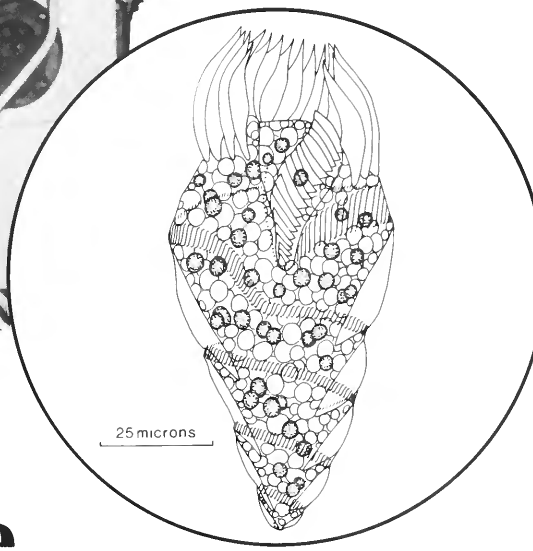
About 2 million years after the E-O division—a period marked by relative faunal stability—there is evidence of a large and abrupt extinction event. Dated at 32.4 million years ago and dubbed the mid-Oligocene extinction event, it saw the loss of still other archaic groups, including the titanotheres (huge, rhinoceroslike animals) and the oromerycids (primitive versions of latter-day camels).

Prothero estimates that the interval of extinction lasted no more than 200,000 years. "Although the event happened relatively rapidly," he says, "it was not catastrophic. The extinctions here were selective, with most of the disappearances happening among groups that were primarily relics from the Eocene. Most of the other changes [dwarfing of some species and origination of new species] were drawn out over the entire transition and do not suggest geologically instantaneous, catastrophic causes." He believes corroborating evidence, from studies of the flora and soils, argues strongly that sweeping ecological and climatic change was responsible for the extinctions.

From appearances, the Alvarez hypothesis, at least in its original shape, has just about joined the ranks of the extinct itself. As one ground-truth paleontologist puts it, "I guess the only thing that would lead me to buy the single-impact hypothesis is if I came across a dinosaur with the top of its head blown off and microtektites embedded in the skull bone."

Whatever the final outcome, Alvarez and his colleagues are just now beginning to receive credit, however grudgingly given, from the paleontological community in appreciation of the effect the impact hypothesis has had upon their own research. "Whether right or wrong," says Keller, "I believe the Alvarez team has done a great service to science in stirring up enormous controversy and interest so that scientists would go back to their data or to their sections and take a second look and critically evaluate what's really there. This would not have happened without the prod of impact."

Ben Patrusky is a free-lance science writer, and the author of Biology's Computational Future *in* Mosaic, *Vol. 16, No. 4.*



Photosynthesis Found in Some Single-Cell Marine Animals

by Diane K. Stoecker

Our concept of the role of microzooplankton in marine food webs is changing. This is largely because many of these small creatures have both animal and plant characteristics. Like other zooplankters, most microzooplankters prey on other organisms. But, unlike most animals, some of the protozoan (one-celled animal) microzooplankters contain functional chloroplasts "stolen" from phytoplankton, and are thus photosynthetic. This observation raises some interesting evolutionary questions.

Chloroplasts are the organelles in plant cells responsible for photosynthesis, the process by which inorganic compounds (water and carbon dioxide) are converted into organic compounds (like sugars) with the use of energy derived from sunlight. Within the chloroplasts, chlorophyll is the primary photosynthetic pigment. It is this chlorophyll pigment that gives land plants and

Above, the author at the microscope, and Laboea strobila, *the largest of the chloroplast-retaining ciliates. This species accounted for 46 percent of the biomass of chloroplast-retaining ciliates in Woods Hole waters. (Drawing courtesy of D. Montagnes, University of Guelph, Ontario, Canada)*

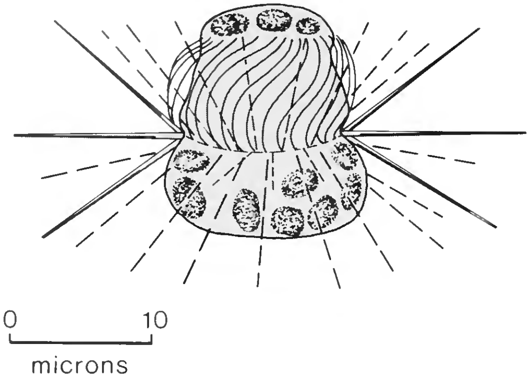


Figure 1. The best known of the photosynthetic ciliates, Myrionecta *(formerly* Mesodinium*)* rubrum. *Unlike other photosynthetic ciliates studied, which retain chloroplasts from ingested phytoplankton, this species is a consortium between a ciliate and an incomplete algal cell living within the ciliate. The dark bodies within the ciliate are the chloroplasts of the modified algal cell. This ciliate does not have a functional mouth, and completely depends on photosynthesis for its nutrition. (From Taylor, 1982)*

Figure 2. A scanning electron micrograph of a photosynthetic ciliate, Strombidium *sp., which retains chloroplasts. (Photo courtesy of D. Montagnes and D. Lynn, University of Guelph, Ontario, Canada)*

green algae their color. In addition to chlorophyll, however, most phytoplankton have accessory pigments in their chloroplasts that, combined with the chlorophyll, give them a yellowish green, golden brown, or reddish color.

In coastal waters, the ciliated protozoa* usually dominate the microzooplankton. These microscopic one-celled animals propel themselves at rates of about 1 millimeter a second by means of their cilia, which also are used to capture food. The role of ciliates as microconsumers in the plankton is well recognized. They are estimated to consume about as much phytoplankton as the larger copepods.** Most estimates of the grazing impact of microzooplankton indicate that these small zooplankters consume about 40 percent of the phytoplankton production.

However, the role of marine planktonic ciliates in photosynthesis is less well known. The best-known photosynthetic ciliate is *Myrionecta* (formerly *Mesodinium*) *rubrum* (Figure 1), a species that sometimes blooms and makes the sea maroon colored. In a letter from 1676, Anton van Leeuwenhoek, the inventor of the microscope, described observing a little animal in seawater that was undoubtedly *M. rubrum*. Charles Darwin observed a large *M. rubrum* bloom off Chile on the voyage of the *H.M.S. Beagle* in the 1830s. The descriptions that were done in the late 1800s and early 1900s of marine ciliates mention the presence of pigmented "bodies" in many marine ciliates. The real nature of these pigmented bodies was not discovered until the 1970s when pigmented marine ciliates were first observed with electron microscopy.

Electron micrographs disclosed that *M. rubrum* was not a single cell, but rather a consortium of a ciliate and a very modified alga.† On the other hand, electron micrographs of pigmented oligotrichous†† marine ciliates were even more surprising. In 1973, David Blackbourn, Max Taylor, and Janice Blackbourn of the University of British Columbia in Canada reported finding that *Laboea strobila* and the pigmented *Strombidium* species (Figure 2) contain isolated chloroplasts, rather than algal cells. More recently,

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* The subkingdom Protozoa is a heterogenous group of microscopic animals united only by their common single-cell structure. The ciliates, in their own phylum, constitute the most homogeneous of the protozoan groups. *Paramecium*, familiar to those who have studied biology, is a common example.

** Small, shrimp-like animals, ranging in size from 0.5 to 10 millimeters. They are important in the food chain of the sea because of their large numbers, and their role as grazers on single-celled phytoplankton and protozoa.

† Another example of this type of relationship is the zooxanthellae, or symbiotic dinoflagellates, found in certain reef-building corals (see *Oceanus* Vol. 29, No. 2, page 22).

†† Refers to the taxonomic order of marine ciliates characterized by cilia largely restricted to the mouth area, with few cilia over the body surface. Most ciliates found to retain chloroplasts are in this group.

Michèle Laval-Peuto and Michèle Febvre of the University of Nice, France, observed isolated chloroplasts in another oligotrichous ciliate, *Tontonia*. The chloroplasts in oligotrichs are structurally similar to those observed in phytoplankton. Thus it was hypothesized that the chloroplasts were derived from ingested algae.

Photosynthetic Ciliates in Coastal Waters

With the exception of *M. rubrum*, which sometimes forms large patches of red water, the widespread occurrence and high abundance of photosynthetic ciliates in coastal waters was not appreciated until recently. There are two principal reasons. Ciliates, like most phytoplankters, rarely occur at densities that cause visible blooms; and, most ciliates are too small and too delicate to be captured by plankton nets. However, when coastal water samples are observed by combination of transmitted light and epifluorescent microscopy (see box, page 53), many chloroplast-retaining oligotrichous ciliates (*Laboea strobila, Tontonia* sp., and *Strombidium* spp.) as well as some *M. rubrum* are seen.

Since the spring of 1985, the author and colleagues at the Woods Hole Oceanographic Institution have undertaken a study to assess the abundance and role of chloroplast-retaining ciliates. Several of the results were unexpected.

We discovered that, in Woods Hole, chloroplast-retaining ciliates are found year-round, and have an average density of 1,167 cells per liter. However, they are much more abundant in the warm months, and can reach densities of more than 5,000 cells per liter in surface waters. Averaged on a yearly basis, 31 percent of the ciliates in the surface waters of Woods Hole have chloroplasts. We further found that chloroplast-retaining ciliates appear to be equally abundant in the bays and sounds near Woods Hole (Figure 3).

Other investigators also have reported chloroplast-retaining ciliates from the eastern Atlantic Ocean, the Pacific Ocean, and the Mediterranean Sea. However, more quantitative data are required on the abundance of chloroplast-retaining ciliates in coastal and oceanic environments before we can assess their general significance.

Active Photosynthesis Verified

Since the discovery of chloroplast-retention by ciliates in 1973, it has been speculated that these ciliates are actively photosynthetic. It was known that some sea slugs (a group of sea snails without shells) and some benthic (bottom-living) protozoa also retain algal chloroplasts and, in some, but not all, cases these chloroplasts are functional.

Recently, we have cultured both *Laboea* and several chloroplast-retaining *Strombidium* species in the laboratory. This has allowed us to investigate their physiology under controlled conditions. These laboratory experiments have shown that chloroplast-retaining ciliates require both algal food and light. Although they can survive for several days without food if they are kept in the light, they do not continue to grow and divide unless they are

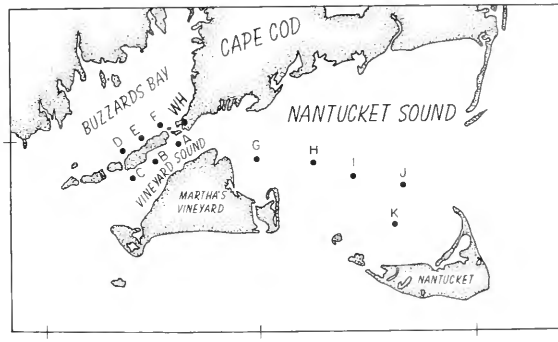


Figure 3. Samples collected from coastal waters in the vicinity of Woods Hole, Massachusetts, were surveyed for chloroplast-retaining ciliates. Water samples were taken weekly from the Woods Hole Oceanographic Institution dock in Woods Hole (WH) from June 1985 to June 1986. During the summer of 1986, a survey was made of chloroplast-retaining ciliates in Vineyard Sound (stations A, B, and C), Buzzards Bay (stations D, E, and F), and Nantucket Sound (stations G, H, I, J, and K), with the research vessel Asterias.

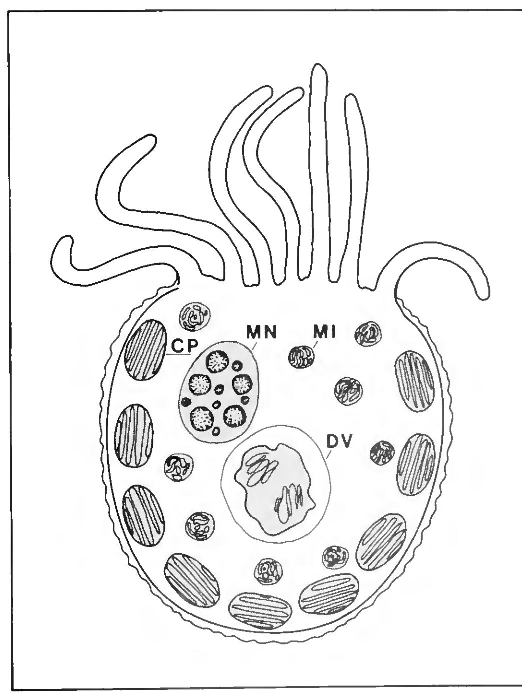


Figure 4. A chloroplast-retaining ciliate—a schematic representation based on electron microscopy. Phytoplankton are ingested by the ciliate and digested in vacuoles (DV) located in the central area of the cell. Some phytoplankton chloroplasts are not digested by the ciliate and remain intact (CP). The process by which these chloroplasts are separated from the rest of the phytoplankton cell is not known. These "stolen" chloroplasts are concentrated in the periphery of the cell. All of the other organelles in the ciliate cell, including the macronucleus (MN) and the mitochondria (MI), are typical of ciliates. The chloroplasts are the only "foreign" organelles.

Microzooplankton—

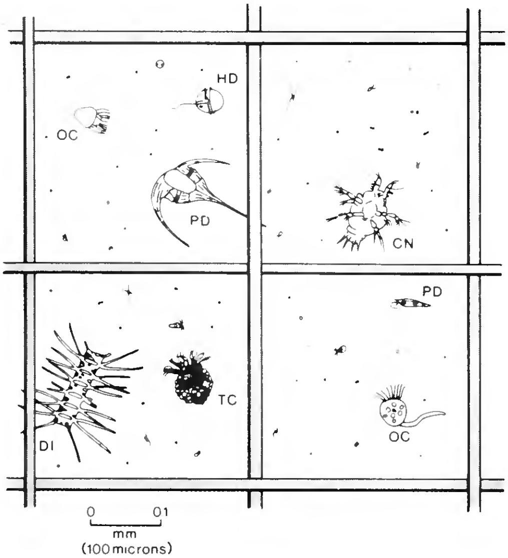
Zooplankton range in size from jellyfish that are up to a meter in diameter down to non-photosynthetic flagellates that are as small as a few microns (a micron is one millionth of a meter). Near the small end of this size spectrum are the microzooplankton, which range from 20 to 200 microns in size. Within the microzooplankton, protozoans (one-celled animals) account numerically for more than 90 percent of the organisms. The dominant protozoans in coastal microzooplankton are planktonic ciliates and non-photosynthetic dinoflagellates. Early life stages of copepods (nauplii) often contribute as much biomass to the microzooplankton as the protozoa, although they occur in lower numbers than the latter; this is because the nauplii tend to be close to the 200 micron upper size limit of this category and the protozoa tend to be closer to the lower size limit, 20 microns.

Fine gauze nets, such as 64 micron mesh, can be used to capture nauplii and other larger microzooplankters with a tough outer covering. However, the nets destroy many protozoans, which are usually naked cells. Therefore, they are usually sampled by collecting water. The samples are preserved (which makes cells tougher as well as killing them), and the samples are gently concentrated in a settling chamber. A compound microscope (250 to 1000X magnification) is usually used to look at the protozoans in fixed microzooplankton samples.

Although microzooplankton, particularly protozoa, were ignored in most of the early plankton studies, biological oceanographers are now paying increasing amounts of attention to this size class. One reason is that the microzooplankton usually outnumber the larger zooplankton by a factor of at least a thousand. Secondly, microorganisms, such as protozoa, have higher weight-specific metabolic rates than larger organisms, such as adult copepods. Thus, microorganisms are thought to have a disproportionately large influence on ecosystem dynamics for their biomass.

Lastly, most of the primary productivity in the oceans is accomplished by phytoplankters only a few microns in size. These algae are too small to be grazed efficiently by most larger zooplankters but are the right size for many protozoans to eat. Protozoa also are important because some can efficiently utilize bacterial production, which otherwise would be mostly "lost" to the food web. Protozoans are in turn eaten by copepods, fish larvae, and other zooplankton. The microzooplankton, particularly the protozoa, appear to be an important link in planktonic food webs.

—DKS



The relative sizes of the microzooplankton, shown in a water sample viewed against the meshes of a typical medium-gauze (333-micron mesh opening) plankton net. In order of abundance, the microzooplankton include ciliated protozoa (OC and TC), non-photosynthetic dinoflagellates (HD), and small copepod larvae, or nauplii (CN). The most common ciliates in the microzooplankton are the oligotrichous ciliates (OC) and the tintinnids (TC). Tintinnids are protected by a non-living outer covering, or lorica, whereas the oligotrichs do not have a lorica. The larger chain-forming diatoms (DI) and photosynthetic dinoflagellates (PD) are phytoplankton that are within the same size range as microzooplankton. However, most phytoplankters are less than 20 microns in size.

also fed. As had been hypothesized, the ciliates "steal" their chloroplasts from phytoplankton. In collaboration with Mary Silver of the University of California at Santa Cruz we have found that the algal chloroplasts are located in the periphery of the ciliate cell (Figure 4), where they should receive the most light and where they are removed from the digestive vacuoles that are concentrated near the center of the cell. We have found that the chloroplasts continue to photosynthesize in the ciliates for weeks, although there is no evidence that the chloroplasts can replicate in the ciliate. Healthy, growing ciliates divide about once a day. Thus, growing ciliates must constantly replace chloroplasts as they become diluted through cell division.

Epifluorescence Microscopy

Some chemical compounds absorb short wavelength light (high energy photons) and then release some of this absorbed energy as longer wavelength light (lower energy photons); this phenomenon is called fluorescence. Some compounds can be identified by their absorption and emission spectra. Two plant pigments—chlorophyll and phycoerythrin—are fluorescent when excited with short wavelength blue light. Chlorophyll, the green pigment, fluoresces red, and phycoerythrin, a reddish accessory pigment found in some algae, fluoresces yellow.

It is often difficult to distinguish between small photosynthetic and non-photosynthetic plankton when they are observed using standard light microscopy. For this reason, epifluorescence microscopy has proven to be an extremely important tool in biological oceanography. Its use has led to the discovery and characterization of new types of photosynthetic plankton.

—DKS

New Questions

The prevalence of chloroplast-retaining ciliates raises several questions for biological oceanographers. If, in general, a large proportion of planktonic ciliates are both grazers and photosynthetic organisms, then the position of ciliates in planktonic food webs needs to be reconsidered. These one-celled animals may be an important "short-cut" between primary production (photosynthesis) and production of animal biomass. Because of their mixed nutrition, they should be extremely efficient producers of animal biomass in the oceans.

The survival of algal chloroplasts in animal cells also raises several molecular and cellular questions. The process by which the chloroplasts are extracted, unharmed, from the algal cells is not understood. Chloroplasts cannot survive on their own; they are dependent on information provided by the plant cell nucleus to synthesize some of their proteins and to replicate. The continued functioning of algal chloroplasts in animal cells remains puzzling.

The direct transfer of chloroplasts between organisms of different species raises the question of whether organelle transfer is important in evolution. Except for bacteria, all cells contain organelles. For example, plant and animal cells both contain nuclei and mitochondria, but usually only plant cells have chloroplasts. Most biologists believe that the ancestors of modern plants and animals arose millions of years ago by a series of endosymbioses (one cell living inside another). The endosymbionts lost some of the characteristics that allowed them to be free-living and became specialized for particular functions in the host cell. Thus, the "host" evolved from a relatively simple cell into a complex cell with organelles.

It is usually assumed that the formation of basically new cell types ceased millions of years ago. Modern day organisms are not expected to acquire new organelles. However, chloroplast-retention demonstrates that organelle transfer between cells still occurs. Since the chloroplasts in the chloroplast-retaining ciliates do not replicate, the host and its "symbiont" are probably not evolving together into a "new" cell line. However, in *M. rubra*, the algal symbiont seems to replicate in the host. Thus, *M. rubrum* may be a present-day example of the evolution of a new one-celled organism from an endosymbiotic event.

Investigation of the microscopic life of the sea has shown us that the distinctions between plants and animals are often blurred. We have found that the transfer of organelles between cells, a process once thought to be very rare, may be quite common among one-celled organisms. We usually think of evolutionary patterns as tree-like, with separate lines of evolution not intermingling once they have branched. However, the study of one-celled marine organisms has shown us that evolution may often be web-like, with distant branches interacting. Biologists are continuing to study the intriguing questions raised by the complex life styles of one-celled plankton.

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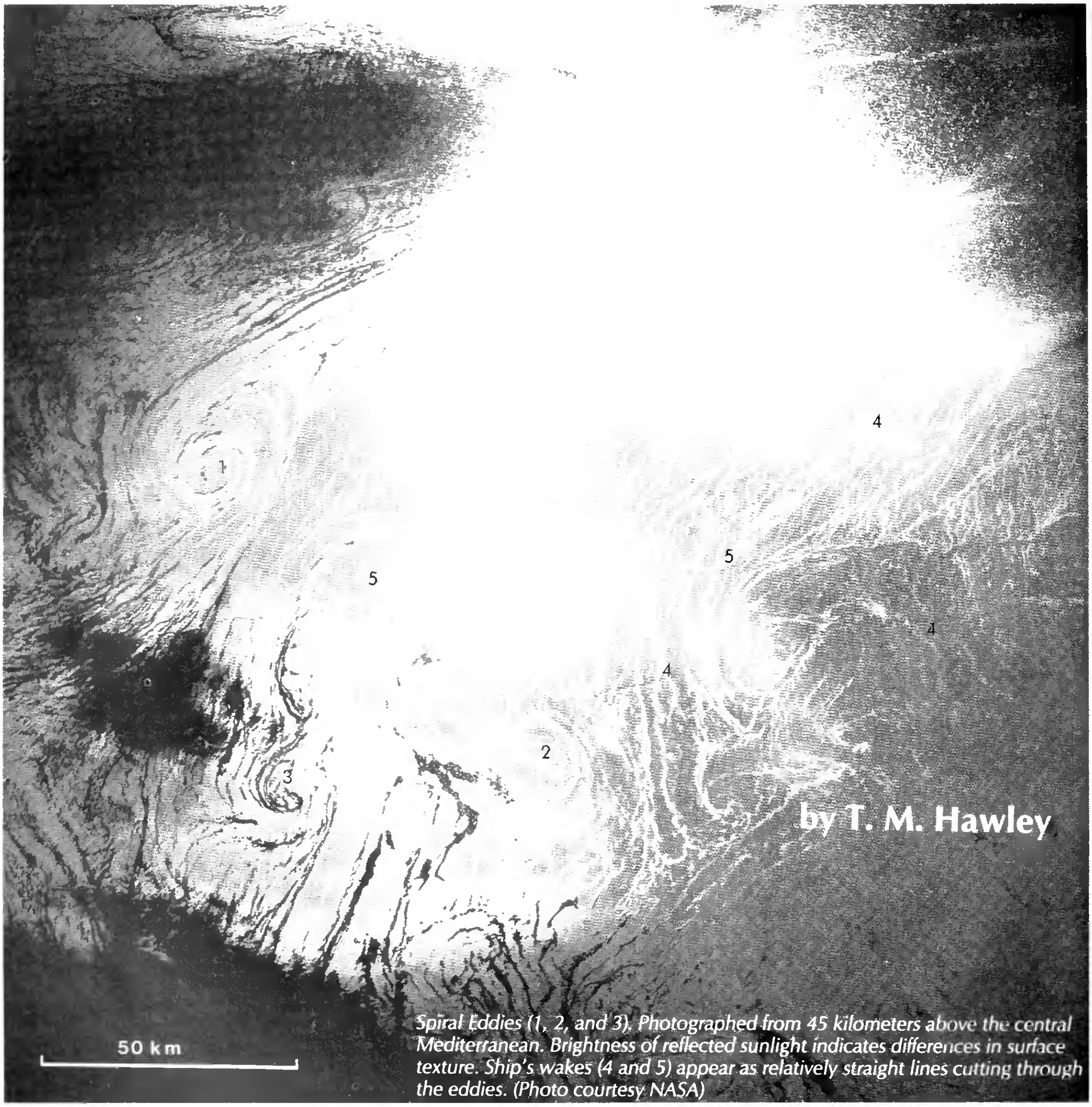

by T. M. Hawley

Spiral Eddies (1, 2, and 3). Photographed from 45 kilometers above the central Mediterranean. Brightness of reflected sunlight indicates differences in surface texture. Ship's wakes (4 and 5) appear as relatively straight lines cutting through the eddies. (Photo courtesy NASA)

One of the most fascinating puzzles attracting physical oceanographers over the years has been the description of the large-scale turbulent circulation of the ocean, visualized by scientists as "the internal weather of the sea." Oceanographers have amassed a store of descriptive information on this "weather," and have on a few occasions tested the feasibility of predicting it. Weather prediction has had a central organization—the National Weather Service—for more than a hundred years, but, until very recently, ocean prediction has been a relatively patchy effort. Established just two years ago, the Institute for Naval Oceanography, or INO, is now a center for ocean prediction research and development in this country. It has set for itself the goal of demonstrating mesoscale,* eddy-resolving ocean prediction systems by 1993.

The elements of the ocean's internal weather consist of meandering jets such as the Gulf Stream, eddies, and fronts. The behavior of these elements has been the subject of study since at least 1959, when the *Aries*** expedition discovered that mid-

* Ocean eddies, or "mesoscale eddies," are phenomena such as Gulf Stream rings. Hundreds of kilometers in diameter, they are similar in many ways to atmospheric high and low pressure systems, which are thousands of kilometers in diameter. *Oceanus* Vol. 19, No. 3, was devoted to research on ocean eddies.

** Oceanus Vol. 7, No. 3, pp. 2–9.

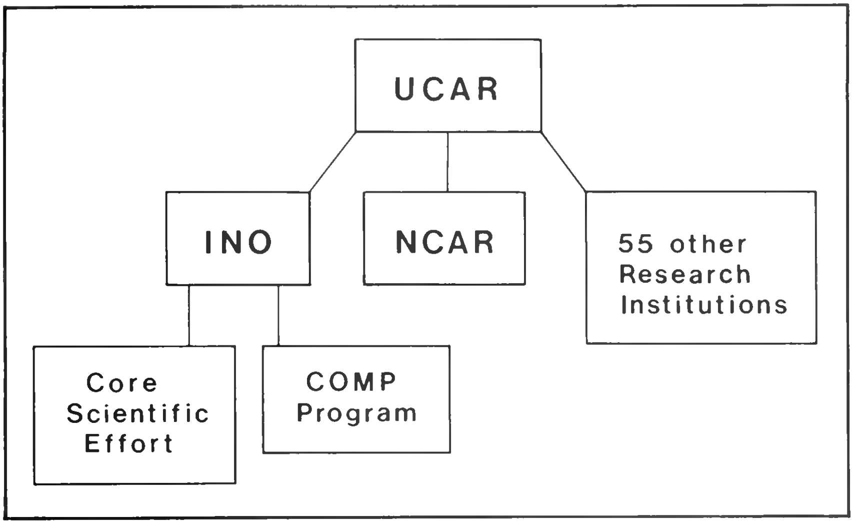

Figure 1. UCAR is a consortium of 57 academic centers doing research in space and earth science. As a governing body, the Boulder, Colorado-based UCAR helps to maintain high standards and develop commercial applications from UCAR-institution research. NCAR (the National Center for Atmospheric Research) is the "original" UCAR institution, and INO is the newest.

ocean eddies in the Gulf Stream can be a hundred times more energetic than the average backround circulation. Since then, explanations for the ocean's internal weather have included everything from the shape of the ocean floor to the interactions between the atmosphere and the ocean.

The vagaries of weather prediction are well-known, but useful ocean prediction may be more feasible since ocean eddies are much smaller than the highs and lows depicted on weather maps, and are much much slower to change than their atmospheric analogs. To keep track of eddies or currents, data buoys and expendable bathythermographs—the oceanic counterparts of weather balloons and radiosondes—are deployed in denser arrays, but can be launched less often. As INO's ocean prediction systems become operational during the next 10 years, many activities, from antisubmarine warfare to fisheries management, could benefit from its work.

Agency and University Ties

Three years ago, then-Secretary of the Navy John Lehman called for the formation of such an institute to ensure a leading role for the Navy in the development of prediction systems for the ocean. One year later, the Navy established the Institute as an in-house operation, and last October the Office of Naval Research (ONR) entered into an agreement with the University Corporation for Atmospheric Research (UCAR, Figure 1), transferring the operation and management of INO to UCAR. ONR remains its lead agency for interfaces to Navy policy and resources.

The grounds of the National Space Technology Laboratories (NSTL), between New Orleans and Bay St. Louis, Mississippi, are the home of INO, and Christopher N. K. Mooers, formerly professor and chairman of the Oceanography Department at the Naval Postgraduate School in Monterey, California, has been its director since it joined the UCAR consortium. Mooers and his growing staff are looking forward to the scheduled installation of a so-called "Class VII" or "supercomputer" at NSTL, purchased by the Naval Oceanography Command for INO and other Navy

Christopher N. K. Mooers, Director of the Institute for Naval Oceanography. (Photo courtesy INO)

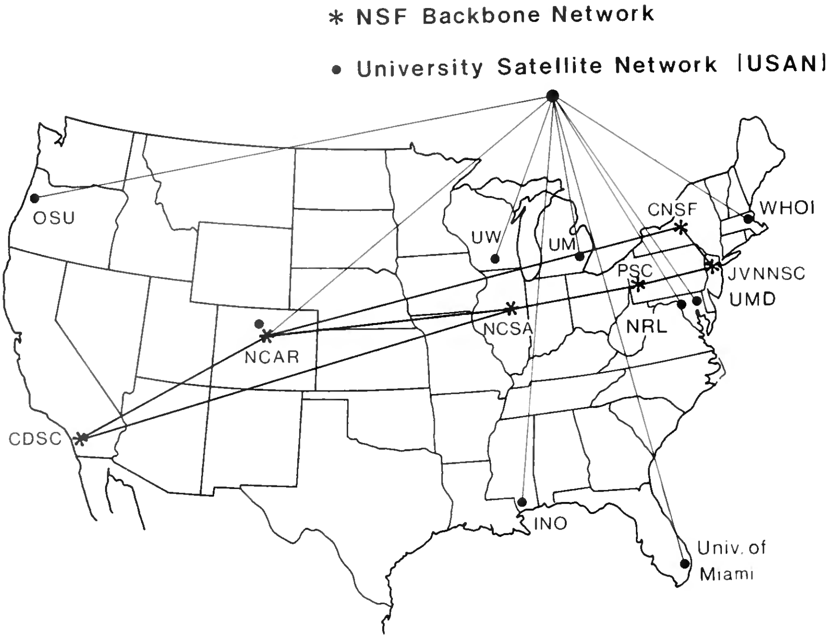

Figure 2. The National Science Foundation computer network backbone, and The University Satellite Network. CNSF, Cornell National Supercomputer Facility; JVNNS, John von Neumann National Supercomputer Facility; NCAR, National Center for Atmospheric Research; NCSA, National Center for Supercomputing Applications; PSC, Pittsburgh Supercomputer Center; SDSC, San Diego Supercomputer Center; OSU, Oregon State University; UW, University of Wisconsin; UM, University of Michigan; NRL, National Research Laboratories.

researchers' use. This powerful resource will enable INO to make good use of historical ocean dynamics data files, to develop and test numerical models, and to integrate in situ and remotely-sensed data relayed by satellite into those models. The Institute will link cooperating academic researchers by national scientific data networks to the supercomputer (Figure 2).

Captain James E. Koehr is the Commander of the Naval Oceanography Command (CNOC), also located at NSTL. The mission of his command is to provide the Navy fleet with operational oceanographic, meteorological, mapping, charting and geodesy services, and he tells why his command is making the supercomputer available to INO: "We're interested in how acoustic energy behaves in the world's oceans. The behavior of acoustics is directly related to temperature, salinity, and depth—quantities we can measure—and hopefully forecast. We need INO to build models that will allow us to forecast the state of the ocean for periods of time, from 24 hours to 14 days, which I believe is a realistic goal."

Because of INO's strong connections to the Navy, director Mooers and his staff see the Institute as a focusing influence among academic ocean modelers doing prediction research. University researchers working with INO in its Cooperative Ocean Modeling and Prediction (COMP) program have participated in such research efforts as the Mid-Ocean Dynamics Experiment (*Oceanus* Vol. 19, No. 3, page 45), the development of acoustic tomography (*Oceanus* Vol. 25, No. 2, page 12), and the Marginal Ice Zone Experiment (*Oceanus* Vol. 29, No. 1, page 66). Mooers sees many roles for the university community in INO's program. "University faculty, post-docs, and graduate students spend various amounts of time here as visiting scientists. We expect to develop graduate traineeships, and have already had an experimental summer internship program for undergraduates."

According to William J. Schmitz, physical oceanographer at the Woods Hole Oceanographic Institution (WHOI) and acting director of INO during its one-year operation as a Navy adjunct, the Navy was always interested in finding an organizational format for the Institute that would attract the relatively small community of ocean modelers. "It's pretty hard to attract academically-oriented oceanographers into the civil service, so part of INO's work will be conducted outside of INO. The people who ordinarily develop these models work at places like NCAR (the National Center for Atmospheric Research), Woods Hole, and MIT." For example, Schmitz retained his position at WHOI while serving as interim director. Hence, one of the roles of the Institute is to provide a vehicle for involving the academic community in ocean prediction research for the Navy. Today, scientists like Schmitz perform INO-sponsored research at their home institutions and during visits to the Institute.

Robert C. Willems, coordinator of the COMP program concurs: "We recognize the wealth of talent in the academic community, and we recognize that there are a number of on-going efforts that feed directly to INO's goal. We're a university-based organization anyway, and we see ourselves as being able to marshal that academic talent and bring it to bear on INO's objectives."

Data Assimilated Into Nested Domains

The Institute's strategy in developing ocean-prediction models is to organize them into a hierarchy of "nested domains." For example, the South Atlantic Bight is a coastal domain nested in the Gulf Stream—a regional domain. The Gulf Stream is itself nested in the basin-scale domain of the North Atlantic Ocean, which is in turn nested in the global domain. The larger domains provide boundary conditions, such as current and temperature fields, for the smaller domains they encompass—the way historical, climatological data provide a baseline of long-term variability for meteorological, weather-prediction models. As INO begins its work, it will also concentrate on the coastal areas of northern California, Straits of Gibraltar, and the East China Sea.

Michele Rienecker, an INO scientist, has participated in the OPTOMA (Ocean Prediction Through Observation, Modeling and Analysis) program in the California Current System, and concentrates much of her effort in developing and testing data-assimilation models. Two examples of data assimilation processes are: 1) providing a prediction model with its initial conditions, which might be relayed from data buoys by satellite, and 2) feeding updated information to the model. Figure 3 shows how model-produced fields may converge or diverge depending on the data assimilation strategy used.

Rienecker believes that one of the challenges of ocean prediction is to determine what is the most relevant information in the available data. "We don't know if we acquire too much data. We'll be tackling that problem, to see how much data we really need, and the answer will probably be domain-dependent," with highly variable regions such as the coastal ocean requiring tighter data-acquisition grids than the more static areas, such as the Sargasso Sea.

Ocean variability occurs on smaller scales than important atmospheric instabilities such as hurricanes. So on a global basis, data acquisition for ocean prediction is far more demanding than for weather forecasting, according to Rienecker. She says that, particularly over land, the meteorological observing system gives a much higher density of coverage than any permanent oceanographic observing system now in place. "Over the ocean, clouds are part of the meteorological information; for us, the clouds cover up the information, and cloud-masking is a big problem with AVHRR data (Advanced Very High Resolution Radiometer, giving sea-surface temperature, see *Oceanus* Vol. 29, No. 4, back cover)."

While the challenge to develop an operational oceanographic observing system is important to INO researchers, making the best use of such a system is their main concern. To ensure that they will be ready for the data when it is available, some INO scientists numerically simulate

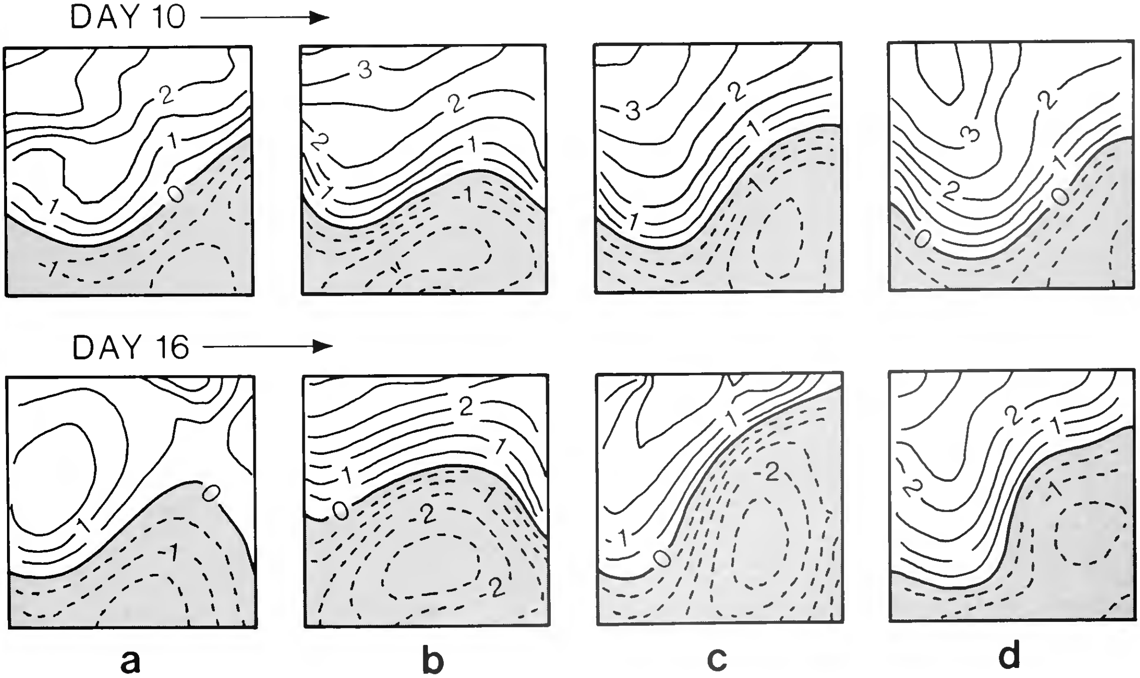

Figure 3. Model streamfunctions (current strength indicated by closeness of contours) at 50 meters, initialized at day 0: a) Statistical forecast, b) Dynamical forecast using persistent boundary data, c) Dynamical forecast using statistically forecast boundary data, d) Dynamical forecast using statistically forecast boundary data, with assimilation of synoptic data. (Figure courtesy M. Reinecker)

ocean processes. One such study at the Institute is being carried out by David Adamec, who says, "The expense of ocean observations necessarily limits the resolution of those observations, and this can lead to ambiguous interpretations of the data. One major benefit of process models is a clear definition of simulated circulation dynamics, which in the best of circumstances, may help to explain some of the observed variability in the ocean."

Adamec is currently testing the capability of an ocean model that is driven by observed winds to reproduce the long-term variability associated with the Gulf Stream. Part of that study includes experiments to determine the effect of the tall and relatively thin New England Seamounts on the Gulf Stream (Figure 4). He says that the Gulf Stream shows a maximum of time-variability, or eddy energy, in the vicinity of the seamounts. "The question is whether or not the seamounts are responsible for any of that variability." By comparing simulations using different topographies, Adamec hopes to provide a clear interpretation of the effect of the seamounts on the flow. But he admits, "The real test of the simulations comes when adequate data becomes available for validation."

Crucial Ocean Observing Systems

Regardless of when operational ocean prediction models have enough "real" data to drive them, the "number one" oceanographic support problem to be solved by the Navy between now and then, according to Captain Koehr, is to estimate deep ocean conditions from surface conditions or instruments floating on the surface. Beyond depths of a few meters, the sea is opaque to electromagnetic radiation, so information from great depths must be relayed to the surface either acoustically or by wires. From the surface, data can be transmitted by radio to satellites, aircraft, or nearby ships.

Satellite remote sensing of ocean variables such as waves, surface temperature, near-surface ice coverage, and winds has been shown to be a very promising regular source for large amounts of global data. This technology may be critical to useful ocean prediction. To make full use of these data, it is essential to have a comprehensive understanding of the processes that determine variations in these quantities. It also is necessary to underpin these remotely-sensed observations with some in situ observations of both surface and subsurface ocean variables. Sources of in situ observations include routine reports from ships, and moored or drifting buoys.

The National Data Buoy Center (NDBC) is also headquartered at NSTL, and is part of the National Oceanic and Atmospheric Administration (NOAA). As a government agency, NDBC has no direct link to INO; but it is the best-equipped organization for obtaining and making available operational data of continuing interest to INO, so directors of both the Institute and the Center are expecting to forge collegial links from time to time. Director Mooers says that NDBC's moored and drifting buoys "would probably be part of any complete operational ocean observing system. We will inevitably use the NDBC data streams (Figure 5) extensively." Jerry C. McCall, director of NDBC, agrees, saying that NDBC should be able to handle any task INO would put to it. "We presume that they will want the kind of ocean measurements that we can do more efficiently than anyone else. We have automated moored buoys, and we have drifting buoys that are automated and air-deployable. If they want a global layout, we can do that too."

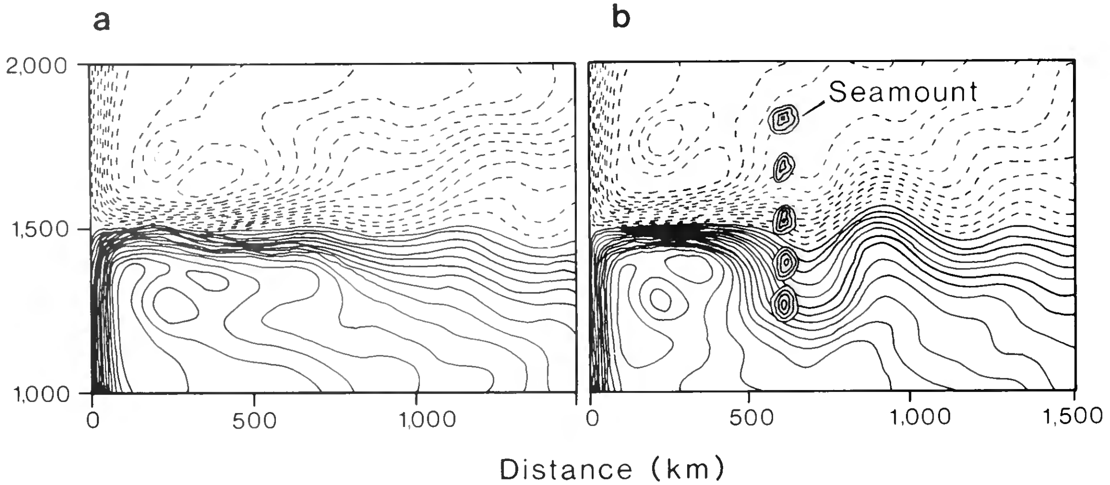

Figure 4. Simulated flow fields over a) a perfectly flat bottom, and b) a bottom with seamounts. Fields are 5-year averages over "small-scale topography." (Figure courtesy D. Adamec)

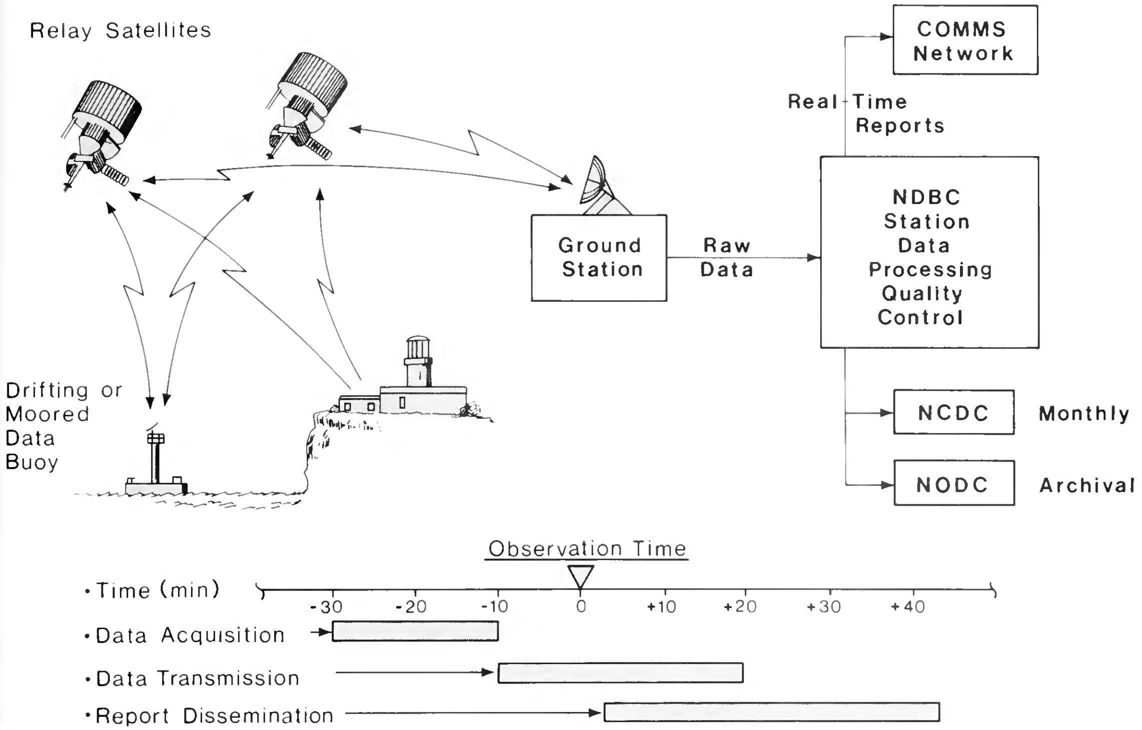

Figure 5. Data flow and processing from a National Data Buoy Center data buoy. Acronyms are: NCDC, National Climatic Data Center; and NODC, National Oceanographic Data Center. COMMS (Communications) network information is made available to the National Weather Service. (Figure courtesy NDBC)

The type of cooperative agreements that McCall expects to enter into with INO are typical of the way INO approaches its mission. The Institute keeps its focus on ocean modeling and prediction, and deals with the other scientific and engineering specialities pertinent to its goals on a contract basis as necessary.

Acoustic tomography (AT) is an oceanographic technique that uses two separate SONAR arrays—one of transmitters and one of receivers—to indirectly measure temperature and salinity gradients across thousands of square kilometers of ocean, to depths of hundreds of meters. Reciprocal-transmission acoustic tomography (RTAT) uses a single array of combined transmitter/receivers, or transceivers, all synchronized by an atomic clock. Ching-Sang Chiu is an INO researcher working to incorporate data from both AT and RTAT, as well as satellite and point sensor arrays, into ocean prediction models. Chiu says that in addition to the standard information extracted from AT, the difference in the travel times of RTAT reciprocal rays can be analyzed to yield current speeds and eddy patterns in the experimental area.

Since RTAT transceivers can have floating radio transmitters tethered to them, they could relay their data via satellite and help enormously in obtaining an image of ocean conditions as they occur, in so-called "real time." Chiu, a former WHOI researcher, has been working in the research program of an upcoming collaborative year-long RTAT experiment in the Greenland Sea, which is to be jointly carried out by researchers from WHOI and the Scripps Institution of Oceanography beginning next summer.

Acoustic tomography is part of an INO activity that the Navy is particularly interested in, the linking of acoustic to dynamic models. Dynamic models represent such things as the movement of currents, and the change of temperature with depth. Acoustic models represent the behavior of sound wave propagation through the sea. Being able to predict how sound waves will travel through variable areas of the ocean is an important part of antisubmarine warfare.

The Supercomputer

The single resource for INO that will bring all the efforts together is the Class VII supercomputer, scheduled for installation at the Naval Oceanography Command in the spring of 1989. Like other supercomputers around the country, the one at NSTL will be nested into a hierarchy of networks, allowing both the INO core and COMP researchers access to a "model library," and meteorological and oceanographic databases. The supercomputer will be available to users at NSTL via a local-area network, and linked via the University Satellite Network to NSFnet, the National Science Foundation's data communications network. The Space Physics Analysis Network (SPAN), one of

NASA's computer networks, will also be linked to the new supercomputer at NSTL.

In advance of the supercomputer installation, Monty Peffley, INO's Computer Services Manager, will be coordinating the installation of an efficient data communications systems for the Class VII, to ensure that INO's model library, and oceanographic and meteorological databases, can be used to their best advantage. He says these systems will "enhance the capability of geographically separated researchers to interact productively with INO."

Ocean modelers will be especially dependent on the auxiliary computers to intelligibly display the results of a model's orchestration of various types of data, according to Peffley. Animation graphics are important tools to aid the interpretation of the enormous quantity of model output, as well as various data streams.

A National Center for Ocean Prediction

The geographic separation among INO researchers is considerable. Presently there is only a handful of full-time core scientific staff working at the NSTL site, while more than 30 scientists are doing INO-sponsored research at their home institutions, as members of the COMP program. The program operates as a research funding administration, based on peer-reviewed, unsolicited proposals appropriate to INO's mission. By funding research proposals coming from academic centers, NCAR, and naval laboratories, the COMP program brings talent to INO that might otherwise be unavailable. As COMP coordinator Willems explains, "We're pulling in some of the talent we don't have in our core scientific effort. One area that I cite is adaptive gridding. The atmospheric community has been doing adaptive gridding for some time now. We in the ocean community have yet to pick up on that capability. An "adaptive grid" is a data acquisition grid that automatically shrinks when a higher density of data-collection points is required. Program participants also have the opportunity to take part in INO's visiting scientist program, and the ongoing series of seminars and workshops sponsored by the Institute.

"COMP operates much like the NASA announcement-of-opportunity program, in the sense of how we're specifying what our interests are," says Willems. "It receives proposals which undergo peer-review by panel." Members of the peer panel are of recognized scientific leadership, not professionally associated with INO, and serve terms of two to five years. The panel reviews proposals on the basis of the researcher's ability to carry out the proposed work, the scientific merit of the proposed work, and the applicability of the proposed work to INO's mission. The COMP researchers are also expected to interact with the Institute and otherwise assist with its development. With the same mission as the core scientific effort, director Mooers is expecting that the COMP program will consume almost as much of INO's budget as the core effort. Mooers sees the success of the COMP program as crucial to INO's overall success, since for the foreseeable future the scientific expertise relevant to INO's mission will be at a premium.

INO is also a center for workshops, drawing other ocean or atmospheric modelers to the Institute for a day or two of highly specialized communication. Willems is also in charge of organizing these symposia. "We will be running a workshop in January, called 'Atmospheric Forcing of Ocean Circulation.' We'll be doing this jointly with WOCE and TOGA (the World Ocean Circulation Experiment and the Tropical Ocean Global Atmosphere program, *Oceanus* Vol. 29, No. 4, page 25)."

Hindcasts and Forecasts

Once the prediction systems are operational, few areas of ocean technology will be able to ignore them. Mooers says, for example, that ocean models could be used by mechanical engineers in the design of offshore structures. The engineers could model maximum stresses due to ocean currents on their (modeled) structure, and improve the structure design if necessary to avoid catastrophic failure during events such as hurricanes.

Forward in time is not the only direction ocean models need to aim. These models could also produce a "hindcast," and give valuable information, as Mooers points out. "A hindcast could be very important for assessing causes of environmental damage. A good example is a fish kill; environmentalists might say, 'It's due to the polluters.' And the polluters might say, 'It's a natural occurrence.' What you really need to do in many cases is to go back and produce a hindcast and see, within the limits of our knowledge and data, if all but one possibility can be ruled out." The source of a dispersed plume of pollution could be more accurately traced, and navigation through the ocean's "internal weather" could be improved once INO's hindcasts and forecasts become generally available.

Those scientists and students interested in learning more about INO are directed to:

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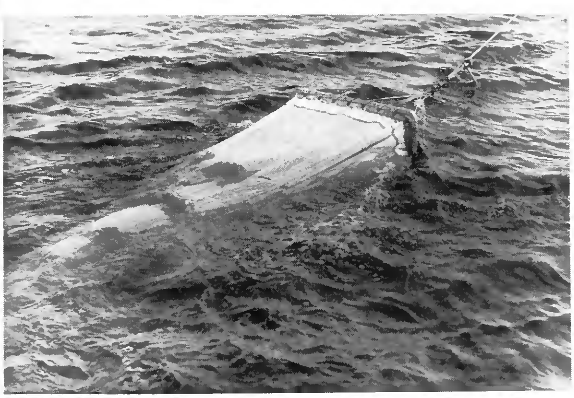
Plastic in the North Atlantic

"I just want to say one word to you—just one word."
"Yes sir."
"Are you listening?"
"Yes sir, I am."
"Plastics."
"Exactly how do you mean?"
"There's a great future in plastics. . ."

Mr. McGuire to Ben
The Graduate, 1969

R/V Westward

by R. Jude Wilber



Neuston Net

The problem of plastic debris in the marine environment is cause for increasing concern today among the public at large. During the last 20 years, the North Atlantic and other oceans have been polluted with plastic debris through careless handling, accidental loss, and indifferent dumping. Although many of the biological effects of plastic in the ocean are unassessed, the negative effects of this debris on seals, birds, and sea turtles are well documented. Strangulation is often the result of seals and birds trapped in plastic netting. But, marine animals also ingest small plastic pellets. The damage done to certain marine communities from this activity may be serious, although the proof of this awaits further study.

Actually, there may be some positive aspects to the presence of floating plastic in the open ocean. Epifauna, such as *Membranipora* (a bryozoan—a small group of colonial encrusting animals) and *Lepas* (a barnacle), may use plastic as an "alternative substrate." These animals are commonly found on organic flotsam, such as wood and *Sargassum*. The use of plastic as a substrate by such organisms is at present a noticeable, though relatively rare, phenomenon in the open ocean.

It is virtually impossible to tow a neuston* net through the surface waters of the Sargasso Sea and not catch plastic debris of some sort.

One of the most common items so sampled are small (1 to 5 millimeters) polyethelene pellets known as "nibs" to the plastics industry. Typical beaches in places such as Bermuda, the Bahamas, the Florida Keys, and Cape Cod may contain millions of such pellets mixed with other plastic debris and natural organic flotsam in the upper wrack lines.**

This picture of the current status of plastic in the Atlantic has emerged during the last three years in part from studies conducted by the scientists and students of the Sea Education Association, Woods Hole, Massachusetts, aboard the research vessel *Westward*. In 1984, we began a survey of plastic pollution along *Westward's* routes of operation in the open ocean and along the shorelines of islands

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** Neuston refers to both the uppermost surface layer of a body of water as well as that group of organisms that occupy this environment. Neuston nets are designed to sample the air/water interface and down to 25 centimeters below it.*
***Wrack refers to marine plant life that is cast up on shores through the action of waves and tides. The uppermost wrack lines are those lines of debris deposited by very high tides and/or storm waves.*

visited during cruises. Begun as a broad qualitative effort, the ongoing study has evolved into a quantitative survey aimed at assessing the amount of plastic in the western North Atlantic. We are also attempting to determine the pathways of plastic pollution in this region.

Survey Methods

Thus far, the survey has consisted of two parts—open ocean neuston tows and beach sampling. While traversing 35,000 nautical miles, we made more than 420 tows using a 1 × .5 meter neuston net with a 333 or 500 micron (one millionth of a meter) mesh opening. With a standard tow length of one nautical mile, the area sampled by each tow was approximately 1,850 square meters. Plastic from the tows was quantified by counting individual pieces regardless of size. Because of their apparent utility as tracers, we counted pellets as a subset of the total.

More than 150 beach surveys gave us an estimate of the amount and type of plastic found and number of pellets present. Beach surveys were conducted on Bermuda, the Bahamas, the Lesser Antilles, the Florida Keys, and Cape Cod. We found that pellets, along with other plastic items, are most often found in a "high-concentration zone" near the uppermost wrack lines. This zone varies in width from 10 centimeters to 3 meters, but is usually 50 centimeters to 1 meter wide. Within this zone we sampled 30 × 30 centimeter quadrants and counted the pellets (Figure 1).

Pellets as Tracers

It is a common misconception that pellets are fragments of larger pieces of plastic. Fragmentation of plastic debris in the marine environment does indeed occur, but pellets are *not* the result. Rather, pellets are the raw material from which larger molded plastic items are made. They are produced in their characteristic size and shape to facilitate transport and handling. In pellet form, plastic can be treated like other bulk cargoes, such as grains or soybeans. Although pellets are made in a variety of shapes, they are most commonly imperfect spheres, flattened disks, or short, cylindrical bits. Most are 2 to 5 millimeters in diameter and either colorless, white or amber (Figure 2).

Of all the different types of plastic, pellets have a number of characteristics which render them useful as tracers for the pathways of plastic in the ocean. First, their relatively uniform appearance makes them easy to identify and quantify. Second, they are quite buoyant, rising 10 centimeters per second in seawater, and are therefore consistently found in the neuston layer and on the uppermost beach face. Third, their composition and compact shape make them resistant to fragmentation during weathering. Prolonged exposure in marine waters will result in checked and brittle pellet surfaces. This condition can be used as an indication of how long a pellet has been adrift. Finally, pellets are ubiquitous, and their overall distribution tends to parallel that of plastic debris in general.

Survey Results

The areas sampled by the crew of *Westward* are shown in Figure 3. The results of the ocean survey are summarized in Table 1 and Figure 4. The beach survey data are summarized in Table 2.

The open ocean results illustrate two important points. First, plastic is present throughout the western North Atlantic ocean. More than two-thirds (68 percent) of all tows sampled plastic and nearly one third (28 percent) sampled pellets. Second, obvious regional differences in both the amount and type of plastic exist.

The highest concentrations of all pieces, as well as pellets, occur in the northern Sargasso Sea (28 to 40 degrees North). In this area *all* tows

Figure 1. Plastic debris from Bermudan beach. Photo shows weathered and tarred fragments typical of beaches on that island.

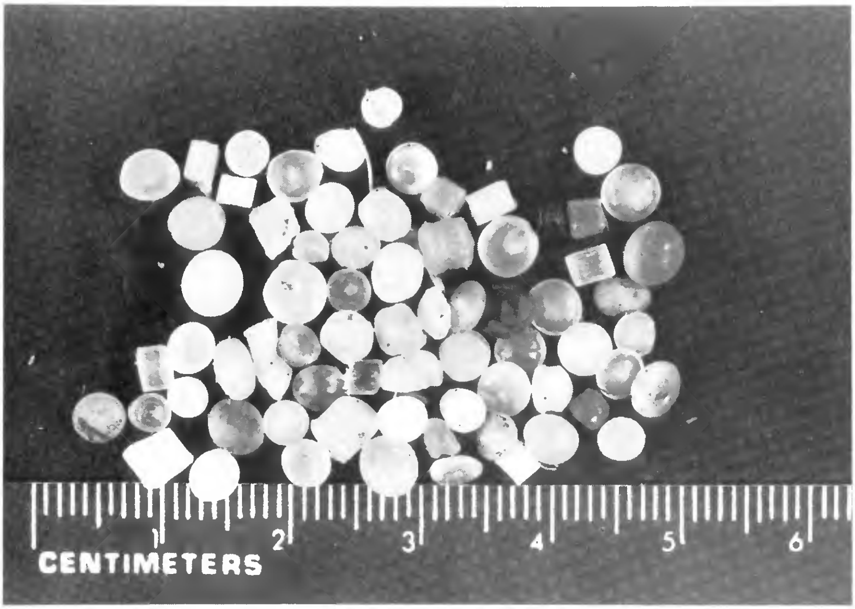


Figure 2. Polyethelene pellets or "nibs." Shown here are pellets typical of the beaches on Cape Cod, Massachusetts.

sampled plastic and more than 75 percent caught pellets. The tows we made in this area indicate that there are more than 10,000 plastic pieces and 1,500 pellets per square kilometer of surface water. The amount of plastic found in all other areas is substantially less, ranging from 2,500 pieces (approximately 360 pellets) per square kilometer in the southern Sargasso Sea to 700 pieces (approximately 80 pellets) per square kilometer in areas north of the Gulf Stream.

In addition to differences in the amount of plastic present, there are important differences in the types of plastics sampled and the degree of weathering shown by individual pieces. In the northern Sargasso Sea, most of the plastic sampled was conspicuously weathered. More than 80 percent of the pellets sampled in this region show evidence of prolonged exposure in the surface waters. By contrast, most of the plastics from the shelf and slope waters north of the Gulf Stream were relatively fresh items of litter or fishing gear that had apparently spent far less time adrift.

The results of the beach surveys (Table 2) confirm the presence of oceanically-derived plastic at numerous sites adjacent to the north Atlantic system. For some areas, such as Cape Cod and the Florida Keys, fresh items of trash and lost gear from recreational and fishing boats operating close to shore account for much of the plastic found. However, even remote island sites far removed from any significant local sources are heavily littered with plastic. Nowhere is this more clearly shown than along the shores of Bermuda and the Bahamas. We recovered a variety of plastic types on all beaches sampled from these islands, and pellets in particular occur in very high concentrations. For example, we found more than 2,000 pellets per square meter on these beaches. Most of the plastic at these sites is noticeably weathered, indicating long exposure in marine waters before it was stranded.

Table 2. Synopsis of beach surveys from four island groups and Cape Cod. Types of plastic listed are those types most frequently found at the sample sites. The ranges of pellet concentrations listed encompass typical values measured at the sites.

Area (# Sites)	Type of Plastic	Pellets per M^2
Bermuda (20)	Weathered fragments Weathered pellets	$.2–1 \times 10^4$
Bahamas (50)	Weathered fragments Weathered pellets	Windward $.5–1 \times 10^3$ Leeward $2–5 \times 10^2$
Antilles (25)	Weathered fragments Weathered pellets	Windward $1–5 \times 10^2$ Leeward $.5–1 \times 10^2$
Florida Keys (60)	Fresh whole pieces Fishing Gear Fresh & weathered pellets, fragments	$.1–1 \times 10^3$
Cape Cod (20)	Fresh whole pieces Fishing gear Fresh pellets and fragments	$.1–1 \times 10^3$

Table 1. Synopsis of plastic data collected from *R/V Westward* for four major oceanic areas.

Oceanic Region	# Tows	# Tows with Plastic	% Tows with Plastic	Pieces per Km^2	# Tows with Pellets	% Tows with Pellets	Pellets per Km^2
Northern Sargasso Sea (B)	78	78	100	1.1×10^4	59	76	1.7×10^3
Southern Sargasso Sea (C)	127	85	67	2.5×10^3	35	28	3.6×10^2
Caribbean (D)	154	93	60	1.4×10^3	21	14	1.5×10^2
Shelf & Slope Water (A)	72	36	50	7.0×10^2	6	8	7.7×10^1
Total/Mean	431	292	68	2.1×10^3	121	28	4.9×10^2

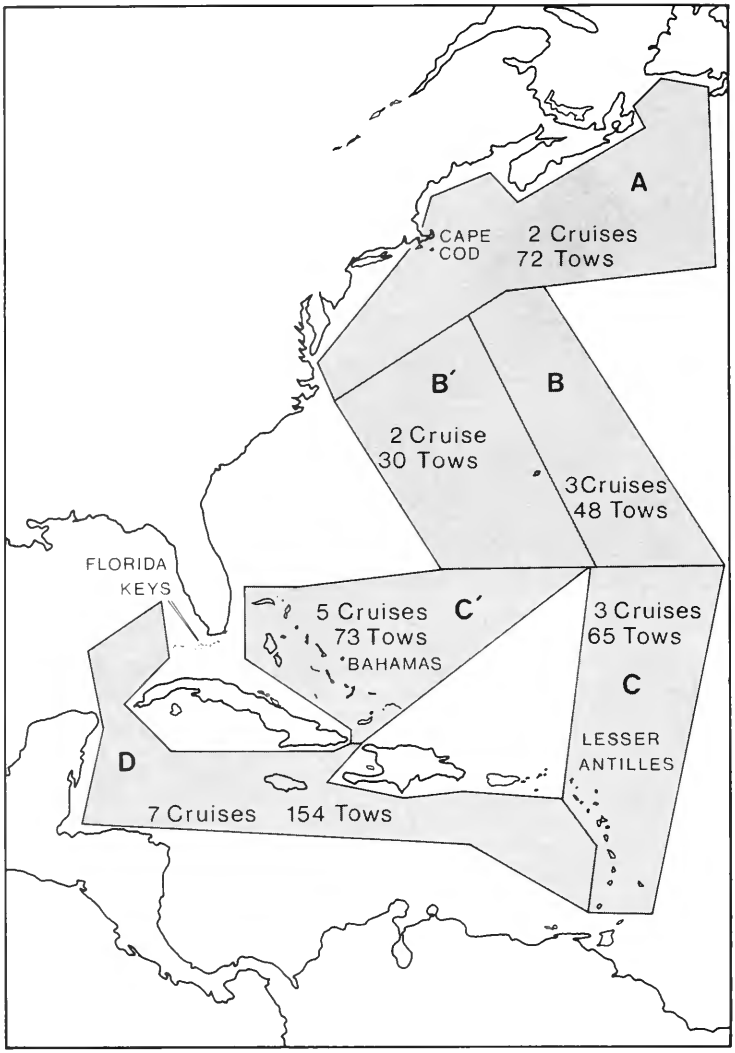


Figure 3. Tow envelopes for the open ocean survey data. Boundaries indicate areas sampled from Westward *between fall, 1984, and summer, 1987. In this article area A is referred to as the slope and shelf waters north of the Gulf Stream. Areas B and B′ are the northern Sargasso Sea. Areas C and C′ are the southern Sargasso Sea and area D is the Caribbean. Island groups sampled for plastic are labeled.*

Surface Currents and Plastic

The plastic distributions reported in this survey suggest that plastic moves through the oceanic system in a predictable pattern. The pattern is related in large part to the motion of surface waters in open ocean areas.

The net recirculation pattern of the western North Atlantic is well known (Figure 5), and water motion on at least three different scales may affect the drift path of a piece of flotsam such as plastic. The largest of these motions is the clockwise circulation pattern known as the central gyre. Most of the western North Atlantic is dominated by this pattern, which is centered north of the island of Bermuda. In addition to net clockwise flow, the gyre is characterized by a slow steady drift of surface water into a broad central area between 28 and 40 degrees North latitude. Nearly 80 percent of the surface water may be routed through this region during a single circulation cycle that can happen during a period of a few months to a few years.

Within this larger area, the distribution of flotsam may be controlled on the "mesoscale" by rotating oceanic features known as rings or eddies (see *Oceanus* Vol. 19, No. 3, Spring 1976). These features may be thought of as relatively small gyres (less than 100 kilometers across), whose meandering paths are constantly traversing the larger gyre and stirring its contents. Finally, on the smallest of the three scales, the effect of the wind over the ocean surface sets up small (10s of meters) circulation patterns known as Langmuir cells, which cause flotsam to be concentrated in long linear features known as windrows.

The pathway of a plastic item in the North Atlantic and where it may ultimately be found is thus related to where, in relation to the gyre, it enters the marine environment. Plastic sources can be viewed as either *extra*-gyral or *intra*-gyral. Extra-gyral input includes plastic from terrestrial sources as well as from commercial and recreational vessels operating in shelf and coastal waters.

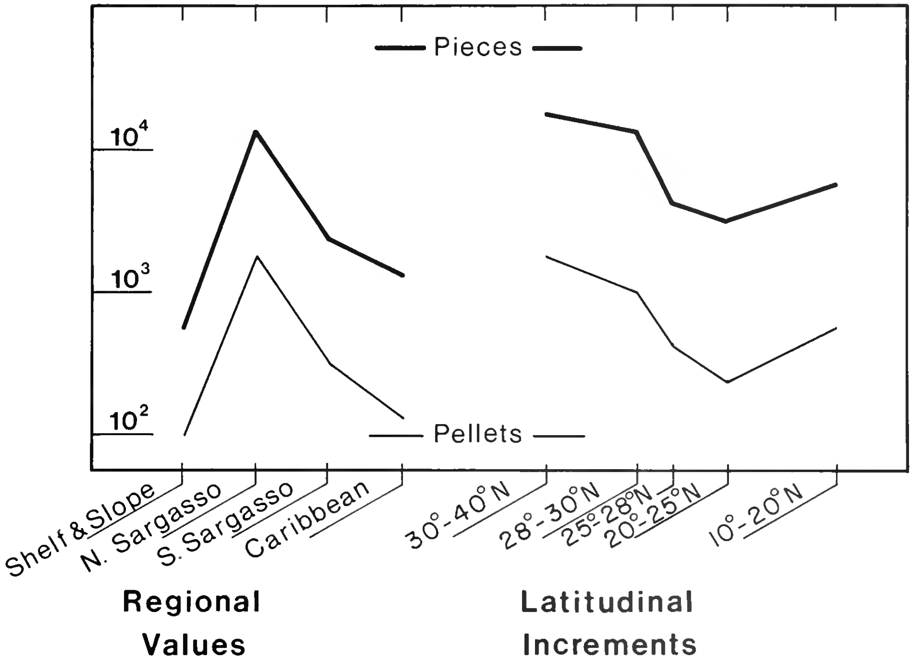


Figure 4. Plastic concentrations in open ocean areas. Upper line in both plots is total pieces per square kilometer. Lower line is pellets per square kilometer. Vertical scale is logarithmic for both plots. The data show highest concentrations of both total pieces as well as pellets in the central gyre, particularly the northern part.

The most common types of plastic dumped in near-shore waters are litter items such as bags, cups, and various disposable plastic containers. In addition, most of the pellets apparently enter the marine system from spillage and loss at coastal manufacturing and shipping sites. Intra-gyral inputs are *solely* from vessels operating within the mid-oceanic system. Most plastic introduced within the gyre comes from indiscriminate dumping of trash, a common practice on most commercial vessels operating in the open ocean.

Extra-gyral plastics may either be removed from the marine system without entering the gyre, or they may become entrained in this circulation pattern. Intra-gyral plastics may be trapped for many cycles of the recirculating water. Data from our oceanic survey suggest that plastic from both intra- and extra-gyral sources becomes concentrated in the center of the gyre, in much the same fashion that *Sargassum* does. Pellets in particular, with no known intra-gyral sources, are concentrated in the northern part of this region.

Removal from Surface Water

Plastic debris does not remain in surface waters forever. Eventually it is "removed" in one of three ways. One way is for individual articles to photochemically degrade, losing their plastic qualities, and become increasingly brittle and fragmented. Thin, sheet-like plastics (films, bags, and others), are most susceptible to this breakdown process. Thicker, or more compact, plastic items are less susceptible to removal through degradation. Such articles may remain as discrete items for years or perhaps tens of years of exposure.

Plastic may also sink from surface waters. Changes in the buoyancy of plastic may occur compositionally during degradation or because of the encrustation of epifaunal organisms, such as hydroids, barnacles, and bryozoans. The significance of sinking as a removal mechanism from the surface remains largely unassessed.

Neither sinking nor minute fragmentation truly removes plastic from the marine environment. In the third removal mechanism, however, a plastic item resists breakdown and does not sink. It is then quite probable that it will eventually be removed from the ocean by stranding on some shore.

Plastic on the Beaches

Popular sources of information on plastic pollution in the marine environment are largely based on studies at sites of removal—in other words, littered beaches. Reports from beaches around the world show that oceanically-derived plastic is common on the global scale. Different beaches, however, are littered for different reasons. The beaches of Bermuda and the Bahamas are heavily littered by plastic delivered from the large supply contained in the gyre. These islands act as "sieves"—continually "straining" plastic debris from the surface waters of the Atlantic. Bermuda, in the heart of the gyre, possesses the highest concentrations of weathered debris removed from adjacent waters (Table 2). But it is the Bahamas, with its hundreds of islands embedded in the gyre's flow, where the analogy of a "plastic filter" most truly holds. These islands have hundreds of kilometers of sandy shoreline that are constantly supplied with plastic from the ocean. Some of these beaches have pellet concentrations as high as those found on Bermuda, and all the beaches we examined had plastic of some type.

Other island groups, such as the Antilles and Florida Keys, also act to a certain extent as sieves for the gyre, although the rocky volcanic islands of the Antilles have relatively few beaches and thus do not accumulate plastic as effectively as the low sandy

Figure 5. Circulation diagram for upper waters of the North Atlantic. Units are in millions of cubic meters of water. Stream lines are five million cubic meters each. Heavy flow lines define the Gulf Stream and the northern boundary of the gyre. Dashed line indicates boundary between northern and southern Sargasso Sea as used in this article. (Figure redrawn from Worthington, 1976).

cays of the Bahamas. On the other hand, the Florida Keys, because of their proximity to the Gulf Stream, catch oceanic plastic when this main current of the gyre meanders close to their shores.

Other shores along the main flow of the gyre also act as removal sites. The Padre Island coast of Texas is a known site of accumulation of oceanically-derived litter. In addition, the east-facing Mosquito Coast of Nicaragua and the Yucatan Peninsula of Mexico are also likely areas of plastic buildup. These western Caribbean shores are located to the west and downwind of the Caribbean Current, the main flow of water out of the Caribbean Sea. This relationship is similar to that of the Florida Keys with respect to the Gulf Stream, and these areas may be major removal sites for plastic in the Caribbean segment of the gyre's flow.

Alternatively, the beaches of Cape Cod, which are well away and "upstream" from the gyre's plastic load, are inundated with numerous plastics from local sources. Although these beaches contain many pellets, most of these are fresh—indicating that they have not cycled through the central gyre.

The common occurrence of oceanically-derived plastic at sites far removed from sources indicate that, eventually, much of the plastic present in the marine environment may be stranded on beaches. As long as the delivery mechanisms operate (the surface currents and eddies of the gyre), plastic will be steadily delivered to the "island sieves" of the western North Atlantic.

Plastic in the Ocean: An Increasing Presence

It has been nearly 15 years since reports by E. J. Carpenter and K. L. Smith of the Woods Hole Oceanographic Institution, and John Colton and associates of the National Marine Fisheries Service established the widespread occurrence of plastic debris in the surface waters of the western North Atlantic. Using neuston nets similar to those used on *Westward*, early studies reported total pieces of plastic as well as the number of pellets present in some of the same areas sampled in our survey. In the first report, Carpenter and Smith predicted that "increasing production of plastic, combined with present waste-disposal practices, will undoubtedly lead to increases in the concentration of these particles (in oceanic surface waters)." Has this prediction been proven correct? By comparing the results of our study with earlier reports, we find a four-fold increase in the total number of plastic pieces in the northern Sargasso Sea. The number of pellets in this same region has increased nearly two-fold. A similar two-fold increase in pellets is indicated for the southern Sargasso Sea and the Caribbean (Figure 6).

The increase in the number of pieces of plastic in the northern Sargasso Sea may be the result of both increased inputs to the oceanic system and the concentrating effect of the gyre. In addition, the continuing fragmentation of plastic debris, as it cycles in this region also may be contributing to this increase. The pellets, which resist fragmentation, increased in number in all areas since the time of the first reports. Their concentration may be the clearest marker of the build-up of plastic in the North Atlantic during the last 15 years.

Laws and Action

The presence of plastic in the ocean is a global concern. Survey results from other areas suggest that the picture of plastic pollution for the western North Atlantic presented in this article is generally applicable to other oceans—each with a central gyre.

Public awareness of plastic pollution in the oceans has been heightened in the last two years by numerous reports in the popular press.

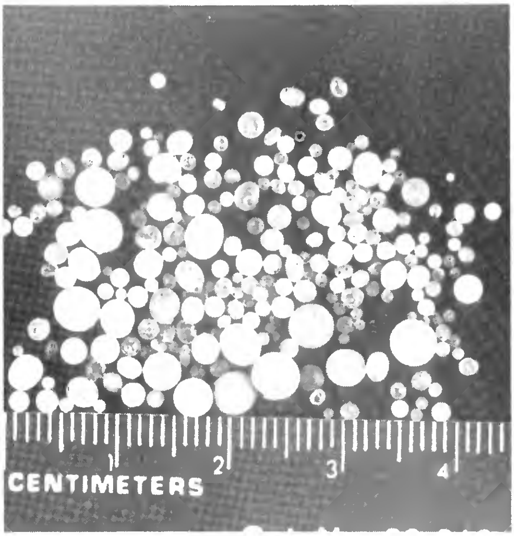
The Case of the Polystyrene Spherules

In addition to polyethelene pellets, another very common form of raw plastic in the nearshore waters of the northeastern United States is also one of the smallest, most durable, and least likely to be noticed. Tiny spheres, or spherules (.1 to 3 millimeters in diameter) of polystyrene were the most abundant plastic items sampled in two studies conducted in the shelf waters of the Mid-Atlantic and New England areas during 1971 and 1972.

The spherules, when mixed with a foaming agent, become the expanded, puffy balls that are the basic structural unit of all "styrofoam" products. White or colorless, the spherules (also known as suspension beads) were found in concentrations up to 8,000 per square kilometer in the shelf waters between Delaware and Massachusetts but were rarely found in open ocean areas.

Where are they today? Many have almost certainly been deposited in bottom sediments throughout the area. Pure polystyrene is very nearly the same density as the low salinity water of near-shore areas, and spherules sink more rapidly than the lower-density polyethelene pellets. Spherules are known to occur in the bottom sediments from a number of inshore sites along the coast of New England; both spherules and fragments of pure polystyrene are found in bottom sediments in British estuaries.

However, not all spherules readily sink. Many contain gas vacuoles (air bubbles), which increase the buoyancy of individual spherules thereby decreasing their sinking rate. In the generally well-mixed waters of the shelf, such "flawed" spherules may stay in suspension far longer than pure polystyrene. In fact, many of these spherules have ended up in very high concentration along the beaches of New England. All Cape Cod beaches sampled in 1987 were littered with polystyrene spherules, most of which contained numerous vacuoles. Because of their size and color, spherules are virtually impossible to detect against a background of rounded quartz sand grains. The separation of spherules from beach sand requires a time-consuming technique involving both flotation-separation and sieving. Perhaps typical of the New England beaches is a sample taken from Martha's Vineyard. We sampled a 10 × 30 centimeter quadrat, and rigorously processed it to recover polystyrene. The sample yielded a concentration of 16,000 spherules per square meter for the beaches of picturesque Menemsha Harbor, a fishing port on the southwest corner of the island.



Polystyrene spherules from beach on Martha's Vineyard. The spherules are the raw material for "styrofoam" products.

Unlike the more buoyant and more widely-distributed polyethelene pellets—which may spend years in the surface waters and be concentrated by the gyre's flow—spherules are apparently typical of the local input/local output cycling of plastic taking place outside the gyre.

—RJW

Tar and Plastic

A better-known and considerably more offensive pollutant than plastic in the open ocean is tar. Although input mechanisms and degradational processes for tar are different than for plastic, the concentrating and stranding mechanisms are largely the same. Overall distribution of tar parallels that of plastic in the open ocean, with the highest concentration of both being found in the heart of the gyre. It follows then, that the heavily plastic-littered shores of Bermuda and the Bahamas are also heavily tarred—so much so that daily "grooming" of Bermuda's beaches is necessary to maintain the tourist trade.

Interestingly, a beach that is effectively raked free of tar may remain littered with hundreds of thousands of pellets—a fact few recognize. Beachgoers were continually surprised when, upon inquiring of our sampling purpose, they were presented with handfuls of pellets picked from their favorite shores.

continued on page 68

"Plasto-tar crust" from the rocky shore of Bermuda. Crust is composed of tar and plastic from the oceanic waters surrounding Bermuda. Upper surface of crusts are commonly a layer of plastic pellets.

Tar and plastic can combine in both the open ocean and along the shores. "Plasto-tarballs" consisting of a core of pelagic tar embedded with plastic debris are picked up in nets and on beaches.

A particularly nasty combination of tar and plastic is found where oceanic tar that has coated a rocky shore is "armored" on its surface by a layer of plastic pellets. Such crusts, which were initially reported from Bermuda, have been found along many stretches of the rocky shores of the Bahamas.

Bermudan crusts, which may be up to 20 centimeters thick demonstrate a distinct tar/plastic layering. The lower part of the crusts are essentially plastic-free, while the upper surfaces are entirely coated with plastic. Such layering may indicate that the amount of tar delivered to the site has declined relative to the amount of plastic during the time since the introduction of both pollutants to the marine system.

—RJW

Environmentalist groups have called for, and received, legislative proposals to rid the oceans and shores of the plastic problem. How effective will such laws be? What further action is necessary?

In February of 1987, Representative Gerry Studds (D-MA) introduced a bill in the House of Representatives aimed at cleaning coastal waters and shores of plastic. This bill (HR 940) calls for a ban on all plastic disposal within the 200-mile Exclusive Economic Zone (EEZ) of the United States. Such a law, if it could be successfully enforced, may be quite effective for those waters and shores primarily littered by the local input of plastics. This bill may, however, also serve to shift the plastic problem to another area. If, instead of being released in the EEZ, plastic is dumped further offshore (a distinct possibility for ocean-going vessels), the plastic load of the central gyre, as well as the delivery of plastic to remote island shores, would both be increased.

The fifth annex to the International Convention for the Prevention of Pollution from Ships (MARPOL) is an international agreement currently under consideration by the United States Congress. This agreement prohibits "the disposal into the sea of all plastics." Such a sweeping proposal presents numerous enforcement problems, yet it is the only measure that will be truly effective in eliminating plastic from open ocean areas. Should this agreement be enacted by the international community, the oceans would eventually cleanse themselves through the removal mechanisms outlined in this article.

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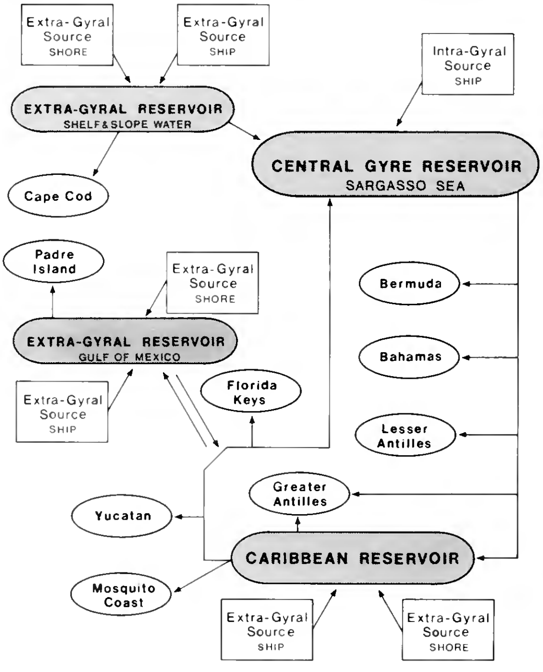


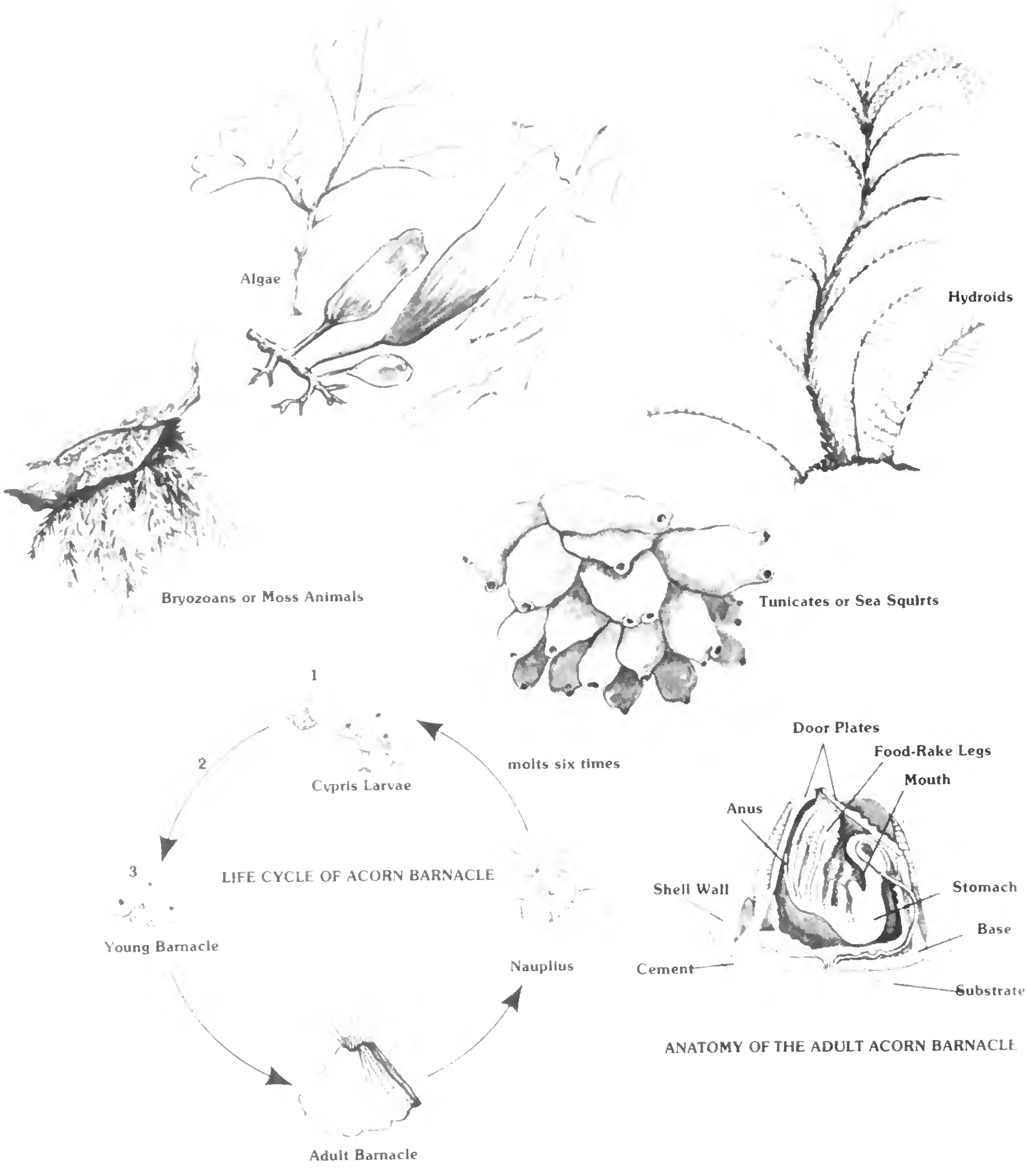
Figure 6. Flow diagram for plastic pollution in the Western North Atlantic Ocean. Sources of plastic are indicated by rectangles. Shaded ovals indicate regional oceanic "reservoirs." Sites of removal discussed in this article are indicated by ellipses. Arrows show possible pathways from sources to sites of removal. The Caribbean is a part of the recirculating gyre but because of its enclosed geography, local input/local removal may be important within this basin. The Gulf of Mexico is also peripheral to the main flow and this area may both contribute plastic to the central gyre via the Gulf Stream as well as receive debris via the Caribbean. The shelf and slope waters adjacent to the United States and Canada are oceanographically "upstream" of the Sargasso Sea, and plastic debris in these areas is either locally removed or transported to the central gyre reservoir.

TBT: The Dilemma of High-Technology Antifouling Paints

by Michael A. Champ, and Frank L. Lowenstein

Since the first days of sail, mariners have been battling fouling—the growth of barnacles, seaweeds, tubeworms, and other organisms on boat bottoms. The Phoenicians, realizing that smoother bottoms translated into easier rowing and faster sailing, nailed copper strips to the hulls of their ships to inhibit fouling.

Marine fouling (Photo from a painting by Lisa Haderlie Baker, Lawrence Hall of Science, University of California at Berkeley © 1980 by the Regents of the University of California, courtesy National Science Teachers Association and the Carolina Biological Supply Company)



The marine hitchhikers. Depicted are examples of the animals and plants that grow on underwater surfaces such as ship hulls—resulting in marine fouling. Ships are most susceptible to fouling when they are in port. How sedentary marine organisms are transported to colonize new surfaces is illustrated by the life cycle of the acorn barnacle at the bottom center: 1) free-swimming larvae must attach to a substrate in order to develop and feed. If they do not attach, they will die in a matter of days, 2) the larvae produce a strong, long-lasting adhesive for attaching themselves to substrates. Scientists have been attempting to duplicate this adhesive, 3) the larva attaches head first, forms a conelike shell around itself, and uses its feet to propel food into its mouth. The anatomy of the resulting adults is shown in the lower left. (From a drawing by Lisa Haderlie Baker, courtesy of the National Science Teachers Association and the Carolina Biological Supply Company)

In naval actions, the cleaner, faster vessel often escaped stronger forces or caught up to weaker ones. Thus fouling was an important factor to navies in the days of sail. Although copper strips went by the boards long ago, fouling remains important today, as aircraft carriers launch aircraft while underway at 40 knots, supertankers crisscross the oceans, and fishing boats plow the coastal waters.

Fouling produces roughness on the surface of a ship, thereby increasing turbulence and drag. A 10-micron (one-thousandth of a centimeter) increase in average hull roughness on a power vessel can result in a 0.3 to 1.0 percent increase in fuel consumption. For large power vessels, fuel costs can amount to 50 percent of the total operating costs. The 1985–86 fuel bill of the *Q.E. II* (one of the world's largest ships), for example, was $17 million—thus a 1 percent increase in that bill would amount to $170,000.

For the projected 600-ship U.S. Navy, fouling is obviously a major problem. In tropical oceans, the Navy finds that ships begin experiencing significant bottom fouling in less than a year if painted with copper-based antifoulant paints. This compares to 5 to 7 years if painted with tributyltin (TBT) based antifoulant paints. According to Navy figures, if the entire fleet were painted with TBT paint, the reduction in costs would be more than $110 million annually (assuming a fuel cost of less than $16 a barrel).

In 1985, however, when the Navy proposed painting its ships with efficient antifouling paints that are widely used by commercial and pleasure craft, it focused scientific and political attention on the effects of these paints in the marine environment. Edward D. Goldberg, Professor of Chemistry at Scripps Institution of Oceanography, has stated on several occasions that TBT, the active ingredient of these paints, is the most toxic compound man has introduced into the marine environment.

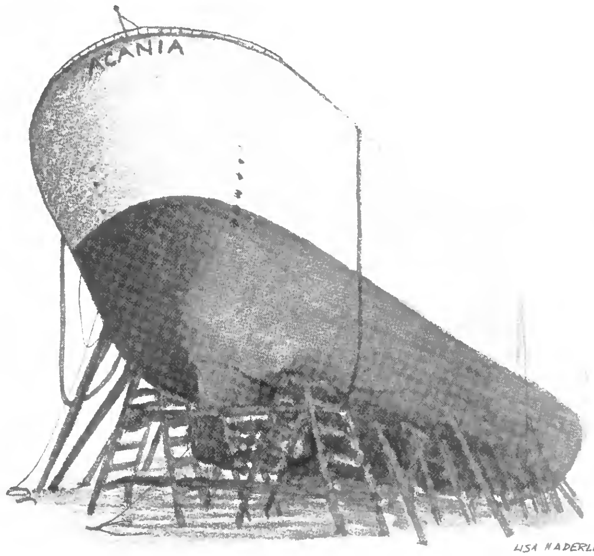
Since the widespread use of TBT-based paints began in the early 1970s, evidence shows that TBT paints harm many forms of marine life other than fouling organisms, including economically important species such as oysters. These untargeted effects have attracted increasing international concern. A number of countries have adopted policies regulating or restricting TBT use. Several states in this country also have taken action, and federal regulation of TBT is imminent, as we discuss later. Meanwhile, one of the largest U.S. ship yards, Newport News Shipbuilding in Newport News, Virginia, has decided to turn down work that requires the use of TBT paints because of potential risks to employees.

But, the use of tributyltin paints on commercial ships, fishing vessels, and private boats could add another $300 to 400 million in fuel savings annually. Hence, the stakes riding on tributyltin paints amount to almost 2 billion gallons of gasoline lost forever, or saved for future use, each year. These figures do not include the sums that would be saved from the decreased wear on propulsion machinery and the decreased down time for hull scraping, cleaning, and painting that would result from the use of TBT paints.

Oyster Studies

One of the first areas where TBT toxicity was observed was in France's Arcachon Bay, an area that produces 10 percent of that nation's oyster harvest. The Pacific oyster, *Crassostrea gigas*, was introduced there in 1968 to replace declining populations of the European flat oyster. The bay is long, has restricted circulation, and has large numbers of marinas and docks.

By 1976, French scientists had observed an abnormal thickening of the shells of juvenile Pacific oysters. A year later, these anomalies were detected throughout the bay. Early researchers noticed an association between marinas, boat moorings, and shell malformations. The degree of shell thickness correlated well with the large numbers of boats in the estuary, suggesting a



It currently costs about $1 million to dry-dock a VLCC (Very Large Crude Carrier), scrape off the fouling organisms, remove the old paint, and apply new anti-corrosion and anti-fouling coatings. Large ships require dry-docking for cleaning and painting purposes about every two years. With a clean hull, fuel savings on a round trip between the East Coast of the United States and the Persian Gulf can amount to over a quarter million dollars. (Drawing by Lisa Haderlie Baker, courtesy National Science Teachers Association and Carolina Biological Supply Company) relationship between the use of TBT paints and growth deformations. This hypothesis was strengthened when French researchers found that the tendency for shell thickening could be reversed by moving the oysters to an area far removed from boating activity.

In addition to the shell deformations, some areas of the bay showed little or no natural oyster larvae settling on hard substrates, suggesting toxic effects in early life stages. Over time, such high spat* mortality could adversely affect oyster populations in the bay. These biological field studies, however, did not include measurements of the concentrations of TBT in the areas where shell deformities occurred. Thus, the link between TBT and oyster deformities was not conclusive.

At the same time, in Britain, similar deformities were observed on the European flat oyster (*Ostrea edulis*). Because the Pacific oyster is more sensitive to TBT than the European flat oyster, the deformities found in Britain were less dramatic. Farming of the Pacific oyster was attempted unsuccessfully in many areas of Britain, particularly in the estuaries of the rivers Crouch and Roach on the east coast of England—in terms of TBT, two highly contaminated areas.

*The larval stage of an oyster characterized by settling onto a substrate and beginning shell formation.

In the United States, examples of Pacific oysters with malformations similar to those in Britain have recently been found in the South Slough National Estuarine Research Reserve near Charleston, Oregon. South Slough is adjacent to a boatyard that has used TBT paints.

Laboratory Studies

Following the findings in France and Britain, Claude Alzieu and co-workers conducted a series of studies at IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer) (Table 1). In Britain, meanwhile, M. J. Waldock, and J. E. Thain and co-workers at the Ministry of Agriculture, Fisheries, and Food (MAFF) laboratory at Burnham-on-Crouch, conducted similar investigations. The results of these studies demonstrated that TBT could cause oyster shell deformations.

According to the French studies, the shell anomalies occur when chambers form in between the calcified layers of the shell (Figure 1). These chambers are filled with a protein gel that differs chemically from those usually seen during shell growth. It seems not to bind calcium or carbonate the way the normal protein does. When this abnormal protein is added to a solution of calcium carbonate ($CaCO_3$), it slows down or prevents the formation of crystals of $CaCO_3$. Thus the conclusion is that the formation of this gelatinous protein is an abnormal process that results in the perturbation of molecular genetic mechanisms.

In the most acute malformations in Arcachon Bay oysters, the anomalous thickening of the oyster shell was more rapid than its lengthwise growth, and the oyster took on a ball shape (Figure 2). These malformations were not observed in the European flat oyster.

Imposex in Common Dogwhelk

More extreme deformations occur in the common dogwhelk, *Nucella lapillus*—a species of thick-shelled snails found around the southwest peninsula of England. Here populations studied by researchers at the UK Marine Biological Station showed the occurrence of imposex—the development of male characteristics, notably a penis and a *vas deferens* (sperm duct), on females. These researchers found a high occurrence of imposex close to centers of boating and shipping activity. The occurrence of imposex correlated significantly with tin concentrations in dogwhelks (up to 2 micrograms per gram of dry tissue). Laboratory studies have confirmed that exposure to TBT will induce imposex.

Because of their feeding habits, dogwhelks accumulate higher concentrations of TBT than that of the water surrounding them. Dogwhelks feed on algae and other microscopic organisms coating rocks and other hard substrates in the intertidal zone. Because higher concentrations of TBT are found in the sea-surface microlayer than in the underlying water column, this layer of microorganisms becomes coated with the high concentrations of TBT. This can lead to TBT in dogwhelks as much as 1,000 times more than the concentration in the surrounding water.

In the case of the dogwhelk, imposex has an ecological significance; those populations in which individuals frequently exhibit imposex show signs of decline. In these populations, fewer females occur than would be expected; and

Table 1. Effects of TBT acetate on *C. gigas* embryogenesis and larvae development (Alzieu, 1986, from His and Robert, 1985).

TBT Acetate (micrograms/ liter (PPB))	Effects on Reproduction
100	Inhibition of fecundity
50	Inhibition of segmentation
25	Partial reduction of segmentation
10	Absence of the formation of trocophores
3–5	Absence of veligers—malformation of trocophores
1	Abnormal veligers—malformation of trocophores
0.5	Numerous anomalies—total mortality in 8 Days
0.2	Perturbation in food assimilation—total mortality after 12 Days
0.1	Normal D-Larvae: slow growth, almost total mortality after 12 Days
0.05	Slow growth; high mortality rate after 10 Days
0.02	No observable effect

juveniles and deposited egg capsules are scarce or absent, indicating a low reproductive capacity. Female dogwhelks exhibiting imposex had oviducts clogged with decomposing eggs that could not be released because the newly formed male reproductive tissues blocked the oviducts. Subsequent laboratory studies have suggested that environmental concentrations of about 1 part per trillion (equivalent to 1 second in 31,000 years) seem to initiate imposex.

In addition to the effects of TBT on dogwhelks and oysters, laboratory studies show that TBT can stress or kill a variety of marine organisms, including lobsters, fish, and many mollusks (Table 2).

Types of TBT Paints

The amount of TBT released into the water varies with the paint formula. Like any paint, antifoulant paints contain film-forming material and pigment, which together determine the final surface's strength, flexibility, capacity for water absorption, and color. In addition, antifouling paints, such as TBT, contain biocides, which are gradually released, killing fouling organisms as they settle onto the hull of the ship.

Tributyltin is used as a biocide in antifoulant paints in three different ways—in free association paints, ablative paints, and copolymers. In free-association paints, the TBT is not chemically integrated into the paint and is leached out by contact with salt water. Ablative paints feature a similar chemistry, but the paint also flakes off in thin layers, continually exposing new biocide. In copolymer paints, the TBT is chemically integrated within the matrix—and is released more slowly, and over a longer period of time.

Free-association paints have high early release rates coupled with short periods of protection from fouling organisms, because they allow seawater to percolate slowly through a tough, insoluble paint matrix (Figure 3). The biocides are mixed into the paint and leach very rapidly initially. After a period of perhaps 2 years, the

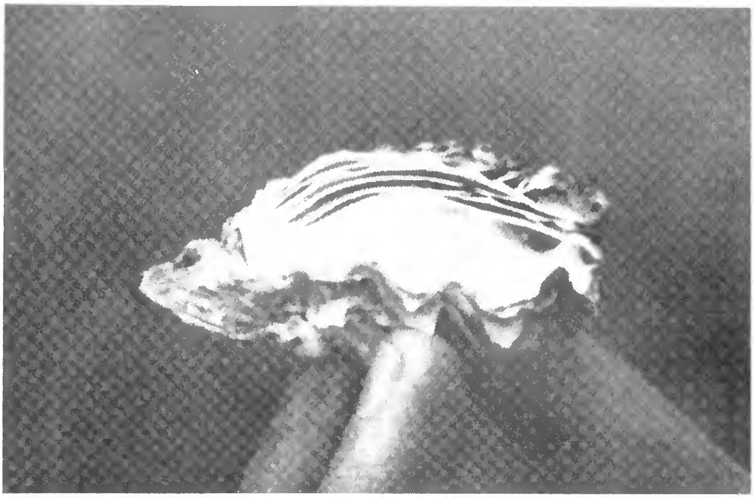


Figure 1. An oyster from Arcachon Bay in France, showing abnormal chambering suspected to be caused by TBT. (From C. Alzieu, IFREMER, Oceans '86 Symposium Proceedings)

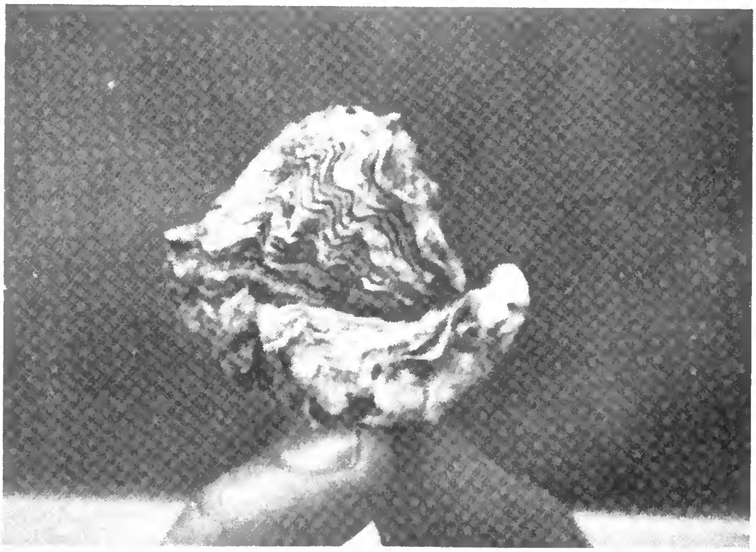


Figure 2. In extreme cases, oysters become malformed, taking a characteristic ball shape that inhibits shell closure. (From C. Alzieu, IFREMER, Oceans '86 Symposium Proceedings)

Table 2. Summary of toxicity and occurrence of TBT. All values given in micrograms/liter (parts per billion (PPB)).

Type of organism	Acute toxicity: lethal to 50% of individuals	Chronic effects seen
Mollusks	0.1–2.3	0.06–0.24
Fish	0.96–24	0.2–10.0
Crustaceans	0.3–41	1.0
Algae	0.33–1.03	—

Source: U.S. EPA, Jan. 1986.

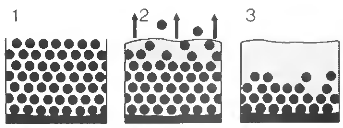


Figure 3. In free-association TBT paints, the TBT molecules are leached from a permeable matrix by seawater percolating through the paint.

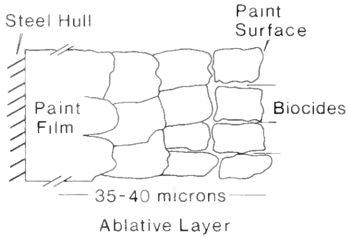


Figure 4. Ablative paints use a less permeable matrix that gradually flakes off, exposing new leaching surfaces.

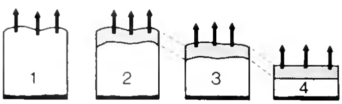


Figure 5. In copolymer paints, the TBT is part of an impermeable matrix, and is released through a chemical reaction with seawater at the paint surface. New TBT is exposed by gradual erosion of the paint.

paint film ages, and calcium carbonate ($CaCO_3$) clogs the microchannels in the paint surface, and inhibits the release of biocide. The surface then becomes fouled. In addition, these paints leave a quantity of biocide unused on the vessel's hull. When the hull is scraped, paint chips often end up in the water, where they again release TBT into the environment.

Ablative paints feature a matrix that sheds during use—as the paint surface roughens, paint particles (very thin microlayers) peel off, exposing a fresh supply of biocide (Figure 4). The biocide is added in free-association form, but only leaches out of newly exposed surfaces. The lifetime of this paint is also about 2 years.

Copolymer paints (Figure 5) were developed in the early 1970s. In these paints, the matrix does not allow seawater to enter; biocide is released by a chemical reaction that occurs at the paint's surface. The TBT is chemically bonded to a polymer backbone. This bond breaks down in the presence of water under slightly alkaline conditions—just the circumstances found in seawater. As the polymer breaks down, the surface of the paint erodes, constantly exposing new surfaces that can release more biocide. Since release of the biocide is governed by the chemical decomposition of the TBT group rather than dissolution of the paint particle, release rates from copolymer paints are typically much lower than for the other two types of paint. An exception is a high release rate during the "conditioning" period (approximately the first month after the freshly painted hull is placed in the water) (Figure 6).

The slow dissolution of the polymer gives copolymer paints a constant, prolonged, low release rate. The fact that the paint dissolves slowly also allows easy control of the paint's life span; the thickness of the initial application of the paint determines how long it will last. Presently, 5 to 7 years is about average. Since copolymer paints can be applied directly to a ship's hull, without having to remove previous copolymer layers, shipyard costs are reduced, and less TBT may enter the environment from scraping.

The differences between the various types of tributyltin paints are important considerations in regulatory efforts now underway.

Regulatory Strategies

Thus far, four European nations have adopted regulations governing the use of TBT paints. In 1984, France prohibited the use of TBT paints containing more than 0.4 percent TBT, except on large vessels and aluminum-hulled vessels. The exception for aluminum is necessary because copper-based paints, which are the only readily available substitute for TBT paints, corrode aluminum hulls. Large ships, because they are usually located in deepwater ports with good circulation, are thought to be less likely to cause high concentrations of TBT than large numbers of smaller boats in semi-enclosed harbors. In 1986,

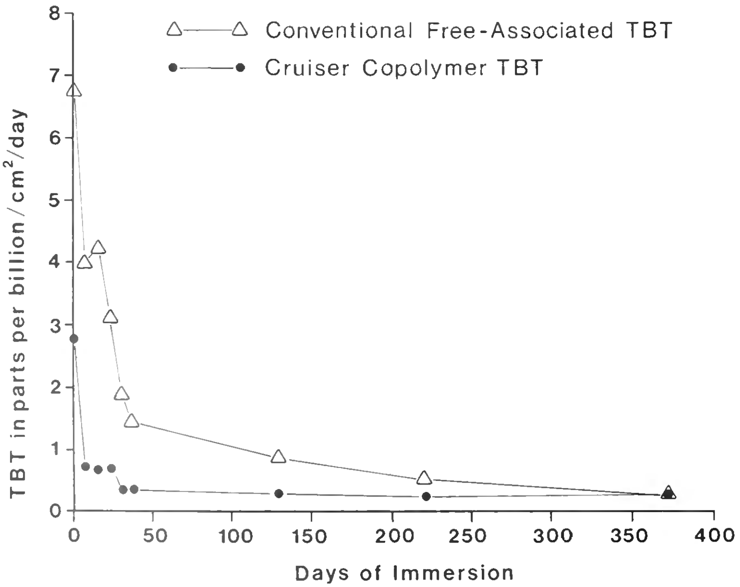
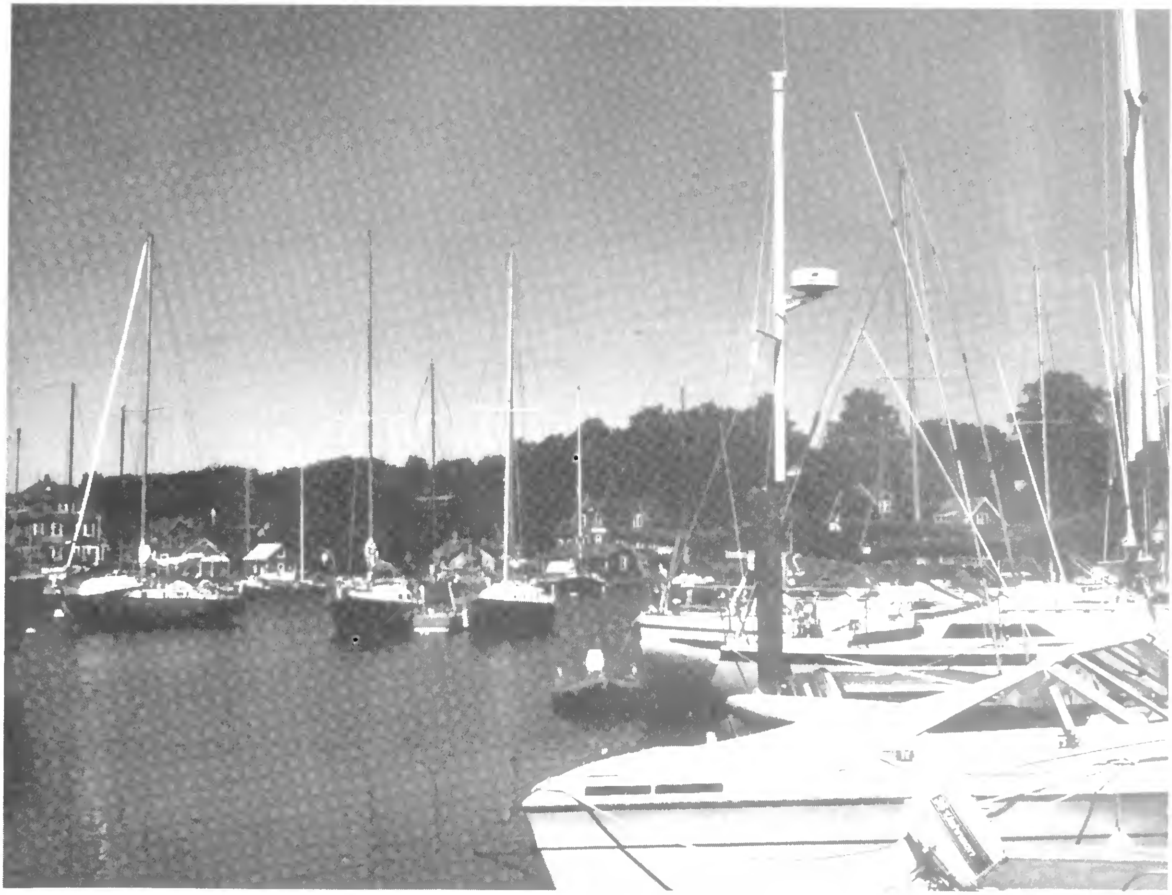


Figure 6. Except for an initial spike of rapid release, copolymer paints show a lower release rate than free-association paints. (From C. Anderson and R. Dalley, Oceans '86 Symposium Proceedings)



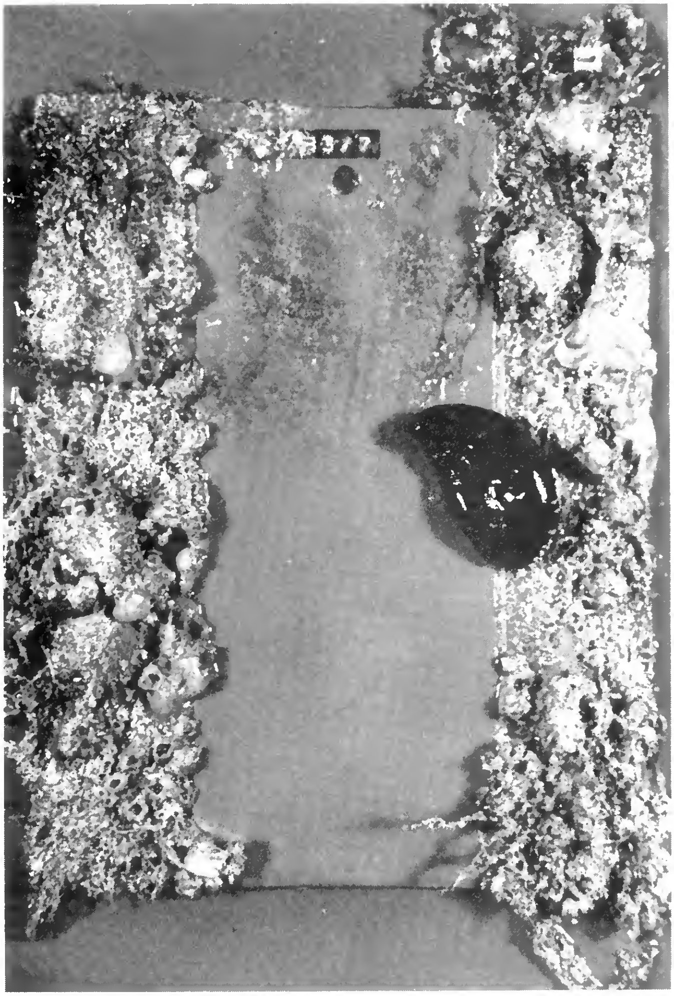
Large numbers of small boats in harbors with poor circulation may contribute significantly to TBT risks. As a result, small boats are a target for new TBT regulations. (Photo by Sheryl Lechner)

Britain followed France's lead with a ban on the sale of paints containing more than 7.5 percent tin (by weight) for copolymer paints, or 2.5 percent tin for free-association paints.

In the United States, four ways to regulate TBT paints are under consideration: a total ban; permitting application only on large or aluminum-hulled vessels; limiting the amount of TBT (on a percentage basis) in the paint; and limiting the release rate of the paint.

Following the Navy's June 1985 proposal to paint its fleet with TBT paints, Congress attached an amendment to the Fiscal Year 1986 and 1987 appropriations bills. This prevents the Navy from using TBT paints until the Environmental Protection Agency (EPA) finishes its Special Review of this high-technology chemical. As *Oceanus* goes to press, the wording of the Fiscal Year 1988 appropriations bill permits the Navy to paint aluminum-hulled vessels and 15 steel-hulled vessels as a research demonstration study to allow scientists to study the release and distribution of TBT from antifoulant paints on Navy ships and the subsequent ecological effects.

Meanwhile, in January the EPA initiated its Special Review under the statutory authority of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). A pesticide product may be sold or distributed in the United States only if it is registered, or exempt from registration, under FIFRA, as amended (7 U.S.C. 136 et seq.). The law states that before a product can be registered, it must be shown that it can be used without "unreasonable adverse effects on the environment," that is, without causing any unreasonable risk to man or the environment, taking into account the economic, social, and environmental costs and benefits of the use of the pesticide. Under the Special Review process, EPA gathers risk and benefit information about previously registered pesticides that appear to pose potentially unreasonable risks of adverse effects to human health or the environment. Through the issuance of notices and support documents, EPA publicly sets forth its position, and invites pesticide registrants, federal and state agencies, user and environmental groups, and any other interested persons to participate in the agency's review process. If EPA determines that the risks



Colonization below the waterline by marine fouling organisms on a test plate containing a narrow section (center) painted with a copolymer paint. The plate was submerged for 21 months. (Photo courtesy of M&T Chemicals, Inc., Woodbridge, New Jersey)

outweigh the benefits, then it can initiate action under FIFRA to cancel, suspend, or modify the terms and conditions of registration.

In initiating the review for TBT, the EPA identified significant gaps in the data bases supporting the registration of TBT as used in antifoulant paints. To obtain the necessary data, EPA has issued a series of Data-Call-Ins (DCIs) to registrants that require extensive data submissions if they wish to continue their registration pursuant to EPA's authority under FIFRA. Through the use of DCIs, EPA has requested extensive data on the release rates of TBT from antifoulant paints, product chemistry, ecological effects, environmental fate, worker exposure, quantitative usage, efficacy of TBT products, specific toxicity tests with a wide range of organisms, and specific environmental monitoring data.

A DCI on release rates was issued in July of 1986. Following this DCI, nearly 300 (or 80 percent) of the chemical registrants voluntarily cancelled their registrations or were threatened with registration suspension by EPA for failure to submit the required information. These 300 products account for about half of the total TBT production. Production of the remaining TBT paints could increase though, if demand increases.

It could take several years for EPA to receive and analyze the information requested in the DCIs. In the meantime, EPA and the National Oceanic and Atmospheric Administration will distribute (with the assistance of the Coastal States Organization) a brochure to registered boat owners on "Safer Use of Boat Bottom Paints," as a self-regulatory device to reduce careless introduction of TBT into coastal waters."

According to John Moore, Assistant EPA Administrator for Pesticides and Toxic Substances, EPA will issue interim measures soon, possibly even as this article appears. Testifying recently to Congress, Moore asserted that "these measures most likely will involve the initiation of actions to restrict or cancel the registrations of antifouling paints, based on release-rate or other criteria as appropriate." Presumably paints with low release rates would still be available. As part of the interim action, EPA is also considering issuing a Provisional Water Quality Advisory for TBT. As long-term ecological effects and environmental fate data become available over the next several years, Moore testified, EPA "might refine its interim decision, including the imposition of more stringent restrictions, if necessary."

These interim measures may be pre-empted, however, by bills presently before the House and Senate. The bills focus on limiting the TBT release rate of the paint as a regulatory mechanism. In hearings before the Senate Subcommittee on Environmental Protection, Moore argued that the bill, known as the "Tributyltin-Based Antifouling Paint Control Act of 1987," is premature. He stated that "there is no rational basis for choosing among various possible regulatory criteria, let alone determining a scientifically relevant release rate value."

In addition to these federal efforts, several states have adopted regulations. Virginia has urged Congress and

EPA to ban the use of TBT compounds in free association paints, and has limited the sale of TBT paints to the general public. In addition, Virginia has prohibited the use of TBT paint on vessels shorter than 25 meters, except for aluminum hull boats. Maryland also has banned the sale of TBT paints to the public, and Washington has banned the use of TBT paints on vessels less than 25 meters in length. Similar legislation is under consideration in California. The New Jersey state senate is considering a bill that would ban all sales of TBT paints.

Research and Monitoring Needs

Many of the monitoring studies conducted to date have focused on determining the concentrations of TBT in marinas or downstream of boat yards and dry docks, and not on the processes that determine the fate and behavior of TBT in the marine environment. Also, most of the toxicity information available comes from tests in which an organism is placed in a test container with a known initial concentration of TBT for a limited period of exposure. Such tests do not accurately reflect the impact of TBT in the environment, or many factors of ecological importance, such as reproductive success.

In July 1986, NOAA's National Marine Pollution Program Office sponsored an interagency workshop on monitoring and detecting organotin compounds. Since this workshop, groups at the state, federal, and international levels have met in the United States, Britain, and France to identify the critical needs in TBT research.

Some recommendations from these meetings include developing advanced analytical methodologies for the identification of TBT and its metabolites at parts-per-trillion levels in marine waters and in tissues and sediments. To explain the concentrations observed in both water bodies and organisms, the environmental fate and behavior of TBT and its metabolites in marine and estuarine waters need to be studied. This includes the identification and quantification of critical pathways (surface microlayer, water column, and sediments) of exposure of marine and estuarine organisms to TBT and metabolites, and the uptake rates and bioconcentration/ bioaccumulation levels of TBT and metabolites by key organisms in all trophic levels from both water and sediments. Also needed are the biological and chemical degradation rates of TBT and metabolites in marine and estuarine waters (under a wide range of salinities and temperatures), in aerobic and anaerobic sediments, and in tissues. This includes the importance of photosynthetic organisms in enhancing TBT degradation rates.

Most of the toxicity studies conducted during the last 5 years have used nominal (one-initial dose) exposure concentrations in which the test organisms were exposed to initial measured test concentrations and not continuous concentrations that have routine chemical quantifications at selected time periods. These nominal tests (usually static and not flow through) are of limited value when conducted at parts per trillion levels. Toxicity tests should focus on low level physiological end-points through chronic or full-life-cycle exposure testing. Proper criteria include reproductive success, gametogenesis, imposex, calcification mechanisms, and immune suppression, rather than mortality as measured by acute short-term, 96-hour bioassay tests.

To determine how contaminated sediments should be removed (dredged) and where they can be placed, tests of the response of benthic organisms to contaminated sediments are needed. The most useful tests would use spiked sediments (4 or 5 times the ranges of contamination typically found) and would be run for perhaps 60 days, because of the part-per-trillion test levels.

Because mollusks have a high sensitivity to TBT and its metabolites, long-term chronic studies should be first conducted extensively with these animals to investigate effects on gametogenesis, settlement of spat, growth, calcification, and reproduction through all life stages. Lastly, on-site bioassays using ambient water from selected high use areas are needed to validate effects observed in the field and in specific laboratory tests. Also, representative large volume toxicity tests, such as can be conducted at the MERL (Marine Ecosystem Research Laboratory) mesocosm tanks at the University of Rhode Island, are needed to validate standard, 96-hour laboratory toxicity tests.

Looking to the Future

Antifouling paints are needed, and at present, alternatives to paints that rely on toxic compounds are in their infancy. Efforts to safely use toxic-based antifouling paints require accurate and comprehensive environmental data. Because TBT causes harm to non-target marine organisms at levels that approach our ability to detect its presence, we are limited in our ability to study the toxic effects. Consequently, there exists a tremendous need for further research on the mechanisms of toxicity, and the fate and behavior of TBT in the marine environment.

Until more is known, evaluation of the effectiveness of innovations, such as new paint formulations or matrixes that have lower release rates, will be tentative and inconclusive. Without a full understanding of the environmental mechanisms and processes that control TBT distribution and critical pathways of toxicity, we cannot unleash the high technology that created these paints to make them more effective and safer.

Michael A. Champ is a Senior Scientist with Science Applications International Corporation, in Rockville, Maryland. Frank L. Lowenstein is a freelance writer, and a former Assistant Editor at Oceanus.

Suggested Readings

Marine Technology Society. 1986. Proceedings—Oceans '86 and '87 Conferences, Organotin Symposia. Washington, DC.

concerns

Matamek: Toward an Uncertain Future

—A conflict between preservation and development exists at and around the site of a former research station in Canada. Will an agreeable solution be found?

by André Delisle

An ecological reserve that has benefited from its status as a conservation area for the last two decades, and a natural hinterland on the north shore of the Gulf of St. Lawrence adjacent to a dormant research station, the Matamek Reserve may soon be opened up to lumbering and to the exploitation of its wildlife. How are we going to decide upon the destiny of this legacy of the environmental conscience?

A related question deals with the fate of the research station itself, lying just outside the southern boundary of the reserve. At the end of 1984, for a variety of reasons, American scientists from the Woods Hole Oceanographic Institution (WHOI) withdrew from the research station at the mouth of the Matamek River on the Gulf of St. Lawrence, where, along with a number of other projects, they had been studying the Atlantic salmon.

To pursue their research, the American scientists had asked that the whole Matamek River basin, an area of some 700 square kilometers (173,000 acres), be given the status of a reserve by the Quebec government, a request that was granted. This status, obtained in 1970, guaranteed the preservation of the natural character of the Matamek river basin and its resources. Hunting and fishing were prohibited from then on, except for research

Above, the Matamek Research Station, on the north shore of the Gulf of St. Lawrence, and at the mouth of the Matamek River.

purposes and on lands where aboriginal peoples held ancestral trapping rights.

However, since the scientists left in 1984, no Quebec institution has taken up the torch. The research station is now for sale by its present owners. Presently, several groups would like to take over this magnificent area. At the same time, its status as a conservation area is being questioned by those groups who may take over the station, and by provincial government ministries responsible for administering public lands, forests, and wildlife.

The Matamek Research Station

Some 150 acres of mostly timberland at the mouth of the Matamek River were given to WHOI in 1966 by the late J. Seward Johnson. The Matamek land was a commercial fishing camp for anglers until that time, and there is a lodge-and-cabin cluster that accommodates up to 30 people. In addition, there are four log cabins in a group on Lake Matamek, and three other cabins scattered in the forest near other lakes.

The Matamek Research Station, as it was named, is located on the north shore of the Gulf of St. Lawrence, 600 kilometers east of Quebec City and 32 kilometers east of Sept-Iles. The station is at the mouth of the Matamek River, which drains a pristine watershed of 684 square kilometers. Along the 10-kilometer course of the Matamek River between Matamek Lake and the Gulf of St. Lawrence, there are five waterfalls. The area is Precambrian shield, and the vegetation is typical of a boreal forest region with virgin stands of black spruce and balsam fir. Inland, the Precambrian bedrock is close to the surface, but the coastal area is overlain by Champlain Sea deposits.

Matamek has a history of scientific endeavor. In 1912 Walter Amory and his son Copley Amory bought the property. Amory was a naturalist and found the area ideal for his interests. He soon observed that fluctuations in the abundance of fish and game had profound and sometimes disastrous consequences for the local Indian population. Determined to do something about this, in 1931 he organized the Matamek Conference on Biological Cycles, and invited the leading ecologists and geographers of the day. Among the contributors was the eminent ecologist, Charles Elton. The conference led to a grant from Amory to Elton that helped found the Bureau of Animal Population at Oxford University. For this and other reasons, the conference marked an early milestone in the study of population dynamics.

Business problems forced Amory to withdraw from Matamek during the mid-1930s. The station was eventually sold, and became a salmon fishing club.

Following its acquisition by WHOI, scientific investigations began in 1967, with studies of the Atlantic salmon and other species of fish in the lower river, and the fish in Matamek Lake. Work continued in 1968 on salmon in the river and brook trout in the lake, along with a preliminary look at other headwater lakes. Discovery of a fishless area led in 1969 to an ecological comparison of four headwater lakes, and studies of brook trout production in other lakes. Because the salmon population was found to be small, examination of the salmon stocks of other north-shore rivers, the Moisie and the Corneille, was started in 1969. By 1972, a general study of north-shore salmon rivers included 14 salmon rivers. Limnological surveys in the Matamek watershed covered 31 lakes, ponds, and bogs. Observation tanks constructed at the second falls provided facilities for behavioral work and experiments on supplemental feeding of salmon parr and brook trout.

In 1984, however, WHOI withdrew from maintaining an active research program at the station. George D. Grice, Associate Director for Scientific Operations at WHOI, reports that, while lack of adequate funding was a factor, there were others. Among them was the decision by WHOI to redirect and concentrate its efforts on the primary mission of the Institution—oceanography. Grice also states, "The research station was not simply put up for sale. A concentrated effort was made by WHOI to turn the station over to an appropriate Canadian group, provided an agreement could be reached to continue Matamek as a research station. Canadian Federal and Provincial organizations were contacted (including Canadian Federal Wildlife Service, Canadian Fisheries and Oceans, Quebec Ministry of Tourism, Hunting, and Fishing), as well as several universities (University of Quebec, McGill University, University of Waterloo, and the University of Laval). As of this date, no proposals have been received."

While WHOI, like most other involved parties, would prefer that the station continue as a research facility, the property on which it is located falls outside the boundaries of the Matamek Reserve, and carries no legal restrictions.

The Road to No Return

The drainage basin of the Matamek River, which until now has been protected against commercial exploitation, would not be threatened were it not for an omission in the legal definition of its protected status. It opens the door to an irrevocable attack on the pristine nature of the area. The omission is this: neither the Cabinet decree establishing the reserve in 1970, nor the subsequent regulations enforcing its protected status clearly prohibit logging. The possibility of such logging is mentioned in the premise of the decree, where it is stated that "any exploitation or exploration of the said territory . . . must be previously submitted to the Minister of Tourism, Hunting, and Fishing, in order that the Minister may study the impact of such exploitation or exploration on the research program, as well as any repercussions on salmon production from the river." Since research activities in this area seem to be a thing of the past, and since research carried out over a period of almost 18 years has demonstrated that the salmon production potential of the Matamek River is modest, this issue has become more ambiguous.

The consequences of this ambiguity are important since the Quebec Ministry of Energy and Resources is looking with great interest at the timber potential of a section of the Matamek Reserve. The Ministry is counting on the timber from a section of the reserve to ensure the supply that it has guaranteed to Cascades, a pulp and paper company, by way of the state corporation Rexfor, with the aim of stimulating the Port-Cartier paper mill. The Ministry of already started building roads to make such exploitation possible. The first centuries-old trees could be cut down by this year. Within a few months, the ecological integrity of the Matamek basin might be lost forever.

Even if the logging is done in compliance with the most strict ecological rules, the intrusion of bulldozers and logging equipment into this virgin territory would certainly cause heavy environmental damage. Moreover, it could be followed by an intrusion by hunters and fishermen—in their all-terrain vehicles, roaring up the lumbering roads looking for game or fresh fish. The local hunting and fishing associations have already made their intentions clear about taking over this precious area.

Looking For a Label

The discussion about the legacy left by the American scientists has only recently been made public, notably by the Société Linnéenne du Québec (the Linnean Society of Quebec). The Quebec Advisory Council for Ecological Reserves made public, a few months ago, an opinion that had been sent to the Quebec Minister of the Environment, Clifford Lincoln.

Long before all this happened, representatives of the environmental community and a few Quebec scientists who had worked at the research station had done their utmost to have the station taken over by someone who would preserve the scientific vocation of the territory. Scientists at the Institut National de la Recherche Scientifique (National Scientific Research Institute) and various Quebec universities were approached. They, however, had to politely decline the offer, an attitude that is quite understandable in these difficult times of budgetary restrictions. No foundation or institute has come forward to shed a glimmer of hope for continuing the research activities that have been carried out for the last 20 years.

The Minister of Tourism, Hunting, and Fishing, who is responsible for the administration of parks and wildlife reserves, today finds himself handling a "hot potato," because he will have to make a decision involving several ministries of the same government, all of which have already made their preferences known, and where the opinions of the representatives of the region involved also seem to be strongly divided.

Of course, the Ministry of Energy and Resources, supported by the Quebec Planning and Development Office, is impatiently awaiting a favorable official decision (by the Council of Ministers) that would legitimize its presence in the reserve. Even within the Ministry of Tourism, Hunting, and Fishing (more precisely in the department responsible for the north shore region) a form of controlled exploitation of territorial resources is strongly favored, most notably by the creation of a zone for controlled exploitation (zone d'exploitation contrôlée, or ZEC). Administration along these lines, if it contributes to a rational exploitation of the wildlife resources, would allow other uses of the resources. Villages and lumbering could then be permitted in certain areas.

The whole question might already have been decided if the environmental community had not sounded the alarm. Following the intervention of the Société Linnéenne, which succeeded in winning support from some regional organizations (notably from the Corporation for the Protection of the Environment of Sept-Iles, the community college in Sept-Iles, the Quebec Union for Nature Conservation, the University of Quebec at Chicoutimi, and even from local political authorities of the MRC (County Regional Municipality) of Sept-Rivières and the municipality of Moisies), the Quebec Ministry of the Environment has proposed establishing an absolute protected status for the Matamek Reserve by designating it as an Ecological Reserve. The Ecological Reserve status, a category adopted by the government sometime after the original Matamek Reserve was established, is considerably more restrictive in the permitted uses of an area and its resources. Some say too restrictive. This proposal is still under review.

Guarding the Reserve's Integrity

Being an untouched region, the basin of the Matamek River has the almost perfect profile of an ecological reserve. On the one hand, the river is one of the last refuges for natural reproduction by the Atlantic salmon.* This being so, it constitutes a river of undeniable scientific interest for the protection of this species that is disappearing from our waterways. On the other hand, the basin of the Matamek River is the only complete ecosystem that is representative of the environment of the mid-north that has not yet been disturbed by human activities.**

To guard the habitat of the salmon from human intervention, those running the research station, as well as several university scientists proposed, as early as 1975, to turn the Matamek River basin

** Robert J. Naiman, former Scientific Coordinator of the Matamek Research Program, and presently Director of the Center for Water and the Environment at the University of Minnesota, states that, "the salmon run in the Matamek River is modest, with up to 100 spawning adults. Indeed, there are quite a few other rivers in the area with equal or better runs of naturally reproducing salmon."*

into an ecological reserve. This proposal was based mainly on the threatened disappearance of the Atlantic salmon and on the interest in preserving intact a north coast ecosystem that was still inhabited by this species, and where it still reproduces in completely natural conditions. The proposal was based on data that had been previously compiled, and on the importance of the area for research and educational activities.

Indeed, the value of this parcel of Quebec rests on the overall integrity of its natural environment. For supporters of a network of ecological reserves, the preservation of this area is also a question of principle. The role of the administrator of these territorial banks, the Quebec government, has come under scrutiny. Is it possible, at the whim of the ministers or partisan politics, to withdraw the status of protected areas, a status that has preserved such areas from groups opposed to this form of conservation?

At the beginning of last February, the Advisory Council for Ecological Reserves took a firm stand and underlined the incongruity of changing the status of a protected reserve: "If we opened up the Matamek reserve to lumbering and exploitation of wildlife, that would signify, ironically, that it had been protected for future exploitation. Its protection becomes, paradoxically, a way of long-term planning for its exploitation, something that is completely at odds with the objectives envisaged when the territory was granted its status."

*** On this point Naiman agrees, saying: "In my view, there are two principal values of the Matamek Reserve: 1) it is an outstanding example of a small to intermediate size river in the subarctic region with a watershed that is largely in a pristine state. We learned a great deal about river systems and their dynamics in an area unencumbered by lumbering and other operations. Many of our original hypothesis about this type of system (based on data from other systems) were proved wrong, and 2) there exists a valuable long-term data set for the Matamek watershed, representing a cost of $3 to 5 million. This considerably enhances the scientific value of the area.*

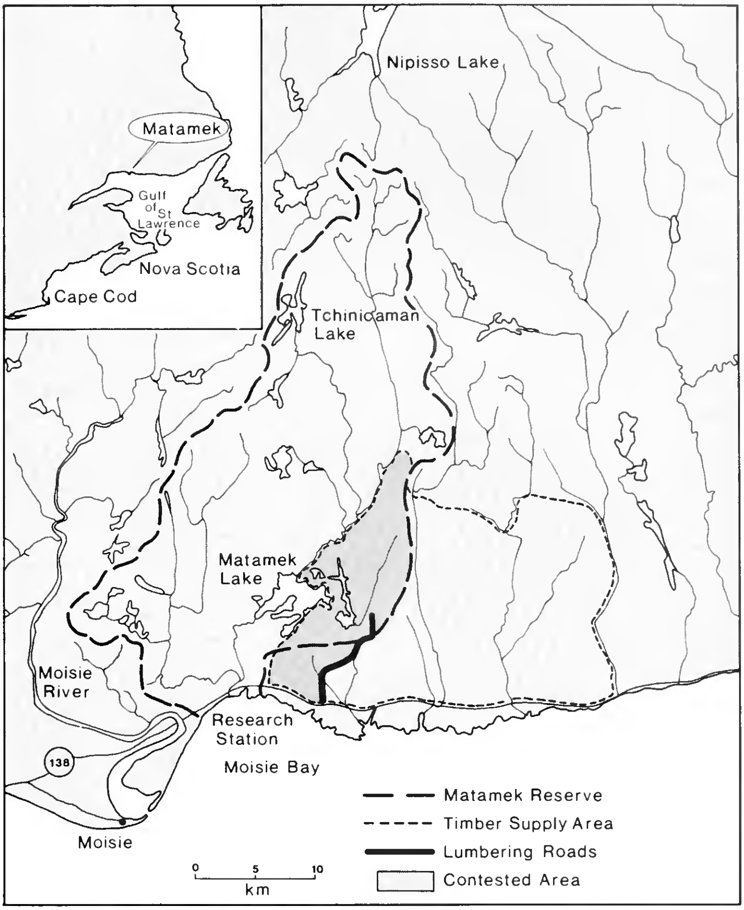


Figure 1. The Matamek Reserve, and the site of the Matamek Research Station.

The Possibility of Sharing

The permanence of the reserve status, and the stability of the ecosystems that are presently under protection, is therefore in question in the debate surrounding the future use of the Matamek Reserve. At the Department of Ecological Patrimony of the Quebec Ministry of Environment, an effort is being made to delineate in a realistic way the territory of an eventual ecological reserve, taking into account the claims of the forest industry as well as the tourist potential of the buildings of the former research station. Compared to the usual requirements of designating an ecological reserve as such, certain concessions would be acceptable, with the aim of avoiding the dangerous precedent of converting a protected area into an area completely open to exploitation.

A definite plan of the limits of a possible ecological reserve on the Matamek would thus liberate a part of the area sought after by Rexfor, as well as the land occupied by the former research station that would be required for any future tourist development. The status of the reserve also could be defined so that certain recreational and educational activities would be permitted, conditional on respecting the natural integrity of the area. In the same way, hunting and fishing rights acquired by aboriginal peoples would be preserved. However, any form of lumbering or wildlife exploitation for commercial purposes would be excluded from the ecological reserve.

For Rexfor, this new carving up of the Matamek area would mean leaving intact a band of territory that had been part of the area designated for commercial exploitation. Rexfor would therefore have to find other sources of supply for the Port-Cartier mill. Cascades, a strong supporter of recycling, might have to accept a slight increase in price for its raw material in order to make such a compromise possible. This would, however, have as much ecological flavor as using waste paper in the production of pulp.

For the anglers, however, the sacrifice will be more difficult, because the potential of the lakes in the Matamek area is very attractive. Suffice to say that the name "Matamek" is a Montagnais word meaning "trout river!" The Ministry of Tourism, Hunting, and Fishing has estimated that between 25,000 and 40,000 chars would be produced annually in any possible future ZEC on the Matamek. As far as hunting is concerned, it would be less painful, since the basin presently supports a relatively small population of moose. This population is similar to neighboring areas, even though no sport hunting has been practiced in the area for nearly 20 years.

Finally, there is the incontestable tourist attraction of the research station on the Matamek, as well as the river itself and the lakes in the neighboring area. However, several questions concerning the station remain unanswered for now. One of these is the use to which the existing buildings could be put, and which group should be designated to administer them. With the instigation of the Société Linnéenne du Québec, which would heartily support an Atlantic salmon information center being installed in the former research station buildings, an organization is being created (Territoire Matamek) that would properly develop the Matamek Reserve. This organization would bring together those who are most interested in the reserve, such as the municipalities, the teaching and research institutions, as well as the local economic development officers.

Priority would be given, initially, to a feasibility study looking at development projects for the Matamek that would be compatible with a vocation as an ecological reserve. The Ministry of Energy and Resources, for its part, is examining the consequences of all foreseeable uses of the territory: ecological reserve, provincial park, wildlife refuge, or other options.

An Orphan Seeking Protection

An orphan since the departure of the American scientists, the territory of the Matamek Reserve is now under the protection of a government with many interests. Those who support the preservation of this area of Quebec are faced with the challenge of finding a magic formula that will satisfy both the needs of the local population as well as the conditions needed to preserve a special ecological inheritance.

Unless a certain ecological conscience slows down the thrust of the forest industry, the next few months will be crucial, because the acts carried out by the various interested parties would have a long-lasting effect. As such, the few thousand trees that would be harvested have greater value than their wood alone. If these trees are cut down, the harmony and equilibrium of a vast natural ecosystem will be destroyed, along with the confidence that the environmentalists have in the governmental institutions that are designated as guardians of ecological preserves.

André Delisle, a journalist from Quebec, is a science communicator, and a contributor to several magazines, including the Canadian conservation magazine Franc Nord.

Acknowledgment

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concerns

Supreme Court Rules Against Public Beach Access

by Timothy K. Eichenberg

Summer is the time the public heads for the beach; it also is the time that the decisions of the United States Supreme Court are released from cases argued during the winter and spring. Next summer it may be a little harder for the public to get to the beach thanks to two recent decisions issued by the Court.

Nollan v. California Coastal Commission (No. 86-133, June 26, 1987), struck down, as an unconstitutional "taking," a California requirement that coastal development provide for public access along the beach. In *First English Evangelical Lutheran Church of Glendale v. County of Los Angeles* (No. 85-1199, June 9, 1987), the Court found that where the government has "taken" private property by land use regulation, a landowner may recover monetary damages even if he was only temporarily denied the use of his property. Read together, the cases appear to indicate a shift in the Court's views on the delicate question of how far government may go in regulating private development for the public good. The consequences may bode ill for communities that wish to provide for public access and other public amenities through development exactions* and other land use planning techniques.

Both cases address the issue of when governmental land use regulation effects a "taking" of private property, which is prohibited by the 5th and 14th Amendments of the United States Constitution without "just compensation." Private property, of course, may be taken where a federal, state, or local governmental entity initiates condemnation proceedings under its power of eminent domain for public purposes, such as highways, urban renewal, airports, and the like. In such cases, the 5th Amendment requires that the property owner receive "just compensation."

Property also may be "taken" when no condemnation proceedings are initiated. In such circumstances, the property is said to be "inversely condemned" and the property owner also is entitled to receive "just compensation." The classic example of inverse condemnation involves government action causing a physical invasion of private property, such as the flooding of land as the result of the

In June, 1987, the United States Supreme Court handed down two rulings that are likely to affect public beach access; Nollan v. California Coastal Commission, *and* First English Evangelical Lutheran Church v. County of Los Angeles. *The Justices of the Court are (seated from left): Thurgood Marshall, William Brennan, Chief Justice William Rehnquist, Byron White, and Harry Blackmun; (standing from left) Sandra Day O'Connor, Lewis Powell (retiring at the end of this session), John Stevens, and Antonin Scalia. Voting to strike down the California access provisions in* Nollan *were: Scalia, Rehnquist, O'Connor, White, and Powell. Voting to award damages for a temporary "taking" in* Lutheran Church *were: Rehnquist, White, Marshall, Powell, and Scalia.*

* *Development exactions refer to a contribution by a developer to a municipality as a condition to carrying forward a project. Examples include contributions of land for streets, parks, and sidewalks; or fees paid in lieu of such dedications to be used toward affordable housing or public transportation.*

construction of a dam; but it also may occur from more temporary and less physically intrusive invasions, such as from airport noise, or even cable TV installations.

Property may even be "taken" without a physical invasion or divestiture of title when government action causes a substantial interference with the free use and enjoyment of property, or deprives land of all its economic value. Such cases typically involve zoning land as open space after unsuccessful attempts to acquire the property. Although zoning ordinances may properly restrict the use of property under governmental police power authority for such purposes as growth controls, historic preservation, open space, and environmental protection, it may become a regulatory "taking" if it "goes too far" and imposes too heavy a burden on property rights.

Conflicting Decisions

Anyone reviewing the Supreme Court's treatment of the "taking" issue is bound to be confused by the conflicting nature of the decisions and the Court's inability to draw a clear line between the proper exercise of governmental police powers and an unconstitutional regulatory "taking." Justice Oliver Wendell Holmes called it a "question of degree," and the Court itself recognized that it "quite simply has been unable to develop any 'set formula' " for making such a determination. As a result, analogies have been drawn between the Court's test for a "taking" and its test for pornography; "I don't know what it is, but I know it when I see it."

The Court has regularly fallen on either side of the issue. It recently found, for example, that federal environmental regulations prohibiting the use of eagle feathers did not "take" pre-existing Indian artifacts, while certain governmental controls of the pesticide industry could amount to a "taking" of trade secrets. It also held that requiring public access to a lagoon that the owners had made accessible to navigable waters was a "taking," but a zoning ordinance that reduced the density of unimproved land was not a "taking."

As perplexing as the question of when governmental police powers "go too far" and become a regulatory "taking" is the question of what remedies should be available to those who have their property "taken." Several legal scholars and a number of state jurisdictions have been of the opinion that even when property is so excessively burdened by regulation that it constitutes a "taking," the appropriate remedy should be invalidation of the regulation rather than payment of "just compensation," which is required when property is taken by eminent domain or is inversely condemned.

The public policy justification for this view was clearly articulated in *Agins v. Tiburon* (24 Cal 3d 266, 598 P. 2d 25, 1978; affirmed on other grounds, 447 U.S. 255, 1980), where the California Supreme Court stated that if local government entities and officials were subjected to claims for damages for designating zoning densities, "the process of community planning would either grind to a halt, or deteriorate to publication of vacuous generalizations regarding the future use of land." The threat of damage awards also would deprive public officials of the "reasonable latitude" necessary to effectively plan for and implement legitimate land use goals. It therefore held that a zoning ordinance that reduced the density of property from 5 units to 1 unit per acre was not a "taking."

The *Nollan* and *Lutheran Church* cases indicate that: 1) the current majority on the Supreme Court may be predisposed to finding that government regulation "goes too far" and therefore constitutes a "taking," and 2) the Court may more favorably view the awarding of monetary damages once a "taking" by regulation has been found.

The Nollan Case

In *Nollan*, by a 5–4 vote, the Court struck down a practice utilized by the California Coastal Commission requiring that public access to and along the sea be provided as a condition for granting permits for coastal development. The controversy arose when James Nollan, an assistant Los Angeles city attorney, and his wife, applied to the Commission for a permit to tear down their one-story 504-square-foot cottage, and erect a two-story structure that covered 2,464 of the 2,800 buildable square feet on their lot.

The Nollans' property was part of the Faria Tract located in Ventura County, consisting of beachfront lots located between two popular publicly used beaches. Since 1979, the State had required that permits for development upon the Faria Tract be conditioned on the dedication of the dry sandy beach area for public use to "pass and repass" between the two beaches. The Nollans did not object to people walking along their beachfront, which was a narrow strip of sand between their 8-foot high seawall and the water. However, they resisted formalizing the public's right to do so as a condition to their development, and sued the Commission for damages alleging that the access condition constituted an unconstitutional "taking" of their beach.

California pointed out that the state constitution guarantees the public's right of access to tidelands and navigable waters (Article X, Section 4), and State law (Section 30212 of the California Coastal Act) requires all new development to provide for public access to and along the sea. It also argued that the access condition satisfied the constitutional requirements for the exercise of valid police powers because it served an important public purpose, did not deprive the Nollans of all economic use of their property, and did not interfere with the Nollans' investment-backed expectations (tests established by previous Supreme Court rulings).

The Nollans' home at low tide (at high tide the beach is covered by water). The Court's ruling invalidates California's requirement that the Nollans dedicate the beach in front of their seawall for public passage. The public's right to cross their beach remains unsettled, unless the beach is purchased or public rights are asserted through additional litigation under the public trust doctrine (as public tidelands) or under the doctrine of implied dedication.

Furthermore, the condition merely permitted the public to pass along the Nollans' beach, most or all of which was public tidelands.

The Court, however, struck down the public access condition as an unconstitutional "taking." It found that the burdens imposed by the reconstruction of the Nollans' house were not sufficiently related to the public access condition required by the state. It also held that appropriating a public easement across their beach deprived the Nollans of the right to exclude others, which is "one of the most essential sticks in the bundle of rights that are commonly characterized as property."

In the Court's view, the enlargement of the Nollans' beachfront house did not impose additional burdens on public access along the beach. California argued that the development increased private use immediately adjacent to public tidelands, created a "psychological barrier" by walling-off the coastline, and interfered with "visual access" thereby preventing the public from knowing public tidelands were accessible nearby. In the words of the California appellate court that upheld the access condition, the Nollans' house was "one more brick in the wall separating the people of California from the State's tidelands."

The Supreme Court, however, found these arguments unpersuasive. While the development could justify a requirement to limit the height or width of the structure, prohibit the construction of a fence, or even provide a public viewing spot on the Nollans' property, it did not sufficiently burden the ability of the public to pass along the beachfront. Therefore, it could not justify the dedication of the Nollans' beach for public use. Without a proper "nexus" (link) between the public access condition and the public burdens imposed by the development, the Court held that the restriction "is not a valid regulation of land use but 'an out-and-out plan of extortion,'" and if California thinks that public access along the Faria Tract serves a public purpose and "wants an easement across the Nollans' property, it must pay for it."

In *Nollan*, therefore, the Court found that exactions not specifically related to the burdens imposed by the development constitute an unconstitutional "taking." The *Lutheran Church* case addresses the issue of what appropriate remedies are available when government regulation "takes" private property.

The Lutheran Church Case

The First English Evangelical Lutheran Church of Glendale, California, operated a campground for handicapped children known as "Lutherglen," which was located in a canyon along the banks of the Middle Fork of Mill Creek in the Los Angeles National Forest. Lutherglen was destroyed by a flood during heavy rains in 1978 and to protect the public safety, Los Angeles County adopted an ordinance prohibiting the construction of any structures within the Mill Creek floodplain. When the Lutheran Church sought damages against the County for, among other things, denying them all use of Lutherglen, the lower courts dismissed the case on the grounds that under *Agins v. Tiburon*, the remedy for a "taking" is limited to nonmonetary relief, such as the invalidation of the ordinance.

The Supreme Court did not find that the floodplain ordinance constituted a "taking" of Lutherglen. However, it did, by a 6–3 majority, remand the case back to California for a ruling on the "taking" issue, with instructions that if the ordinance was found to be a "taking," then the government must provide compensation for the period during which the "taking" was effective. Simply invalidating the ordinance without payment of fair value for the use of the property during the period of the "taking" would be a "constitutionally insufficient remedy."

The Psychological Effects

The psychological effects of these two cases is likely to be greater than their legal effect. In *Lutheran Church*, the floodplain ordinance was not ruled to be a "taking." However, by specifying that monetary damages may be an appropriate remedy during the time that government regulation effects a "taking," the Court has subjected local governments to risks that they may be unwilling to take. Cautious planning boards and city councils may now balk at adopting measures that restrict development for public safety, growth controls, or environmental protection because they are advised by counsel that they may be forced to purchase the property or pay damages if successfully sued for a "taking." No longer may they simply invalidate the ordinance without considering the economic effects of damage awards.

Likewise, in *Nollan*, the Court did not prohibit the use of development exactions in providing for public access. In fact, it even suggested that a more onerous condition requiring the placement of a public viewing area on the Nollans' property would be acceptable. Nevertheless, the case also may cause a reluctance to utilize creative land use planning techniques, such as development exactions, because the linkage between the exaction and the burden imposed by the development must be made unmistakably clear.

This may discourage the use of development exactions to obtain public benefits, like parkland dedications and beachfront access. It may jeopardize existing programs, in such cities as Boston and San Francisco, where extensive regulations require downtown office development to provide low-cost housing and transportation amenities if specific links to the burdens imposed by the development cannot be substantiated. *Nollan* also raises the question of whether the Court will be willing to recognize the cumulative effects of individual projects, which by themselves may not have adverse impacts, but taken together may significantly impact a community.

There will undoubtedly be overly cautious planners and opponents of public access who will use the decisions to discourage the use of exactions, and other land use planning techniques, to obtain public benefits from private development. Furthermore, the cases seem to indicate that the Court is now headed toward the direction of protecting private property rights and away from the use of local police authority to provide public benefits. As a result, access to public tidelands and the sea may suffer.

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Letter Writers

The editor welcomes letters that comment on articles in this issue or that discuss other matters of importance to the marine community.

Early responses to articles have the best chance of being published. Please be concise and have your letter double-spaced for easier reading and editing.

profile

Robert George Weeks

A Man of Many Skills

by Michelle K. Slowey

Versatility has been Robert G. Weeks' trademark for the 36 years he has worked at the Woods Hole Oceanographic Institution (WHOI). Currently the supervisor of the WHOI mechanical shop, he also has served the Institution as a machinist, welder, rigger, qualified SCUBA (self-contained underwater breathing apparatus) diver, aircraft pilot for single and multi-engined planes, and in many other capacities.

I met Robert Weeks in his tiny office on the WHOI dock—right in the thick of the deafening commotion of machine work. A ruddy-faced man of medium build with a quick, friendly smile, he sat down in his chair, leaning forward, then back, then forward again. Here was someone who obviously was not used to sitting still. "So," he said, "let's get started."

Robert (Bobby to everyone) George Weeks is a genuine Cape-Codder—born in Falmouth 60 years ago, just 2 miles from Woods Hole, near Quissett Harbor. Like the rest of the Cape, Falmouth has changed dramatically in the course of his lifetime. "When I was born," he tells me, "Falmouth had a population of about 5,000. Now it has a winter population of about 27,000 and a summer population of around 70,000." Weeks came by his love for boats honestly, growing up on the harbor, where his father, George Weeks, was a master boat builder. "When I was a kid, I never got involved in sports; I was too busy with the boats. I spent all my time on the water—sailing, racing, quahogging, clamming." As a boy, Bobby quickly learned the many aspects of boat maintenance, while at the same time delivering Western Union telegrams, and the local paper. At 14, he joined the Falmouth Fire Department as a junior callman, accompanying firemen on alarms.

Weeks first worked for WHOI in the summer of 1944 as a deckhand for its small, wooden research vessel called the *Asterias*. His job included setting off explosives, dredging, and the placement of scientific instruments.

That fall he left to serve 3½ years in the Navy as a Boatswain's Mate—gaining experience in the navigation and rigging of Navy transports.

After discharge from the Navy in 1947, Weeks returned to Quisset Harbor boatyard, where he did carpentry, painting, and engine work for three seasons—scalloping and quahogging in the off-seasons. In his spare time, he managed to acquire a private pilot's license under the GI Bill.

Bobby Weeks and scientist Ted Spenser alongside the Stinson Voyager in Florida in the late 1950s.

In 1951, he had an offer to come to WHOI as a member of the mechanical shop, or so-called "garage gang" responsible for getting the WHOI ships and equipment ready for sea, as well as a variety of other projects. There was little specialization at the time, and the members of the crew were necessarily men of many skills. Young Weeks did whatever was needed of him—"The more things you can do, the more valuable you are, that's been my philosophy." He was a mechanic, welder, painter, rigger, and electrician. But his newly acquired pilot's license opened up a new phase of his career.

Pilot

The walls of Weeks' office are covered with photos of ships and planes, mostly planes. He points to a small single-engine craft. "That's the Stinson Voyager, the first plane I flew for the Institution." WHOI acquired the Stinson in 1951 and found an eager and able pilot in Weeks. Whenever asked, which was often several times a week, Bobby would leave the "garage gang" to spend an afternoon, a day, or perhaps a week, flying. Sometimes this involved ferrying about Institution equipment or VIPs. Often it meant actively doing research with one of the scientists.

"One of the main things we used her for at first was studying lightning. Al [Alfred] Woodcock (a WHOI meteorologist) and I would fly to Florida because that was a good area to observe thunderstorms. We attached a fiberglass pole with radioactive material on the end of it to each wingtip, with wires coming back to record the positive and negative charges. We flew all around the storms like that, checking out the electrical currents. It was pretty exciting.

"Later the biologists used the plane for whale-watching. Bill [William E.] Schevill and Bill [William A.] Watkins and I spent many hours flying up and down the coast, in search of whales (mostly right whales) and porpoises." Whale-watching in the Stinson was somewhat awkward though, as the plane could not fly slow enough to closely observe the mammals' behavior.

In 1959, at the request of Schevill, WHOI bought a helio-courier pontoon plane. Much lighter than the Stinson, the helio-courier could fly as slow as 30 miles per hour, and, if manipulated properly in a headwind, could fly at a standstill, or even backwards. The plane's pontoons allowed the pilot to fly low over water and to land in inland bays and lakes if necessary.

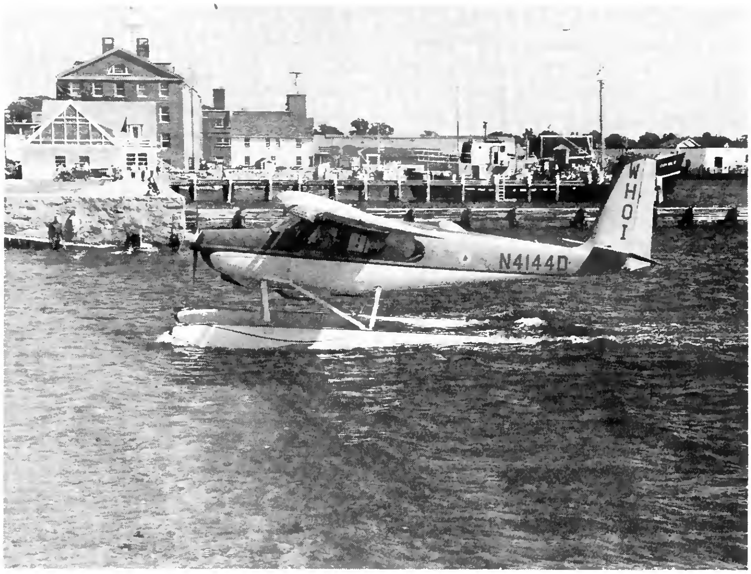
The helio-courier was ideal for whale-watching. Weeks spent the next 10 years flying with Schevill and Watkins—observing and photographing whales along the New England coast, and along the coasts of Florida, Canada, and the Bahamas.

Schevill (now Scientist Emeritus at WHOI) remembers requesting that Weeks be the sole pilot of the plane, as he felt he was "the consummate, careful pilot. Bobby was smart enough to know when to fly and when not to fly. He was always learning more about what the plane was capable of—he could get her in and out of any tight spot. He knew all about inlets, sandbars, and about open water. He knew how to stay in the same piece of water after a whale had dived, even with the wind blowing—and that's a very difficult thing to do. He knew how to tell one whale from another better than most scientists."

The same attributes that made the pontoon plane ideal for whale-watching made it well-suited for dropping and picking up oceanographic instruments, searching for lost instruments, and for aerial photography. Several times a year, Weeks would fly down the coast, from Rhode Island to Florida, with a time-lapse camera, photographing the coastline 600 feet off the water—documenting coastal erosion and changes. He had some amazing experiences: on one occasion he reached Florida just before a hurricane ripped up the coast; on the return trip he was able to document the terrific damage done.

Weeks was involved in many other projects, and flew several other planes (he also was co-pilot for WHOI's four-engine C-54Q aircraft operating in the Indian Ocean and elsewhere). His extensive flying for the Institution has resulted in the collection of considerable scientific data.

WHOI phased out most of its flying program and sold its planes in the early 70s. Today most observational work is done by satellites and buoys. Weeks is still the chief pilot for the Institution though, and sometimes is asked to charter a small, single-engine plane to check on various instruments and buoys deployed for scientific purposes.



Weeks at the controls of the helio-courier near the Woods Hole Oceanographic Institution docks in the early 1960s.

Diver

Though flying took up much of his time during his first two decades at WHOI, diving became an integral part of Week's job as well. As a boy, he went diving in Quisset Harbor with a home-made helmet built from a copper tank. Later, in the Navy, he did more diving with a "hard hat" helmet. So, when the Navy bought WHOI two sets of SCUBA gear in 1952, Weeks was quick to volunteer to use it.

SCUBA diving was a relatively new phenomenon at the time. Encouraged by the exploits of Jacques Cousteau, and reports from the Scripps Institution of Oceanography, which had started a diving program the year before, WHOI decided that diving might play a role in its research as well. Yet there was still much convincing to be done when Weeks and David Owen, a deep sea photographer who would later (in 1955) become the supervisor of the WHOI diving program, started diving for the Institution. The two virtually taught themselves the first year.

They began by using the equipment where it was most obviously useful—in dock and vessel inspection, mooring inspection, recovery of lost objects, and repairs—taking countless nets and wires out of propellers. In 1953, the Institution sent them to an intensive training session with a Navy Underwater Demolition Team. They soon became involved in a variety of scientific projects all along the East Coast—studies of beach profiles, examination of scallop beds and lobster holes, observation of otter-trawl nets in action, experiments with underwater acoustics, and the placing of oceanographic instruments on the ocean floor.

Like the flying, the diving was done on an "on-call" basis. Whenever needed, often with little or no notice, Weeks left his job at the machine shop to don diving gear. Many times this involved going to sea for several days or weeks as part of a diving expedition.

Richard (Dick) Edwards, a much-decorated Navy diver in the Korean War, joined the small diving team of Owen and Weeks in 1954. He remembers riding around on the tops of trawl nets with Weeks in Cape Cod Bay. The Biology Department was studying the effectiveness of certain nets: holding on to the nets, the divers would be towed along by fishing boats—observing firsthand how different nets caught or did not catch fish. Edwards describes those dives as being terribly cold: "SCUBA gear was considerably different back then. It was much harder to get in and out of—and it was much thinner (only ⅛ inch thick). We did a lot of diving in New England waters in the winter and it could be miserable." But, according to Edwards, Weeks often made the work fun. "He was such a great person to be with. So versatile, so friendly. He had such a rapport with people. He would shuffle around, meeting strangers, next thing you know, everyone was giving us a hand."

Weeks made his last dive for the Institution in 1980, but his impact on the WHOI program, along with that of Owen and Edwards, can certainly be attested to. Due in large part to the early divers' groundwork, others at WHOI were introduced to diving—including scientists. Today the informal "in-house" diving program has grown from a handful of employees to more than 70 Institution-affiliated people.

But Weeks did not confine his diving to the Institution. In 1953, he bought his own SCUBA gear and set about working on the side as a commercial diver in a variety of situations, including wharf construction, dam inspection, and ship salvaging. It was as a consultant to a recovery team that Weeks made three 10-day trips on the *Chain*, searching for the *Alvin*, WHOI's submersible, which was lost for nearly a year in 1968. The Navy finally located the sub and hauled it up—but Weeks was the first on board. Inside he found the famous bag lunch left behind when the occupants of the submersible made their quick escape. Due in part to the extreme cold and lack of oxygen, the ham and cheese sandwich was soggy but edible! Its discovery led to new areas of chemical research at the Institution.

The WHOI dock area in the summer of 1945.

Mechanical Shop Supervisor

Between diving and flying for WHOI, Weeks found time to maintain his close ties with the Institution's mechanical shop, where he continued to help with ship maintenance. In 1974, noting his years of varied experience, WHOI designated Weeks supervisor of the mechanical shop. He is responsible for organizing and supervising personnel required for the support of WHOI's ships and scientific departments.

The job is demanding. At any given moment he and his "gang" may be involved in repairing engines, generators, plumbing—or designing a chemical hood or sediment trap for a scientist. The work sometimes takes place in the shop, but often is done in the bowels of the ship, under difficult conditions. Weeks' enthusiasm and friendliness are obviously the keynotes of his managerial style. He and the other shopworkers seem to take a personal interest in each cruise.

The team has an outstanding project completion

Weeks, "flying" off the WHOI dock in the late 1950s, while shopworkers watch.

record. In fact, Weeks accepted the job because "we had always been so proud of getting the ships ready for their cruises on time. I was afraid someone else would come in and botch it all up." His crew has never been the cause of a cruise delay. How does he do it? "Priorities," says Weeks. "I've got so much talent in this shop—I just turn a job over to the right people and it gets done." There is indeed a lot of talent among the staff. As Elizabeth T. Bunce, Scientist Emeritus at WHOI, and one who has worked closely with the mechanical shop on many occasions, notes: "The shop is an absolutely key part of this Institution, because sea-going cruises still form the backbone of oceanography."

Weeks showed the author around the large shop and dock—through the electricians' area, the welding shop, and mechanical shop. He pointed to the huge cranes—one capable of lifting 5 tons, another capable of lifting 25 tons. The noise was overwhelming, but some of the equipment lies idle. "When I have work," he says, "I love this job. When there's not enough work for everyone, it's a pain. We used to be busy all the time, used to work around the clock. Now funding is down and there aren't quite so many cruises. We only have three boats—the *Knorr*, the *Atlantis II*, and the *Oceanus*. See the *Knorr* out there on the dock? It'll sit out there for nine months this year."

A Sense of Responsibility

Clearly a man who thrives on work, Weeks has never confined his energies to his job. He speaks proudly of his wife Doris, three grown children—Phyllis, Wayne, and Carolyn—and granddaughter Ashley. If one can conceive of another activity in this man's life—he lives on a horsefarm, which he and his wife run along with his daughter, Carolyn. "I do all the maintenance and transportation of the animals," he says. "We like to keep busy, that's what keeps us young."

All the years Weeks dived and flew for the Institution, he also was on call as chief diver and Emergency Medical Technician for the Falmouth Fire Department. He's still active in the Fire Department today. "Tonight will be my third night on duty this week. It's my hobby and I guess it's a service to the town. I'm in radio contact with the department 24 hours a day, seven days a week. When you call for an ambulance, chances are we'll be there first." For many years, he was the department's only diver, using his own equipment. He has recovered more than 30 bodies from Cape waters. "Somebody has to do it—it's nothing you'd pin a medal on for," he says quietly.

Over the years, Week's emergency training has served the Institution well. In his files, I found many laudatory letters, thanking him for his presence of mind and assistance in various hurricanes, snowstorms, floods. "When there's a hurricane or a storm," he explains, "I first mobilize the people here in the shop—get the ships and equipment secured, send everyone home, and then spend the night at the Fire Department."

This sense of responsibility to the Institution, to the community, this sense of pride is perhaps Bobby Weeks' greatest contribution. Pride in his flying. "It's more than just flying the damn airplane. I hope I helped all the people I flew for over the years." Pride in getting the ships out on time. "I almost never refused to work overtime—nights, weekends, Christmas Eve." Pride in being part of a team. "I worked with some of the nicest people. They always understood your problems, always helped you out. Today so many people do their job and go home. It is always more than that for me."

Michelle K. Slowey is an Editorial Assistant at Oceanus, published by the Woods Hole Oceanographic Institution.

letters

To the Editor:

It is difficult to be very concise when commenting upon an article such as that by Dr. Kilaparti Ramakrishna in your summer 1987 issue [The Galápagos Marine Resources Reserve, Vol. 30, No. 2, p. 17]. If authors are also enjoined to be concise, perhaps that accounts for his legal opinion leaving the following questions:

1. What language in the Ecuador decree of May 13, 1986, claimed the waters within the baseline as archipelagic waters? I can find none.

2. On what basis does Ecuador claim authority to join the islands by straight baselines?

3. What language in the decree claimed "sovereignty" over the 15-mile zone beyond the baseline? Does the term "exclusive domain" make such a claim?

4. In what sense is the 200-mile territorial sea claimed by Ecuador "comparable" with a 200-mile exclusive economic zone? Has Ecuador retreated from its 200-mile territorial sea? If it has not, why is the 15-mile belt considered important? Is it the author's view that a 200-mile territorial sea is inconsistent with international law?

5. The author says it is unclear what restrictions Ecuador proposes in the 15-mile belt. He later refers to "required restrictions" in this area. What are these and where did they come from?

6. In light of the unilateral decree, in what way is it helpful to Ecuador that other nations elsewhere have reached international agreements calling for international consultations and cooperation for the protection of other ocean areas?

7. The author states that there is no "clearly recognizable general principle of international law" concerning protected areas and that customary law is not well developed. In this light, what are the "valid legal bases" for Ecuador's "required restrictions" in the 15-mile belt.

8. What competence does the United Nations Food and Agriculture Organization have in respect of proposed special area regulation?

9. The author seems to suggest that Ecuador is bound to follow the procedures of Part XII of the 1982 Convention before instituting pollution regulations in the 15-mile belt. If this is so, what is the authority for instituting such regulations without following those procedures?

I hope the author will be permitted the space required to address the above questions to the extent of their relevance.

William T. Burke,
Professor of Law,
University of Washington
School of Law,
Seattle, Washington

REPLY: The author, though overwhelmed, would like to thank Professor Burke for the opportunity to clarify and elaborate on some of the points made in the article in question. To begin with, it is difficult to be concise in responding to Professor Burke on his many queries. Given the scope of the *Oceanus* article, the following answers should suffice.

At the outset, the author would like to state that his intention in commenting on the international legal issues of the Galápagos Marine Resources Reserve is more to look at a hypothetical situation where any developing country, wishing to establish a marine reserve, is confronted with the question of deciding on the area that such a reserve should encompass, and the jurisdictional issues that might arise when this is beyond the internationally recognized limits of territorial waters. Considering the initiative taken by the Sanctuary Programs Division, National Oceanic and Atomospheric Administration (NOAA) of the U.S. Department of Commerce, it is not going to be long before many developing countries embark upon the creation of marine protected areas in their respective jurisdictions, making it imperative for them to deal with such issues.

For this reason, the following assumptions are made in the article. First, the article does not deal with the question of Ecuadorian claim to archipelagic status for the Galápagos islands. Nor does it deal with the appropriateness of joining the islands by straight baselines. Likewise, the article does not deem it necessary to offer a view on whether a 200-mile territorial sea is consistent or not with international law. For the sake of argument, it might even be said that the article accepts the Ecuadorian position on all these issues.

Before answering the remaining questions, it may bear repetition to concede that the reasoning advanced with respect to the specific case of Galápagos would stand or fall depending on how the issues referred to above are resolved. All this notwithstanding, it is contended that issues raised in the article are relevant for other countries interested in creating marine reserves for the protection and preservation of their marine environment.

That said—the question of comparableness of 200-mile territorial sea with the 200-mile exclusive economic zone is raised. It is true that Ecuador has not retreated from its 200-mile territorial sea. But the writings by Latin American scholars and others interested in the region when focused on the kind of jurisdiction exercised by Latin American coastal states in their claimed territorial seas, there does appear an understanding that the claimed territorial seas are comparable with the now recognized concept of the exclusive economic zone. Francisco Orrego Vicuna in his edited book on the *Exclusive Economic Zone: A Latin American Perspective* (Westview Press, Boulder, 1984), on the other hand, dealt with the question of the legal status of the exclusive economic zone (EEZ). The following excerpt from page 3 would be of interest:

> *The problem that has been of most lively concern to the Latin American countries in regard to the Exclusive Economic Zone has indubitably been that of its legal status. The long-standing discussions as to whether the jurisdiction exercised by a coastal state over its adjacent seas is (1) a type of specialized projection of its powers, or (2) a manifestation of its territorial sovereignty, identical with or similar to its sovereignty over the territorial sea, have continued to crop up in relation to the legal status of the EEZ. These differences arose at the outset among the members of the Permanent Commission of the South Pacific; Chile was decidedly in favor of the first approach; Ecuador leaned towards the second; while Peru adopted special modalities that revealed a preference for the latter.*

It comes out that Ecuador is in favor of attributing the traits of territorial seas to that of the EEZ. This obviously appears as a contradiction given the distinction between sovereignty and sovereign rights. It hardly needs explaining that if Ecuador indeed had claimed sovereignty over 200 miles under its earlier decree there is no reason whatever to wish to have sovereignty over the 200-mile EEZ too. Likewise, if Ecuador seriously believed that it is exercising sovereignty over 200 miles, there would have been no need to claim "exclusive domain" over the 15-mile buffer zone around the Galápagos.

The next set of questions from Professor Burke deal with the procedure to be followed in the creation of a special zone. The article under reference sought to establish: that the UN Convention on the Law of the Sea, and other multilateral conventions provide for the procedures to be followed; that some countries pursuant to these have concluded international agreements; and that there is nothing objectionable in attempting to set up a special legal regime in anticipation that it would eventually get wider acceptance.

For these reasons, the article holds that while Ecuador is within its rights to create the special zone, it had done very little to gain acceptance from the competent international organizations. The last paragraph of the article reads in fact as a sermon of sorts on how and what Ecuador should do to gain wide international acceptance of this zone.

Lastly, the question of "required restrictions." It is widely held that a coastal state can declare any or all of its EEZ as a special protected area. Reference was made to the establishment of a protected area—"contiguous to the frontier or to the limits of the zone of national jurisdiction of another party." Such measures indeed were lauded as paving the way for better protection and preservation of the marine environment. Only when these measures conflict with navigation and/or fishing activity would the concurrence of the competent international organizations, in the present case, the International Maritime Organization and the Food and Agriculture Organization, be needed. It is true that the Ecuadorian proclamation did not state the restrictions that it would like to impose in the area. For the reasons given earlier in this reply, the author believes that Ecuador seeks to impose certain restrictions and that they are likely to be in the area of navigation and fishing. If that indeed is the case, it is argued that Ecuador is on a firm footing, given the fragility and uniqueness of the Galápagos, to impose the required restrictions.

Kilaparti Ramakrishna,
Marine Policy and Ocean Management Center,
Woods Hole Oceanographic Institution

To the Editor:

This letter is in regards to your summer 1987 issue on the Galápagos Marine Resources Reserve. The articles and photographs of this unique group of islands were very interesting and I enjoyed reading them. However, I do have a question pertaining to a caption to a photograph on page 27 of that issue. It is located at the end of the article on "Diving in the Galápagos" by Godfrey Merlen.

The lower photograph has the caption naming the pictured animals Galápagos manta rays. It appears to me to be a school of spotted eagle rays (probably *Aetobatus narinari*). In my experiences at The Living Seas, I have found that there seems to be a lot of confusion between the two —especially by the general public.

I just wanted to inform you of this and if I am mistaken I would appreciate it if you would let me know.

Sherri Betros,
Living Seas Aquarist,
The Living Seas,
Walt Disney World Co.,
Lake Buena Vista, Florida

—They were spotted eagle rays. We made an editorial error.—Ed.

Books Received

Aquaculture

Handbook of Mariculture, Vol. I: Crustacean Aquaculture, edited by James P. McVey. 1986. CRC Press, Inc., Boca Raton, FL. 442 pp. $132.00.

Handbook of Microalgal Mass Culture by Amos Richmond. 1986. CRC Press, Inc., Boca Raton, FL. 528 pp. $198.00.

Atmospheric Science

History of the Earth's Atmosphere by M. I. Budyko, A. B. Ronov, and A. L. Yanshin. 1987. Springer-Verlag, Berlin. 139 pp. + vi. $42.00.

Biological Science

Animals Without Backbones, Third Edition by Ralph Buchsbaum, Mildred Buchsbaum, John Pearse, and Vicki Pearse. 1987. The University of Chicago Press, Chicago, IL 60637. 572 pp. + x. $25.00 cloth, $17.00 paper.

Biology by Neil A. Campbell. 1987. The Benjamin/Cummings Publishing Co., Menlo Park, CA. 1101 pp. + xxxii. $39.95.

Corals of Australia and the Indo-Pacific by J. E. N. Veron. 1987. Angus & Robertson Publishers, London, United Kingdom, W1R 4BN. 644 pp. + xi. $95.00.

Frogfishes of the World by Theodore W. Pietsch and David B. Grobecker. 1987. Stanford University Press, Stanford, CA 94305. 420 pp. + xxii. $67.50.

Long-term Changes in Coastal Benthic Communities, edited by C. Heip, B. F. Keegan, & J. R. Lewis. 1987. Developments in Hydrobiology 38. Dr. W. Junk Publishers, Dordrecht, The Netherlands. 340 pp. + xvi. $118.00.

Oceanic Processes in Marine Pollution, Vol. 1: Biological Processes and Wastes in the Ocean, edited by Judith M. Capuzzo and Dana R. Kester. 1987. Robert E. Krieger Publishing Co., Malabar, FL. 265 pp. $43.50.

Population Genetics and Fishery Management, edited by Nils Ryman and Fred Utter. 1987. Washington Sea Grant Program, Seattle, WA. 420 pp. $17.50.

Predation: Direct and Indirect Impacts on Aquatic Communities by W. Charles Kerfoot and Andrew Sih. 1987. University Press of New England, Hanover, NH. 386 pp. + viii. $60.00.

Toxicity of Pesticides to Fish: Vol. I by A. S. Murty. 1986. CRC Press, Inc., Boca Raton, FL. 178 pp. $96.00.

Toxicity of Pesticides to Fish: Vol. II by A. S. Murty. 1986. CRC Press, Inc., Boca Raton, FL. 143 pp. $72.00.

Catalogs and Directories

Out of Print and Rare Periodicals, Books, and Expeditions on Marine Sciences: Catalogue 51, 1986/87. Dieter Schierenberg BV, Amsterdam, The Netherlands. 103 pp. Price unavailable.

Diving

Stress and Performance in Diving by Arthur J. Bachrach and Glen H. Egstrom. 1987. Best Publishing Co., San Pedro, CA. 183 pp. $26.50.

Earth Sciences

Limnology in Australia, edited by P. DeDeckker and W. D. Williams. 1986. Monographiae Biologicae 61. Dr. W. Junk Publishers, Dordrecht, The Netherlands. 671 pp. + xiii. $115.00.

The Fundamentals of Paleohydrogeology of Ore Deposits by Evgeny A. Baskov. 1987. Springer-Verlag, New York, NY. 253 pp. + viii. $79.00.

Geohistory: Global Evolution of the Earth by Minoru Ozima. 1987. Springer-Verlag, New York, NY. 165 pp. + viii. $26.50.

Sand and Sandstone, 2nd edition by F. J. Pettijohn, P. E. Potter, and R. Siever. 1987. Springer-Verlag, New York, NY. 553 pp. + xviii. $85.00.

Three-dimensional Models of Marine and Estuarine Dynamics: Proceedings of the 18th International Liege Colloquium on Ocean Hydrodynamics, edited by J. C. J. Nihoul and B. M. Jamart. 1987. Elsevier Science Publishers, Amsterdam, The Netherlands. 360 pp. + xii. $120.00.

Environmental Science

Ecology of Estuaries: Physical and Chemical Aspects by Michael J. Kennish. CRC Press, Inc., Boca Raton, FL. 254 pp. $117.00.

Environmental Management of Water Projects, edited by Edward O. Gangstad and Ronald A. Stanley. 1987. CRC Press, Inc., Boca Raton, FL. 158 pp. $83.00.

Estuarine Ecosystems: A Systems Approach, Vols. I & II by George A. Knox. 1986. CRC Press, Inc., Boca Raton, FL. 230 and 289 pp. $285.50.

Human Induced Damage to Coral Reefs, edited by Barbara E. Brown. 1986. UNESCO Reports in Marine Science 40. UNESCO, Paris. 180 pp. Free.

Lecture Notes on Coastal and Estuarine Studies, vol. 13: Seawater-Sediment Interactions in Coastal Waters, An Interdisciplinary Approach, edited by J. Rumohr, E. Walger, and B. Zeitzschel. 1987. Springer-Verlag, Berlin. 338 pp. $49.50.

Wastes in Marine Environments. 1987. The Office of Technology Assessment, Washington, DC. 312 pp. Price unavailable.

Fisheries

Ocean Forum: An Interpretative History of the International North Pacific Fisheries Commission by Roy I. Jackson and William F. Royce. 1986. Fishing News Books Ltd., Farnham, Surrey, England. 240 pp. $31.50.

General Reading

Animals in their Places by Roger Caras. 1987. Sierra Club Books, San Francisco, CA. 297 pp. + x. $18.95.

The Mariner's Trivia Book by Rustie Brown. Blue Harbor Press, Lomita, CA. 280 pp. $9.95.

World Record Game Fishes, 1987 edition. The International Game Fish Association, Fort Lauderdale, FL. 320 pp. $9.75.

Year of the Crab: Marine Animals in Modern Medicine by William Sargent. 1987. W. W. Norton & Co., New York, NY. 191 pp. $14.95.

Marine Policy

Cities on the Beach: Management Issues of Developed Coastal Barriers, edited by Rutherford H. Platt, Sheila G. Pelczarski, and Barbara K. R. Burbank. The University of Chicago Department of Geography Research Paper No. 224. 1987. The University of Chicago Department of Geology, Chicago, IL 60637. 324 pp. + vii. $10.00.

Natural Resources Economics and Policy Applications: Essays in Honor of James A. Crutchfield, edited by Edward Miles, Robert Pealy & Robert Stokes. 1986. The University of Washington Press, Seattle, WA. 440 pp. Price unavailable.

The Whale War by David Day. 1987. Sierra Club Books, San Francisco, CA 94109. 168 pp. $9.95.

Physical Science

Stable Isotope Geochemistry, 3rd edition by Jochen Hoefs, Springer-Verlag, Berlin. 1987. 241 pp. + x. $49.50.

Topics in Geophysical Fluid Dynamics: Atmospheric Dynamics, Dynamo Theory, and Climate Dynamics by M. Ghil and S. Childress. Applied Mathematical Sciences 60. 1987. Springer-Verlag, New York, NY. 485 pp. Price unavailable.

Science Communication

Scientific Controversies: Case Studies in the Resolution and Closure of Disputes in Science and Technology, edited by H. Tristram Engelhardt, Jr. and Arthur L. Caplan. 1987. Cambridge University Press, New York, NY. 639 pp. + x. $59.00.

Ships and Sailing

Battlecruiser Invincible—*The History of the First Battlecruiser, 1909–16* by V. E. Tarrant. 1987. Naval Institute Press, Annapolis, MD 21402. 158 pp. $14.95.

The Construction and Fitting of the English Man of War 1650–1850 by Peter Goodwin. 1987. Naval Institute Press, Annapolis, MD 21402. 276 pp. + xi.

The 100-gun Ship Victory by John McKay. 1987. Anatomy of the Ship. Naval Institute Press, Annapolis, MD 21402. 119 pp.

Strategic Antisubmarine Warfare and Naval Strategy by Tom Stefanick. 1987. Institute for Defense & Disarmament Studies, Lexington Books, Lexington, MA 02173. 390 pp.

Warrior—The World's First Ironclad, Then and Now by Andrew Lambert. Naval Institute Press, Annapolis, MD 21402. 192 pp.

Vol 27:4, Winter 1984/85—Options for the U.S. EEZ

- **Deep-Sea Hot Springs and Cold Seeps,**

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Vol 22:4, Winter 1979/80

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Vol 20:2, Spring 1977—The use of acoustics in navigation and oceanography

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Galápagos Marine Resources Reserve

Vol. 30:2, Summer 1987—In 1986, Ecuador declared the waters and seabed surrounding the Galápagos Islands a marine reserve. The legal, political, management, and scientific aspects are described. Includes description of 1982-83 El Niño, and historical articles on Darwin, and on the taking of whales and tortoises in the 1800s.

Japan and the Sea

Vol. 30:1, Spring 1987—The first comprehensive view of Japanese ocean science written primarily by Japanese authors. Describes how tradition and innovation combine to continue forging a strong link between Japan and the sea. Includes fishing, submersibles, SWATH vessel, recovery of uranium, ocean space, and much, much more.

Changing Climate and the Oceans

Vol. 29:4, Winter 1986/87—Forecasts of near-term climate change have challenged scientists to understand complex interactions between the atmosphere, the ocean, and the Earth. The wobbling Earth, changing sunlight, carbon dioxide, polar ice sheets, and deforestation—along with a new generation of research satellites—are described.

The Titanic Revisited

Vol. 29:3, Fall 1986—The second visit to the site, and the first visit by *Alvin* and the remote vehicle, *Jason Jr.*, is described, and new findings are reported. Other articles address the radioactivity of the Irish Sea, the growth of U.S. aquaria, Japanese ocean architecture, and the collaboration of John Steinbeck and Ed Ricketts.

Other available issues . . .

- **The Great Barrier Reef: Science & Management,**
Vol. 29:2, Summer 1986—Describes the world's largest coral reef system.
- **The Arctic Ocean,**
Vol. 29:1, Spring 1986—An important issue on an active frontier.
- **The Oceans and National Security,**
Vol. 28:2, Summer 1985—The oceans from the viewpoint of the modern navy, strategy, technology, weapons systems, and science.
- **Marine Archaeology,**
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Vol. 27:4, Winter 1984/85—Options for the U.S. EEZ.
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- **Summer Issue,**
1981, Vol. 24:2—Aquatic plants, seabirds, oil and gas.
- **The Oceans as Waste Space,**
Vol. 24:1, Spring 1981
- **Senses of the Sea,**
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Vol. 20:2, Spring 1977—The use of acoustics in navigation and oceanography.

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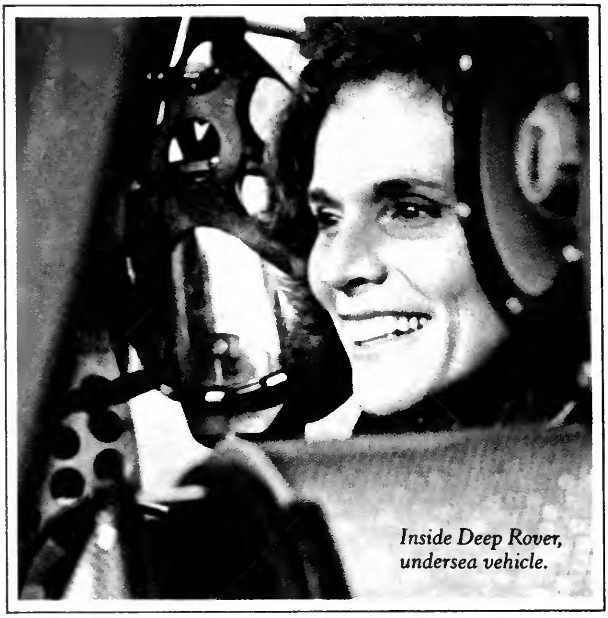

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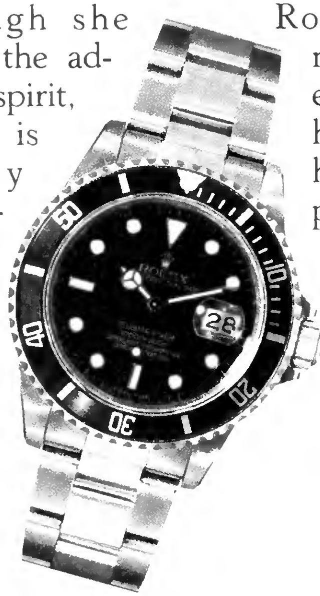

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