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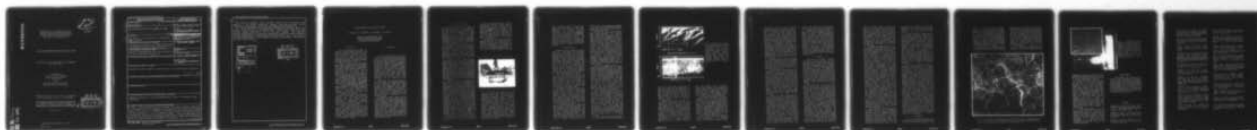
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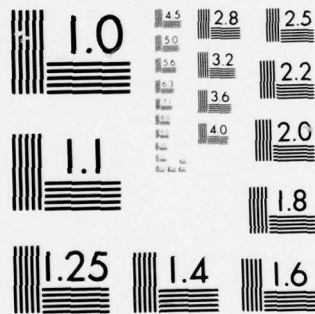
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FINE SCALE MAPPING NEAR THE DEEP SEA FLOOR

F.N. Spiess, C.D. Lowenstein, D.E. Boegeman
and J.D. Mudie

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FINE SCALE MAPPING NEAR THE DEEP SEA FLOOR

F.N. Spiess, C.D. Lowenstein, D.E. Boegeman, and J.D. Mudie

University of California, San Diego
Marine Physical Laboratory of the
Scripps Institution of Oceanography
San Diego, California 92132

Abstract

Over a period of fifteen years our group in the Marine Physical Laboratory has developed a system for mapping various quantities associated with the deep sea floor, and has used it extensively in both the Pacific and Atlantic Oceans. Although some elements of the system have been in successful use for many years, new capabilities have been added in more recent time.

The basic concept is to use instruments towed close to the sea floor, thus allowing fine spatial resolution of the parameters, (or in some instances giving the possibility of measuring aspects which could not even be sensed from the sea surface). Position determination is a key element. This is achieved by use of acoustic transponders and related computational procedures which can yield accuracy of the order of a few meters.

The present instrument suite includes routine use of precision echo sounder, 4 kHz bottom penetration sounder, side looking sonar, proton magnetometer, photography, television, and temperature instrumentation.

In use on an intermittent basis are newer capabilities including conductivity measurement, near bottom plankton sampling, filter system to sample suspended fine particulate material, controlled water sampling, and an instrument to measure the optical properties of the water.

All of the subsystems are powered and controlled from the ship, using the coaxial electrical core to the towing cable. The signals from the various sensors (hydrophones, magnetometer, thermometer, television, etc.) are telemetered up the wire using various methods geared to the requirements of the particular unit.

A major recent advance has been the move toward quantitative use of the sonar systems. The 4kHz unit produces actual acoustic reflectivity information, giving the added capability in some circumstances of calculating sound absorption as well. Most recently the side-looking sonar has been adapted to produce quantitative measurements of backscattered energy.

1. Introduction

We were invited to present this paper to give an up-to-date account of the state of the art in deeply towed survey techniques. Our group has been active in this field since 1961 when we began development of a system to do fine scale mapping of the topography of the sea floor as part of the Marine Physical Laboratory program in underwater acoustics. Although our initial goal was to determine the statistics of the slope of the sea floor, averaged over distances of a few tens of meters, we were well aware that many other interesting fine scale aspects could be most simply studied by using deeply towed instruments. Our approach to the initial system was thus one emphasizing growth potential.

Since that time a wide variety of research problems have indeed been attacked. The two principal (and complementary) fields of most importance have been marine geophysics and (triggered by the Thresher incident) the development of sea floor search technology, particularly with emphasis on aspects related to the environment. Both of these aspects will be treated below - the first by discussion of system use and outputs and the second by description of the equipment itself.

Although we speak of a deep tow system there has never been any single, static set of components nor an engineering design for a finite, complete system. The approach has been an evolutionary one in which immediate research problems were carefully attacked while future possibilities were perceived broadly and allowed to develop as circumstances changed. From time to time opportunities to consolidate and improve existing functions have presented themselves, usually by moving to a new generation of components in the towed body itself. The most extensive recent description is given in Spiess and Tyce, 1973.

2. Mechanical Equipment

The primary requisite of systems of this type, no matter what the level of electronic sophistication, is the combination of a ship, a towed body, a good wire, a winch and deck handling equipment. The ship naturally drives the form which the other components take. We started with a modest developmental installation in a converted Navy tugboat (R/V OCONOSTOTA) and since that time have worked from two pairs of Navy-built oceanographic ships - THOMAS WASHINGTON/DE STEIGUER and KNORR/MELVILLE.

The principal ship requirement is low speed maneuverability. This means, particularly, some form of lateral thrust available forward since the rudder's effect is small at the typical towing speeds of 1 to 2 knots (0.5 to 1 meter/sec). In the case of WASHINGTON and DE STEIGUER there is a trainable, retractable bow thruster, while the other two have the much more flexible Voigt-Schneider propulsion units fore and aft.

The winch used is a hydraulic type, with a double-drum capstan and separate storage reel. Three of the ships have such winches installed as regular equipment, below decks. Since KNORR did not have an adequate built-in capability it was necessary to assemble and install the winch on deck, a job which was carried out initially by the Woods Hole Oceanographic Institution engineering and shop staff. These winches have good long term low speed performance, with a capability for remote control from the laboratory where the operator can view the echo sounder output and be in close touch with other aspects of system operation.

The most important single component of the system is the wire. Our preference is for one type of so-called well-logging cable. It has a coax electrical conducting core, with dimensions about comparable to RG8U. In a properly built wire this will allow use of about 500 kHz bandwidth for an 8 or 9 km length. We typically utilize about 350 kHz at the present time. The coax is overlain with two layers of steel strands which carry the mechanical load. The wire has a breaking strength in excess of 30,000 lbs (about 14,000 kg wt), and is approximately torque balanced. It weighs about 0.7 lbs per foot (1.1 kg wt per meter). In these days of developing new technology the question most often asked is why not use Kevlar or some equivalent. The answer is that the amounts of wire required are so long (8 or 9 km typically) that one must have significant distributed weight in order to depress the wire against the lift forces generated by towing, even at these low speeds. A stronger, denser wire would be the most attractive innovation for towing purposes.

The wire is rigged through our crane and the fish is held solidly at the end of its articulated boom during launch and

recovery. While towing the crane is allowed to swing freely, so that it is not subject to side loading. This also insures that the effective towing point is forward of the rudder - an important factor for ship control with WASHINGTON and DE STEIGUER. The capability to pull in wire and lock the vehicle to the end of the crane boom allows us to launch and retrieve in fairly high sea states - a recent recovery in a 45 to 50 knot blow is an example.

The fish itself (Fig. 1) is primarily a pressure case for the electronics and a mounting place for the various transducers. Since it is heavy (about a ton in water), and operates at low speed it is not necessary to be very concerned with streamlining the vehicle - its existing form is such that the drag force is small compared to the fish

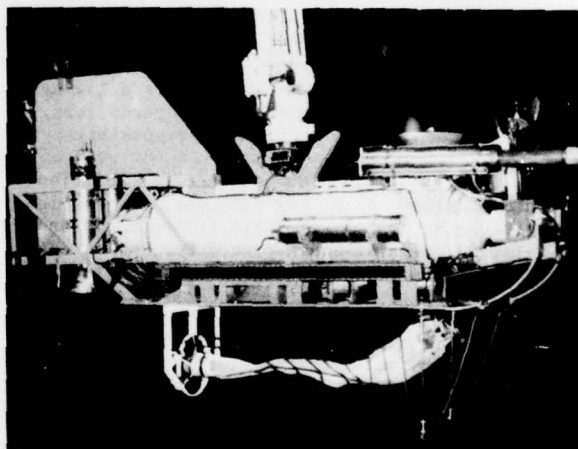


Fig. 1. Deep tow fish secured to end of articulated boom crane prior to a night launching. On the tail the transponder call and receive transducer, backup transponder hydrophone and wide angle camera are visible. Amidships at the crane coupling is the slip ring assembly, below that a case for rechargeable batteries for the photo strobe light, and the starboard side looking sonar transducer. At the bow are the up-looking sounder transducer/reflector, the forward looking nephelometer (under development), the propeller drive for the pump of the millipore filter system, bracket for mounting forward camera and, farthest ahead, the obstacle avoidance sonar transducer. Below the fish is an early version of our plankton net system and extending aft is the cable to the magnetometer and 4 kHz sonar transducer.

weight, giving very nearly a vertical wire angle at the fish. We rely on left right symmetry and the drag of the tail wire to the magnetometer to maintain azimuthal orientation. The tow wire, under tension and lying in a curve controlled by hydrodynamic forces, moves easily along its length, thus transmitting wave-induced motions of the stern of the ship directly to the fish. The resulting vertical heave excites both pitching and yawing motions of a few degrees, which at high sea states introduce some degradation into the performance of the sonar systems.

3. Sensor Systems

Reference to Fig. 1 provides a starting point for a description of the subsystems currently in use. There are 6 sonars to cover a variety of functions. All are fairly unsophisticated in that they involve single transducer sections and were originally designed in echo sounder style to provide good timing and only a gross representation of received sound intensity variation. The narrow beam echo sounder is centered at 125 kHz and can operate with a high repetition rate (up to about 30 pulses per second) to provide smooth monitoring and control information when we are working very close to the sea floor. Its beam width of 5 degrees assures us of good resolution even when we are several hundred meters off bottom.

The conical up-looking transducer is the source and receiver for the 23 kHz sounder used to define the depth at which the fish is operating below the sea surface. A common operating mode is to transmit its signal, recognize the returning surface echo and use it to trigger the narrow beam down-looking unit, thus on a single display we can track fish depth, fish height off bottom and actual full ocean depth.

A simple 40 kHz forward looking sonar provides advance warning of approaching obstacles out to ranges of the order of 500 meters. The ship's normal echo sounder naturally provides early warning of our approach to major features (scarps, peaks, etc). Between these two information sources plus information compiled on adjacent survey tracks the winch controller in the lab can operate intelligently to avoid collision with the irregularities of sea floor.

The side-looking sonar system (long narrow transducers mounted on the side of the fish) has been one of our most productive, in both geological and search contexts. Our current units operate at 110 kHz (both sides) and have a horizontal beamwidth of about $3/4^\circ$, with a broad vertical pattern. Large outcropping rocks (Luyendyk, 1970) or concentrated ship wreckage (Spiess and Sanders, 1971) will produce useful echoes out to nearly a kilometer on either side of the

vehicle's track. Time varied gain is applied in the fish to conserve dynamic range before putting the output signal onto the line for transmission to the ship.

Although this system was designed originally for qualitative depiction of sea floor roughness patterns, it is currently being reconfigured (Lowenstein, 1976) to provide quantitative measurements of deep sea floor acoustic backscattering. The primary changes involved are the elimination of some amplitude limiting circuits, provision of an in situ calibration capability (Pavlicek et al 1975) and implementation of a digitizing capability at the shipboard end of the system. This then allows us to compensate for the changes of intensity which occur with range as well as those variations which are introduced because of changing height of the fish off the bottom. Not only does this make it possible to map intensity variations quantitatively, it allows for ping-to-ping averaging which can form the basis for an adaptive time-varied-gain curve. This in turn makes it possible to optimize the use of the display medium, whose dynamic range is always less than that inherent in other parts of the system.

Use of the computer (PDP-11) as a signal processing component opens up further display possibilities as well. For example most side looking sonar records plot received acoustic intensity as a function of range (as in Fig. 2) with the recording paper moving forward steadily as a function of time. This leads to two forms of distortion - first the distance scales along and across the paper are not equal and second the cross-paper coordinate is proportional to slant range, not horizontal distance from the fish track. The computer can easily generate the necessary slant to horizontal range correction and, given information on vehicle position, can also control the rate of advance of the paper to produce a true x-y plot of the roughness of the sea floor.

The other sonar system of particular importance in the geological context is the broad beam 4 kHz echo sounder. This provides 50 to 100 meter penetration into the sea floor under most conditions, with one meter resolution or better, allowing one to map buried reflecting horizons. Although its beam is essentially omni-directional it achieves a good measure of horizontal resolution simply from being operated close to the sea floor. Given that many reflectors, at 4 kHz, show some measure of directionality, our experience has been that the effective horizontal resolution is about one third to one fourth of the height which we are operating off bottom - typically 40 meters - giving 10 to 15 m lateral resolution.

This system has been operating in a quantitative mode for several years (Lonsdale

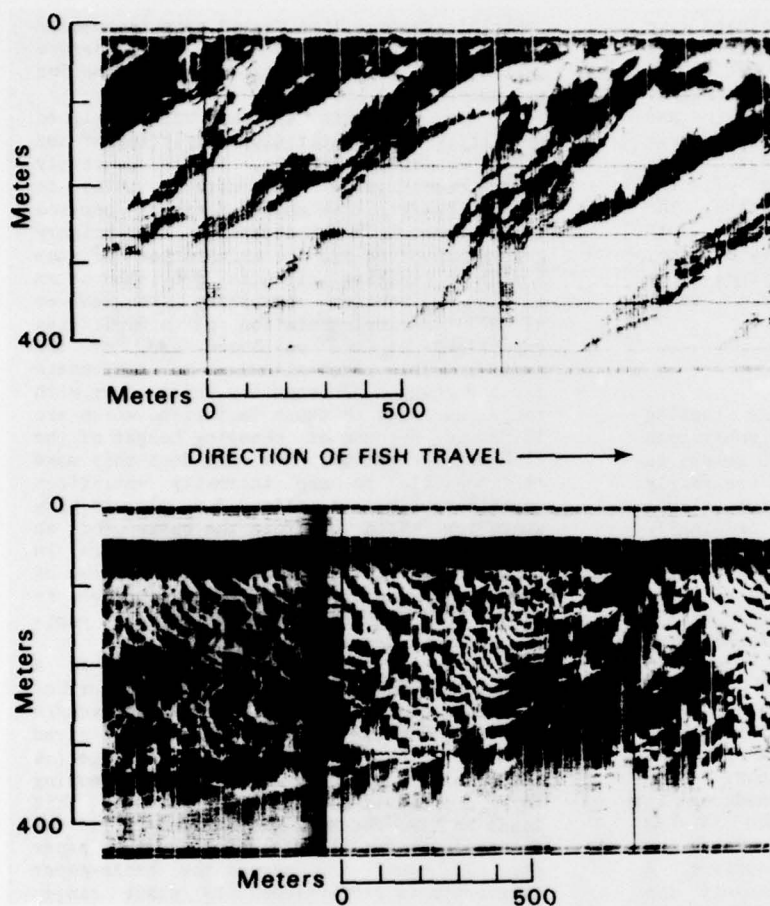


Fig. 2. Patterns on side-looking sonar records caused by textural variations, shadowing and slope differences. The white patches are dunes of poorly reflective foraminiferal sand lying on a highly scattering manganese pavement. This field was discovered during a survey of the Carnegie Ridge between the Galapagos Islands and the Ecuadorian mainland (Spiess et al, 1973, Lonsdale and Malfait, 1974)

et al 1973, Tyce 1975). This has led to ability to correct for spreading loss and plot the actual effective combination of layer reflectivity and sound absorption. We find, for example that our in situ measurements of sound absorption in clays are in good agreement with the work of Hamilton (1976) and others, however, absorption is lower by a factor of three in equatorial carbonate sediments.

Among the non-acoustic systems there are some which have been in use for a very long time and others which are only now being brought into reliable operation. The first such component to be added was the proton precession magnetometer. This type of system lends itself very well to this application since one is dealing with sizeable variations in the field over short distances. A one nanotesla (one gamma) least count is quite adequate and easy to achieve. The principal instrumentation problem is that the tow wire and pressure case are made of ferrous materials - this is overcome by towing the magnetometer head 20 to 30 meters behind the

fish. This system is not a continuous reading type. Rather the polarization current is applied to align the protons, and then quickly cut off, allowing one to receive and measure the frequency with which the protons precess in the remaining earth's field. Typically we take readings at a 30 second interval (about 20 meters spacing).

The principal challenge in the magnetic measurement area is not so much in the instrument as it is in the data analysis calculations which must follow. We are working quite close to highly magnetized material in order to achieve the best possible spatial resolution, and topographic effects must be taken into consideration. Development of the necessary approach to carry out the calculations with minimal computer time has relied on adaptation of conventional fast Fourier transform methods to this problem (Klitgord et al 1975, Parker 1974).

The other major non-acoustic system is the optical one. This is a combination stereo photographic and television capability, with both systems using the same

illumination. Since one wants to operate with the vehicle as far off the bottom as possible, to provide a large field of view as well as to minimize possible collision with the sea floor, one must follow some philosophy to maximize the effectiveness of the illumination. We chose to put the light close to the bottom, spreading it out horizontally to the maximum extent. This has several advantages - it uses minimum power while also decreasing the volume within which obscuring backscattered radiation is generated. It also enhances one's ability to see small scale features, which are difficult to photograph with the very flat illumination field which a distant source provides. Its disadvantages are that the light itself, operating only a few meters off bottom on the average, must be considered as a semi-expendable element, and occasionally shadows will obscure large portions of the field of view.

The cameras are derivatives of standard deep sea 35 mm equipment, with our own format including an LED matrix to print the date and time of the picture directly on the edge of the frame. Usually a pair of cameras will be used, one with a 50° field and one 90°, and with separation of 1.5 m to provide stereo capability for every shot.

Our television is designed to provide a low resolution quick look capability. This enhances our operations by insuring the validity of the photographic work and giving us a real time view of the sea floor from which we can make survey decisions without bringing the fish up to process the film. The TV camera looks at the same field as the film camera and when the strobe fires the resulting image is stored on the vidicon. We then scan the vidicon over the next half second to produce a signal which requires only a narrow (50 kHz) telemetry band. The signal is fed up the wire into a scan converter which provides temporary image storage and also gives an output compatible with conventional video monitors and tape recorders.

Beyond the sonar, magnetometer and optical systems there are several additional measurement and sampling capabilities. These are only used intermittently when they are particularly pertinent to the objectives of the operation. Most frequently employed is the temperature measuring system, which uses a quartz crystal sensing element capable of resolving short term changes of the order of 0.001°C with a time constant of a few seconds (one to two meter spatial resolution at normal towing speeds). We also operate occasionally with a net system for near bottom plankton collection - an early version is shown on the fish in Fig. 1. As presently configured this consists of a set of three nets which can be opened and closed by remote control to obtain three independent samples on any one lowering. There is also a remotely controlled pump and millipore filter

system to allow collection of fine suspended material in the water as we cruise along.

The most recent addition is an entire major subsystem, built jointly between our group and one of the geochemical research groups in Scripps - Craig, Bainbridge and Weiss. This consists of a large frame bolted to the underside of the fish to hold a set of 8 water bottles. Each bottle is capable, when remotely triggered, of quickly (within 2 seconds) trapping a fresh, 10 liter water sample to be brought to the surface for later analysis. The rack also holds an oxygen measuring probe and a temperature/conductivity combination for determining salinity. This system is being used at sea for the first time in May, 1976, as part of a study of hydrothermal emissions on the crest of the East Pacific Rise and at the Galapagos spreading center.

4. Navigation

Navigation is an essential element of any survey or search system - to allow correlation of data taken on different passes through an area, to assure full coverage of the region being examined, and to allow one to return to interesting features for further investigation. We use two complementary systems for this purpose. To establish geographic coordinates with reasonable precision we employ conventional satellite techniques to fix the position of the towing ship. Local, high precision determinations of fish positions, on the other hand, are made using a long base line, near-bottom acoustic transponder system. The ship is also located relative to the transponder net at times of satellite fixes to tie the two systems together.

The transponders are small, battery powered units. The normal cases, with batteries and electronics, are about 16 kg wt in water and are held up from the bottom by glass floats. They are anchored with a piece of scrap iron on a line which can be of any length. Typically we operate them about 90 m above the sea floor to ensure adequate range in spite of the upward sound refraction typical of deep ocean locations (Spiess et al, 1966). Each transponder is set to answer interrogation on one of three frequencies (10.0, 10.5 or 11.0 kHz). The recognition circuit (McGehee and Boegeman 1966) is based on comparing the signal received in a broad band filter with that from a narrow filter centered on the chosen call frequency. All transponders reply at 12 kHz, so that conventional echo sounder receivers and recorders can be used when positioning the ship relative to these navigational marks. The transducer used is a simple PZT cylinder of about 8 cm diameter and 8 cm long mounted on one end of the pressure case or secured just above it on the line to the floats. Acoustic power output is about 50 watts. With a normal battery pack the units will

listen for about six months and give the order of a million replies. Larger battery packs can be added or lithium batteries installed in the normal pressure cases to give lives of a few years. They are equipped with an additional reed relay system which will recognize the call signal when it is modulated at a specific frequency in the 100 to 300 Hz range. This second recognition circuit is used to activate the electrochemical release mechanism (Boegeman and Pavlicek, 1974) to detach the anchor line and allow the transponders to be recovered for future use.

Programmed interrogation sequences (one pulse per second) are transmitted from both fish and ship. The signals received at the fish (whether triggered by calls from fish or ship) are transmitted up the coax in the tow cable and displayed on a range recorder, usually operating on a one second sweep. While in some ways this is cumbersome it does allow one to work in marginal signal to noise ratio conditions since one benefits from ping-to-ping averaging. It also provides a means for smoothing the data and for interpolating to obtain simultaneous ranges from several transponders. The range information for each transponder is read into the navigation computer (PDP-11 or IBM 1800) by positioning a cursor over the appropriate sequence of arrivals. The computer, starting from an approximate estimated position, calculates the x, y coordinates of fish and ship in such manner as to minimize the sum of the squares of the differences between the observed and calculated ranges. The results are presented numerically to the navigator, including a measure of the spread in the ranges to evaluate fix accuracy. If he accepts the result it is then printed on the 30" flatbed plotter which maintains the continuing navigation record. The computer also logs the raw range information so that at a later time, with improved estimates of the transponder coordinates, it can recalculate all the previous fish positions. The computational routine can work with ranges from up to six transponders, although it rarely occurs that the geometry will lead to positions involving more than four units at a time. An expansion of the normal position calculation method allows one to assemble up to a few hundred fixes and carry out an inverse calculation which adjusts the transponder positions to minimize the same quantity to improve on the original estimated transponder coordinates.

The operational approach to effective transponder navigation is straightforward. The first step is to achieve a preliminary understanding of the topography of the area in order to plan the strategy of transponder placement to maximize the area of coverage. With this one can choose actual sites, preferably ones which can be located easily on the basis of ordinary echo sounder data. If possible one should maintain contact with the initially planted units while installing

the latter ones. In this way one can start navigating with estimates of transponder coordinates which are better than dead reckoning or satellite positions of drop points.

Once the units are in place and the first estimated transponder coordinates are in the computer, the survey or search should be started, preferably using initial tracks which cross baselines and take one to disparate points in the work area. In spite of some doctrine to the contrary, it is not necessary to carry out a preliminary transponder surveying phase before beginning the data collection phase. With appropriate computer logging and re-calculation capabilities one can effectively gather data and improve the description of the transponder array simultaneously. Our experience is that, although the navigation will be very rough initially, after 24 to 36 hours of transponder navigated towing it is possible to achieve consistency such that the position errors in regions of good geometry are less than a few meters - adjusting and replotting earlier locations to comparable accuracy.

While it is clear that with this navigation and survey system one can map the distribution of many variables it is equally clear that one would like to place other instruments or take conventional samples (e.g. piston or box cores) in such manner as to relate them to the survey data. For this purpose we have developed a relay transponder (Boegeman and Miller, 1972) which can be clamped to the wire being used to lower the heat flow probe, box corer, or other device. Basically the unit is an adaptation of our normal transponders, but with a built in programmer which cycles through a sequence of replies at various frequencies, rather than replying at only one. In operation the unit is triggered from the ship with a 14 kHz signal, normally at a one second repetition period. The transponder, replies to the first few of the interrogations with a 12 kHz signal which can be heard at the ship. It then shifts successively to 10, 10.5, and 11 kHz replies which interrogate the various transponders in the area, and whose replies are then also received at the ship. During the same period the ship will interrogate the transponders directly, but in differing time sequence. The result is that the information received at the ship is of three kinds - ranges from ship to relay unit, ranges from ship to each transponder and, finally, travel times covering the paths from ship to relay to bottom transponder to ship. These data are inserted into the computer where they are sorted out to determine the x, y coordinates of the relay transponder.

5. Operations

Most of the subsystems described above have been used at sea for a number of years. The sites at which we have worked are shown

in Fig. 3. These range from intermediate depths on various continental or island slopes or in the borderland off Southern California to our deepest operation at 7,000 m. in the Aleutian Trench. Our objective has generally been to document the nature of the sea floor, although in some instances we have been concerned with man-made wreckage. There is at least one printed report for almost every station shown. These are not listed in the reference section here because of the number involved, but we will be glad to provide information on request.

One of the most interesting in the wreckage category was an operation carried out in about 2500 m of water off the coast of

Washington (Spiess and Sanders, 1971) for the Oceanographer of the Navy. The purpose was to find, mark, and photograph the debris fields associated with five ships which had been sunk and detonated as a means for disposing of outdated explosives. This we did in a few days on station, given a circle ten miles in diameter as initial estimate for the site. The side looking sonar (SLS) and transponder navigation were our principal tools. Fig. 4 shows the SLS trace and a photograph of the related debris at one of the wreck locations.

Some aspects of our work have been related to matters of concern in sonar development and utilization, particularly our

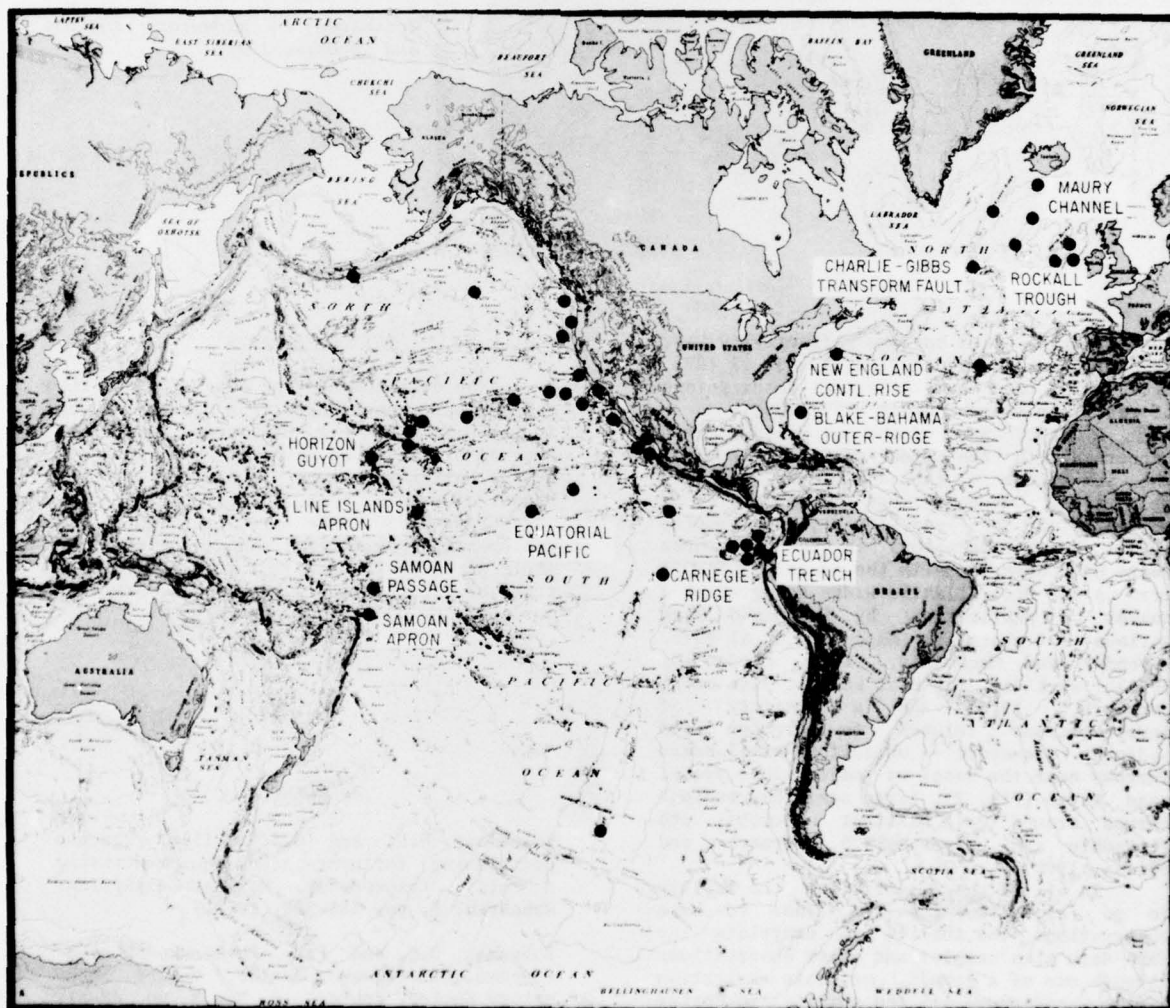


Fig. 3. Chart showing locations of deep tow surveys made to date. Callouts relate to sites primarily concerned with sediment erosion and transport (Lonsdale and Spiess, 1976). Others are concerned with plate tectonics and underwater acoustics.

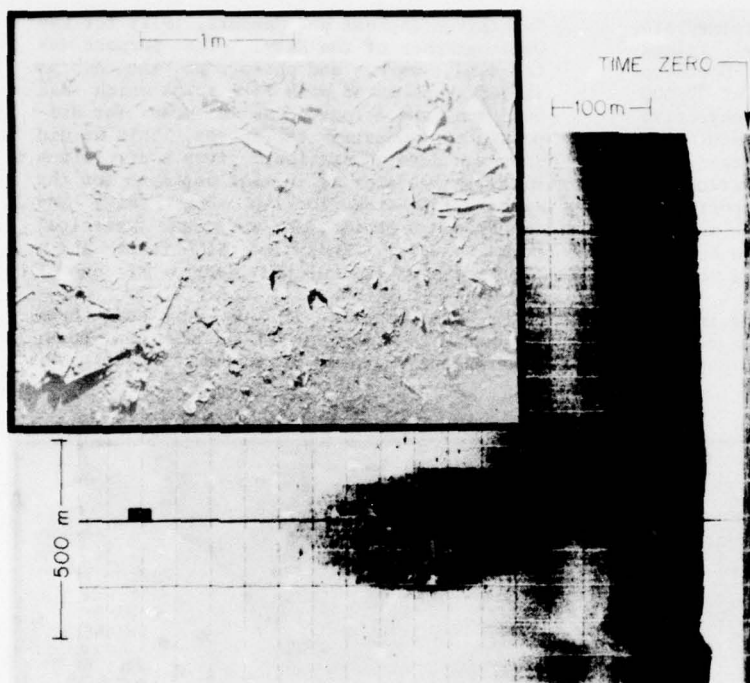


Fig. 4. Side-looking sonar picture resulting from debris scattered on the sea floor. A photograph taken on a later pass through the wreckage area is shown in the inset. Calculations based on shadow dimensions show that essentially no large sized pieces remain from the munitions-laden ship which was detonated in midwater. (Spiess and Sanders, 1971)

quantitative 4 kHz bottom reflectivity and absorption measurements (Lonsdale et al 1973, Tyce 1975) and our statistical descriptions of sea floor slope (Spiess et al 1969).

A major part of the output has been concerned with the fine scale structure of the sea floor - its shape and magnetic properties. Our early work is summarized in volume IV of the Seas (Spiess and Mudie, 1970). Major operations in the last three years have been those in the so-called FAMOUS area on the Mid Atlantic Ridge reported in a number of publications by Macdonald with various collaborators (Macdonald et al 1975, Luyendyk and Macdonald, 1976, Macdonald, 1976), work at the East Pacific Rise crest (Normark, 1976) and a variety of investigations related to erosion and sediment transport -- ubiquitous small scale furrows near the bases of major slope areas, sand waves (Fig. 2), large scale depressions carved around small basement outcrops, etc (Lonsdale and Spiess, 1976, Normark and Spiess, 1976).

In all of these operations the ability to go close to the sea floor to make observations, the ability to correlate the fish data with samples and other observations through use of a common, accurate navigation system, and above all the ability to bring many types of near bottom observational techniques to bear simultaneously have contributed to a very much improved understanding of the dynamic nature of the sea floor environment.

ACKNOWLEDGMENTS

The development and operation of this system has been funded from various sources in the U.S. Navy (e.g. ONR, Deep Submergence Program Office). We have also been supported by the National Science Foundation through a number of grants, most recently DES 74- 03690 and OCE-74-01830. We are indebted to many collaborating scientists and technicians for their participation and to the officers and crews of the research ships which have made our seagoing operations possible.

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