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Generic Assessment of Steep-Slope Seabed Environments: Identification of Sediment Cover and Evaluation of Swath Sonar Systems for OTEC Site Mapping

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I. INTRODUCTION

Ongoing development of prototype designs for obtaining electrical power through Ocean Thermal Energy Conversion (OTEC) systems has been accompanied by evaluation of sites suitable for this non-fossil-fuel source of energy. Table 1 and Figures 1 and 2 indicate potential sites for OTEC development. Figure 3 provides geographic data and sea-floor topography within the areas of interest. The difference in temperature between warm surface water and colder deeper water provides the basic energy resource for OTEC (Quinby-Hunt, in press). Large volumes of the warm and cold water are used to run either open- or closed-cycle turbine systems to produce electricity. A temperature difference of 20°C is generally considered a minimal requirement for efficient operation of an OTEC facility. The vertical separation of the water masses providing the necessary temperature difference provides a critical limit to the design of OTEC plants. In general, design has centered on a limit of 1,000 m for the required temperature difference (Figures 4 and 5; Ocean Data Systems, 1978). Figure 6 illustrates sea surface salinity within the general zone of potential OTEC energy resource.

Assessment of the sea-floor topography and engineering properties of the sediment and/or rock materials underlying the sea floor are additional parameters for design of any OTEC facility. This assessment activity has not been conducted even in a general reconnaissance for many of the sites listed in Table 1 and Figure 2. For plant design, site specific surveys need to focus on areas approximately 10 to 20 km in width that extend from the shore zone to 2,000 m water depth.

The OTEC Seabed Assessment activity has been a joint venture between the Marine Sciences Group of the University of California Berkeley (UCB) and the Pacific Marine Geology Branch of the U.S. Geological Survey (USGS). The UCB/USGS program evaluated a variety of conventional geologic/geophysical technologies that could be utilized for substrate and morphologic evaluation (pre-engineering design phase) of steep slopes off tropical volcanic islands in regions with a substantial potential for development of OTEC facilities (Normark et al, 1982; Winters and Lee, 1982; Normark et al, 1985). In 1984, all activities related to geotechnical studies in areas of potential application for OTEC deployment (previously associated with the Ocean Engineering Program through NOAA) were transferred to the Solar Energy Research Institute (SERI). This report, conducted under the SERI agreement with UCB, provides a state-of-the-art review of marine geologic, geophysical, and geotechnical techniques as well as optimum survey strategies for ocean energy development. This report is a continuation of the existing steep-slope Seabed Assessment Program and is intended to help direct testing, sampling, and model projects.

(A) Objectives

This project will focus on two topics:

1) the identification and distribution of marine sediment types that might impact steep-slope ocean-energy design. This includes (a) a catalogue of sediment types based on existing data, (b) lists of

relevant properties (that need to be determined) as a function of sediment type, and (c) maps and profiles of appropriate generic seabed characteristics. This report emphasizes the general lack of both geotechnical characters and sediment samples in the most likely areas for OTEC development.

2) the evaluation of the applicability of sidescan sonar, wide-beam swath-mapping advanced photographic/video, and submersible systems to OTEC bottom-assessment strategy. A review of the capabilities and limitations of state-of-the-art systems is presented along with suggestions on survey strategies to overcome these limitations.

(B) Methods

The purpose of this report is to evaluate geologic/geophysical/geotechnical properties of the seafloor within steep-slope areas in order to identify procedures for design and construction of foundations necessary for the ocean structures associated with ocean-energy options in those locations. This will be accomplished through the completion of two activities: a compilation of existing data from seafloor sediment samples (using all readily available data inventories) and a review and evaluation of existing remote-sensing (acoustic) techniques for determination of fine-scale relief and substrate characterization.

The first activity involved a search and retrieval of existing marine-sediment data bases maintained by the federal government (NOAA, USN) and academic research groups. Data relevant to areas with potential for OTEC development were reviewed and are presented in map and tabular compilations (see especially, Open-File Report 86-333-B).

The second activity is covered by an examination of state-of-the-art equipment that can be used for site evaluation of topography and surficial structure. Equipment that allows a reconnaissance view of the sea floor has been slow in developing and therefore has produced a difficult situation for marine investigators. In the past, marine geologists had to produce regional-scale maps from a synthesis of detailed but widely-spaced geophysical information, typically by conducting a seismic-reflection survey of the unknown area. Although seismic-reflection techniques provide detailed information in the form of vertical slices through the seafloor and subbottom, no large-scale reconnaissance view of the seafloor is available to further refine the data because the lateral extent of a feature cannot be extracted without a lengthy survey. A reconnaissance view is typically derived from interpretation of and extrapolation between the widely-separated seismic-reflection and echo-sounding profiles. Recent refinement of sidescan sonar systems has enabled these systems to provide a plan view of relatively wide expanses of the seafloor. Thus, the combination of seismic and sidescan profiling dramatically increases the informative value of an oceanographic trackline. Survey strategies involving sidescan survey technology are a major focal point of this report.

The evaluation of sidescan and other swath-mapping technologies includes: (1) a description of the various sidescan sonar and other wide-swath seafloor mapping systems that are presently available including their capabilities, limitations, and applicability to OTEC bottom-assessment studies; (2) development of survey strategies that would use a multipurpose geophysical system in order to obtain the optimum data from an oceanographic trackline; (3) suggestions to overcome limitations using existing technology.

This Open-File Report is presented in two parts. OFR 86-333-A covers a discussion of the sediment types and distribution, evaluation of geotechnical properties, review of swath-sonar and sidescan mapping systems, and a discussion of survey strategies. OFR 86-333-B presents map and table summaries of available geologic sample data and oceanographic and geologic parameters within the area of interest for OTEC development that include data in Figures 1-9 of this report; these data summaries are prepared for distribution independent of the equipment review and survey strategies that form the main body of this report.

II. SEAFLOOR SEDIMENT TYPES

A list of potential areas for OTEC development is presented in Table 1 and their locations plotted in Figures 2A to 2D. These sites cover a broad range of physiographic settings and oceanographic conditions. In this section, we will discuss these geologic settings and the types of marine sediment that may be encountered during the development of an OTEC power plant. It must be emphasized that this discussion is generic in nature and not site or procedure specific because of: (1) a general lack of site-specific data (sampling programs and geophysical surveys have not been conducted over many of the potential areas for OTEC development); and (2) the extreme variation of sediment type in these relatively shallow (less than 2,000 m) water depths.

The geologic setting within areas for consideration as OTEC sites can be grouped into a variety of types of continental, island, or atoll shelves and slopes (Figs. 7A to 7G). "Shelf" is used in this report to define the submerged extension of either a continent, island, or atoll to where a sharp increase in sea floor declivity occurs. This steeper region is termed the "slope" (Fig. 7A). The average water depth, width, and declivity (typically less than 2^{o}) of shelves vary throughout the potential OTEC sites. Sea floor declivities on slopes can vary from approximately 3^{o}, such as the continental slope off west Africa, to greater than 15^{o}, such as the island slope off Johnston Island, central Pacific.

The boundary between the shelf and slope is referred to as the "shelfbreak" (Fig. 7A). The shelfbreak is a physiographic boundary that separates shallow and deep-ocean depositional environments. In the vicinity of the shelfbreak, oceanographic phenomena interact to produce complex processes and complex patterns of sediment transport that produce a variety of sedimentary deposits (Stanley and Moore, 1983). At present, due to a general lack of adequate sample data (Figs. 8A to 8D), marine geologists can only fall back on conceptual models of sediment dynamics, conventional low-resolution geophysical data, and theoretical models of water motion to deduce the factors that influence shelf, shelfbreak, and slope sedimentation and to infer the relative importance of benthic boundary layer processes (bottom currents) that operate in these zones.

It is beyond the scope of this report to discuss in detail the varied factors that control continental/island/atoll shelf and slope sedimentation, and therefore sediment type, but they can be grouped into geologic, biologic, and oceanic factors. Geologic factors controlling sediment types include regional tectonism, shelf-width, depth of shelfbreak, slope gradient, bathymetric irregularity, sediment supply and type, and climate (Karl and others, 1983). Biologic factors include fluctuation in planktonic productivity, coralline buildup versus terrigenous sediment input, and the modification of surface sediment by infaunal and epifaunal organisms (Rhodes, 1974; Jordan, 1978; Jumars and others, 1981; Kennett, 1982). Oceanic factors include tides, waves, internal waves, fronts between water masses, and meteorological-induced currents that all interact to create a wide range of unsteady and quasi-steady water motion that, in turn, influence sediment entrainment and dispersal (Karl and others, 1983 and references therein). The geologic, oceanic, and biologic factors interact to control sediment transport and depositional processes on the shelf and slope. Because of the number of factors and variability (one or several can dominate at different areas), it is impossible to describe a "typical" shelf or slope sedimentary deposit.

The general types of sediment found in the world ocean can be divided into continental-margin sediment, biogenic ooze, glacial-marine sediment, deep-sea clay, and other volcanic-marine sediment (Figs. 9A to 9D). The distribution of these generic sediment types within the area of discussion (40° N to 40° S) is non-uniform. The scale of Figures 9A through 9D generally cannot allow distinction of continental-margin and glacial-marine sediments which both occur within 100 miles of the coastline and are combined for the maps. In contrast, the extensive areas of biogenic ooze and deep-sea clay can be broken into two base subgroups for map representation. Of these broad and, in some cases, overlapping divisions, glacial-marine sediment and deep-sea clay do not occur in the potential OTEC sites due to latitude and water depth constraints and will not be discussed any further. Continental margin sediments can be subdivided into carbonate and non-carbonate sediments, biogenic ooze can be subdivided into siliceous and carbonate oozes, and volcanic-marine sediment can be subdivided into pyroclastic, epiclastic, and authigenic components.

Sediment that veneers present day continental/island shelves consists of modern sediment in equilibrium with present-day environments and relict sediment that is not in equilibrium. On non-carbonate shelves, such as the shelf off New Jersey, modern sands are generally deposited near the shore to within approximately 6 km of the shoreline and are dispersed by longshore and other currents (Curray, 1969; Tillman and Siemers, 1984). Beyond this sandy nearshore facies are either relict sand or modern mud deposits on the central and outer shelf. Relict sediments are typically coarse-grained sand and gravel lag deposits resulting from current- and wave-induced winnowing away of the fine-grained component of the original sediment distribution. Modern shelf muds (silt and clay) occur typically off rivers, in depressions, in some coastal/estuarine areas, and are thought to represent dynamic accumulations (Swift, 1974; Doyle and others, 1979). It is possible for rock to outcrop anywhere on the shelf, especially on shelves with mountainous coasts.

Carbonate shelves are areas where carbonate sedimentation rates dominate terrigenous sedimentation rates. These shelves can be found off continents, such as the shelf off Florida, tropic or subtropic islands such as Barbados, and atolls such as Majuro, Marshall Islands. Carbonate shelves typically occur in tropical or sub-tropical areas where little terrigenous detritus is available. Production of carbonate material and its preservation is linked to climate, oceanographic factors, and terrigenous sedimentation rate (Milliman, 1974; Cook, 1983). Terrigenous sedimentation is more important in nearshore areas of carbonate shelves and in areas off rivers. Therefore, the carbonate concentration typically increases toward the outer shelf. The two most important types of shallow water carbonates are nonskeletal carbonates and reef-building corals (Cook, 1983). Nonskeletal carbonate sediment principally consists of fecal pellet-aggregates and rounded accretionary inorganic precipitates (ooliths). Modern reefs contain approximately 10% of corals in the original growth position which provide the reef framework. The remaining 90% consists of organisms inhabiting the intrareef frame, reef rubble, and unconsolidated sediment (Sellwood, 1978). Some benthic plants, bryzoans, and coralline algae are major producers of muddy carbonate sediment that can form a prominant shelf facies or cement for reef framework (Ginsberg, 1972; Kennett, 1982). Most of these carbonate sediments are sand-size, however, mollusk and reefal debris can contribute gravel-size sediment.

The type of carbonate sediment that dominates any one particular carbonate shelf depends on the type of carbonate shelf, or type of reef. In some cases such as in the Bahamas, a protected shelf lagoon is enclosed by a barrier reef further offshore that has been established by carbonate-coralline growth. The shelf lagoon would be a low energy environment, being protected from waves and currents by the barrier reef, and therefore dominated by muddy sediment. A similar situation exists on atolls, where a circular barrier reef encloses a central lagoon containing no island or with low lying carbonate cays or patch reefs.

Another type of carbonate shelf is the open shelf; for example the shelves of the Yukatan Peninsula or west Florida. On these open shelves there are no barrier reefs and therefore, the shelf exhibits coarse carbonate detritus with finer material transported to deeper waters (similar to the non-carbonate shelf).

The slope generally is a narrow province, its width ranging from 20 to 100 km, that displays steep gradients relative to the shelf. Off major deltas, this seafloor declivity may be 1.3°; off faulted coasts with narrow shelves about 5.6°; off young mountain coasts 4.6°; greater than 10° on the walls of submarine canyons, and up to 45° with some areas near vertical off coral islands and atolls (Emery, 1960; Fairbridge, 1966; Shepard, 1973). Note that these are average declivities. In any of these areas, localized near-vertical cliffs can be found.

A dominant characteristic of most slope morphology is the incision of many canyons that cut the slope more or less transversely (Fig. 7C). Submarine canyons may start near the top of the slope or even incise the shelf and extend to, and in some cases across, the abyssal plain. Submarine canyons are the feeders for sand and silt moving from shelves and slopes to continental rises and abyssal plains (Bouma and others, 1985). Canyons are influenced by a variety of dynamic processes and contain in their axes sediment that can differ from that normally found on the adjacent uncut parts of the slope (Shepard and others, 1977). Mud is the predominant sediment on slopes off non-carbonate shelves and off carbonate shelves that lack a barrier reef. The slope (especially the upper slope) seaward of a barrier reef, however, can consist primarily of reef rubble (Johns, 1978; Mullins and Neuman, 1979). Rock outcrops are also common on steep slopes off narrow shelves adjacent to mountainous coasts (Bouma, 1979).

In general, most slopes are temporary storage areas for sediment in transit to deeper water. Slope sediments off continents and large islands generally lack the coarse sediment typical of the adjacent shelf but are close enough to land to be dominated by terrigenous clay and silt. These upper slope deposits typically grade into biogenic ooze with increasing distance from shore. Biogenic ooze is a common slope sediment type, especially on small island and atoll slopes, and is composed of greater than 30% skeletal remains of pelagic organisms, the remainder being clay. The microfossils that form biogenic ooze are too small and not plentiful enough to form shelf sediment (with the exception of foraminifers which can add to the volume of shallow water sediment).

Biogenic ooze can be subdivided into carbonate ooze (which is composed of foraminifera, nannoplankton or pteropod microfossils, sponge spicules, etc.) and siliceous ooze (which is composed of diatom or radilarian microfossils). The character or type of biogenic ooze that is deposited is controlled by the supply of biogenic material, the dissolution of biogenic material, and the dilution of the biogenic material by terrigenous sediment (Kennett, 1982). The supply of biogenic material is controlled by the relative fertility of the organism producing the material which in turn is relative to the availability of sunlight and nutrients needed for growth (Cook, 1983). Equatorial areas and areas of coastal upwelling are richer in nutrients at or near the surface and are therefore areas of high productivity. Most dissolution of silica takes place in silica-undersaturated surface water (water depths less than 1000 m) while carbonate dissolution increases with depth. Therefore, the most common slope sediment type in areas with potential for OTEC development with little terrigenous sediment, such as atolls or small islands, is nannoplankton-foraminifera (carbonate) ooze (Figs. 9A to 9D).

Mass movement, defined as the movement of sediment by gravity rather than by interstitial fluid (Middleton and Hampton, 1976), is the principal sediment transport process operating on slopes and in canyons (Nardin and others, 1979). Mass movement also occurs on shelves although it is less common here than on slopes. Types of mass movement on slopes range from rockfalls, such as those associated with carbonate-barrier reef buildups, to slumps or rotational blocks of sediment displaying relatively small downslope movement (Nardin and others, 1979), to sediment gravity flows (Middleton and Hampton, 1976), such as the turbidity current reported along the proposed pipe-line route for the OTEC pilot plant at Kahe Point, Oahu, Hawaii (Dengler and others, 1984).

The last sediment type that may be encountered at many of the areas of interest for OTEC development is volcanic-marine sediment. Volcanic-marine sediment can be an important component of shelf or slope marine sediment at any site in the vicinity of active volcanism, particularly near island arcs where sedimentary wedges consisting largely of volcanic components can be several thousand meters thick (Kennett, 1982). Volcanic-marine sediment can be composed of pyroclastic, epiclastic, or authigenic deposits. Pyroclastic sediment, commonly called tephra or ash, is formed as a result of aerial volcanic explosions. Pyroclastic sediment varies widely in grain-size, shape, and composition. It can be composed of dense or porous particles that are crystalized from magma, solidified volcanic rocks from previous eruptions, and incidental fragments of country rock. Epiclastic sediment is composed of reworked fragments of volcanic rock and can be similar to pyroclastic sediment. Authigenic volcanic-marine sediment is the result of submarine eruptions or hydrothermal activity and again varies in size, shape, and composition.

It is evident from the above discussion that the areas for potential OTEC deployment are affected by a multitude of environmental processes that, in turn, control the sedimentary environment. The sedimentary environment at any given installation is, therefore, a site-specific property and must be considered as such when planning and conducting a geologic survey for site mapping.

III. GEOTECHNICAL PROPERTIES OF MARINE SEDIMENT

The design and siting of offshore structures are influenced by geologic conditions. There is a need for identification of active and potential slope failure and for quantitative assessment of the potential for mass movement because of the hazard such mass movement poses to engineering structures. Although seismic-reflection profiles, sidescan sonographs, bottom photographs and sediment samples are an essential part of specifying the type and extent of slope failure, these studies leave several unanswered questions. For example, these data do not specify the causes of slope failure nor predict the effects of earthquake or storm events. The quantitative methods of geotechnology can provide insight into the significant environmental variables and sediment properties that are responsible for slope instability (and affect the sediment bearing capacity) and therefore can be used to explain the geologic observations and serve as a general guide to engineering activity.

Although there is a general lack of data pertaining to the varied sediment types in areas of potential OTEC sites, a generic assessment can be made based on published marine geologic investigations; however, marine geotechnology is still in its infancy. As recently as the mid 1970's, the few actual observations of submarine slumping presented in the literature were mainly qualitative. This is because slope stability analysis requires knowledge of the slope topography, the shape of the major slip surface, the pore-water pressure conditions at the time of slope failure, the sediment strength, and the sediment density; information that is seldom available from submarine slopes.

It is difficult and inherently incorrect to relate geotechnical properties solely to sediment type. Specimens of sediment can occur in very different density states as a result of different sequences of compression and unloading (stress history). These initial conditions are complicated, and it is a problem to decide how rigid a particular specimen is and what will happen when it begins to fail. For example, a loosely compacted sandy deposit may liquefy and flow under the influence of a critical static load while the same deposit compacted to a denser state by bottom-current or storm-wave activity may be unaffected by a similar load (Schofield and Wroth, 1968). In this case, the same type of sedimentary deposit can display two distinctly different geotechnical behaviors. The behavior of silty deposits is similar to that of sand (Lee and Schwab, 1983), however, unlike sand, a convenient method for characterizing the density state of silt does not exist. Thus, it is impossible to list specific geotechnical behavior as a function of sediment type; i.e., the geotechnical behavior of marine sediment is a site-specific phenomenon which is a function of both the sediment type and its stress history. A detailed discussion on marine geotechnology is beyond the scope of this report. For a more detailed discussion of this subject refer to Sangrey (1977) and Lee (1986).

Marine sediments probably have much more in common with soils on land than they have differences. There are, however, a few conditions that tend to occur more commonly offshore than onshore, such as: (1) charging of pore water with dissolved and/or bubble-phase gas; (2) interparticle cementation and grain crushing resulting from the presence of calcium carbonate; (3) the dominant influence of repeated loading (from storm waves and earthquakes); and (4) poor sample quality severly limits the accuracy of geotechnical analysis.

The occurrence of gas is apparent as acoustically impenetrable or "turbid" zones observes on seismic-reflection profiles (Whelan and others, 1976). The production of interstitial bubble-phase gas from the decay of organic matter causes an increase in pore-fluid volume. If the gas is produced more rapidly than pore water can drain, positive excess pore pressure (in excess of hydrostatic) will develop. In time, an increase in excess pore pressure will lead to a decrease in sediment strength and reduced stability for gaseous sediment (Sangrey, 1977). How much strength decrease can, or does, occur in actual sedimentary deposits is unknown, but nonuniformly distributed bubble-phase gas can load the sea floor with its bouyancy and blowouts can result if the degree of buoyancy becomes high enough (Lee, 1986).

The carbonate content of sediment has been suggested to be an engineering index property by some investigators (Demars and others, 1976; Lee, 1982). One of the real challenges to marine geotechnology at present is to identify the unique strength properties that certain calcareous sediments have and develop laboratory or in-place techniques to measure them. Most investigators believe that grain crushing and interparticle cementation are the unique characteristics that lead to the unusual behavior of certain carbonate sediments (Valent, 1979; Lee, 1986). For example, load tests on piles in calcareous sediment disclose frictional capacities as low as one-tenth of those normally used in conventional design cohesionless (sandy) sediment (Lee, 1986). A goal in carbonate sediment research is to derive techniques for quickly recognizing grain crushing and cementation. According to state-of-the-art understanding, the engineering behavior of calcareous sediment may result from cementation, grain crushing, or simply changes in particle shape and size (Demars and Chaney, 1980). Much more research is needed to resolve the relative importance of these factors (Lee, 1986).

Cyclic or repeated loading of loose sand and soft clay also can lead to an accumulation of excess pore pressure and subsequent reduction in sediment strength (Sangrey and others, 1978; Committee on Earthquake Engineering, 1985). Although cyclic loading resulting from earthquake shaking is not unique to the marine realm, lower frequency storm-wave induced cyclic loading is. The amount of excess pore pressure accumulation in a sediment subjected to cyclic loading in general depends on the pressure range of the cyclic stress, the number of stress cycles applied, and the permeability and compressibility characteristics of the sediment (Sangrey, 1977). Many recent publications point out the complications and limitations of the various techniques used to determine the influence of storm waves on slope stability (for example Henkel, 1970; Seed and Rahman, 1978; Clukey and others, 1984; Rahman and Layas, 1985). Future research in marine geotechnology is necessary to improve the understanding of repeated-loading effects.

A special problem that overshadows all marine geotechnical investigations exists because most engineering measurements are made on samples rather than from in-place testing even though in-place testing is the preference of most practitioners. This is because: (1) samples are often taken for geologic reasons and geotechnologic studies are ancillary being used to shed light on geologic processes; (2) in-place tests without adjacent samples provide data that are difficult to interpret; (3) a greater variety of stress states can be applied in the laboratory over a much longer period of time (Lee, 1986), and (4) the high cost of in-place testing. Because it is not economically feasible to obtain deep drill-hole samples or in-place geotechnical measurements routinely, investigators often are forced to rely on short, limited-penetration sediment cores for stability analysis. For these analyses to be valid, it must be assumed that the composition of the sediment (grain size, texture, mineralogy, etc.) at the failure plain is basically the same as that near the sea floor and that the disturbance resulting from sampling does not affect the in-place geotechnical properties of the sediment.

A convenient means of extrapolating sediment strength data below the level of sampling and correcting for sample disturbance exists through the use of normalized-strength parameters (Ladd and Foott, 1974; Mayne, 1980). It has been demonstrated that the normalized-strength parameter approach can be used in conjunction with slope stability analyses (Morgenstern, 1967; Seed and Rahman, 1978) to determine the cause of submarine slope failure and to quantitatively evaluate the sediment properties that lead to failure (Edwards and others, 1980; Lee and others, 1981; Winters and Lee, 1982; Schwab and Lee, 1983; Lee and Edwards, 1986). However, the universal application of this approach is still a matter of debate (Ladd and Foott, 1980; Tavenas and Leroueil, 1980, 1981; Mesri and Choi, 1981).

In summary, the geotechnical behavior of the sediment types occurring within areas of interest as potential OTEC sites is, for the most part, unknown. Furthermore, this behavior is site-specific and under no circumstances should be considered a generic property of a particular sediment type. Geotechnical assessment (slope stability analysis, etc.) at specific OTEC sites will have to be conducted as a basic research project, particularly when involving carbonate sediment.

IV. APPLICABILITY OF SIDESCAN SONAR AND WIDE-BEAM SWATH-MAPPING SYSTEMS TO OTEC BOTTOM ASSESSMENT STRATEGY

Seismic-reflection techniques are useful for identifying the gross physiography of the sea floor and the character of the underlying strata. Seismic-reflection techniques are less useful for sea floor development studies because the lateral extent of a feature cannot be demonstrated without a lengthy survey. The combination of seismic-reflection surveying with swath-mapping systems dramatically increases the informative value of an oceanographic trackline.

In the last 25 years, a variety of sea floor mapping systems have been developed that can provide a plan view of relatively wide expanses of the sea floor. In this section, we will discuss some of these technical developments and how they can be applied for OTEC site assessment. This equipment can be separated into wide-swath bathymetric, sidescan sonar, and photographic systems. Due to the great number of sea floor mapping systems presently available, we will not attempt to name or describe them all, but we will use examples when necessary.

(A) Wide-Swath Bathymetry Systems

Systematic soundings of the deep sea started in the 1930's when acoustic methods replaced the use of lead-line sounding. An acoustic sounding value, typically measured at high repetition rates (2 sec. on the average) and at a 12-kHz frequency, corresponds to the first echo received in a non-stabilized (i.e., rolling and pitching vessel) cone of sound of wide aperture (30° to 60°) originating from the ship. For some more sophisticated systems, a cone of a few degrees (narrow beam) is stabilized for the roll and pitch of the ship. In either case, the first echo is always from the area that is closest to the echo-sounder, which is not necessarily directly beneath it. In areas of irregular relief, multiple echoes can be received. The accuracy of the water depth measured depends on the aperture angle and water depth. For example, a conventional hull-mounted echo-sounder with a beam width of 10^{o} operating in 300 m of water results in sounding a sea-floor area some 52-m-wide. This could mask some considerable seabed irregularities. Add a 5^{o} ship roll that oscillates the echo-sounder beam over a total corridor of approximately 104 m, and the bathymetric accuracy is further diminished. If, however, hull-mounted systems are to be used, multi-beam sonar systems are recommended to obtain greater accuracy and detail (Normark and others, 1985). The acoustic signal must be corrected for the speed of sound in seawater, which varies with water temperature and salinity, and then merged with ship-position data in order to produce a bathymetric map. Only narrow-beam sounders can be used for precise mapping in deep water and steep terrane, but even these systems insonify an area of the sea floor and not a single point.

Multi-beam echo sounders, or wide-swath bathymetric systems, provide at each outgoing acoustic pulse, or ping, several depth values transverse to the ships track (Fig. 11). As the ship moves along, a swath of sea floor is swept with soundings over a width depending on the number of acoustic beams and their aperature. The depth values are digitized and plotted in real-time as contour lines. Therefore, sea floor declivity and relief are immediately available to the scientific party onboard. The time saving and resolution of sea floor topography is proportional to the number of and aperature of the individual beams.

In the mid-1960's the U.S. Naval Oceanographic Office began to conduct bathymetric surveys with a multi-narrow beam acoustic system for classified applications for the U.S. military (Glenn, 1970, 1976). In the last five years, the commercial variant of this system, Seabeam, has been deployed increasingly on oceanographic survey ships of several nations and is revolutionizing the understanding of ocean floor topography. Detailed information on the Seabeam bathymetric system is given by Renard and Allenou (1979) and in technical manuals published by the General Instrument Corporation.

Seabeam is used to map bathymetry in water depths greater than 500 m. Seabeam consists of a narrow-beam echo sounder (NBES) array and an echo processer. The NBES array contains 20 transducers that are mounted fore-aft along the keel of the ship. Operating at a frequency of 12 kHz, these transducers insonify a rectangular area of the sea floor subtending an angle of 54° across the ship track and 2.67° along the ship track (Fig. 11). The return signal is received by a group of 40 hydrophones mounted perpendicular to the keel. The echo processor synthesizes up to 16 discrete returns, calculating the depth and the transverse distance to the ship for all beams. Each return covers an along-track angular width of 20° and an across-track width of 2.67°. Therefore, each depth sample corresponds to a depth averaged over a box on the seafloor subtending an arc of 2.67° x 2.67°. These "sample boxes" do not overlap in the cross-track direction. However, because the signal generation and return occur rapidly as compared to the ships forward velocity, there is usually considerable overlap in the along-track direction. For example, at a water depth of 4000 m, each depth estimate corresponds to a sample covering an area of the sea floor approximately 200 m x 200 m. If the ship speed is 10 knots and the system pings every 3 sec, a new set of depth samples would be acquired each 15 m in the along-track direction. This scenario brings to light one of the main limitations of the Seabeam system. Sea floor topography, especially slopes within areas for potential OTEC development, has components with wavelengths shorter than can be properly sampled by the Seabeam system. This and other limitations will be discussed below.

The Seabeam product is a computer-generated contour map in real time with a swath width equal to approximately 2/3 of the water depth (or 16 beams x 2.67° arc width = 43° swath width) (Fig. 12). The computer also integrates the roll and pitch of the ship (obtained by reference to a vertical gyroscope) with the average sea floor depth calculated from each of the 16 beams in order to produce a contour map with the proper plan perspective. With Seabeam, the time for a given survey is reduced by a factor of 10 or more over a mono-beam system and the resolution generally increased by a factor of 2 to 5.

Whereas use of the Seabeam system can be applied to reconnaissance surveys and the deepest water (> 500 m) parts of site specific surveys, a shallow-water equivalent is also necessary. The Bathymetric Swath Survey System (BS^3, produced by General Instrument Corporation, who make Seabeam) is used to map shelves and slopes, where the water depth is less than 650 m. The BS^3 consists of a 21 beam BO'SUN sonar combined with a digital data processing subsystem and produces a real-time contour chart of bathymetry with a cross-track swath width 2.4 times the water depth. The BO'SUN sonar is a 36 kHz bathymetric system employing 21 adjacent 5^o beams arranged to simultaneously take multiple sonar samples of the ocean bottom along a line perpendicular to the ship track. Similar to Seabeam, the BO'SUN beams are formed by the intersection of orthogonally transmitted and received beams by the General Instrument Corporations patented cross-fan beam technique. The digital data processing subsystem will integrate the roll (±20°) and pitch (±5°) of the ship with the average sea floor depth calculated from each of the 21 beams.

Seabeam and BS^3 permit the investigator to explore new study areas rapidly. However, the resolution of both systems decrease with increasing obliquity of the beams and therefore it is not uniform over the width of the contour plots. An alternative to mapping bathymetry from a hull-mounted or surface-towed system is to carry out the large area "coarse" survey from the sea surface and investigate critical areas with a deeply-towed instrument.

The travel path of acoustic waves that are generated near the surface of the ocean are complicated by a number of factors including gradients in salinity, temperature, and pressure in the water column. Correction for these factors is difficult because some of these gradients vary rapidly as the ship moves. Additional corrections must be made for yaw, pitch, and roll of the ship. Noise generated within the ship and by its passage through the water can also complicate the acoustic signal. Finally, the problems of beam spreading and signal attenuation with increasing depth and side-echos in steep terrain also need consideration.

Studies (for example Dempsey and Westwood, 1984) show that the acoustic travel path variability problem can be significantly reduced by positioning the acoustic source, or transducers, at least 50 m below the ocean surface within a towed body. A tow body will exhibit much less yaw, pitch, and roll resulting from ocean surface waves than a hull-mounted system. A separate tow body will almost eliminate ship noise from the acoustic signal and, if properly designed, generate little of its own noise. The major disadvantages of a towed body are mostly economic such as, launch/recovery difficulties and its vulnerability while being towed. The increased bathymetric accuracy far outweigh these disadvantages.

In a study of deeply submerged volcanoes (water depth = 3000 m) off southern California, Theberge and Lonsdale (1983) were able to compare Seabeam data with bathymetric profiles obtained using a 125 kHz single, narrow-beam acoustic system towed 10 to 70 m above the sea floor. It was found that the Seabeam system was unable to resolve the steepest slopes (greater than approximately 13°) and failed to discriminate between fault scarps and their basal talus slopes. These shortcomings of the Seabeam data were exacerbated because the bathymetric contour algorithum assumes that the along-track soundings are averaged to have the same density as the across-track soundings, which is not the case (Theberge and Lonsdale, 1983).

Mono-beam echo sounders are common on most deeply-towed instrument packages (National Oceanic and Atmospheric Administration, 1979). For example, the Deeply Towed Instrument Package (Deep-Tow) built by the Marine Physical Laboratory, San Diego, contains a 125 kHz narrow-beam (5^o beam width) acoustic system that provides the tow body's height off the sea floor (Spiess and others, 1978). The acoustic travel time obtained from this system is digitized to the nearest 0.1 msec and logged yielding a vertical resolution of ±10 cm. The principal limitation of this depth resolution is not the accuracy of timing, but that the tow body moves up and down in response to surface waves during the time it takes for sound to traverse the entire water column. Waves may produce tow-body depth excursions of several meters with a period of 5 to 10 sec. This introduces a random error of the order of the surface wave amplitude. The effect of this motion on bathymetric accuracy is partially corrected with a pressure-measuring device and simple auxiliary circuits yielding a ±2 m vertical resolution. This vertical resolution is a great improvement over the ±10 m resolution obtained from Seabeam data but: (1) deeply-towed instrument packages typically operate at speeds less than 2 knots, as compared to the 10 to 15 knot survey speed used during Seabeam or BS^3 surveys; and (2) deeply towed bathymetric systems are mono-beam systems. Because of increased survey time, deeply towed bathymetric systems are not economically feasible as reconnaissance tools to choose sites for OTEC installation. Deeply towed systems greatly enhance the bathymetric resolution in critical site-specific areas when used in conjunction with faster surface-towed systems and as a part of a deeply towed instrument package (containing sidescan sonar and/or photographic systems) (Speiss and others, 1978). Examples of deeply towed instrument packages will be described below.

(B) Sidescan Sonar

Sidescan-sonar imaging has been considered by some investigators to be the submarine equivalent of aerial photography with near-source oblique illumination, but it is actually more analogous to side-looking radar imagery (Sabins, 1983). Sidescan-sonar techniques can provide a plan view of relatively wide expanses of the sea floor and can address problems related to sea-floor processes, or recent sedimentary environments, that could not be resolved using echo-sounding techniques and data of previous studies.

Chesterman and others (1958) were the first to report on a standard hull-mounted echo sounder positioned in a nearly horizontal position. Later, Tucker and Stubbs (1961) modified this system using a 1^o narrow beam (horizontal) with gyro-stabilized transducers to correct for the effects of ship roll while Haines (1963) mounted sidescan transducers on a towed vehicle to alleviate the problems of ship noise and motion.

Following the loss of the nuclear submarine THRESHER in 1963, work on sidescan sonar technology began to accelerate because the search for the wreck made clear to the Navy the inadequacies of deep-water sea-floor remote sensing. The Marine Physical Laboratory Deep-Tow system was developed as a result of this directive. The research capabilities of this system were first presented by Spiess (1967) and Normark and others (1968). The Deep-Tow system was able to successfully insonify and map a 1.5-km-wide swath of the sea floor. Since then, both narrower-swath high-resolution systems and wider-swath sidescan-sonar systems such as GLORIA and SeaMARC I and II have been perfected (Laughton, 1981; Ryan, 1982). These systems will be discussed below in greater detail.

The principle of sidescan sonar is relatively simple. A towed instrument, commonly referred to as a fish, sends out a beam of sound that insonifies the sea floor and the reflected acoustic energy is received by the towfish. Variations in the topography of the sea floor alter the amplitude of the energy in the signal bounced back to the receiver and these acoustic signals are used to produce an image of the sea floor. Acoustic reflectivity values of different sediment types (both grain-size and compositional differences) as well as surface texture or roughness also alter the energy of the acoustic echo. Thus, sidescan-sonar systems are able to resolve the distribution of materials, such as sand and gravel, as well as morphology. These data are then transmitted via a mechanical conducting cable to a shipborne recorder that analyzes and displays them in a graphic form as a sonograph of the sea floor. The reflected acoustic energy is generally displayed on gray-level fascimile recorders as intensity-varying scanlines that gradually build up an image of the sea floor as the fish traverses the seascape (Fig. 13).

Conventional sidescan sonar (available from many different companies) can insonify sea floor swaths typically less than 500-m-wide. These systems operate at relatively high frequencies (approximately 100 kHz or higher) to obtain high-resolution sonographs. The effective range of sonar is inversely related to the frequency because higher frequency sound waves are attenuated more rapidly in water. Thus, conventional sidescan sonar are towed close to the sea floor (generally 10 to 20% of the range). For example, the 105 kHz 272-T sidescan fish, built by EG&G Corporation, operates at a maximum range of 500 m. At this range, the fish is flown approximately 50 m above the seafloor yielding a vertical resolution of approximately 1 m (George Tate, U.S.G.S., personnal communication). At smaller ranges, the resolution increases and the tow height off-bottom decreases. Therefore, when operating in deep water, most sidescan sonar systems require extremely long electrically conductive cables. This towing complexity requires deep-water sidescan surveys to be conducted at speeds generally less than 3 knots. The towing arrangement also must be capable of maintaining constant fish altitudes over variable bottom topography. In order to achieve deep towing configurations, specialized shipboard cable-handling equipment is needed, such as: large-diameter storage reels capable of handling up to 8500 m of cable; hydraulic traction winches which can wind and let out cable under large loads; pressure compensators to decouple ship motion from the cable and reduce towing strain; and towfish-to-short baseline navigation to locate and track the towfish in real time (Prior and Coleman, 1981). These problems have led to the development of multipurpose deeply towed vehicles that combine sidescan sonar and other remote sensing systems to be deployed close to the sea floor on extremely long cables. Some of these systems will be described below.

Many people relate the resolution of sidescan sonar only to the frequency of the acoustic pulses. There is some basis for this, however, the actual wavelength of acoustic energy is less important than the transmitted pulse length (Fig. 14). Sidescan sonar systems are actually envelope detection devices, and except for factors such as modal resonance, the length of the transmitted pusle and bandwidth of the detector are more important to target resolution than the number of wavelengths within the pulse. For example, a Klein 100 kHz sidescan sonar system with a pulse length of 0.2 msec transmits a pulse approximately 30-cm-long while the 30 kHz SeaMARC I (Sea Floor Mapping and Remote Characterization) sidescan system, whose pulse length is 0.15 msec, transmits a pulse approximately 22.5-cm-long. Both of these systems produce sonographs with a resolution of less than 1 m operating at a range of 500 m despite the different operating frequencies. This is made possible by increasing the bandwidth obtained from the SeaMARC I transducers. The SeaMARC I system has the unique capability of obtaining sonographs that have the same resolution as systems operating at frequencies higher by a factor of 3 with the increased range of the lower frequency.

The SeaMARC I system was built cooperatively by International Submarine Technology, Redmond, Washington, and Lamont-Doherty Geological Observatory (Ryan, 1982; Kosalos and Chayes, 1983; Chayes, 1983). The sidescan sonar portion of the SeaMARC I sea floor mapping system consists of a 27 kHz port and 30 kHz starboard transducer fixed to a deeply towed fish. These transducers operate at a beamwidth of 50° included angle in the vertical plane and 1.7° in the horizontal plane. The pulse length is step-adjustable by surface control from 0.2 to 3.2 msec. SeaMARC I can operate at a 1, 2, or 5 km total swath width with an optimum resolution of 1/2048 of the range scale (Fig. 15). SeaMARC I provides sufficient resolution to define topographic features having dimensions of a few meters when operating at the 5-km-swath range (Farre and others, 1983). The 5-km-swath images of SeaMARC I span the gap between the high resolution Deep Tow system (Speiss and others, 1978) and the long-range, low-resolution GLORIA system (Laughton, 1981).

The disadvantages of operating a sidescan sonar system on a deeply-towed fish precipitated the development of SeaMARC II. SeaMARC II is a 12 kHz, long range, shallow-towed, high tow-speed sidescan sonar system that produces ocean floor images up to 10 km wide (Blackinton and others, 1983). A 10 knot tow-speed capability (by contrast SeaMARC I operates to tow-speeds typically less than 2 knots) allows more than 4000 km^2 to be surveyed per day. The SeaMARC II fish is flown 100 m below the sea surface on a 180-m-long mechanical conductor cable. Although the resolution is lower than SeaMARC I, and in rugged or steep terrain the problems of side echos, ray bending, etc. come into play, SeaMARC II is a powerful mid-range sidescan sonar system that can be used to investigate potential OTEC sites.

The Institute of Oceanographic Sciences, United Kingdom, developed GLORIA (Geological Long Range Inclined Asdic) to survey large areas of the ocean floor rapidly (Fig. 16). The GLORIA fish is towed approximately 400 m behind the ship and 50 m below the ocean surface (Fig. 17). The transducers are aligned in two rows of 30 elements on each side. The operating frequency is within the range of 6.2 to 6.8 kHz with a 100 Hz swept frequency pulse of 5.33 m active length. This produces a 2.5° horizontal angular beam width and a 30° vertical angular beam width at a fixed inclination of 20° below horizontal. GLORIA operates at tow speeds of 6 to 10 knots with ranges of 7, 15, 22.5 and 30 km available to each side simultaneously. Thus, GLORIA is capable of mapping as much as 27,700 km^2/hr. The signals collected by GLORIA are transmitted to the ship via the cable where they are recorded digitally on magnetic tape and played on a photographic recorder. The raw data are slant-range and anamorphically corrected aboard the ship and are presented through a mosaic of photographic prints as a reconnaissance plan view of the sea floor that resembles an aerial photograph taken from high altitude. Because the data are in a digital format, they are amenable to a multitude of computer-aided image processing and enhancement techniques. GLORIA has the capability to identify features only 20 cm high, features separated by only 45 m in the direction perpendicular to the ships track, and features about 100-m-long in the direction parallel to the ships track. As with other sidescan systems, GLORIA images also include the effect of reflectivity characteristics of sea-floor materials.

Although GLORIA is relatively low-resolution sidescan sonar system, it can provide large-scale reconnaissance views of the sea floor. GLORIA can operate in water as shallow as 150 m and has no maximum-water-depth limit. Thus, GLORIA surveying may be applicable to general reconnaissance in regions of potential OTEC development, especially in remote or frontier regions.

Sidescan sonar imagery provides data that is essential in developing an understanding of sea floor surficial processes. However, like all technical systems, there are limitations. The output from sonar scan line recorders cannot be conveniently registered to a cartographic map base because of distortion inherent in the image scanning technique. Unless ship tracklines are perfectly straight, the resulting image printed will poorly represent the "footprint" of the scan lines on the sea floor. Chart paper (or in the case of GLORIA data, photo prints) are not amenable to the resectioning and rectification needed to remove these distortions and fit the image to a standard map projection (Paluzzi and others, 1981).

Distortion in sidescan sonographs is introduced by the geometry of the side-looking process and by the mismatch between the way scan line recorders display the image and the way the sea floor is scanned. Scan line recorders register sonar echoes as a function of time, not distance, where time is proportional to the slant range, not the true range, from the transducer nadir (Fig. 18). If the terrain is flat, the true range is given by simple trigonometry (towfish altitude must be known) but if the sea-floor slopes, or is irregular, distortion becomes more important. The distortion resulting from sidescan geometry makes the distance between objects appear closer at the near-range field than at far-range.

Sidescan imaging depends on the forward motion of the transducers to construct the image raster. The sonar pulses recur at fixed repetition rates while underway. Therefore scans are made at constant time intervals, not fixed intervals of distance along a trackline. This scenario results in an along-track distortion that is caused by ship-speed variation when the scan line is written on a recorder with a fixed feed-rate. Some recorders (for example the E,G,&G SMS 960) can alter the paper-feed rate according to water speed. Aside from the problems that arise with strong currents or drift, shipboard navigation is seldom accurate enough (in real time) to automatically correct for short term variability in ship speed.

Most recorders write each scan line normal to the direction of paper or film feed. Usually, corrections are not made to accomodate changes in transducer pointing direction that can result from yaw or crabbing of the fish. This sonograph distortion is minimal for conventional short-range systems but is important in long-range devices. Varied ship heading is a more fundamental problem similar to this towfish attitude problem. As ship heading is altered for course correction, the towfish also changes heading. Even if a scan-line recorder could be modified to compensate for limited yaw angles, correction for varied towfish heading requires the chart paper to be deformed to match the trackline.

Computer processing of sidescan sonar data in order to remove artifacts and distortions is an important aspect of sea floor mapping (for example see Lowenstein and others, 1980; Paluzzi and others, 1981; Farre, 1985 and references therein). Processing techniques include digitization, filtering, slant-range correction, trackline correction, and mosaicking.

Some sidescan data are collected in digital format whereas some systems record only in analog format. Analog signals must be digitized and transferred to 9-track magnetic computer tape, using an analog-to-digital converter. Once the data is in a digital format, processing can begin.

Different filtering techniques can be used on digital sidescan data (Farre, 1985). For example, D.C. notch or high-pass spatial filters can suppress illumination gradients. These illumination gradients arise from signal attenuation at far ranges and diminished sea floor acoustic backscatter at shallow grazing angles. Drifting gain or alteration of settings during data collection also change the background brightness in the sidescan image. Illumination gradient suppression forces the background brightness to a common mid-gray level for all images. This greatly improves the gray-level matching of adjacent images for mosaicking. Other frequency modification algorithms can be used in accentuating particular features or trends in sidescan images, but these are not too useful in yielding greater geological insight.

Image resampling used to reshape an image involves vector mapping of each pixel from the uncorrected image into the corrected image. Slant-range (Fig. 18) correction normally derives the elevation by finding the first return, or nadir, within the image and measuring the width of the water column for each scan line. This slant-range processing redistributes the received signal to remove much of the geometrical distortion. A second order correction using the average change in depth down-range requires detailed knowledge of the bathymetry, water temperature, and salinity data; i.e., thermal and salinity stratification in the water column distorts the ray paths and produces focussing and cut-off effects (Laughton, 1981). The effects of sound velocity variations thus affect sidescan images even more than acoustic reflection profiles.

Trackline correction is a function of navigational accuracy. The finer the desired detail (resolution), the more important the accuracy of the towfish path becomes. A discussion of various navigation systems is beyond the scope of this report, however, the reader is encouraged to review the report by Dempsey and Westwood (1984).

After correcting the sidescan data for distortion, navigation errors, and illumination gradients, it is possible to mosaic the data producing an acoustic map of the sea floor (Fig. 19). In some cases, sidescan sonar is unable to discriminate reflectivity variations that result from bottom roughness and that of local slope. To minimize this ambiguity, the navigation-corrected sidescan mosaic is merged with detailed bathymetry. This approach allows the images to be displayed in stereo, color, or perspective, therefore rendering relief and texture simultaneously (Ryan and Farre, 1983; Farre and Ryan, 1984). At present, however, bathymetric mapping, even with multibeam systems, will only depict the larger morphologic features while sidescan systems have much finer resolution.

Advances in computer enhancement techniques have allowed sophisticated manipulation of sidescan imagery. Although these techniques develop clearer images, many are not too useful in yielding greater geological insight. An enormous amount of insight can be obtained from well-navigated slant-range corrected sidescan data (Fig. 19). Further processing may have to be justified on a site by site basis. Future developments may include being able to classify the sediment texture (sediment type) using the backscattered signal from sidescan sonar (Reut and others, 1985), especially if samples or photographs are available to provide groundtruth.

Thus, sidescan sonar surveys are highly applicable to OTEC site evaluation, particularly conventional (high-resolution) sidescan systems and mid-range systems, such as SeaMARC I. The applicability of GLORIA, however, is questionable because it is a reconnaissance tool, not a site-specific tool. Large-scale, or regional geologic studies can be greatly enhanced by the existence of GLORIA data. The U.S. Geological Survey is currently involved in a program (EEZ-SCAN), using the GLORIA system, which will result in a broad, regional reconnaissance survey of the entire 200-mile Exclusive Economic Zone of the United States seaward of the 400 m isobath. This program was formed in order to provide a foundation for subsequent, more detailed studies (such as OTEC site evaluation) focused on areas identified as being of special interest (Gardner, 1984). To conduct a GLORIA survey with the sole purpose of evaluating a particular OTEC site would not be cost effective nor provide sufficient resolution.

(C) Photographic Systems

The use of submarine camera and video systems may be applicable at late stages of OTEC site evaluation after use of the appropriate acoustic systems. The importance of gaining ultra-high resolution imagery of the sea floor is demonstrated by the large number of existing sea floor mapping systems that contain cameras (for example see National Oceanic and Atmospheric Administration, 1979 and literature from Ametek-Straza Division Corp.). Recent major advances in underwater television have occurred through the development of color video cameras and high resolution low-light monochrome units (Dempsey and Westwood, 1984 and references therein). Color video can now be provided from most shallow-water submarine vehicles while high-resolution monochrome video can be provided from deep-water systems. Horizontal resolution of approximately 300 video lines are available in off-the-shelf color video systems. However, there is still considerable variation in performance between various manufacturer's products, and comparisons are difficult because of the lack of a common standard for video camera performance (Dempsey and Westwood, 1984).

The performance of all video systems is limited by the low resolution of conveniently sized recording systems. Although monochrome video cameras now offer resolution in excess of 700 video lines and very low light level requirements, the highest quality 3/4-inch UMATIC recorder is only able to output a resolution of 370 lines on a monochrome picture.

High quality still cameras remain the work-horse of many geological investigations. High-resolution 35 and 70 mm stereo color photographs can be easily taken and processed onboard the ship (for example, see the literature on Benthos Camera Systems, Mass.).

Camera systems can be applied to OTEC site-specific evaluation in a number of ways. For installations of pipeline, cable, or sea-floor platforms, only photographic data coupled with pressure-depth data for the camera can provide sufficient bathymetric resolution of restricted (0 to 50 m wide) areas of the sea floor on submarine slopes. Camera systems also can be used to study the distribution of benthic megafauna as well as to idenify fragile communities which might become endangered as OTEC activities intensify. Bottom photography also helps the geologist or engineer interpret the hydraulic regime or bottom current activity through the identification of small (cm's) primary sedimentary structures, such as bedforms or scours (Middleton, 1977 and references therein).

V. SEA-FLOOR MAPPING SYSTEMS

A wide variety of commercially available sea-floor mapping systems exist. Some stress photographic capabilities, some sidescan-sonar systems, and others subbottom seismic-reflection systems. A towed underwater vehicle can provide an ideal stable platform for survey sensors and permits correlations between data from a number of sensors; for example, a direct comparison between sidescan sonar and color video. In this section of the report, some of these more comprehensive multi-sensor systems will be described. In the following section, we will explain how these sea-floor mapping systems can be applied for site selection and evaluation.

A wide variety of remotely controlled, unmanned vehicles have been developed for monitoring, cleaning, deploying, and constructing sea floor installations at shelf water depths. These vehicles could be adapted for certain aspects of site-specific survey activities, but a review of the capabilities of such systems is beyond the scope of this report. The reader is referred to the comprehensive tabulation of unmanned remotely operated vehicles by the National Oceanic and Atmospheric Administration (1979).

The acquisition of high-resolution data in water depths greater than 300 m has identified several important problems, many of which have already been described. For example, surface-towed acoustic sources and sensors suffer from problems of signal attenuation and beam spreading. High frequency, low-power acoustic sources such as 3.5 kHz seismic-reflection systems (subbottom profilers) lose penetration and resolution as the water depth increases. Also, high-resolution conventional sidescan-sonar systems, capable of providing good bottom target resolution, must be towed close to the sea floor. In areas of rough topography, this requirement is difficult.

These problems have led to the development of multi-purpose deeply towed vehicles that are towed close to the sea floor on extremely long cables. These systems have been built by a number of companies such as, Huntec, EG&G, EDO-Western, Klein Associates, Hydro Products, and others.

(A) EDO Western 4075 Sidescan-Sonar System

An example of a dual-purpose system that combines a sidescan and subbottom system is the EDO-Western 4075. This system uses a positively buoyant deeply towed vehicle (see National Oceanic and Atmospheric Administration, 1979; and Coleman and others, 1982 for approaches including negatively buoyant, neutrally bouyant, and positively bouyant towed vehicles). A 100-kHz sidescan sonar that can operate at swath widths of 50, 100, 200, and 400 m is combined with a subbottom profiler that can be operated at frequencies of either 3.5 or 7.0 kHz. The EDO-Western 4075 can operate in a maximum water depth of 3000 m. The data are multiplexed and transmitted through a single-conductor armored cable to shipboard recorders. Surveys using this system are conducted at slow vessel speeds (< 2 knots). This system is rather simple in that the sidescan sonographs are strictly analog and are not automatically processed for slant-range. However, the towing technique used is basically self-controlling in terms of altitude maintenance. The positively bouyant tow-fish is connected to a tow cable and to a length of anchor chain that is used as a deadweight (Fig. 20). As the chain drags on the sea floor, the chain length in contact with the sea floor varies with the topography. The towfish, in turn, responds and therefore achieves a constant altitude. This arrangement facilitates uniform sidescan coverage and maximum subbottom penetration and resolution. It has, however, limited application in areas without complete sediment cover and in areas of rugged topography as the chain snags on or wedges on relief on the sea floor.

Prior and Coleman (1981) used the EDO-Western 4075 system on the continental slope and Mississippi Fan in the Gulf of Mexico. The 3.5 kHz subbottom profiler was able to obtain penetration to more than 60 m below the seafloor in 818 m of water. The resolution of individual horizons is excellent; stratigraphic units less than 1 m apart 20 to 45 m below the sea floor can be identified. The 100 kHz sidescan sonar system is able to resolve sea-floor features less than approximately 1 m high when operating at the 200 m swath setting. Similar to many other sidescan systems, target resolution is excellent within 125 m of the tow fish track, but declines toward the outer edges of the sonograph.

(B) <u>Hydro Products DSS-125 Deep Sea Survey System</u>

Similar to the EDO-Western 4075, the DSS-125 system built by Hydro Products operates from a deeply towed stable platform. This system is a relatively simple television/photographic system that can operate to a maximum water depth of 6000 m at tow speeds up to 1.5 knots. Ship motion is effectively isolated from the viewing instrument platform on the DSS-125 system by using a tandem, or two-body, towing arrangement. This system employs a separate depressor and instrument platform (Fig. 21). The depressor platform is easily attached and removed from the cable allowing the system to be readily deployed at sea.

The DSS-125 system employs a low light level SIT (Silicon Intensified Target) television camera (monochromatic) and thallium iodide lamps, and a 70 mm still camera for higher-resolution photography. This system is designed for a 10-m altitude survey. The SIT camera includes a 10:1 zoom lens that is controlled from the surface vessel. Zoom viewing angle indicators are presented directly on the video picture to give the operator a continuous indication of zoom lens position and the angle of view of the television system. This information is recorded on videotape for later analysis. In addition, two high-intensity spot lights are used for scaling and determining height measurement directly from the television picture.

A magnetic compass is located on the instrument platform for heading indications and is presented directly on the bottom of the video picture.

A digital telemetry system transmits all control and data signals over a single coaxial cable with the video signal. This includes control of lights, zoom lens, camera focus, photo camera, video data, zoom position, and compass heading. Several spare analog and digital channels are available in the telemetry system for additional instrumentation.

Applications for this system include any requirement where an accurate, efficient ocean bottom visual survey is needed. Complex shipboard heave compensation equipment is not required due to the use of a cable depressor which results in a highly stable viewing platform. Utilizing the television system as a continuous viewfinder, high-resolution 70 mm photographs can be taken of any specific area of interest.

(C) <u>ANGUS</u>

The Acoustically Navigated Geological Underwater Survey system, or ANGUS, is a color camera system designed to work primarily in extremely rugged terrain in maximum water depths of 6000 m. This system is available through the Deep Submergence Laboratory, Woods Hole Oceanographic Institution. ANGUS's subsystems are mounted in a heavy duty steel frame in order to withstand collisions with bare rock outcrops (Fig. 22). ANGUS is designed to maintain continuous visual contact with the bottom at tow speeds of approximately 1.5 knots. However, unlike the Hydro Products DSS-125 system, ANGUS is not a real-time photographic system. The film must be processed onboard the vessel. ANGUS is towed on a standard 1/2-inch trawl wire (non-conductive) and therefore is a relatively simple and portable system.

The ANGUS subsystems include up to three Benthos 35 mm color cameras each capable of shooting 3200 photos. Collectively, the three cameras can be arranged to photograph a swath of sea floor approximately 60-m wide or, alternatively, provide stereo images for details in a swath 20 to 30 m wide, but the selection is fixed for each tow. A temperature telemetry system transmits to the surface the temperature of the water through which the sled is passing. Also, a 12 kHz sonar systems telemeters to the surface the height of ANGUS above the bottom. This permits the operator to control the flying altitude by letting cable in and out.

The electrical power for ANGUS is supplied by a bank of pressure-compensated 12 volt batteries. A high power (1500 watt-second) strobe-light system allows ANGUS to be flown up to 15 m above the bottom and see further than conventional deep sea photo systems. ANGUS photos are typically taken at 20-sec intervals which provides a photo overlap, or continuous photo coverage along the tow path.

(D) Deep Tow

A deeply towed system for fine-scale deep-ocean surveys has been assembled over the last 20 years at the Marine Physical Laboratory, SCRIPPS Institute of Oceanography (Spiess and others, 1978). Better known as Deep Tow, this system is continuously under development with new subsystems being introduced and older, proven elements modified.

The Deep Tow fish is basically a pressure case containing most of the in-water electronics and with the acoustic transducers, cameras, and other sensors or samplers mounted externally to it (Fig. 23). The fish is flown on a coaxial core well-logging (single coaxial conductor) cable that provides for electrical power, control signals, and data telemetry. The subsystems are adjusted and controlled from the surface vessel. Data are digitally logged by computer and are also displayed in analog form on fascimile recorders.

The use of underwater acoustics for remote sensing has been emphasized in the Deep Tow system. Deep Tow consists of five sonar systems. The first is a 23 kHz up-looking sounder that ranges on the sea surface to determine the depth of the fish. The height of the fish off bottom to within about 10 cm is provided by a 125 kHz narrow beam down-looking sounder (5° beamwidth). Both the up-looking and downlooking systems are operated in a linked fashion in order to obtain a picture of both the fish depth history and the actual water depth. These acoustic travel time data are digitized and logged on the shipboard computer.

The principal limit of water depth resolution is the ship heave created by surface waves which may produce resultant fish depth excursions of several meters with a period of 5 to 10 sec. Compensation for this motion is done with a pressure gauge whose output is logged by the computer as an alternative to the up-looking echo sounder. In this case, depths are generated by combining the corresponding pair of pressure and height-off-bottom readings.

A 40 kHz sonar (10° beamwidth) that scans in front of the vehicle is used to detect bottom roughness and large obstacles. Use of this subsystem minimizes the risk of collision with rock outcrops.

A 4 kHz subbottom sounder is streamed slightly astern of the fish to minimize background noise. This system is operated with both a simple analog and a digitized display. In deep-sea sediment this system can detect internal reflectors to a subsurface depth of 50 to 100 m with a vertical resolution of less than 1 m. The frequency of this subbottom system can be shifted to 6 kHz for specified applications.

Deep Tow also contains a 110 kHz sidescan sonar system (horizontal beamwidth of 0.75°) with a maximum range of 750 m with the fish operating 50 m off bottom. Operating at a normal speed of 1.8 kts, 3 km^2 of sea floor can be imaged in one hour. The combination of sidescan and photographic systems on one vehicle allow photo runs (towfish approximately 10 m off-bottom) to provide groundtruth for the sidescan sonograph interpretation and the acoustic data allows an extrapolation of the photographic information over a much larger area.

The components of Deep Tow's photographic system are a 250 watt/sec strobe, three 35 mm still cameras, and a slow-scan television camera. The cameras are mounted to provide stereo coverage photographs with a 1.5 m baseline. The slow-scan TV uses the same strobe as the still cameras. The strobe recharge time, the camera fields of view, and the vehicle speed of advance are such that continuous strings of overlapping pictures can be obtained. Standard format allows production of a strip of pictures about 10-m-wide and over 10 km in length on the sea floor.

Other subsystems of Deep Tow include electrical conductivity sensors, current meters, nephelometer, sediment filters, plankton nets, and 9-liter water sample bottles.

(E) Hydrosonde Deep Tow Seismic System

The Huntec Limited, Hydrosonde Deep Tow Seismic System (DTS) was designed by the Bedford Institute of Oceanography, Canada, for continental shelf mapping. The Hydrosonde DTS is capable of producing processed subbottom seismic-reflection data that can resolve reflection events to a precision of approximately 60 μsec (6 to 8 cm at the sound velocity within sediment) while obtaining subbottom penetration up to 100 m in mud or 50 m in sand. This system includes an optional 50 kHz (1.5°) or 100 kHz (1.0°) sidescan sonar subsystem.

The Hydrosonde DTS consists of a Huntec ED-10B electrodynamic (boomer) source, a Huntec M3 energy storage unit, an Atlantic Research LC-32 hydrophone mounted within the tow body to maintain a fixed source-receiver geometry, a second hydrophone towed 5 m behind the fish, and a fish attitude package (series of accelerometers that sense the orientation of the fish) (Fig. 24).

The sound source is a pressure compensated 500-to 1000-joule boomer which generates a high-intensity short-time-duration pressure pulse with well-defined directional characteristics. The energy is distributed over a bandwidth of 500 Hz to over 6 kHz providing both high-resolution and deep-penetration acoustic components. The boomer is driven by the discharge of energy from the M3 energy storage unit housed in the fish. Therefore, the radiated source energy is independent of the depth of the towfish. The internal hydrophone is mounted in a position that shield it from downward travelling acoustic signals and noise. The streamer hydrophone has a better signal-to-noise ratio at low frequencies than the internal hydrophone, resulting in greater penetration in hard bottom areas.

The Hydrosonde DTS system may also be configured to include a sparker. This allows the user the flexibility to obtain high-resolution seismic-reflection records in stiff sediments or in areas where greater penetration is desired.

(F) SeaMARC I

SeaMARC I is a deeply towed sidescan sonar system (Fig. 25) developed cooperatively by International Submarine Technology and Lamont-Doherty Geological Observatory and is currently operated by the Deep Submergence Laboratory, Woods Hole Oceanographic Institution and Williamson and Associates, Seattle. SeaMARC I (Seafloor Mapping and Remote Characterization) generates rectilinear plan view acoustic images of the sea floor in swaths up to 5-km-wide. SeaMARC I is a two-body system consisting of a 900 kg cable depressor and a neutrally bouyant fish connected by a 100-m-long neutrally buoyant umbilical cable. This towing arrangement decouples the ship motion from the sonar vehicle. Due to a unique combination of wide bandwidth low frequency, stable tow platform, and advanced image processing, the SeaMARC I is able to operate at ranges 10-times-greater than conventional high-resolution sidescan sonar systems of comparable resolution.

The acoustic sensors of SeaMARC I consist of a 27 kHz port and 30 kHz starboard sidescan transducers with a 1.7° horizontal beam. The system also contains a 4.5 kHz downlooking subbottom profiler. A selectable frequency navigation responder is contained within the fish and can interogate and receive signals from bottom-moored transponders. A towfish heading sensor consists of a fluxgate compass with a 0.36° resolution and a towfish 2-axis inclinometer (0.15° resolution) produces attitude information. A multiplexed digital communications system transmits system commands down-link and vehicle data uplink while an analog telemetry system transmits all acoustic signals up-link. Before uplink transmission, in order to maximize the use of the available dynamic range of the telemetry system the sidescan sonar signals are normalized in gain to correct for spherical spreading loss and signal attenuation within the water column.

The shipboard telemetry system decodes all up-link digital data and isolates the various analog acoustic signals. Therefore, the analog sidescan sonar data are available for output to graphic recorders and analog tape. A shipboard digital interface supplies all slant range corrected acoustic imaging data, sensor data, navigation information, and system operating parameters to computer-controlled logging devices. The end result is high fidelity acoustic images of the sea floor with all data recorded in both analog and digital form for post-cruise data processing (Fig. 26).

SeaMARC I can be selected to transmit every 1, 2, or 4 sec, corresponding to 1.5, 3, and 6 km total swath width. These swath widths are slant-range corrected and digitally processed for projection onto 1, 2, or 5 km orthorectified images. With the 1.7^{o} effective horizontal beam, the sea floor distance insonified, in the along-track direction, by each ping varies from 9 m beneath the fish to 85 m at the maximum 6 km total swath length. Resolution of the slant-range corrected images is approximately 1/20 of the swath width.

(G) SeaMARC II

SeaMARC II, operated by the Hawaii Institute of Geophysics, is a long-range, shallow-towed, high-speed sidescan-sonar system as compared to SeaMARC I which is a relatively slow-speed, deeply towed system. The SeaMARC II system consists of a tow body, cable depressor, and shipboard electronics (Fig. 27). The sidescan-sonar system consists of two acoustic transducer arrays (port and starboard). The port array transmits and receives 11 kHz signals while the starboard array uses 12 kHz signals to allow separation of signals coming from two sides. The towfish emits two fan-shaped beams 2°-wide in the horizontal dimension concentrated to angles between straight below the tow body and the horizontal.

Each transducer array is composed of two lines of transducers. When transmitting, the two lines are driven in parallel, but while receiving, the two are measured separately. The phase difference between the two received signals is a measure of the arrival angle of the incoming acoustic echo. Therefore, each sea floor reflector can be characterized by the echo amplitude, the acoustic travel time, and the arrival angle. These three parameters are measured by the subsurface electronics package and corrected for geometry before being telemetered through a coaxial tow cable to the ship for processing.

The acoustic travel time and the arrival angle of the echo at the tow body can be used to calculate the water depth of the reflector using certain assumptions about acoustic travel paths in the ocean and the height of the tow body from the ocean floor. A major difference between SeaMARC I and SeaMARC II is its ability to measure the angle from which acoustic energy arrives at the tow body. When the data tapes are processed following the cruise, a wide-swath bathymetric map with a width 3.4 times the water depth is produced. Sidescan images are a combination of small-scale reflecting properties of the bottom (micro-reflectivity) and the specular reflections from sea-floor declivity (macro-reflectivity). The merging of bathymetry with sidescan data allows a more accurate and rapid understanding of bottom character than with either output by itself.

SeaMARC II is towed approximately 100 m below the sea surface at speeds up to 10 knots. This tow speed and maximum 10-km-wide swath width allows more than 4000 km^2 to be surveyed per day. Although this system appears ideal for sea-floor mapping, all of the problems of shallow-towed systems exist; i.e., signal attenuation, beam spreading, etc. Recently, SeaMARC II bathymetry maps were used in a detailed investigation of a submarine ridge in deep water off the coast of Oregon. These maps lacked resolution of sea floor topography in plan view and were not as compatible with GLORIA sidescan data as supposedly lower-resolution Seabeam charts (J. Gardner, U.S.G.S., personnal communication). As the SeaMARC II system develops, it has the potential of becoming an ideal marine geologic tool.

(H) ARGO/JASON

The Deep Submergence Laboratory, Woods Hole Oceanographic Institution, is currently developing an unmanned submersible called ARGO/JASON. ARGO is a deeply towed vehicle capable of operating to a water depth of 6000 m from a coaxial cable (Fig. 28). JASON is a remotely operated vehicle that can leave ARGO on its own tether for close-up or more detailed functions (Fig. 29).

To visualize the ocean floor, ARGO employs both acoustic and optical imaging systems. Real-time video (monochromatic) is transmitted up the cable from three SIT cameras. These cameras are a 12 mm down-looking wide angle, a forward-looking 24 mm, and down-looking 24 to 80 mm zoom. Lighting is provided by high energy incandesent lights and strobes mounted on the main vehicle. Through use of the strobes, slow-scan television capability allows images to be grabbed by electronic frame stores for viewing and digital enhancement. In real-time video mode, ARGO is flown approximately 15 m off bottom while in slow-scan mode it is flown up to 25 m off bottom. This allows ARGO to photograph sea floor swaths up to approximately 40 m wide with excellent resolution.

Other systems of ARGO include a Benthos 372 35 mm still camera, capable of taking 800 high-resolution color photographs. ARGO also is outfitted with a Klein 100 kHz sidescan sonar (also available with a 50 kHz optional system). Although presently being used as an avoidance sonar system, the Klein system is capable of being used as a conventional sidescan with a 1-km-swath width capability. A 200 kHz altimeter and 12 kHz pinger allow the water depth and fish altitude to be accurately monitored, and sea-floor-anchored acoustic transponders (Fig. 29) or shipboard short-base-line acoustic navigation sensors allow the towfish to be accurately navigated in real-time. ARGO has the capability of adding other systems as desired, including a subbottom acoustic profiler, thermister, hydrophone, current meter, transmissometer, etc. Towfish attitude information is recorded constantly, including pitch, roll, heave, and heading. A shipboard heave compensator is used to decouple ship motion from the fish (Fig. 30).

JASON is still under development, but a proto-type is now being tested. The concept controlling JASON's design is to have a vehicle with the same viewing and manipulative capabilities of a manned-submersible. JASON would leave its hanger in ARGO on its own tether. It should be able to perform close-up inspection, precision sampling, and other manipulator functions using stereo color television and dual robot manipulator arms (Fig. 29). Samples obtained by JASON would be taken back to ARGO for temporary storage, permitting the two systems to remain on the bottom for extended time periods.

All ARGO data is multiplexed and telemetered to the surface through an armored coaxial cable. Here the imagery is displayed on video monitors and recorded on both 1/2 and higher-resolution 3/4 inch tape, or etched directly on laser disc.

The ARGO system has been used on only two cruises thus far. Although the finding of the HMS TITANIC in September, 1985, was spectacular (see Science, vol. 229, p. 1368-1369), the recent ARGO-RISE cruise over the East Pacific Rise proved the applicability of the ARGO system toward sea floor mapping and site evaluation in rugged volcanic terrains.

VI. OTEC SITE EVALUATION: SURVEY STRATEGY

Until recently, the marine geologist had to study the sea floor and the rock layers beneath it in a sequence that is the reverse of subaerial geologic investigative procedure. Geologists working on land typically study an unknown area by first obtaining Landsat satellite images of the region in order to investigate large-scale trends. Next (or before satellite imagery, first), the geologist could study aerial photographs. The final step would be to visit the area using topographic maps and take samples or photographs of interest. Thus, the land geologist focuses his attention from a large-scale reconnaissance survey to the details of a site-specific survey. The marine geologist usually does not have access to a large-scale reconnaissance view of the sea floor; the reconnaissance-scale view is derived from interpretation of widely separated survey lines, or sample locations, or data from small area, detailed studies. The development of sophisticated sonar and photographic systems is rapidly changing the investigative approach of marine geologists.

(A) Step 1: Literature Search

The first step in conducting a sea floor assessment study for selection or engineering assessment of an OTEC site is to collect any existing data. The earlier section of this report demonstrates the general lack of site-specific data, but with systematic mapping programs such as EEZ-SCAN more information is becoming available. Although the GLORIA wide-swath sidescan sonar system is not directly applicable to OTEC site surveys, regional trends, including geological hazards, are important to sea floor development. For example, GLORIA data has shown that the structural style and degree of incision of submarine canyons into slopes differs significantly from previously published maps (Scanlon, 1984; Gardner, 1984). It is important for OTEC planners to avoid the dynamic environments of these conduits of sediment transport.

(B) Step 2: Reconnaissance Survey

A reconnaissance survey to select appropriate sites for OTEC development should be based on a combination wide-swath bathymetric mapping and sidescan sonar imaging in addition to conventional marine geophysical systems (seismic-reflection profiling, both high-resolution and deep penetration). The choice of sidescan system is a function of water depth; in extremely shallow water (< 50 m), only short-range, conventional high-resolution sidescan systems such as the EDO-Western 4075 can be used. In deeper water areas, the choice of system must consider the relative requirements for the area to be surveyed, time and funds available, and desired resolution (detail of mapping). Figure 31 illustrates the relation between survey speed (time and money) and effective area insonified by the various sidescan systems.

Comprehensive reconnaissance surveys using a combination of techniques as outlined above should allow selection of appropriate sites for OTEC development within areas where such a need has been identified. These surveys should also be effective in identifying regional geologic hazards or engineering constraints. Such surveys will not, however, be sufficient for engineering design.

(C) Step 3: Site-Specific Surveys

Once a site has been chosen for an OTEC installation, two or more phases of marine geologic/engineering studies are required. Such site-specific surveys would generally focus on limited areas 5 to 10 km in width (parallel to the coast) and extending from the shore zone to approximately the 2000 m contour. The initial goals of the site-specific surveys should include detailed bathymetry and identification of geologic constraints on engineering design. In addition, this phase of investigation must include photographic analysis and sample collection for groundtruth of both acoustic and photographic data. This phase of study allows identification of rock outcrops, smooth versus rugged topography, types of sedimentary deposits, areas of mass wasting or slope instability, areas of current scour (erosion), and other sea floor characteristics.

Accurate bathymetry is extremely important in OTEC development (Normark and others, 1985). In order to make best use of ship time, the wide-swath BS^3 (shallow-water) or Seabeam (deep-water) systems are ideal for collecting preliminary bathymetry. SeaMARC II has the potential of collecting wide-swath preliminary bathymetry and mid-range sidescan sonar simultaneously and because of its shallow-towed configuration, can collect this data at survey speeds comparable to BS^3 or Seabeam surveys. However, until the bathymetric capabilities of SeaMARC II are proven, or further tested for accuracy, it would be more productive to use SeaMARC II on a vessel that is also equipped with BS^3 or Seabeam so that preliminary bathymetry and mid-range shallow-towed sidescan sonar imagery can be collected simultaneously.

In areas of steep slopes (greater than approximately 15 m) or of rugged terrain, detailed data can only be obtained from deeply-towed systems. Although deeply towed systems operate at speeds less than approximately 2 knots, this type of imagery is essential for specific site evaluations. SeaMARC I or Deep Tow are examples of systems that generate rectilinear plan view acoustic images of the sea floor in swaths as much as 5-km-wide. In addition, high-resolution seismic-reflection profiles are collected simultaneously.

The second phase of site-specific study enables the geologist/engineer to identify areas with the selected OTEC site that need further, or more detailed, investigation and, also important, areas that do not. This second phase of a site investigation is difficult to plan from a generic standpoint.

At this point of the investigations, the questions to be studied should be specific to the type of OTEC installation selected, i.e. cold-water pipe along the sea floor, anchor systems for floating plant, etc. The tools selected could be the same or similar to those for the earlier phase, or step, but the area studied is restricted and the necessary resolution is much greater. If a variety of information is needed, a complex system such as Deep Tow may be applicable whereas in other areas a simpler system, such as ANGUS may be all that is necessary. A general rule-of-thumb that is central in defining the type of system needed is, "the more complicated a system is, the more things that can go wrong". Nothing is more disturbing or economically devastating to sea-floor exploration than to waste valuable ship time while electronic and mechanical technicians attempt to repair oceanographic systems. Thus, the site investigator should bring with him the simplest system that can do the job.

In engineering assessment for development at OTEC sites, the best possible bathymetry is necessary. In order to overcome the problems of beam spreading and signal attenuation, a deeply towed system will have to be used. Unfortunately, a wide-swath deeply towed bathymetric system has not been developed yet. Therefore, the investigator must rely on monobeam systems. If bathymetry is all that is needed, the Huntec Hydrosonde system would provide high-resolution bathymetric data, with discrimination of down to 10 cm at the sea floor along with subbottom data (this assumes that the navigational position of the vehicle is known precisely). To assess the effects of bottom current activity, the Hydro Products DSS-125 system outfitted with a subbottom system on one of its spare analog (or digital) channels would yield appropriate bathymetric and photographic information. If slope instability is suspected, a high-resolution sidescan sonar system with a subbottom profiler such as the EDO Western 4075 system would be applicable to such a survey. The system, or combination of systems used to determine the detailed bathymetry is therefore related not only to the bathymetry but also to the other needs of the survey.

If multiple problems need to be addressed in an installation-specific survey, it may be practical to use a system such as Deep Tow or ARGO, both of which are capable of collecting sidescan sonar, subbottom seismic-reflection, bathymetry, video, and photographic data. However, a backup system should always be available in case the more sophisticated system fails, or is lost. For example, on a cruise using the ARGO system, where photographic data is of critical concern, a simpler system such as ANGUS can be used as a backup. ANGUS is a self-contained system that does not need a coaxial or conducting cable. Although real-time video and the other capabilities of ARGO would be missed, a backup system like ANGUS would enable the investigator to salvage some data from the valuable ship time.

Another phase of a site-specific investigation is the detailed study of the environmental factors that affect the sea floor; i.e., geotechnical or physical oceanographic studies. Oceanic factors that erode sediments, or oversteepen slopes, can impact the sea floor in cycles that vary from instantaneous to seasonal. Thus, even though complex systems such as ARGO and Deep Tow are capable of measuring bottom currents and other physical oceanographic phenomena over a short time span, this data may not be sufficient to assess the long-term effect. Multi-instrument tripods such as the Geoprobe (Cacchione and Drake, 1979; Fig. 32) or tripods used in the HEBBLE experiment (Kaharl, 1984) can be deployed during the fine-scaled survey and picked-up at a latter time (after a period of weeks or months). These systems are used to collect time-series data on physical and geological parameters that are important in bottom sediment dynamics. Simultaneous in-situ digital recording of pressure, temperature, light scattering, and light transmission, in combination with current velocity profiles measured with a near-bottom array of either electromagnetic or Savonius rotor current meters, is used to correlate bottom shear generated by a variety of oceanic processes with incipient movement and resuspension of bottom sediment. These tripods also contain bottom camera systems that are activated when current speeds exceed preset threshold values and provide a unique method to identify initial sediment motion and bed form development.

Geotechnical analysis of submarine sediment typically involves collecting cores and conducting sophisticated tests in shore-based laboratories (for example see Winters and Lee, 1982). However, without in-situ geotechnical information it is difficult to assess the reliability of laboratory results (for example see Lee and Schwab, 1983; Lee and Edwards, 1986). Instrumentation has been developed to directly measure sediment shear strength, pore-water pressure, and sediment density (Lee, 1986). However, most of these systems are too large and expensive to use except for specific site evaluation. What are applicable to more regional surveys for evaluation of OTEC development are a series of inexpensive in-situ sampling devices that can be deployed from manned submersibles or remotely operated vehicles such as ARGO/JASON or a series of vehicles built by Ametek, Straza Division. Instruments such as gamma probes, static cone penetrometers, piezometers, vane shear, and push-sample corers are available off-the-shelf (Perlow and Richards, 1972; Lambert, 1982; Prindle and others, 1983).

In areas of rugged slopes, especially on the flanks of volcanic islands, tethered remotely controlled vehicles may be difficult to utilize. A final phase of investigation might require the use of manned submersibles. The submersibles are untethered, thus free of any effects of sea-surface motion, and allow the geologist or engineer to observe firsthand the sea floor. This controlled observation, together with photographs and samples, would provide the most detailed information that can be obtained by techniques presently available.

VII. CONCLUSIONS

In summary, evaluation of areas that might provide suitable location for OTEC development and sea floor assessment of selected sites must be an integrated program that maintains the flexibility to answer questions as they arise. Starting from a review of existing data, the principal investigator must first understand the regional geologic and oceanographic setting of the site. A general lack of appropriate base maps and sample information within the most likely areas for development of OTEC facilities require a dedicated cruise, or cruises, using a wide-swath bathymetric system, conventional high-resolution seismic-reflection systems, and a mid-range sidescan sonar system as the initial phase of the study. A sampling program (cores, grab-samples) to provide background information for engineering design must be based on the bathymetric, sidescan, and seismic-reflection analog data whether at regional or site-specific scales.

If more than one task is to be conducted within the site-specific survey, a multi-instrument system or approach should be used. Typically, an investigator must decide if seismic-reflection, sidescan, or photographic systems are the most applicable for the job. A multitude of off-the-shelf remotely operated and towed vehicles containing a variety of subsystems are available to choose from (National Oceanic and Atmospheric Administration, 1979, and more recent proceedings of the Annual Offshore Technology Conference, Houston, TX). It may be necessary to deploy long-term measuring devices like the GEOPROBE. If so, deployment should be conducted early in the site-specific step of the study, so retrieving these systems is possible during later phases of the investigation; i.e., so as not to waste valuable ship time just to pick up a piece of gear and return to port. Finally, bottom samples and in-situ geotechnical measurements can be collected. Sophisticated in-situ geotechnical measurements are time consuming and typically involve manned submersibles, or remotely operated vehicles such as ARGO/JASON.

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FIGURE CAPTIONS

Figure 1. Location map depicting latitudinal band (40°N to 50°S) across the world ocean that includes areas with potential for development of OTEC facilities. Subdivisions depicted show map areas of Figures 2, 3, 4, 5, 6, 8, and 9.

Figure 2. Geographic identification of sites suggested for development of OTEC facilities. Names indicate coastal cities, islands, and island groups with appropriate population and oceanographic conditions (Table 1). A. Atlantic Ocean; B. Caribbean Sea and Eastern Pacific Ocean; C. Western Pacific Ocean; D. Indian Ocean. See Figure 1 for location.

Figure 3. Maps identifying major sea floor topographic features (adapted from Chase, 1975). Map areas same as in Figure 2.

Figure 4. Contours of the difference in water temperature between sea surface and 1,000 m depth and general circulation pattern of surface water during northern hemisphere summer using data from Bialek, 1966, and Ocean Data Systems, Inc., 1978. Map areas same as in Figure 2.

Figure 5. Contours of the difference in water temperature between sea surface and 500 m depth and general circulation pattern of surface water during northern hemisphere summer using data from Bialek, 1966, and Ocean Data Systems, Inc., 1978. Map areas same as in Figure 2.

Figure 6. Contours of mean sea-surface salinity (0/00) adapted from Bialek, 1966. Map areas same as in Figure 2.

Figure 7. Schematic representation of types of continental and island margins showing profile and physiographic sketch.

Figure 8. Location of sea floor samples from water depths less than 1,000 m (from C. Moore, NGDC/NOAA, 1985). Map areas same as in Figure 2.

Figure 9. Distribution of major sediment types adapted from Rawson and Ryan, 1978 (see text for further explanation). Map areas same as in Figure 2.

Figure 10. Example of seismic-reflection profile using 15 cu. in. watergun sound source. Profile shows depression caused by continuing activity on a fault during deposition of the sedimentary sequence.

Figure 11. Schematic representation of Seabeam wide-swath bathymetric mapping system (from Renard and Allenou, 1979). (A) Zone insonified by transmitted pulse; (B) distribution of effective beam pattern for receiving transducers; (C) effective sounding zones of multiple beams of 2 2/3° by 2 2/3°.

Figure 12. Computer generated contour map from single trackline swath of Seabeam system. The water depths printed at the bottom of figure correspond to depth directly beneath the ship at corresponding position on trackline (courtesy of Prakla-Seismas, GMBH, West Germany).

Figure 13. Sidescan sonographs (100 kHz) from a water depth of 80 m. (A) Dark bands caused by coarser-grained deposit in erosional scours in sandy sea floor; (B) field of megaripples formed by bottom currents acting on fine-sand-size substrate.

Figure 14. Schematic representation showing geometry of sidescan transmission (courtesy of F. N. Spiess).

Figure 15. Schematic depicting towing configuration for SeaMARC I that uses a cable depressor and near neutral bouyant towfish (from International Submarine Technology).

Figure 16. Photograph of GLORIA sidescan-sonar towfish in launching cradle (courtesy of Dan Blackwood, USGS, Woods Hole).

Figure 17. Schematic representation of beam pattern characteristics for GLORIA system (Gardner, 1984).

Figure 18. Geometry and terminology for sidescan sonar analysis. From Paluzzi and others, 1981.

Figure 19. Mosaic of 105 kHz slant-range-corrected sidescan sonographs depicting an area sediment sliding and slumping on the continental shelf, Gulf of Alaska. The mosaic area is 1.73 by 1.93 km.

Figure 20. Schematic illustration of towing arrangement for the EDO-Western 4075 sidescan sonar system (100 kHz). Modified from Prior and Coleman, 1981.

Figure 21. Major components of Hydro Products DSS-125 Deep Sea Survey System (from Hydro Products brochure).

Figure 22. Photograph of ANGUS deeply towed photographic system.

Figure 23. Photograph of deep-tow vehicle developed at Marine Physical Laboratory.

Figure 24. Major components of Huntec Limited Hydrosonde Deep Tow Seismic System (from Huntec brochure).

Figure 25. Photograph of SeaMARC I sidescan sonar towfish (courtesy of Kathy Scanlon, USGS, Woods Hole).

Figure 26. SeaMARC I sidescan sonograph (5 km total swath width) across Wilmington submarine canyon in 2,000 m water depth. Towfish was 500 m above the sea floor. Photograph courtesy of J. Robb, USGS, Woods Hole.

Figure 27. Towing configuration for SeaMARC II sidescan sonar system (from Blackinton and others, 1983).

Figure 28. Photograph of ARGO towfish.

Figure 29. Schematic representation of ARGO photographic system with the JASON remote control vehicle near sea floor. Geometry for navigation with acoustic transponder net shows ray paths for positioning both ARGO and surface ship with towed hydrophone. Courtesy of R. D. Ballard, Woods Hole Oceanographic Institution.

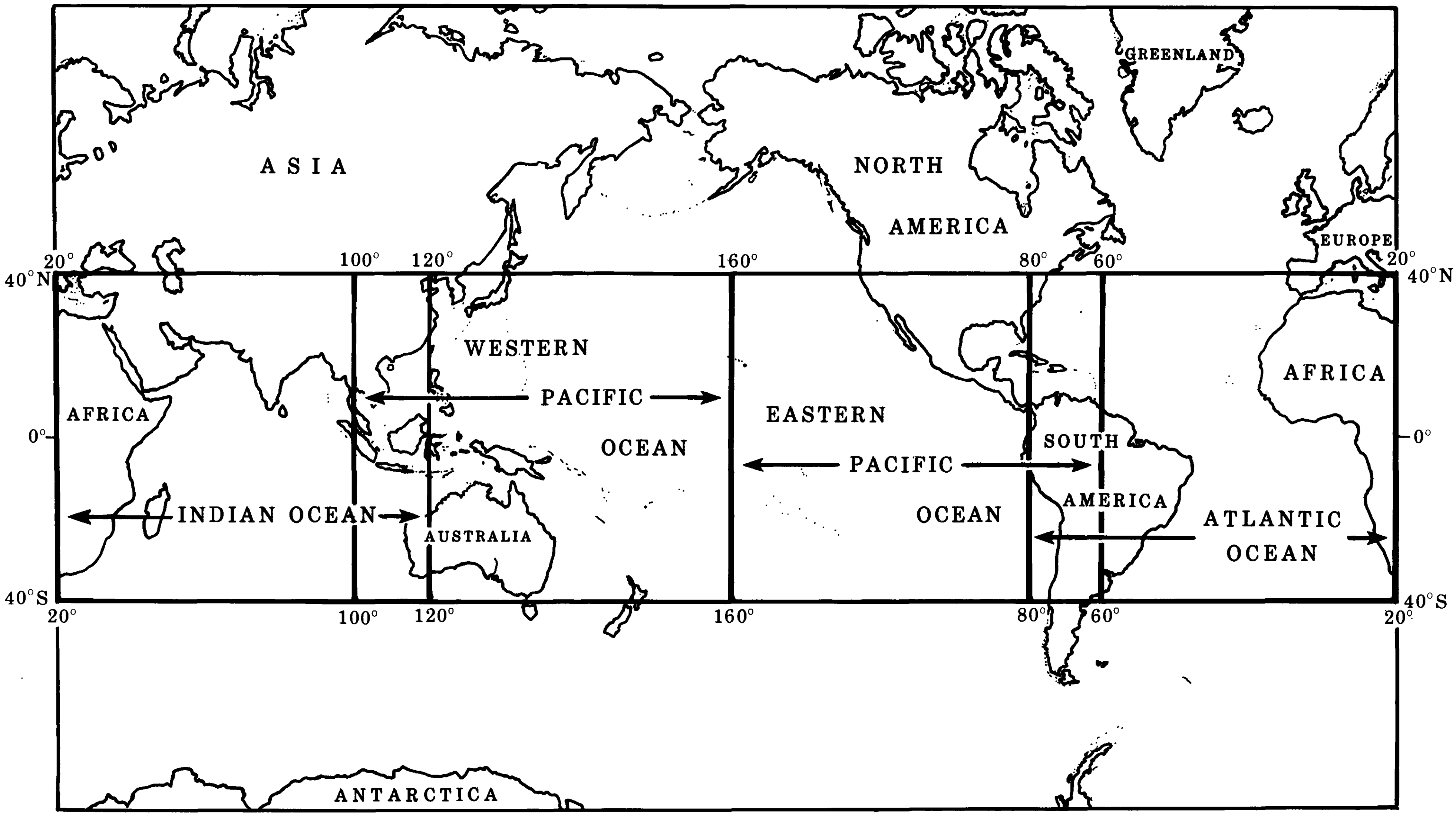
Figure 30. Photograph of heave compensator used for damping ship motion from surface waves during use of deeply towed vehicles.

Figure 31. Graphic illustration of parameters affecting choice of appropriate sidescan sonar system (from Ryan, 1985).

Figure 32. Photograph of Geoprobe oceanographic tripod (courtesy of G. Tate, USGS, Menlo Park).

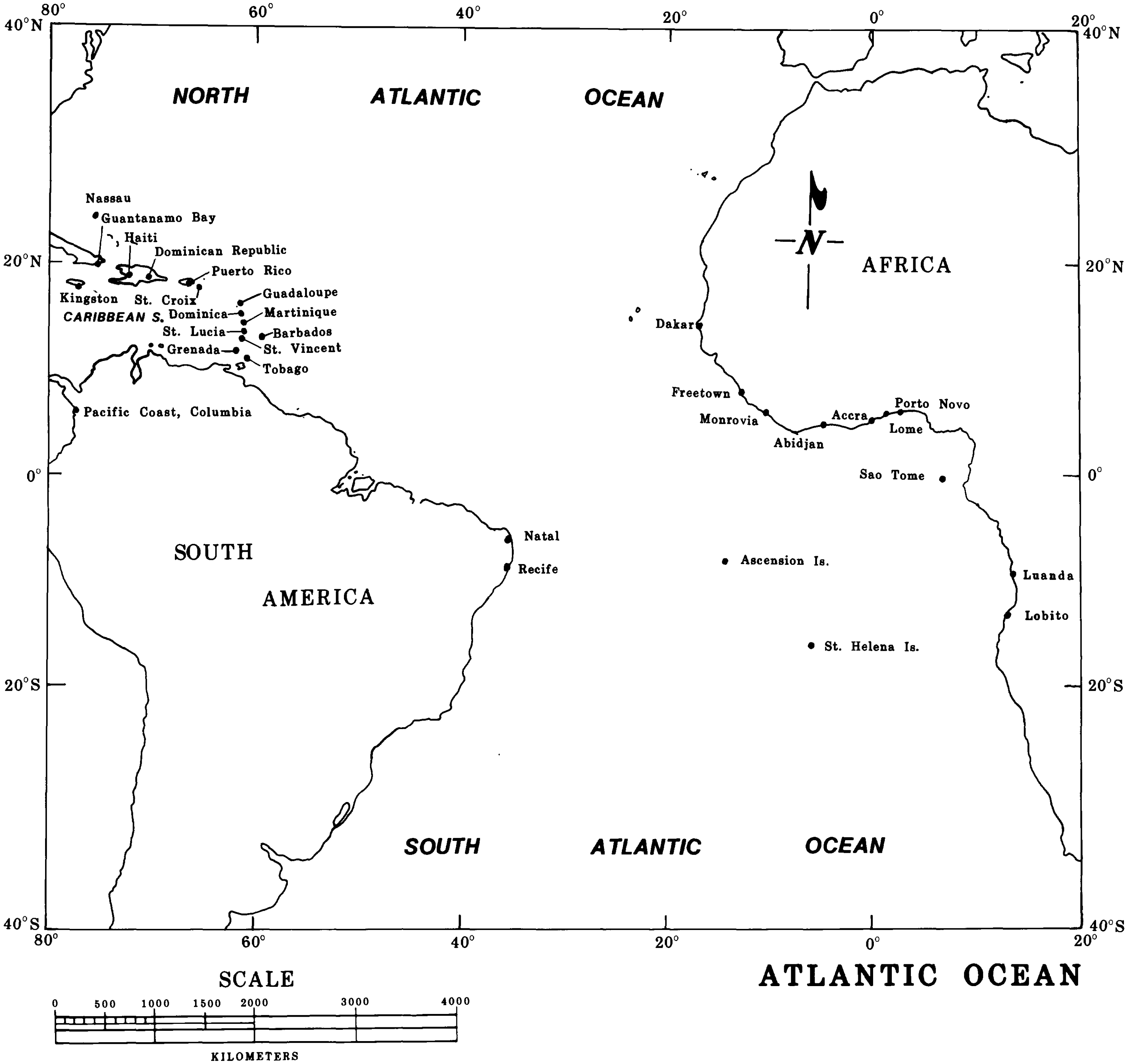
POTENTIAL SITES	COUNTRY	LOCATION (APPROXIMATE)	POPULATION (ESTIMATED)	GEOLOGIC TYPE	COLD WATER PIPE 20° C DELTA T			DISCHARGE PIPE MIXED LAYER			USE POWER		WATER
					DEPTH (m)	OFFSHORE (km)	BOTTOM (km)	DEPTH (m)	OFFSHORE (km)	BOTTOM (km)	DOMESTIC	INDUSTRIAL	
PACIFIC OCEAN													
Hawaii, Keahole Point	USA	156°W 20°N	75,337	High Island	600	1	1	100	0.3	0.3	X	X	
Maui	USA	157°W 21°N	54,985	High Island	700	3	3	100	1	1	X		X?
Oahu, Kahe Point	USA	158°W 21°N	705,381	High Island	700	4	4	100	1.5	1.5	X	X?	
Majuro	Marshall Is./USA	171°E 07°N	10,000	Atoll	425	1	1	100	0.5	0.5	X		X
Ponape	Fed. St. Micronesia	158°E 07°N	23,140	High Is./Reef	375	3	3	100	3	3	X		
Truk, Moen	Fed. St. Micronesia	152°E 07°N	12,000	Atoll	375	4	4	90	4	4	X		X
Yap	Fed. St. Micronesia	138°E 09°N	6,200	Atoll	350	1.5	1.5	90	0.5	0.5	X		X
Palau	Belau	134°E 07°N	14,800	High Is./Reef	350	2	2	80	1	1	X		
Saipan	N. Mariana Is./USA	146°E 16°N	14,600	High Island	500	1	1	120	0.5	0.5	X		
Guam, Agana	USA	145°E 13°N	105,979	High Island	425	1	1	120	0.5	0.5	X	X?	
Am. Samoa, Pago Pago	USA	171°W 14°S	32,297	High Island	650	1	1				X		
Kwajalein	Marshall Is./USA	167°E 09°N	11,000	Atoll	425	1	1	100	0.5	0.5	X	X	X
Johnston Island	USA	168°W 17°N	370	Atoll	550	2	2	100	1	1	X	X	X
Kosrae, Lelu	Marshall Islands	163°E 05°N	5,000	Atoll?	425	1	1	100	0.5	0.5	X		X
Punta Arenas	Costa Rica	84°W 09°N	26,331	Cont./Trench	600	10	10	30			X	X	
Acapulco	Mexico	100°W 17°N	402,188	Cont./Trench	500	5	5	30			X		
Puerto Vallarta	Mexico	105°W 21°N		Cont./Trench	750	10	10	30			X		
Pacific Coast	Columbia	77°W 06°N		Continental	750	10	10	30			X		
Tahiti, Papeete	France	150°W 18°S	36,784	High Island	650	2	2		1	1	X		
Suva	Fiji	178°E 18°S	66,108	High Island	700	7	7		2	2	X	X	
Nauru	Nauru	167°E 01°S	8,000	High Island	450			100			X	X	X
Port Vila	Vanuatu	168°E 18°S	14,797	High Island	900	10	10		1	1	X		
Espirito Santo	Vanuatu	167°E 15°S	5,500	High Island	800	6	6		1	1	X		
Tongatapu	Tonga	175°W 21°S	18,356	Atoll	1000	5	5		1	1	X		X
Apia	Western Samoa	172°W 14°S	32,099	High Island	650	0	8		7	7	X		
Tarawa	Kiribati	173°E 02°N	20,000	Atoll	450	3	3	120	1	1	X		X
New Caledonia, Noumea	France	166°E 22°S	113,700	Cont. Island	900	10	10	100	5	5	X	X	
New Britain, Raboul	Papua New Guinea	152°E 04°S	19,000?	High Island	500	2	2	100	0.5	0.5	X		
New Guinea, Wewak	Papua New Guinea	144°E 04°S	19,554	Cont. Island	500	5	5	100	1	1	X		
Admiralty Is., Manus	Papua New Guinea	147°E 02°S		High Island	500	4	4	100	0.5	0.5	X		
Guadalcanal, Honiara	Solomon Islands	160°E 10°S	14,942	Cont. Island?	550	3	3	100	1	1	X		
Bougainville, Kieta	Papua New Guinea	156°E 06°S	128,890	Cont. Island	500	3	3	100	2	2	X	X?	
Bougainville, N. Coast	Papua New Guinea	155°E 06°S	128,890	Cont. Island	500	1	1	100	0.5	0.5	X	X?	
Irian Jaya, Biak	Indonesia	136°E 03°S		Cont. Island	425	2	2	80	1	1	X		
Irian Jaya, Sorong	Indonesia	132°E 01°S		Cont. Island	425	3	3	80	1	1	X		
Timor	Indonesia	126°E 08°S		Cont. Island?	550	3	3	80	1	1	X		
Mindanao	Philipines	124°E 07°N		Cont. Island	450	2	2	80	1	1	X		
Luzon, Lingayan	Philipines	120°E 16°N		Cont. Island	500	3	3	80	1	1	X	X?	
Taiwan	Taiwan	122°E 23°N	14,505,400	Cont. Island	650	3	3	100	1	1	X	X?	
Kyushu	Japan	132°E 32°N	13,073,000	Cont. Island	1000	40	40	120	13	13	X	X	
Okinawa, Naha	Japan	128°E 26°N	276,380	Cont. Island	700	13	13	120	3	3	X		
INDIAN OCEAN													
Bali, Den Pasar	Indonesia	115°E 08°S	2,120,338	High Island	600	3	3	80	1	1	X		
Java, Djakarta	Indonesia	106°E 07°S	342,267	Cont. Island?	600	5	5	80	0.5	0.5	X		
Sumatra	Indonesia	104°E 05°S	20,812,682	Cont. Island?	550	10	10	80	2	2	X		
Ceram	Indonesia	128°E 03°S		High Island?	450	3	3	80	2	2	X		
Christmas Island	Australia	105°E 10°S		Atoll	650	1	1	80	0.2	0.2	X	X	
Columbo	Sri Lanka	80°E 07°N	1,450,000	Cont. Island	800	10	10	80	2	2	X		
Trincomalee	Sri Lanka	81°E 08°N	44,000	Cont. Island	600	5	5	80	1	1	X		
Diego Garcia	USA/Britain	72°E 07°S		Atoll	900	2	2		1	1		X	X
Madagascar	Malgasy Republic	49°E 12°S		Cont. Island	650			90			X		
Seychelles, Victoria	Seychelles	55°E 04°S	15,559	Cont. Island	1000			90			X		X
Mauritius, Port Lewis	Mauritius	58°E 20°S	141,022	High Island	950			90			X		X?
Zanzibar	Tanzania	40°E 06°S	110,669	Cont. Island	950	20	20	90	2	2	X		
Dar es Salaam	Tanzania	39°E 07°S	757,346	Continental	950	50	50	90	2	2	X		
Mombasa	Kenya	40°E 04°S	391,000	Continental	950	40	40	90	1	1	X		
Mogadiscio	Somalia	45°E 02°N	371,000	Continental	950	20	20	90	5	5	X		
North Coast	Mozambique	41°E 15°S		Continental	950	5	5	90	1	1	X		
Comoro, Moroni	Comoro Islands	44°E 12°S	22,000	High Island	950	7	7	90	1	1	X		
ATLANTIC OCEAN													
Lobito	Angola	13°E 13°S	59,528	Continental	1300	20	20	120			X		
Luanda	Angola	13°E 09°S	540,000	Continental	1100	70	70	100			X		
Monrovia	Liberia	11°W 06°N	204,000	Continental	550	25	25	80			X		
Abidjan	Ivory Coast	04°W 05°N	950,000	Continental	575	20	20	80			X		
Freetown	Sierra Leone	13°W 08°N	274,000	Continental	550	30	30	80			X		
Dakar	Senegal	17°W 15°N	798,792	Continental	1300	45	45	90			X		
Lome	Togo	01°E 06°N	148,443	Continental	575	20	20	80			X		
Sao Tome	Sao Tome	07°E 00°N	82,000	Cont. Island	650	5	5	70			X		
Porto Novo	Benin	02°E 06°N	104,000	Continental	575	30	30	80			X		
Accra	Ghana	00°W 06°N	564,194	Continental	575	20	20	80			X		
Ascension Island	Britain	14°W 08°S		High Island	650	3	3	90			X		X?
St. Helena Island	Britain	05°W 16°S		High Island	1400	10	10	120			X		X?
Recife	Brazil	35°W 08°S	1,046,454	Continental	600	10	10	120			X		X?
Natal	Brazil	35°W 06°S	250,787	Continental	500	10	10	120			X		X?
Barbados, Bridgetown	Barbados	60°W 13°N	279,000	High Island	700	11	11	70			X		
Tobago	Trinidad/Tobago	60°W 11°N		High Island?	700	11	11	70			X		
Hispaniola	Dominican Rep.	70°W 18°N	4,006,005	Cont. Island	700	3.5	3.5				X		
Hispaniola	Haiti	74°W 18°N	4,314,628	Cont. Island	650	2.5	2.5				X		
Nassau	Bahamas	78°W 25°N	105,352	Carb. Platform	1100	7	7	150			X		X
Key West, Florida	USA	82°W 25°N	25,000	Carb. Platform	700	70	70	70			X		X
Tampa, Florida	USA	83°W 27°N	280,000	Cont. w/Shelf	800						X		
Mobile, Alabama	USA	88°W 31°N	196,000	Cont. w/Shelf	800						X		
CARIBBEAN SEA													
St. Croix, N. Coast	USA	65°W 18°N	49,725	Cont. Is./Trench	700	1	1	100			X		X
Puerto Rico, N. Coast	USA	67°W 19°N	2,712,033	Cont. Is./Trench	700	6	6	90			X		
St. Lucia	St. Lucia	63°W 14°N	121,000	High Island	650	6	6	80			X		
Martinique	France	61°W 15°N	310,000	High Island?	675	4.5	4.5	80			X		
Grenada, St. Georges	Grenada	62°W 12°N	106,000	High Island	650	3.5	3.5	80			X		
Dominica, W. Coast	Dominica	62°W 16°N	78,000	High Island?	675	3	3	90			X		
Guadaloupe, W. Coast	France	62°W 16°N	312,000	High Island?	675	3	3	90			X		
St. Vincent	St. Vincent	63°W 13°N	111,000	High Island?	650	2.5	2.5	80			X		
Montego Bay	Jamaica	78°W 18°N	50,000	Cont. Island	650	3.5	3.5				X	X	
Kingston	Jamaica	77°W 18°N	600,000	Cont. Island	675	3.5	3.5				X		
Guantanago Bay	USA	75°W 20°N		Cont. Island	700	3	3				X	X	
Santiago	Cuba	76°W 20°N	322,000	Cont. Island	700	2.5	2.5				X		
Isla de Pinos	Cuba	83°W 22°N		Cont. Island	700	5	5				X		
Corrientes	Cuba	84°W 22°N		Cont. Island	700	5.5	5.5				X		
Cozumel	Mexico	87°W 20°N		Carb. Platform	700	8.5	8.5				X		X?
Puerto Cortes	Honduras	88°W 16°N		Continental	650	10	10				X		
Grand Cayman	Britain	81°W 19°N	10,652	Carb. Platform	650	2.5	2.5				X		X

Table 1. LIST of POTENTIAL OTEC SITES



LOCATION MAP

Figure 1



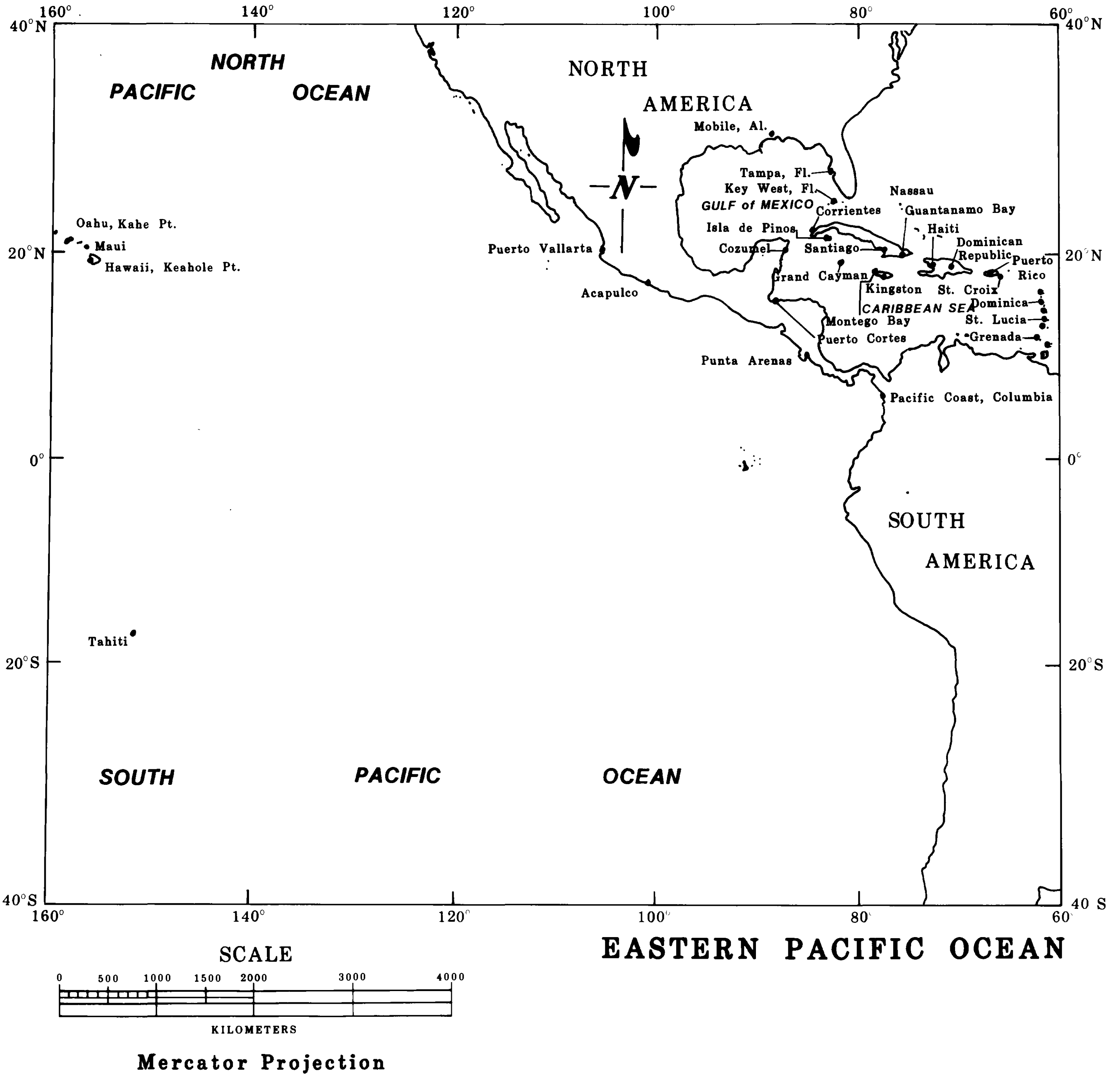
ATLANTIC OCEAN

Mercator Projection

POTENTIAL OTEC SITES

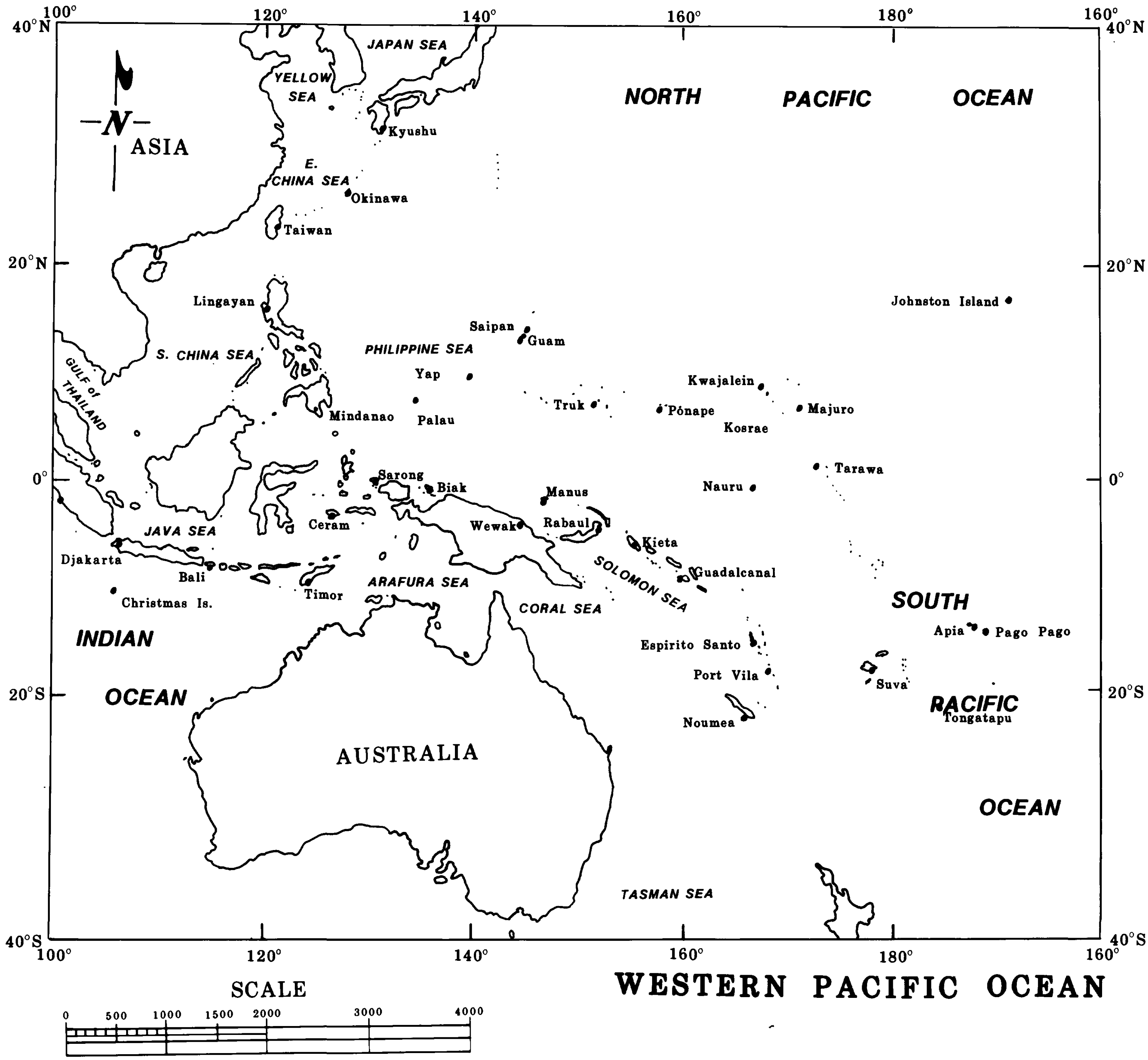
between Latitudes 40°N and 40°S

Figure 2A



POTENTIAL OTEC SITES
between Latitudes 40°N and 40°S

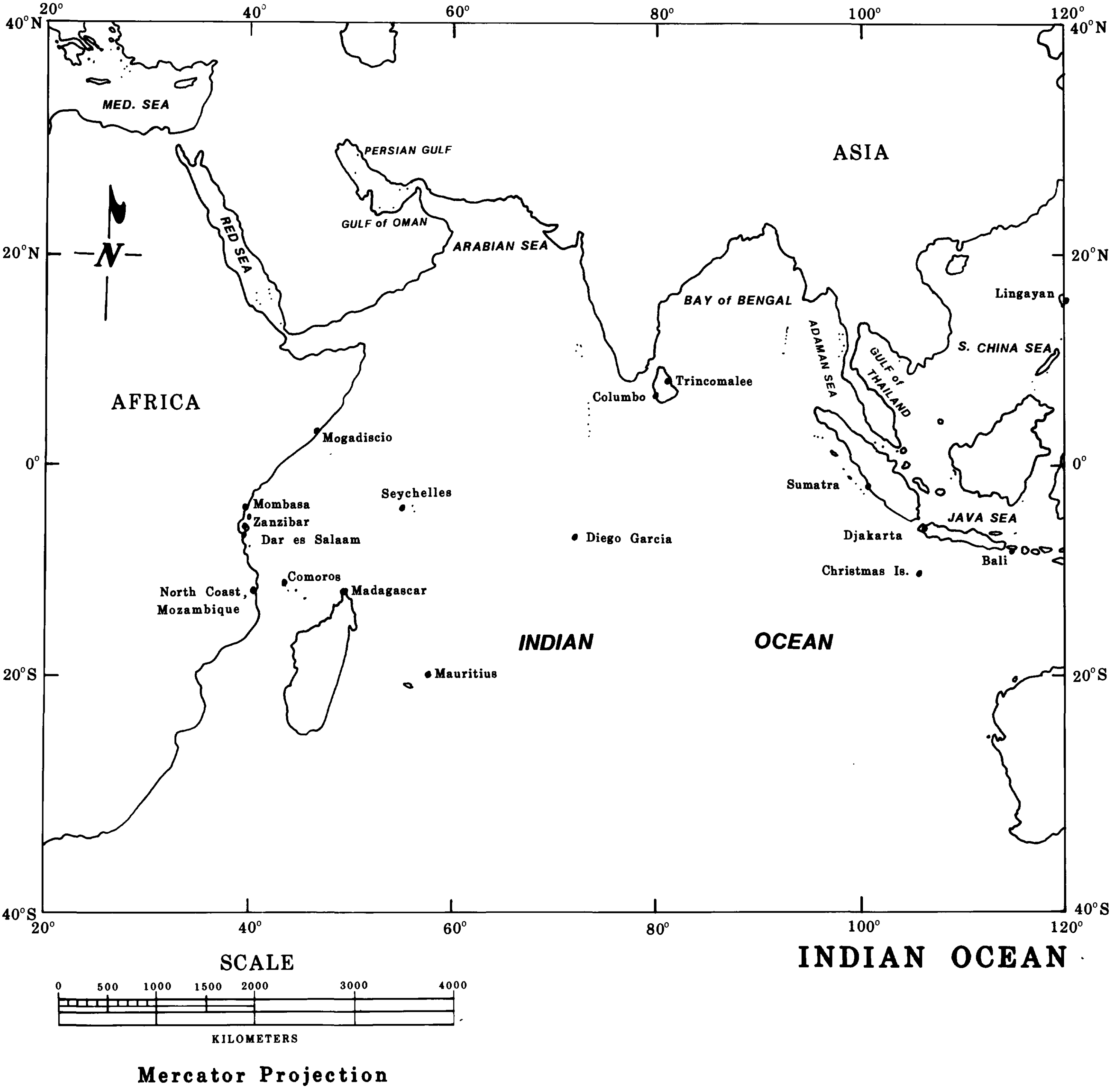
Figure 2B



Mercator Projection

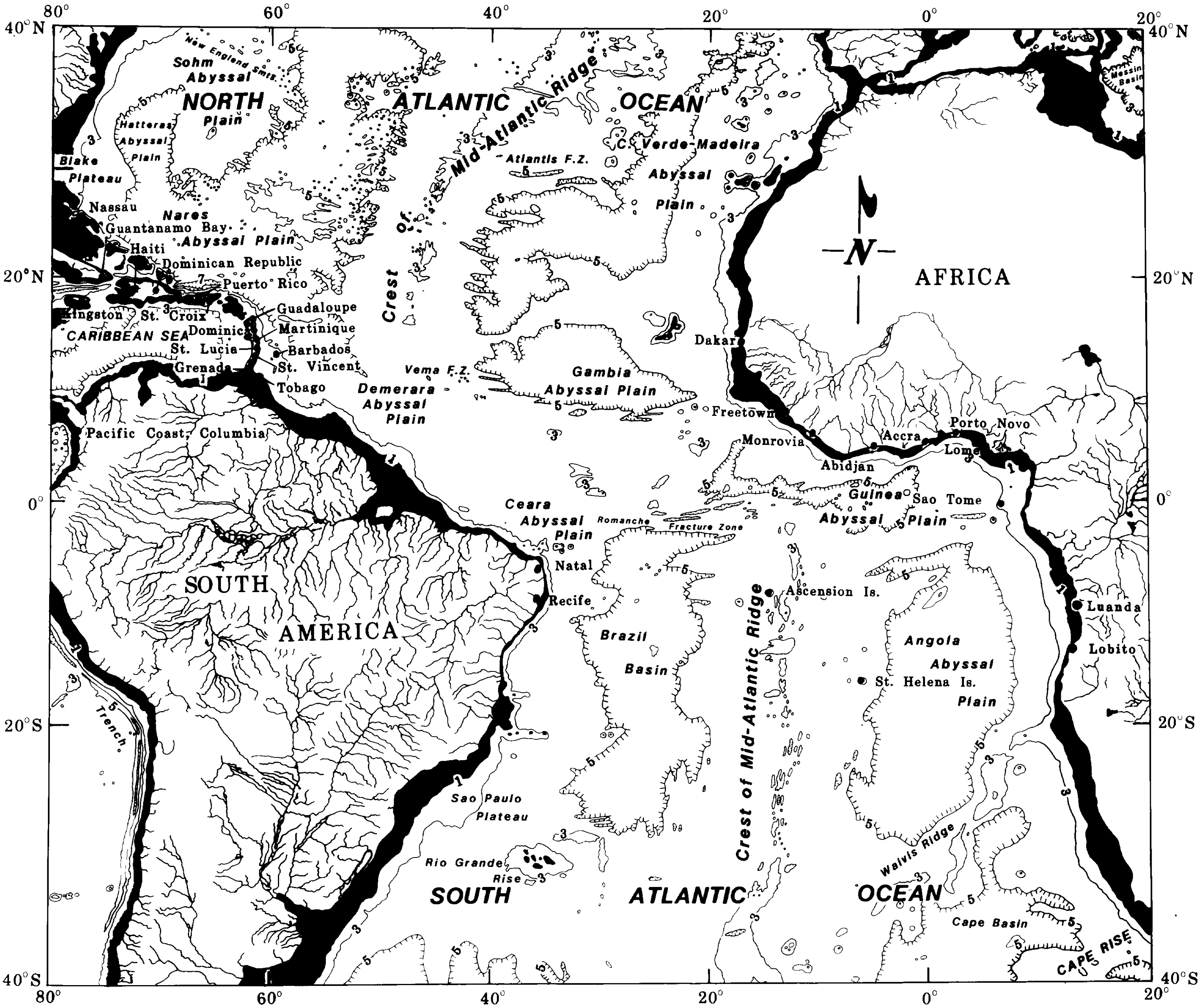
POTENTIAL OTEC SITES
between Latitudes 40°N and 40°S

Figure 2C



POTENTIAL OTEC SITES
between Latitudes 40°N and 40°S

Figure 2D



ATLANTIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

Mercator Projection

Contour Intervals 1,3,5,7,9 Kilometers

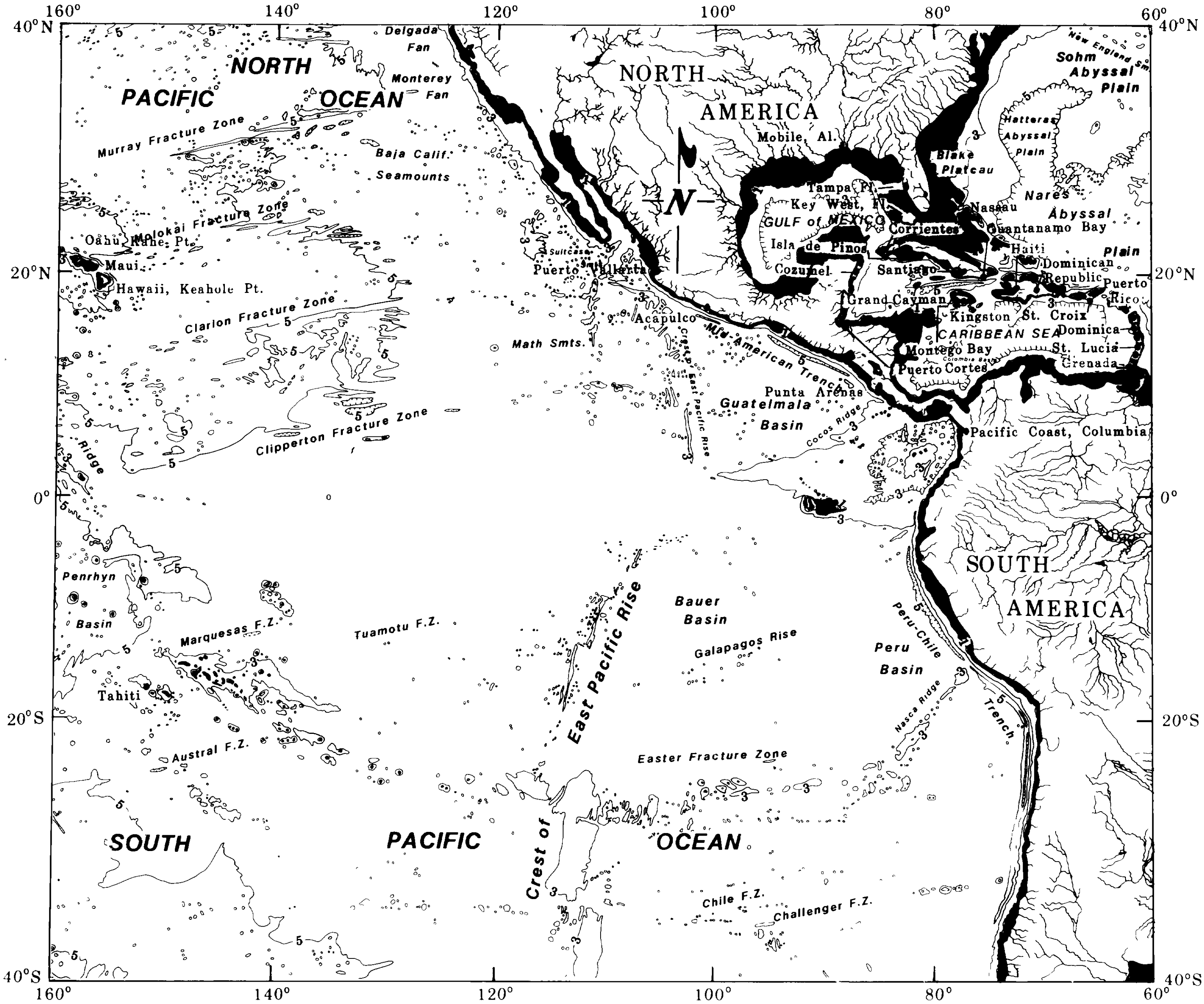
● **Potential OTEC Site**

Depth to 1000 meters

MAJOR SEA FLOOR TOPOGRAPHIC FEATURES

Between Latitudes 40°N and 40°S

Figure 3A



EASTERN PACIFIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

Mercator Projection

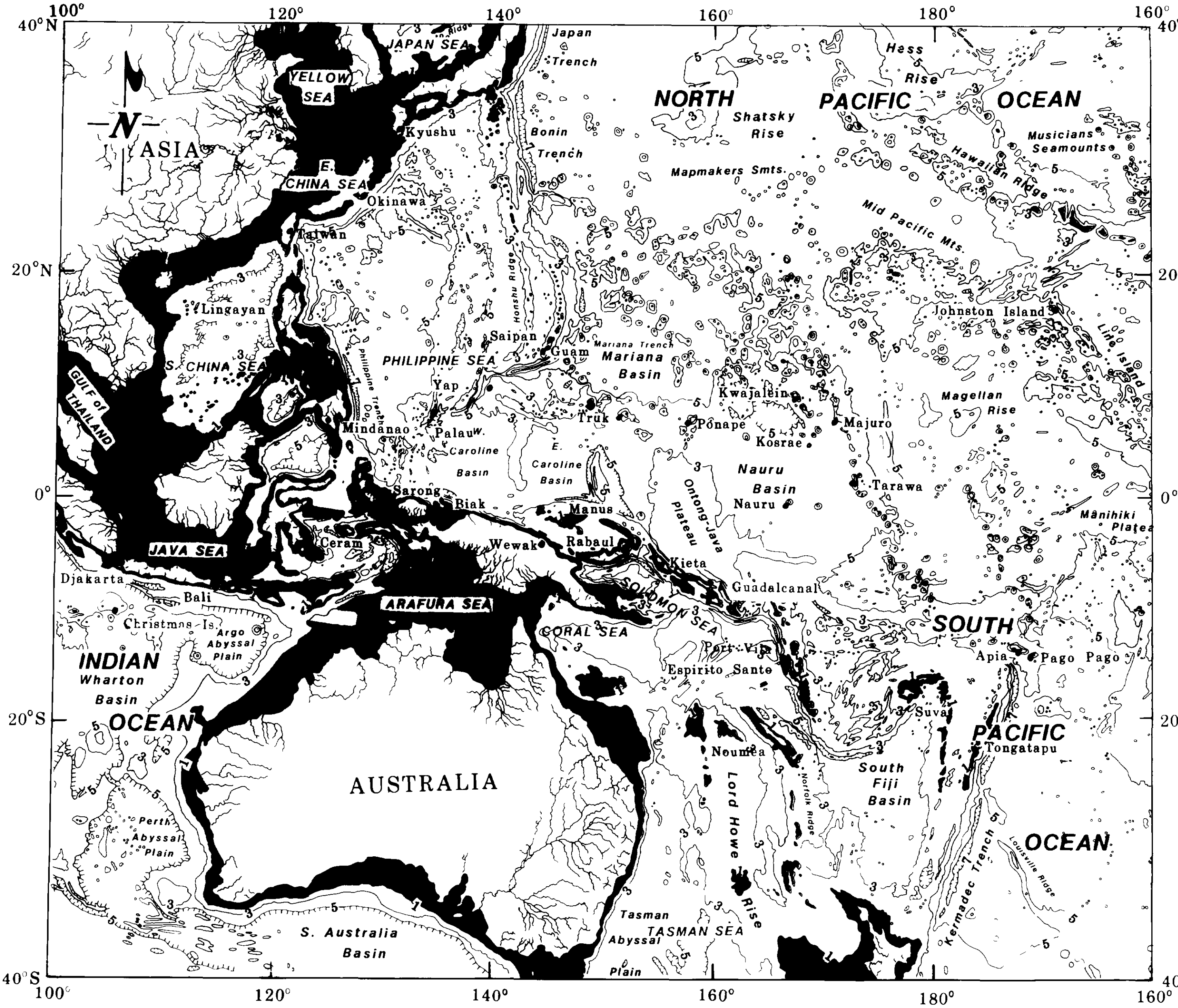
Contour Intervals 1,3,5,7,9 Kilometers

● Potential OTEC Site

Depth to 1000 meters

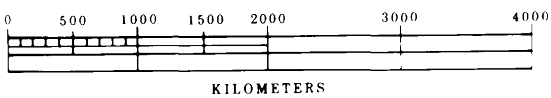
MAJOR SEA FLOOR TOPOGRAPHIC FEATURES
Between Latitudes 40°N and 40°S

Figure 3B



WESTERN PACIFIC OCEAN

SCALE



Mercator Projection

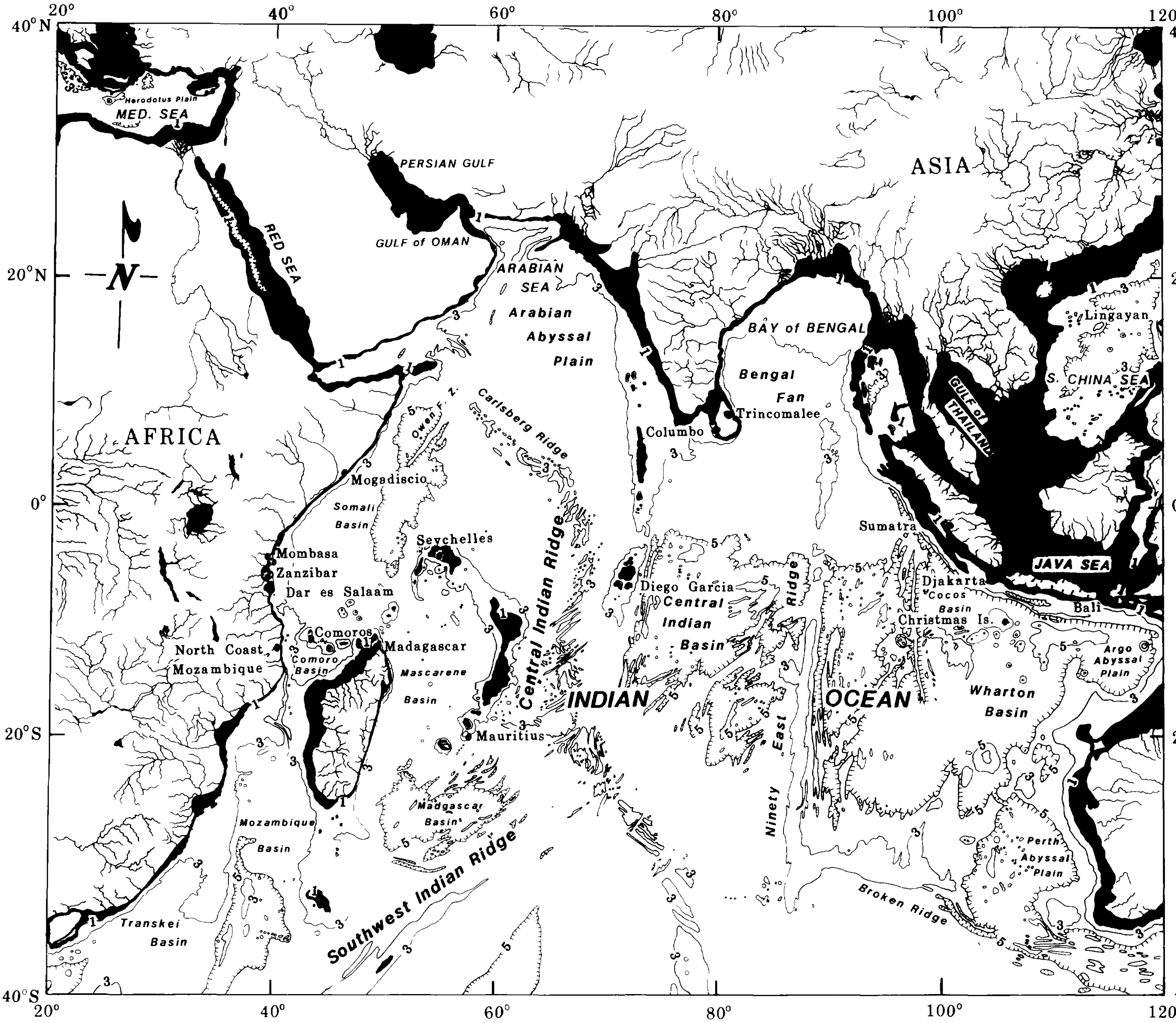
Contour Intervals 1,3,5,7,9 Kilometers

● **Potential OTEC Site**

Depth to 1000 meters

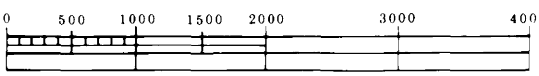
MAJOR SEA FLOOR TOPOGRAPHIC FEATURES
Between Latitudes 40°N and 40°S

Figure 3C



INDIAN OCEAN

SCALE



Mercator Projection

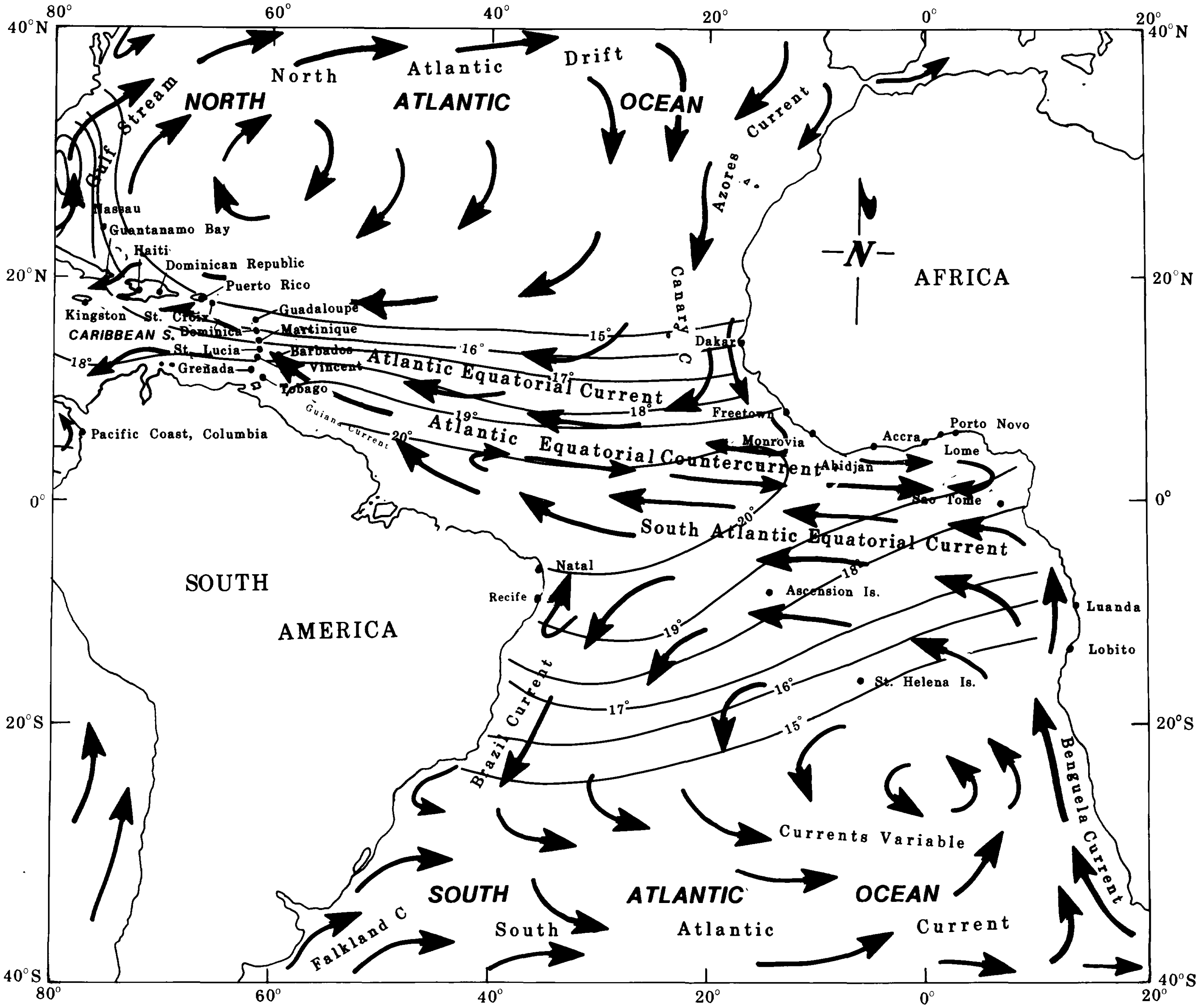
Contour Intervals 1,3,5,7,9 Kilometers

● **Potential OTEC Site**

Depth to 1000 meters

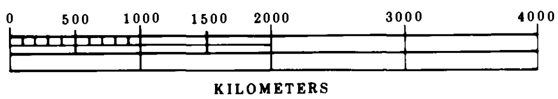
MAJOR SEA FLOOR TOPOGRAPHIC FEATURES
Between Latitudes 40°N and 40°S

Figure 3D



ATLANTIC OCEAN

SCALE



Mercator Projection

NOTE: The surface currents shown occur during the northern hemisphere summer. Shifts in location and direction can occur in other seasons.

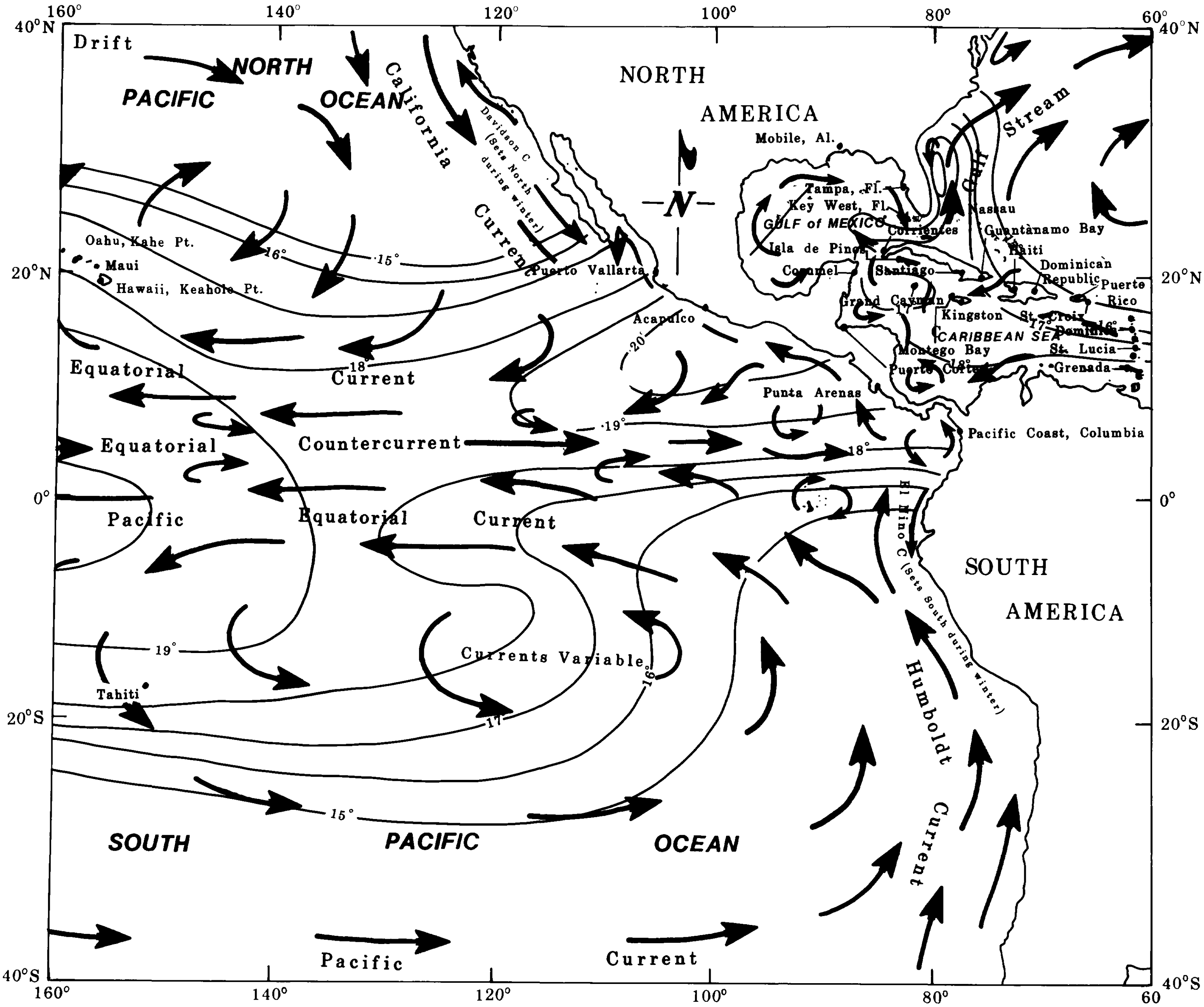
Delta T contours in degrees centigrade.

Current arrows denote direction only, not velocity.

TEMPERATURE DIFFERENCE BETWEEN SEA SURFACE and 500 METERS and SURFACE CURRENTS

Between Latitudes 40° N. and 40°S.

Figure 4A



EASTERN PACIFIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

Mercator Projection

Delta T contours in degrees centigrade.

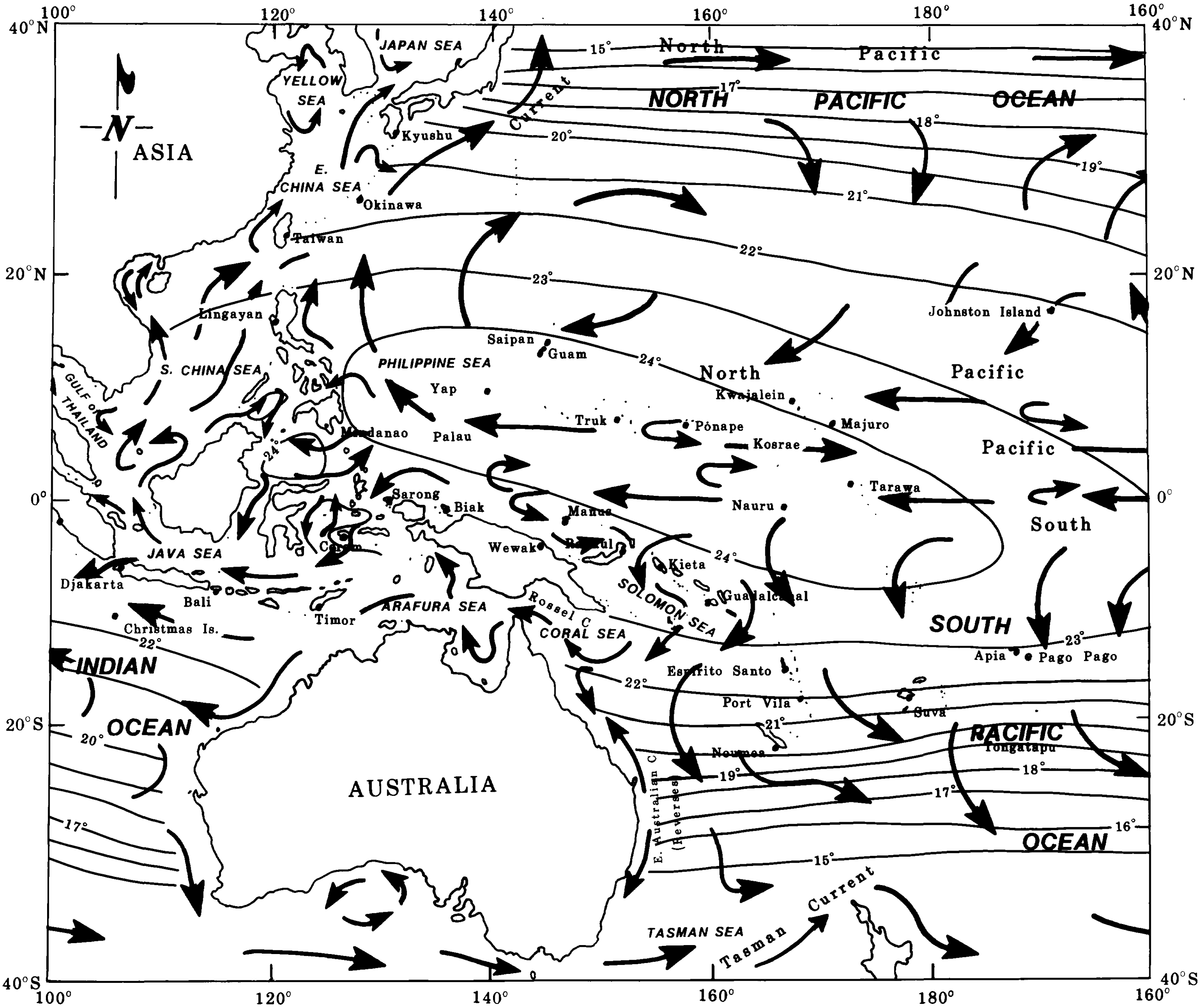
Current arrows denote direction only, not velocity.

NOTE: The surface currents shown occur during the northern hemisphere summer. Shifts in location and direction can occur in other seasons.

TEMPERATURE DIFFERENCE BETWEEN SEA SURFACE and 500 METERS and SURFACE CURRENTS

Between Latitudes 40° N. and 40°S.

Figure 4B



WESTERN PACIFIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

Mercator Projection

Delta T contours in degrees centigrade.

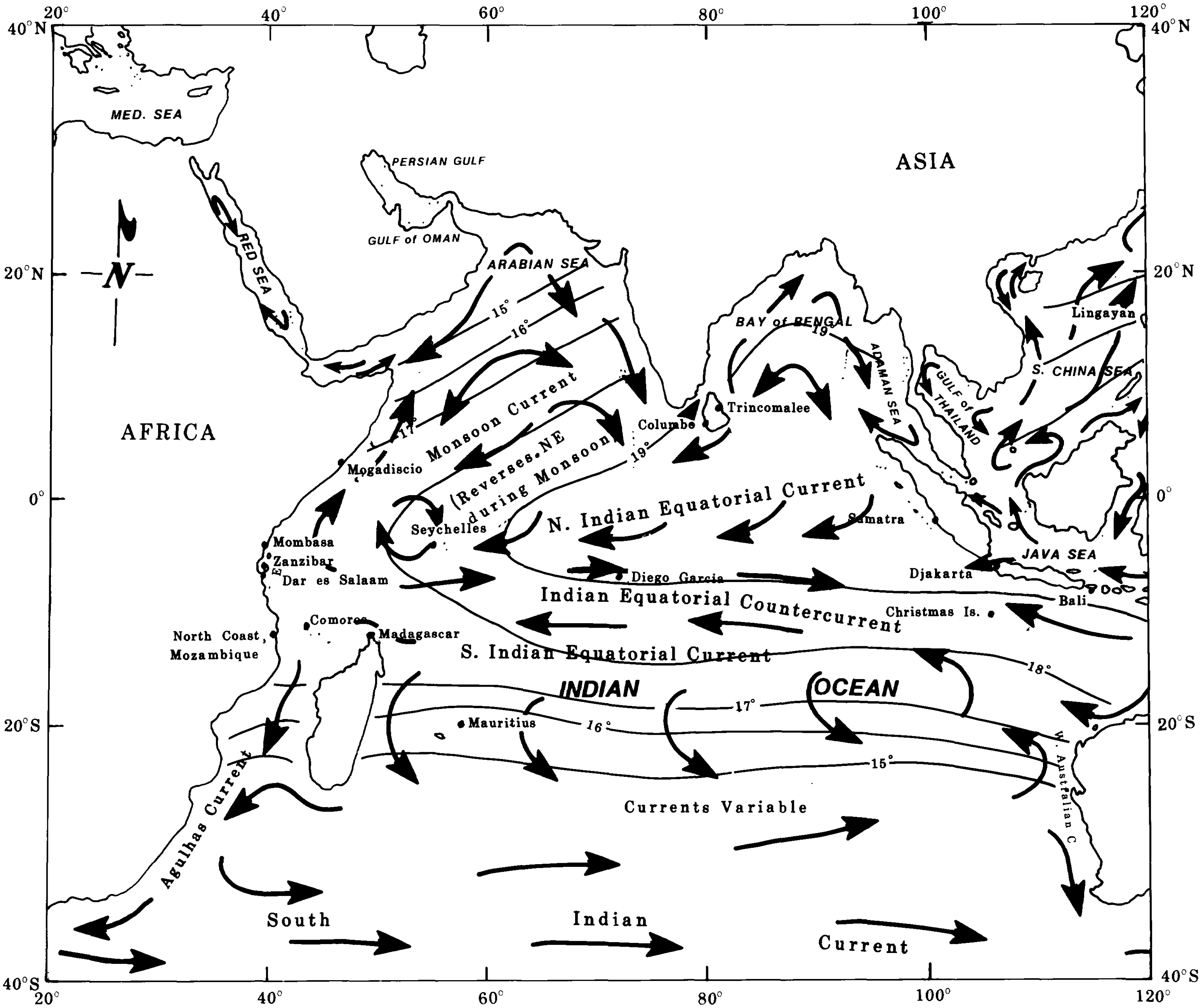
Current arrows denote direction only, not velocity.

NOTE: The surface currents shown occur during the northern hemisphere summer. Shifts in location and direction can occur in other seasons.

TEMPERATURE DIFFERENCE BETWEEN SEA SURFACE and 1000 METERS and SURFACE CURRENTS

Between Latitudes 40°N. and 40°S.

Figure 4C



INDIAN OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

Mercator Projection

Delta T contours in degrees centigrade.

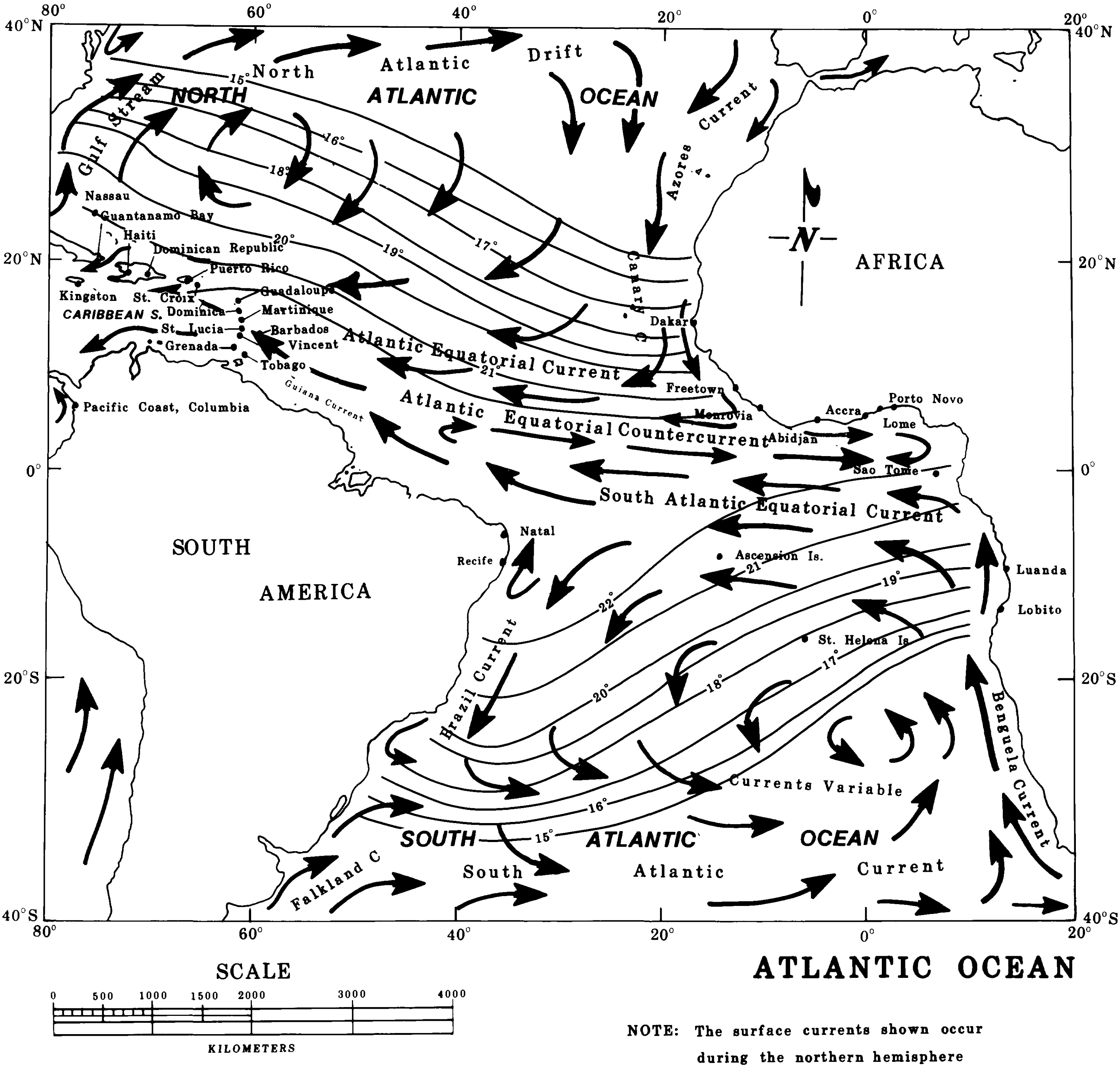
Current arrows denote direction only, not velocity.

NOTE: The surface currents shown occur during the northern hemisphere summer. Shifts in location and direction can occur in other seasons.

TEMPERATURE DIFFERENCE BETWEEN SEA SURFACE and 500 METERS and SURFACE CURRENTS

Between Latitudes 40° N. and 40°S.

Figure 4D



Mercator Projection

Delta T contours in degrees centigrade.

Current arrows denote direction only, not velocity.

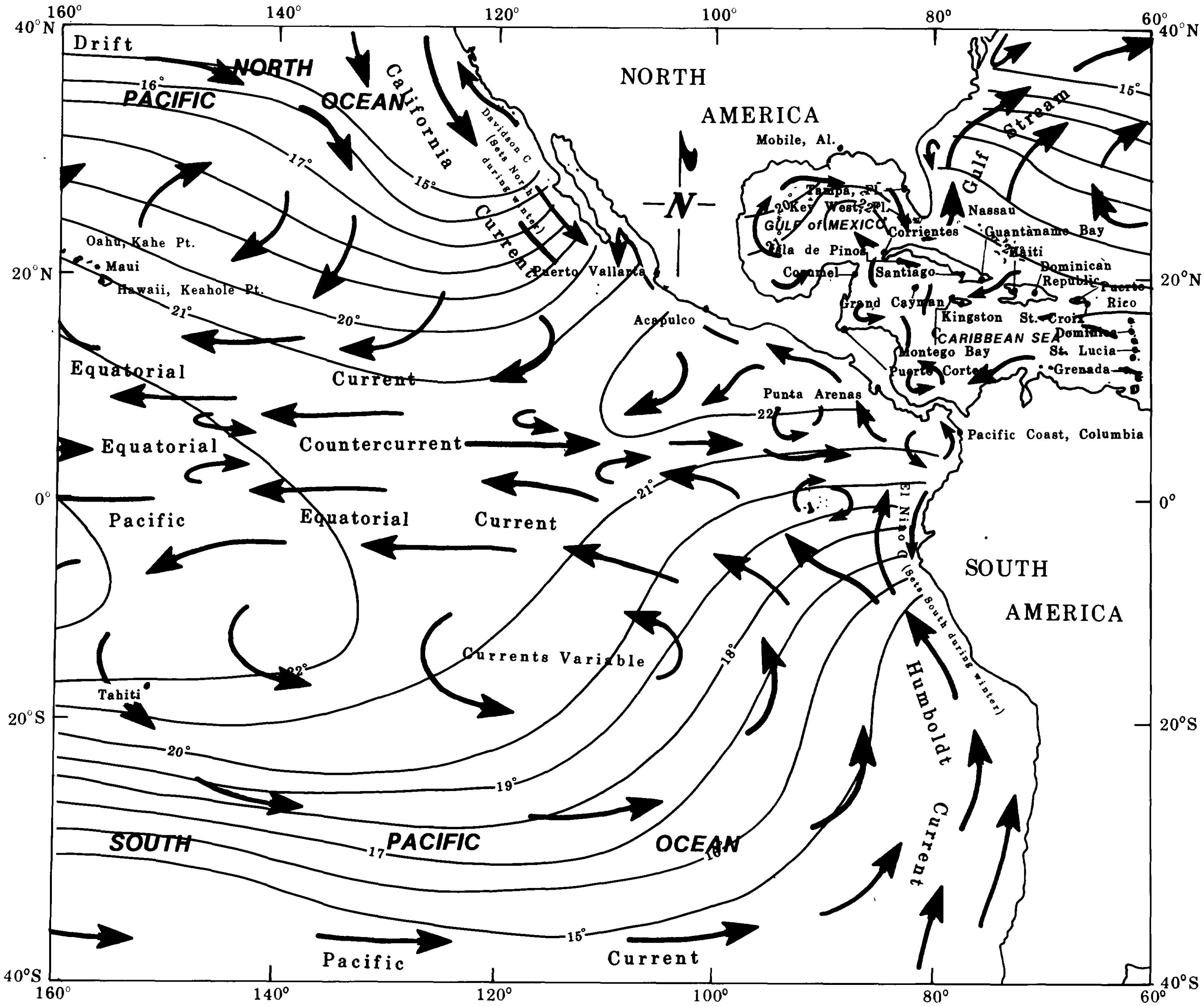
ATLANTIC OCEAN

NOTE: The surface currents shown occur during the northern hemisphere summer. Shifts in location and direction can occur in other seasons.

TEMPERATURE DIFFERENCE BETWEEN SEA SURFACE and 1000 METERS and SURFACE CURRENTS

Between Latitudes 40°N. and 40°S.

Figure 5A



EASTERN PACIFIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

Mercator Projection

NOTE: The surface currents shown occur during the northern hemisphere summer. Shifts in location and direction can occur in other seasons.

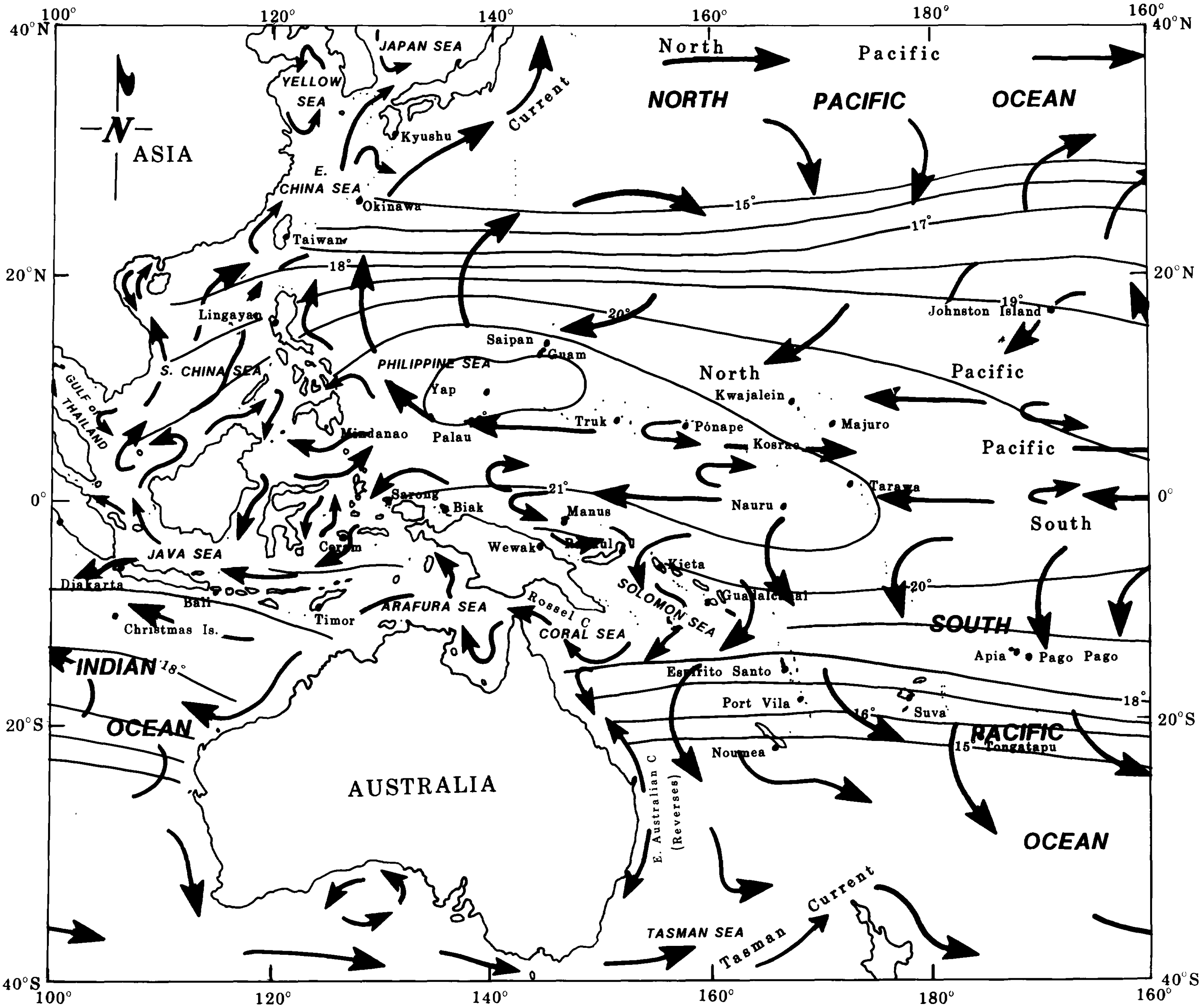
Delta T contours in degrees centigrade.

Current arrows denote direction only, not velocity.

TEMPERATURE DIFFERENCE BETWEEN SEA SURFACE and 1000 METERS and SURFACE CURRENTS

Between Latitudes 40°N. and 40°S.

Figure 5B



WESTERN PACIFIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

Mercator Projection

Delta T contours in degrees centigrade.

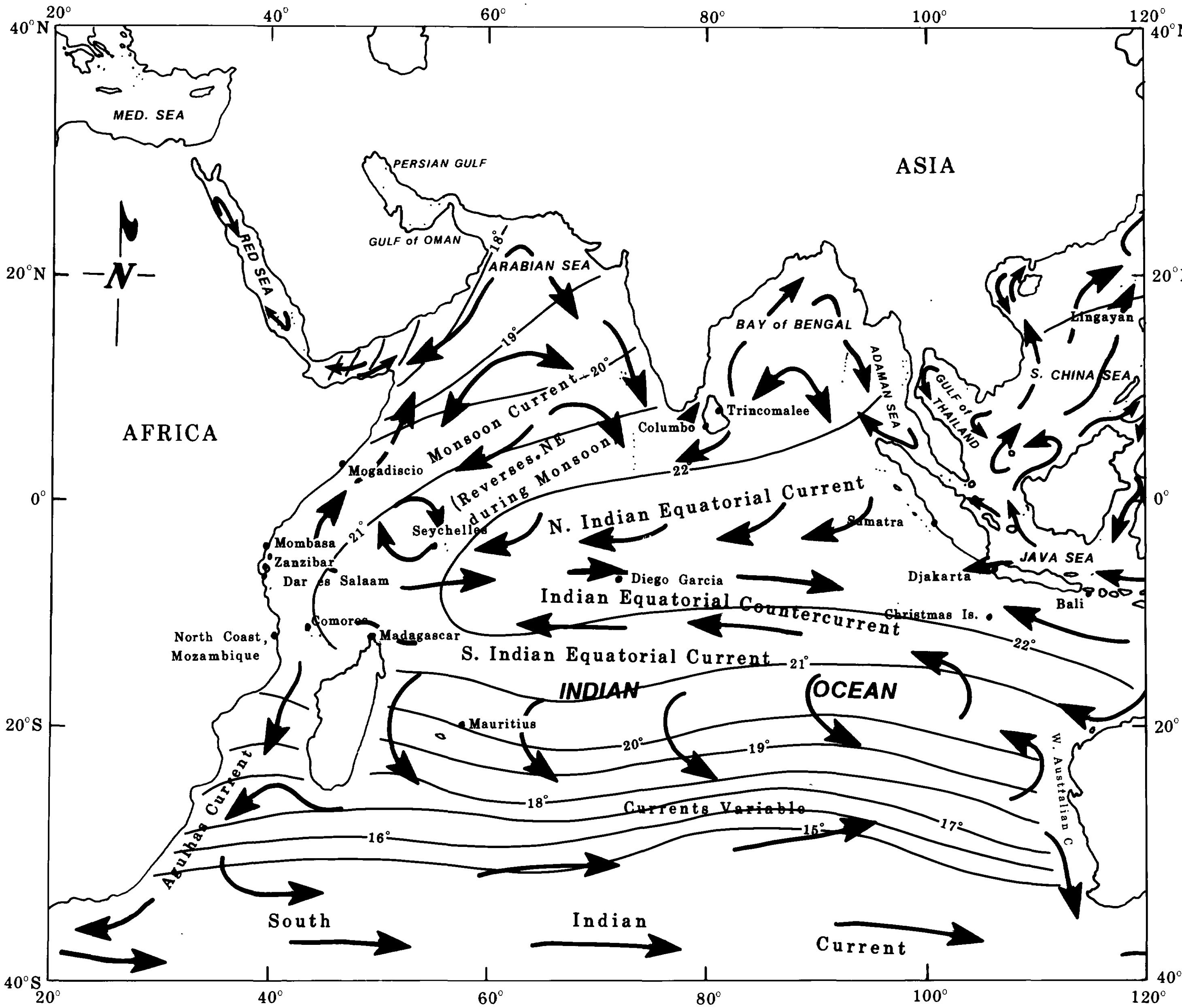
Current arrows denote direction only, not velocity.

NOTE: The surface currents shown occur during the northern hemisphere summer. Shifts in location and direction can occur in other seasons.

TEMPERATURE DIFFERENCE BETWEEN SEA SURFACE and 500 METERS and SURFACE CURRENTS

Between Latitudes 40° N. and 40° S.

Figure 5C



INDIAN OCEAN

SCALE

Mercator Projection

NOTE: The surface currents shown occur during the northern hemisphere summer. Shifts in location and direction can occur in other seasons.

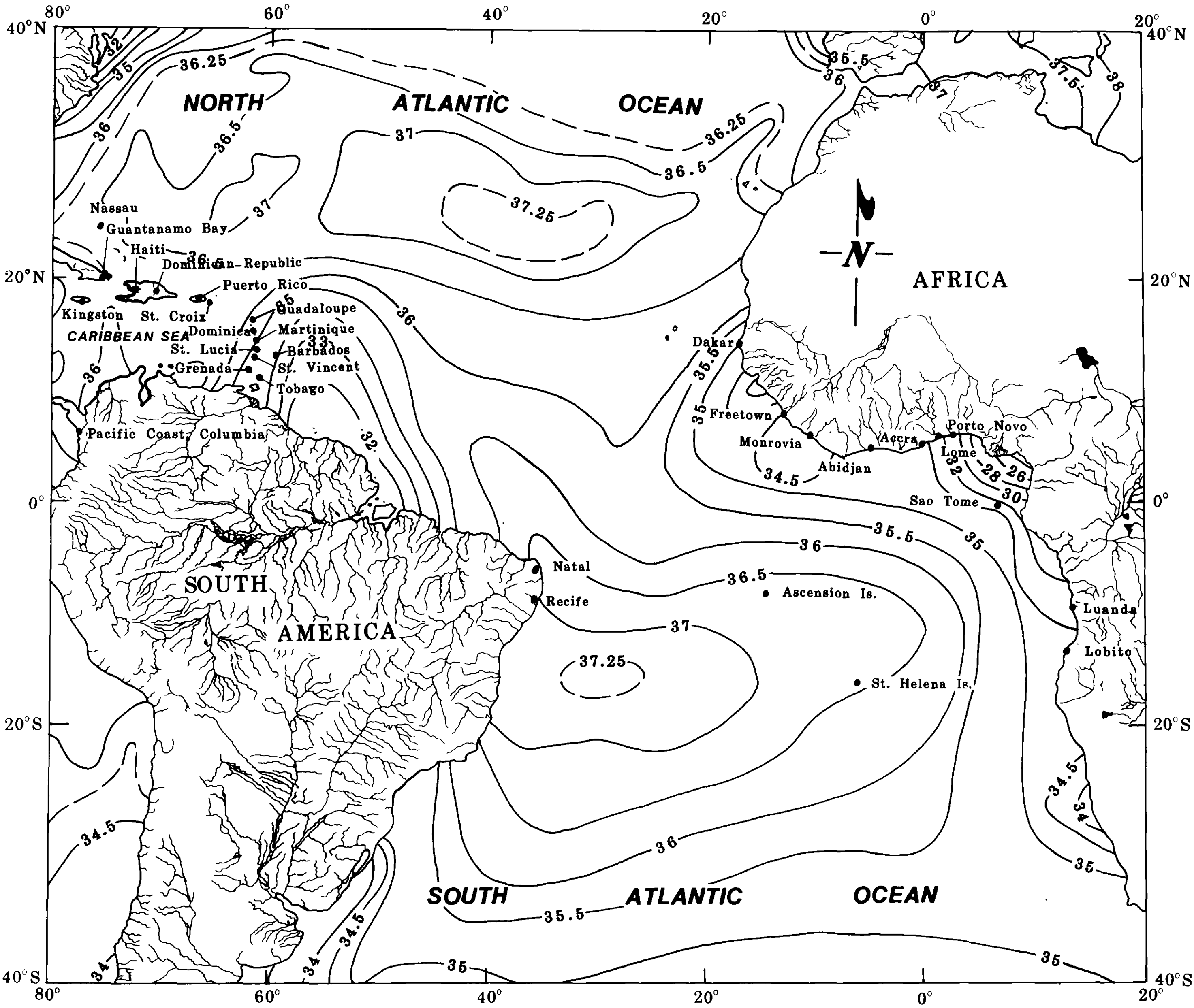
Delta T contours in degrees centigrade.

Current arrows denote direction only, not velocity.

TEMPERATURE DIFFERENCE BETWEEN SEA SURFACE and 1000 METERS and SURFACE CURRENTS

Between Latitudes 40°N. and 40°S.

Figure 5D



ATLANTIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

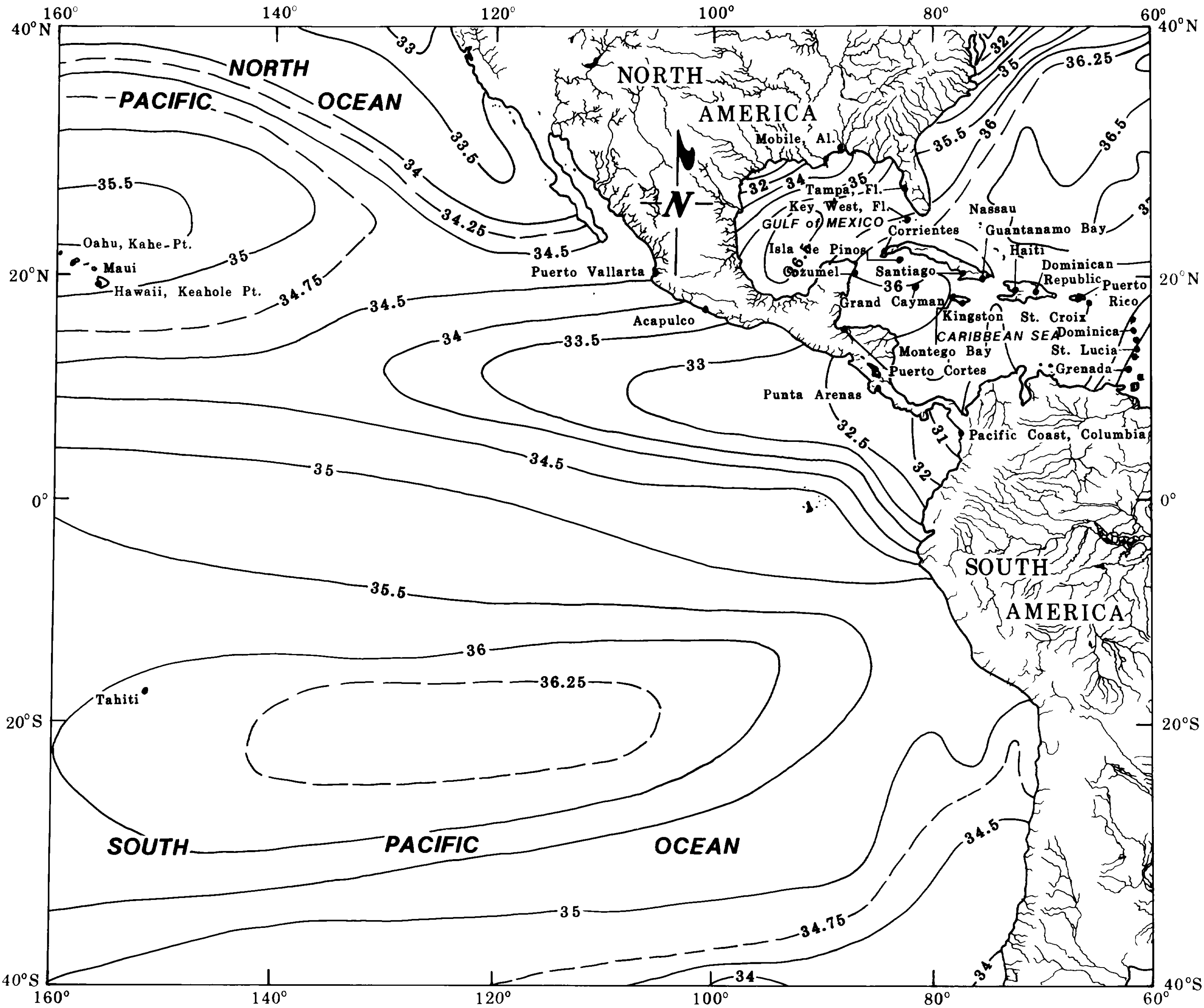
Mercator Projection

Measured in parts per thousand.

MEAN SEA SURFACE SALINITY

Between 40° N. and 40° S.

Figure 6A



EASTERN PACIFIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

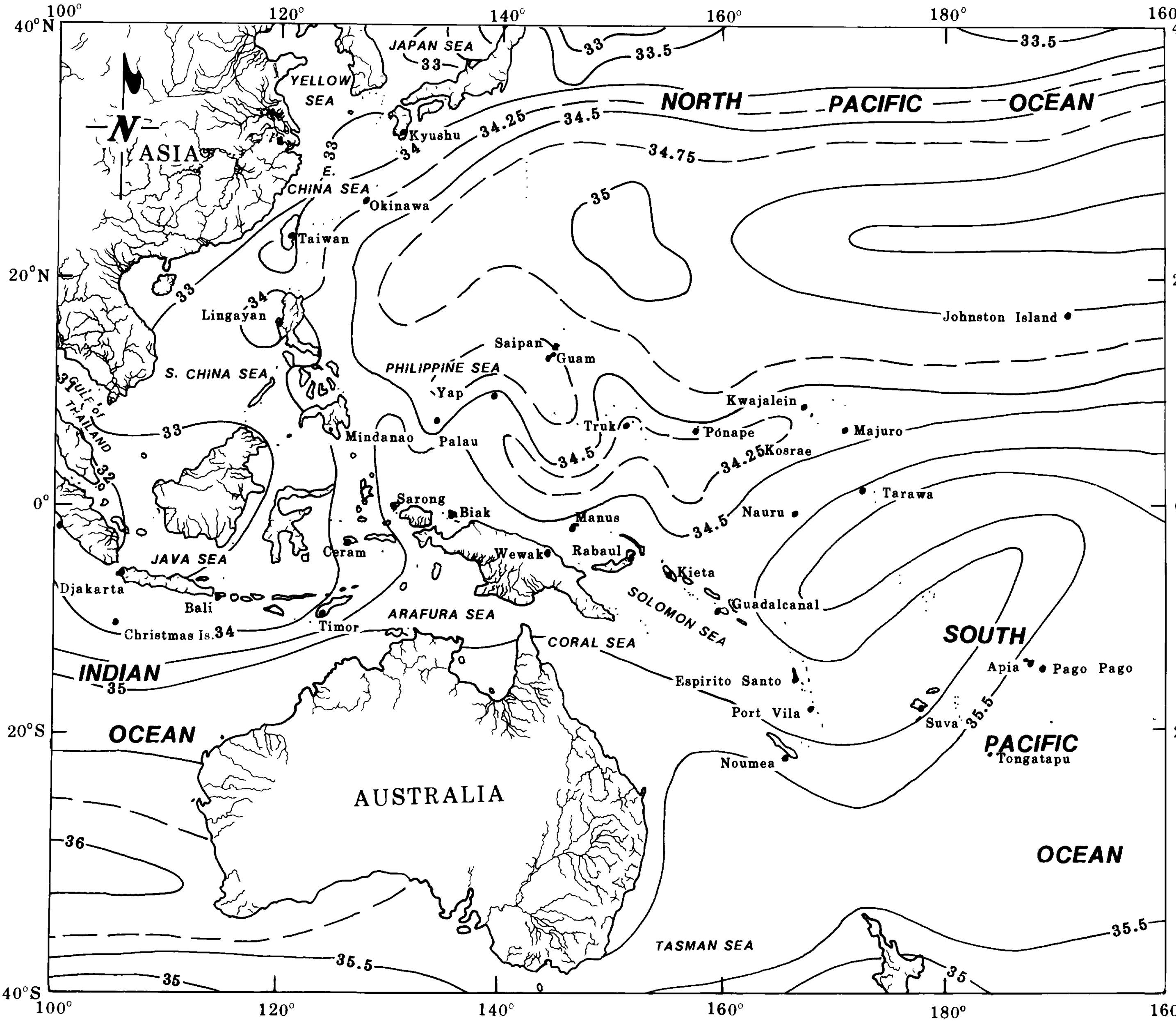
KILOMETERS

Mercator Projection

Measured in parts per thousand.

MEAN SEA SURFACE SALINITY

Figure 6B



WESTERN PACIFIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

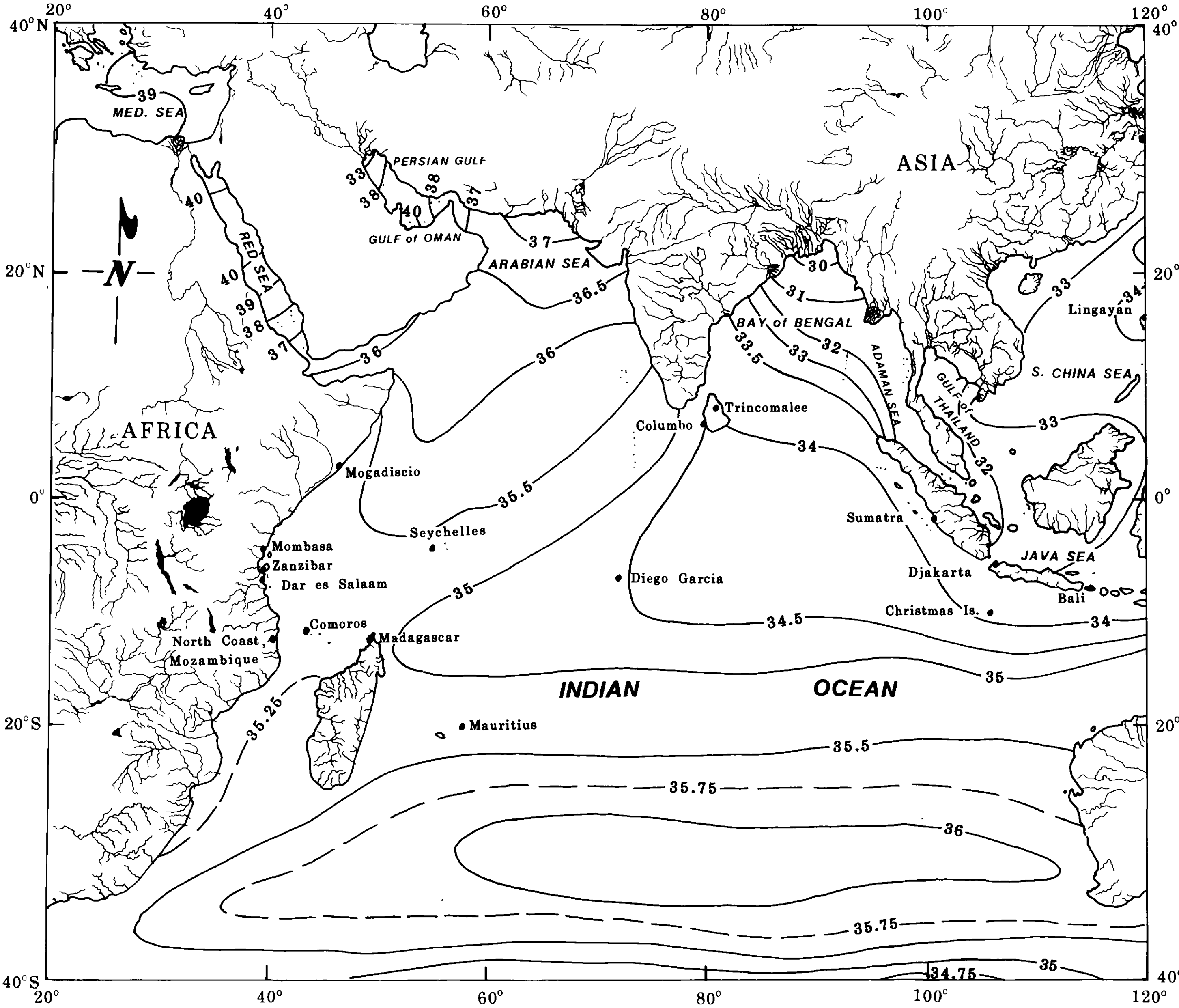
KILOMETERS

Mercator Projection

Measured in parts per thousand.

MEAN SEA SURFACE SALINITY
Between 40° N. and 40° S.

Figure 6C



SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

Mercator Projection

INDIAN OCEAN

Measured in parts per thousand.

MEAN SEA SURFACE SALINITY
Between 40° N. and 40° S.

Figure 6D

Ideal Continental Shelf, Slope and Deep Sea Floor

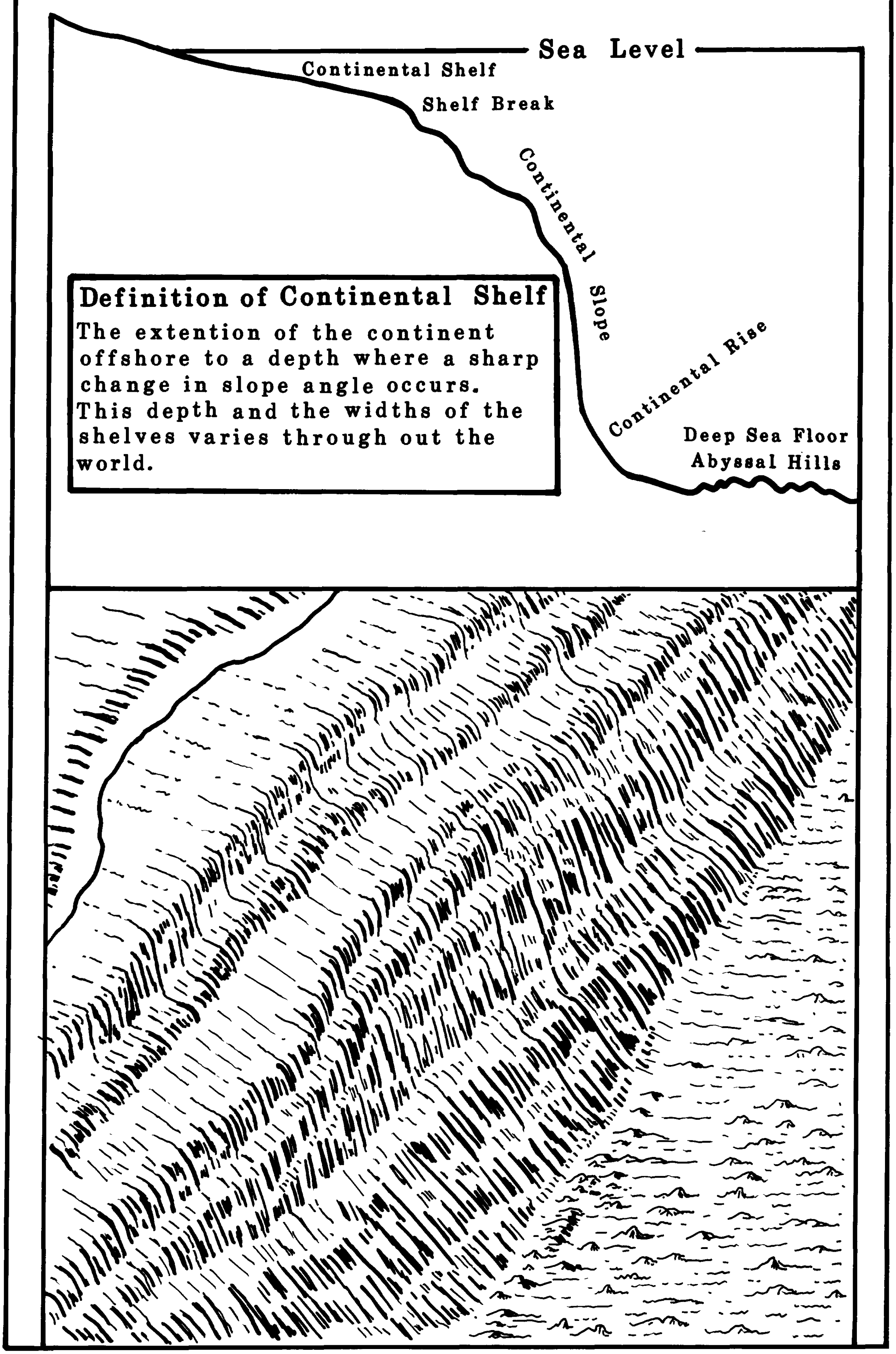
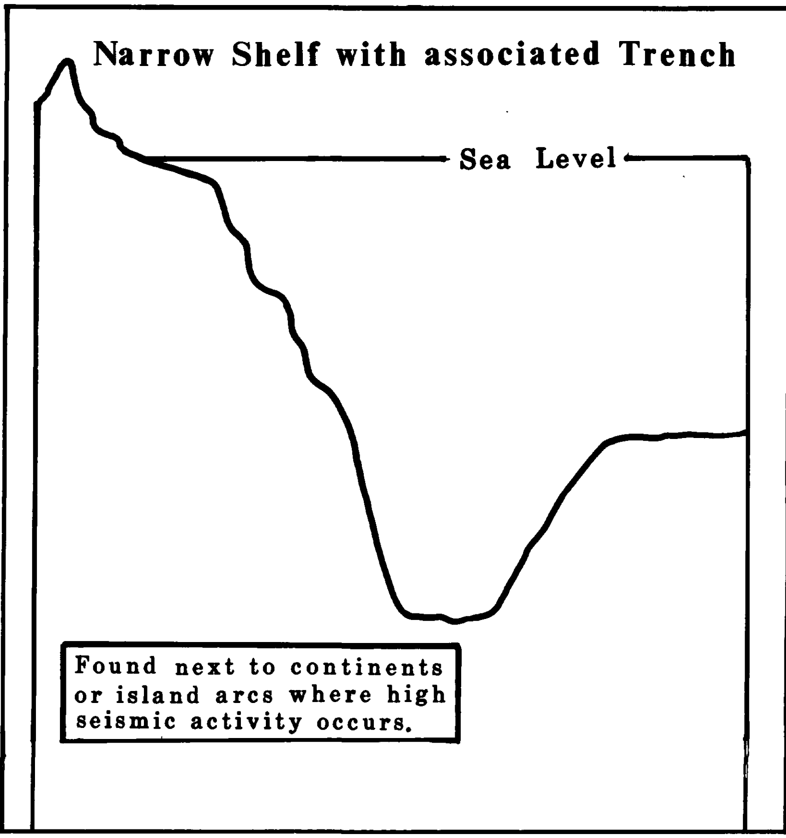


Figure 7A


Narrow Shelf with associated Trench
Sea Level
Found next to continents or island arcs where high seismic activity occurs.

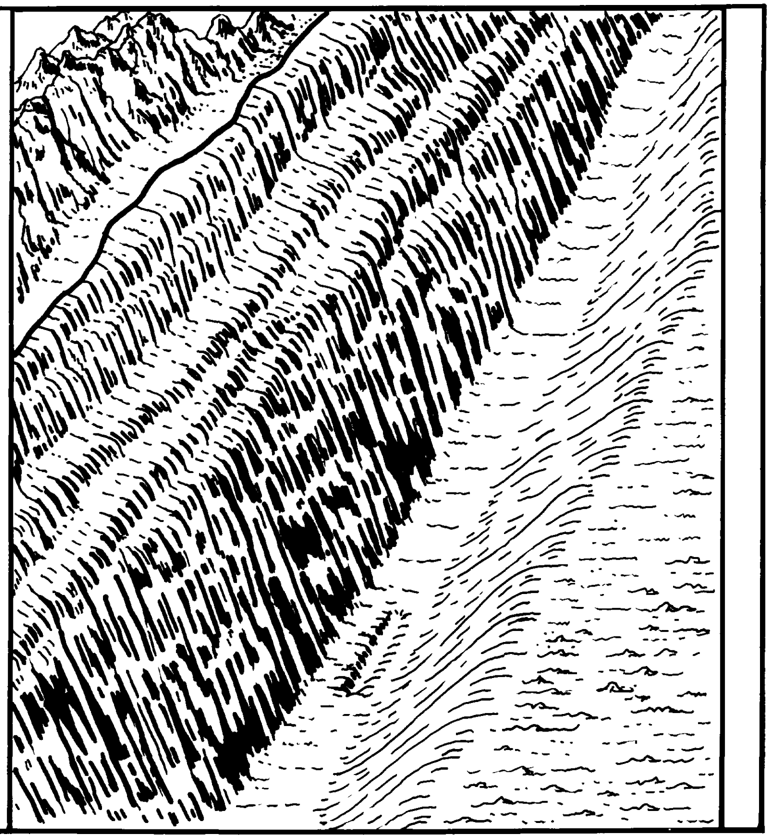


Figure 7B

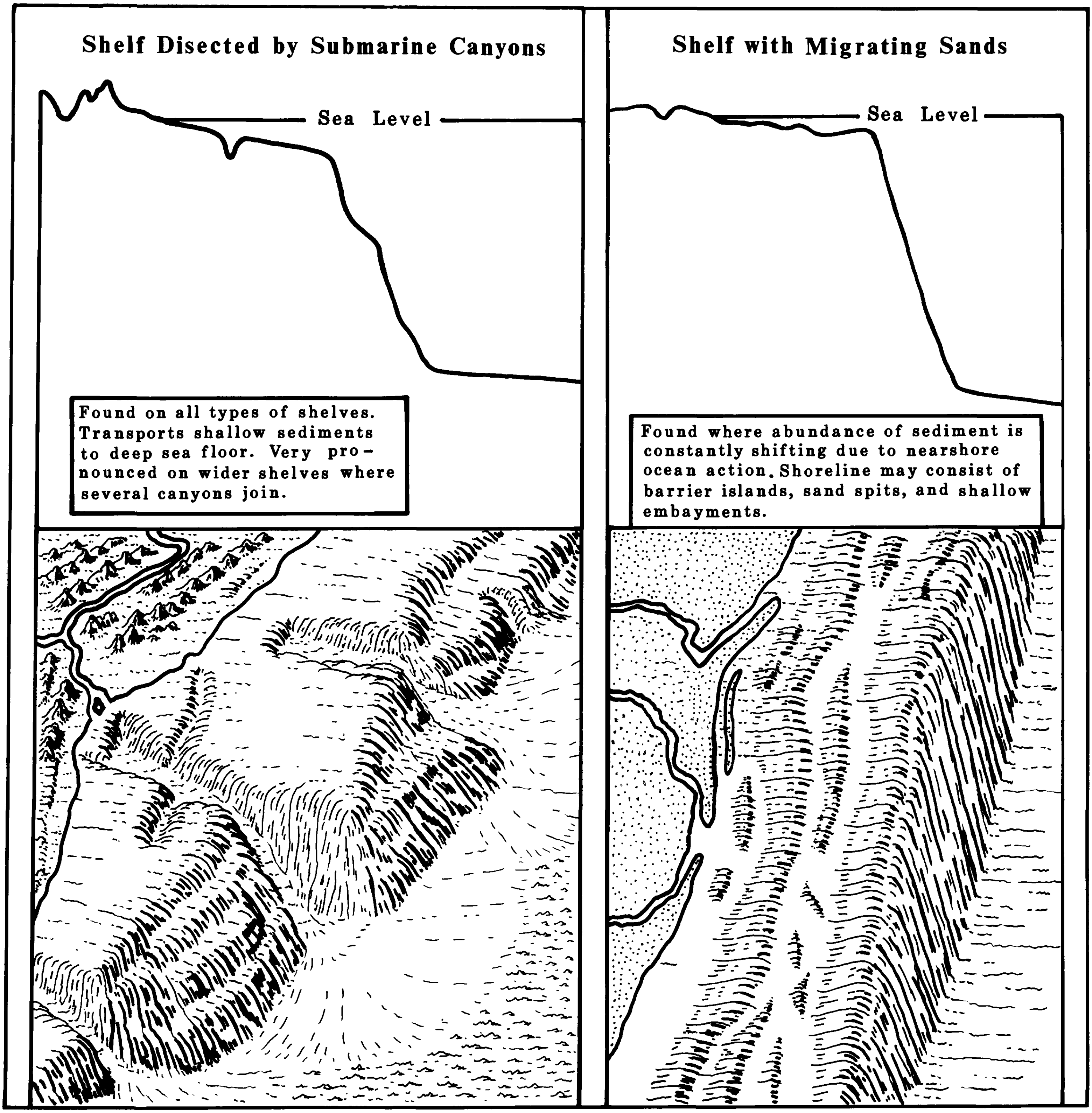
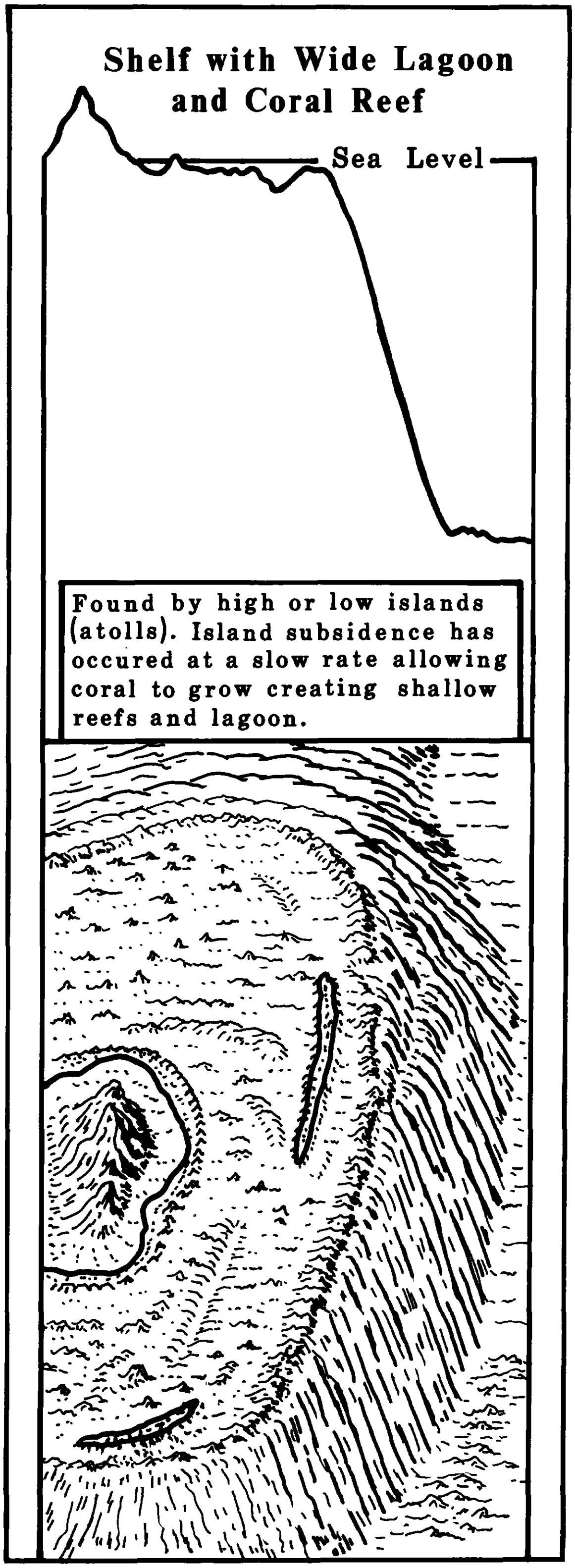

Shelf Disected by Submarine Canyons
Sea Level
Found on all types of shelves. Transports shallow sediments to deep sea floor. Very pronounced on wider shelves where several canyons join.
Shelf with Migrating Sands
Sea Level
Found where abundance of sediment is constantly shifting due to nearshore ocean action. Shoreline may consist of barrier islands, sand spits, and shallow embayments.

Figure 7C,7D


Shelf with Wide Lagoon and Coral Reef
Sea Level
Found by high or low islands (atolls). Island subsidence has occured at a slow rate allowing coral to grow creating shallow reefs and lagoon.

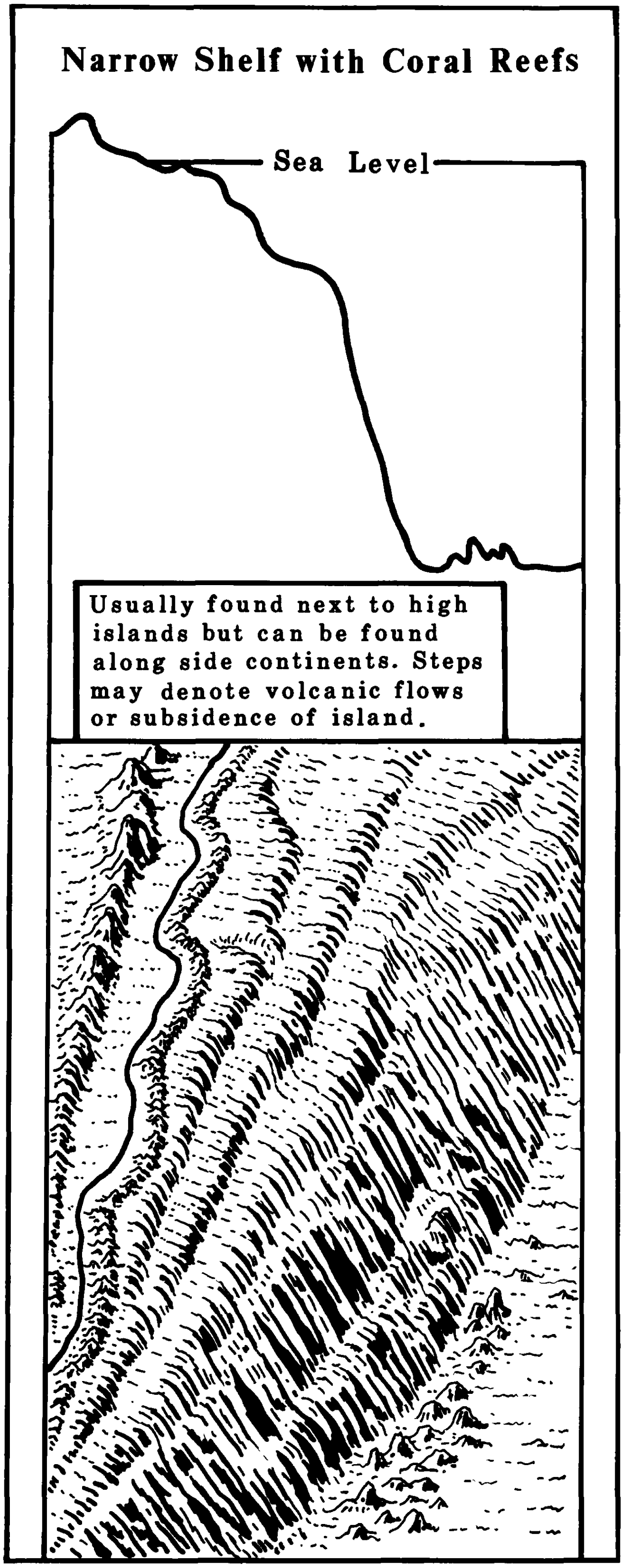

Narrow Shelf with Coral Reefs
Sea Level
Usually found next to high islands but can be found along side continents. Steps may denote volcanic flows or subsidence of island.

Figure 7E,7F

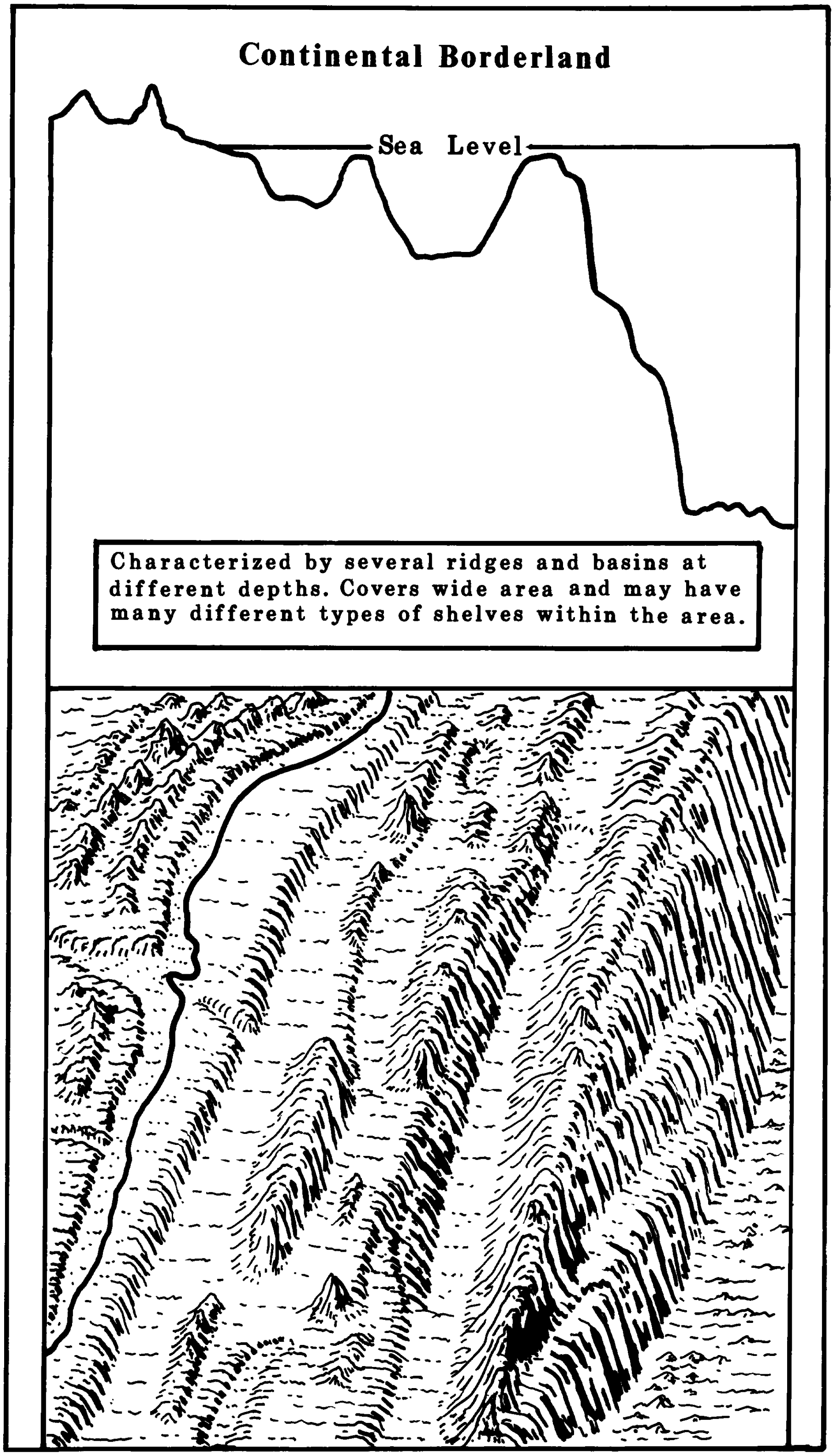
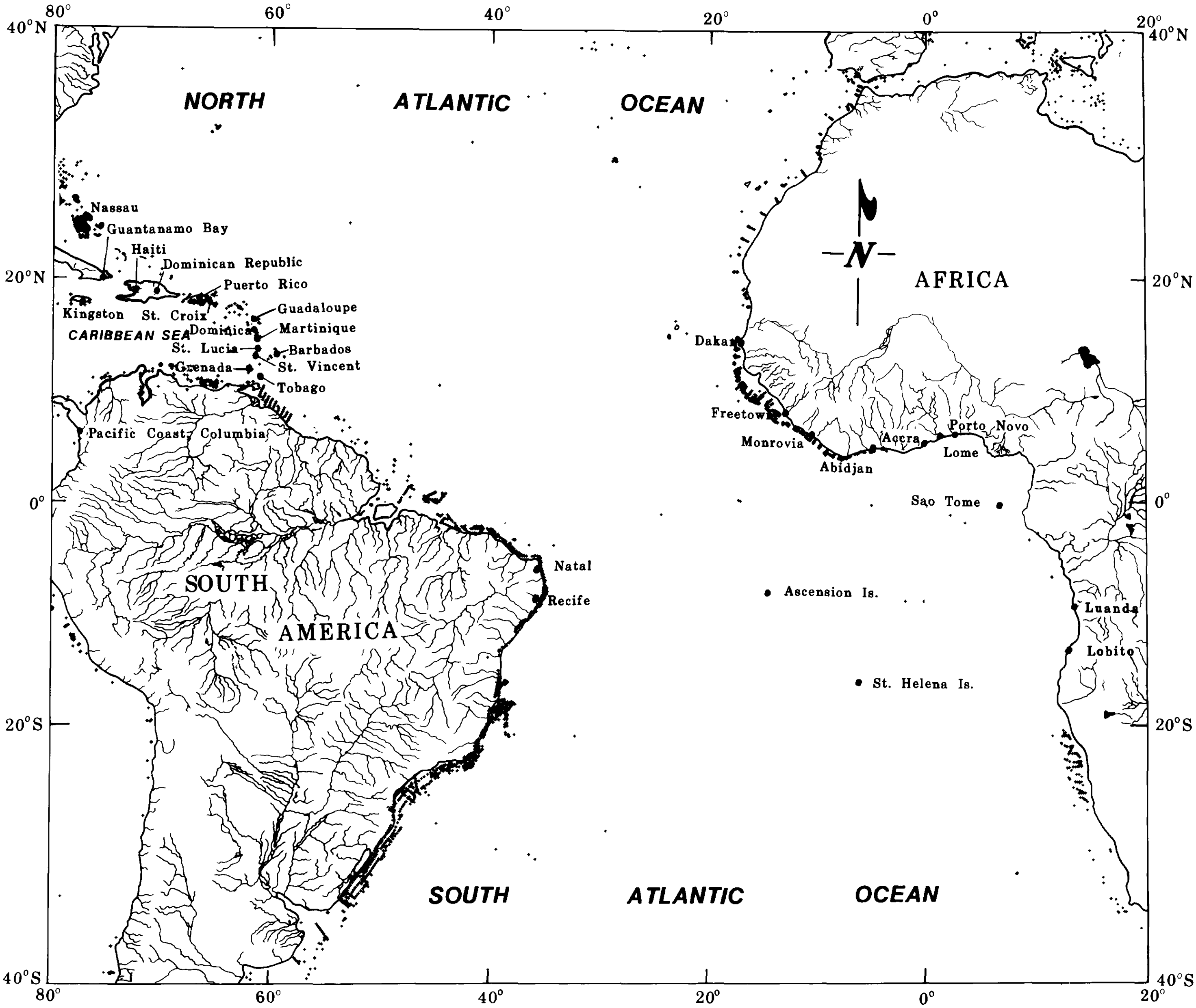

Continental Borderland
Sea Level
Characterized by several ridges and basins at different depths. Covers wide area and may have many different types of shelves within the area.

Figure 7G



ATLANTIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

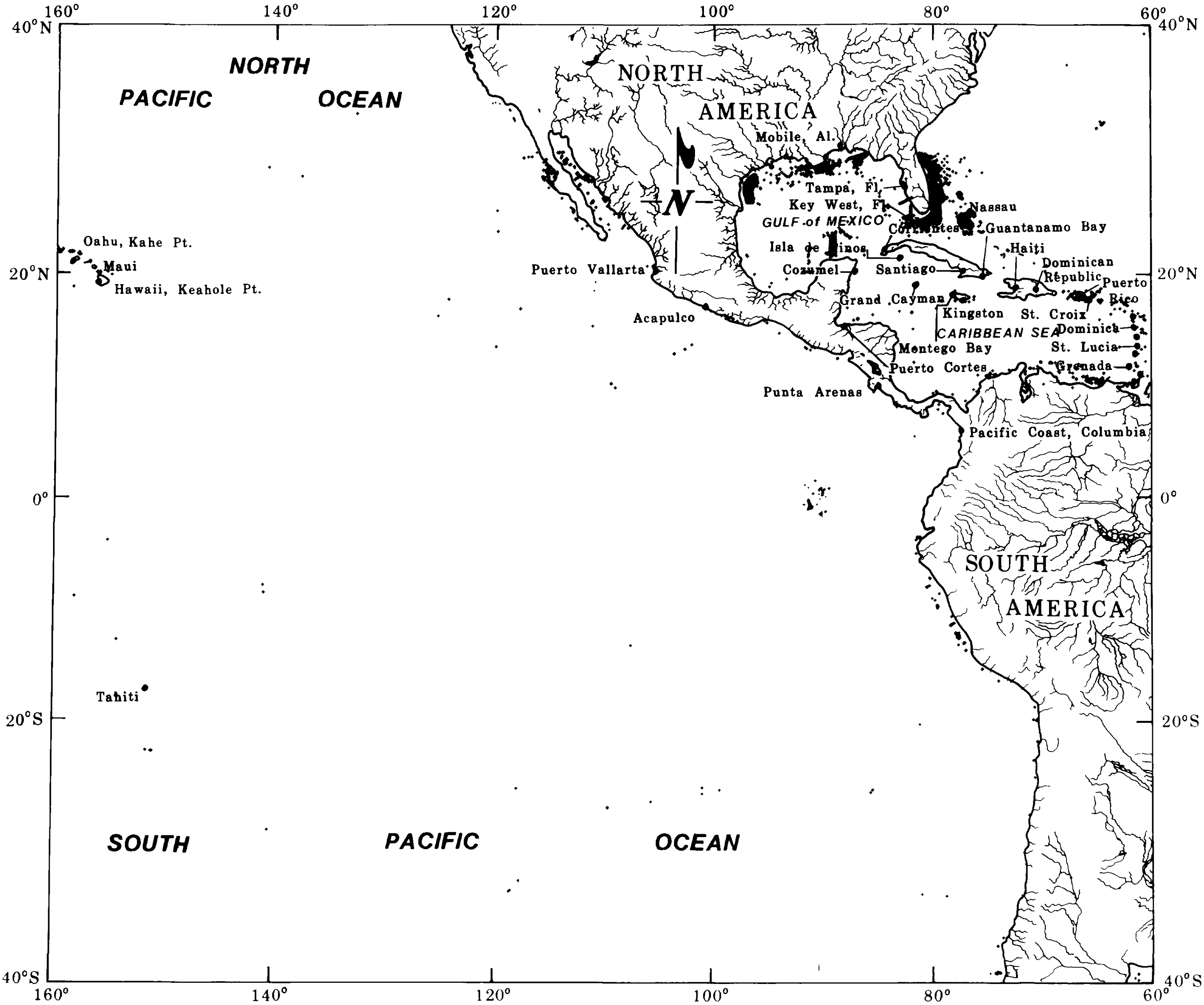
Mercator Projection

For information about these samples, contact:
Carla Moore
National Geophysical Data Center
NOAA,
Boulder, Colorado 80303

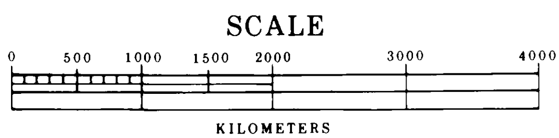
SAMPLE LOCATIONS IN LESS THAN 1000 METERS DEPTH

Between Latitudes 40°N. and 40°S.

Figure 8A



EASTERN PACIFIC OCEAN



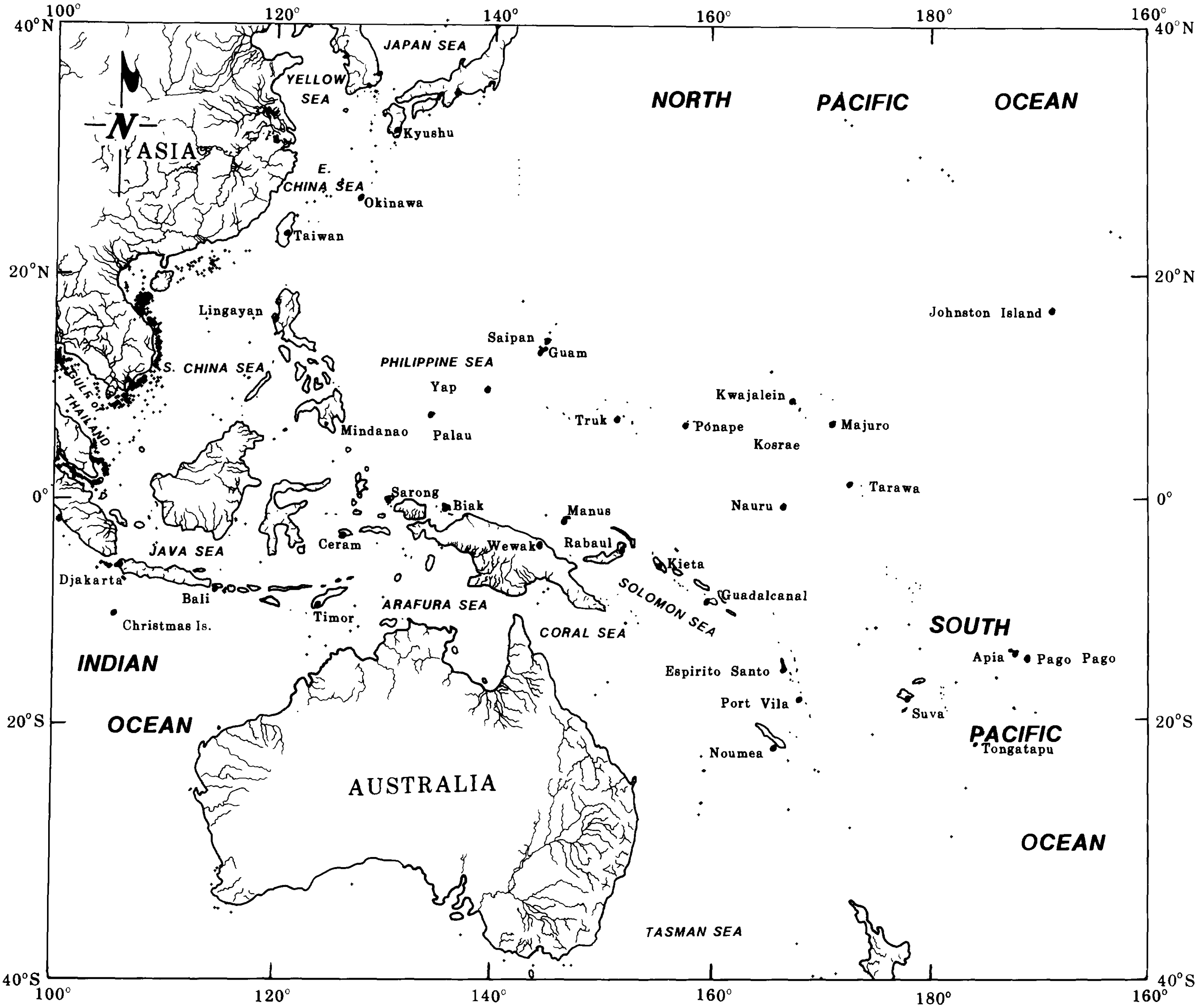
Mercator Projection

For information about these samples, contact:

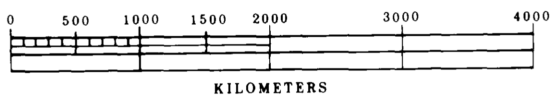
Carla Moore
National Geophysical Data Center
NOAA,
Boulder, Colorado 80303

SAMPLE LOCATIONS IN LESS THAN 1000 METERS DEPTH
Between Latitudes 40°N. and 40°S.

Figure 8B



SCALE



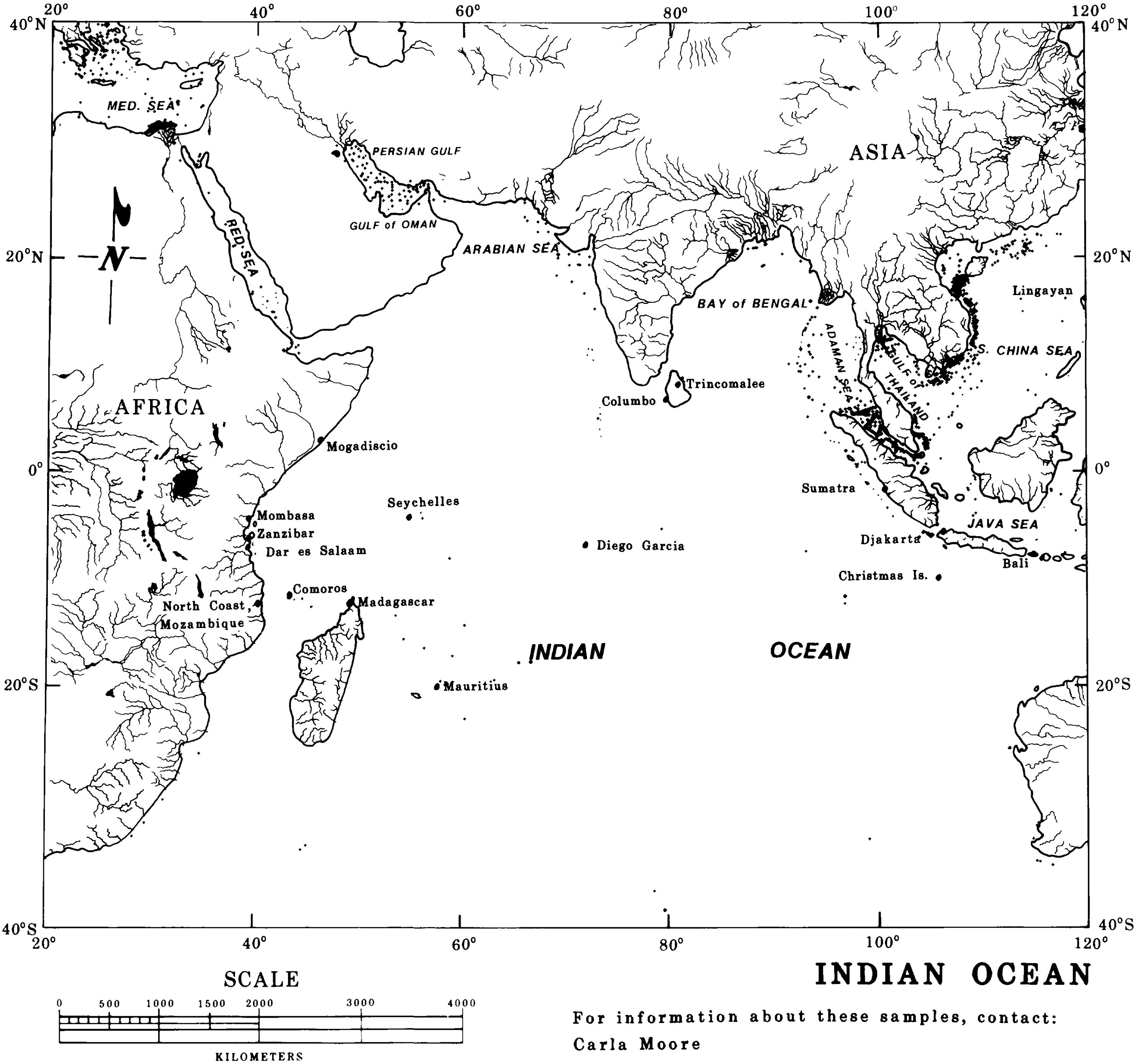
Mercator Projection

WESTERN PACIFIC OCEAN

For information about these samples, contact:
Carla Moore
National Geophysical Data Center
NOAA,
Boulder, Colorado 80303

SAMPLE LOCATIONS IN LESS THAN 1000 METERS DEPTH
Between Latitudes 40°N. and 40°S.

Figure 8C



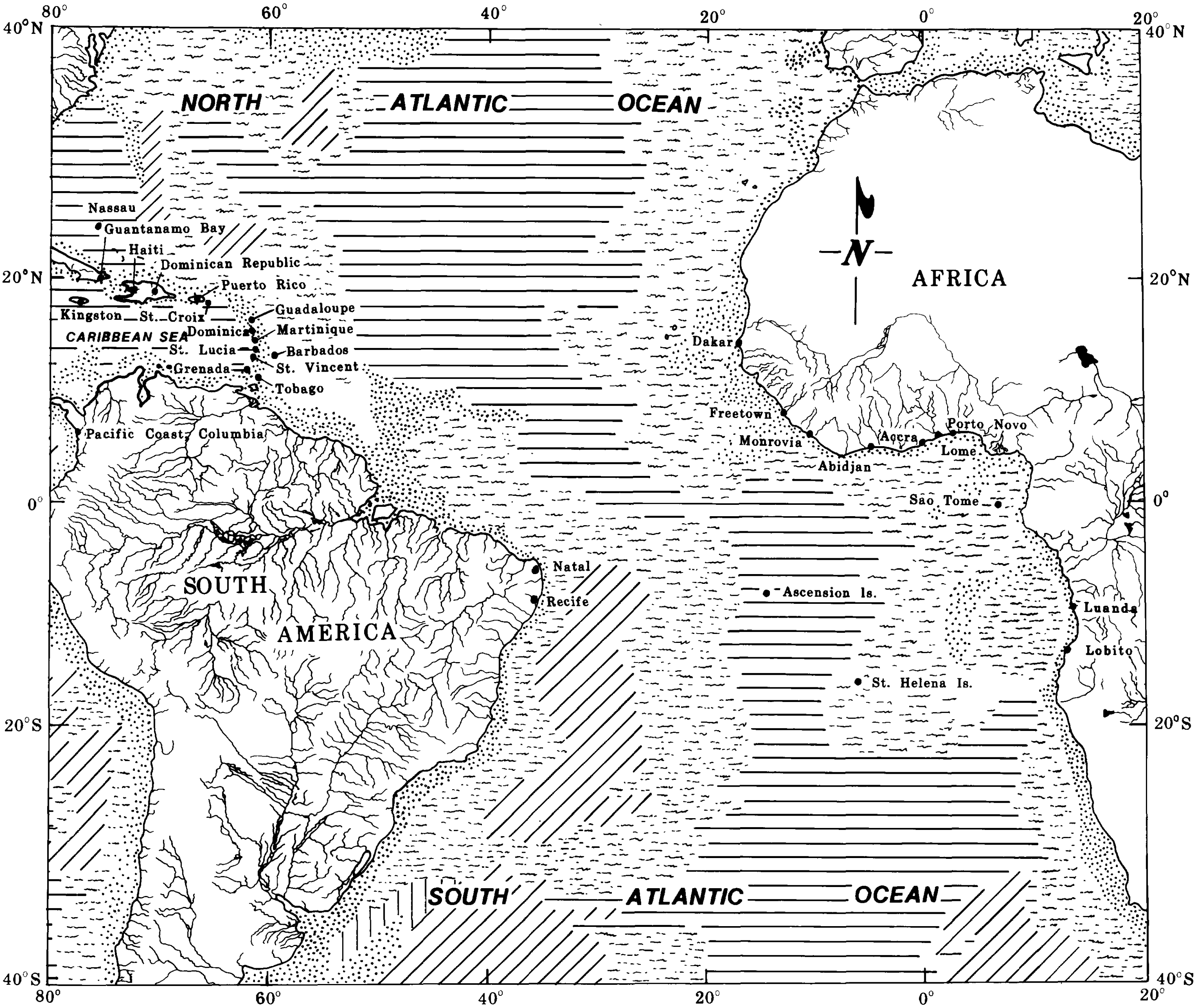
Mercator Projection

INDIAN OCEAN

For information about these samples, contact:
Carla Moore
National Geophysical Data Center
NOAA,
Boulder, Colorado 80303

SAMPLE LOCATIONS IN LESS THAN 1000 METERS DEPTH
Between Latitudes 40°N. and 40°S.

Figure 8D



ATLANTIC OCEAN

SCALE

0 500 1000 1500 2000 3000 4000

KILOMETERS

Mercator Projection

LEGEND

BIOGENIC OOZE

Skeletal remains greater than 30%

- Carbonate Ooze
- Siliceous Ooze

DEEP-SEA CLAY

- Authigenic Clay/Mud — From erosional or chemical activity
- Pelagic Clay — Skeletal remains less than 30%.

CONTINENTAL MARGIN/ISLAND

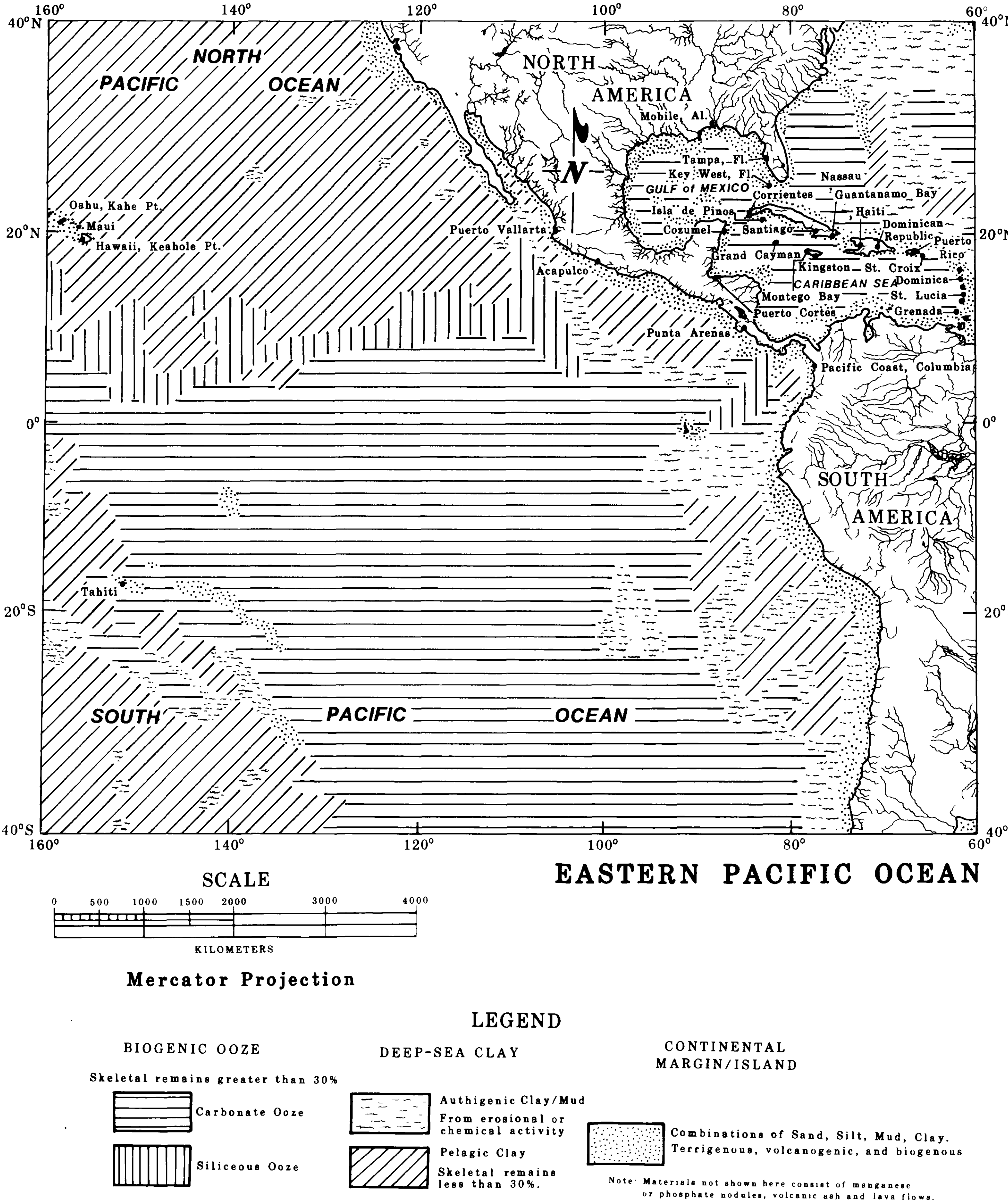
- Combinations of Sand, Silt, Mud, Clay. Terrigenous, volcanogenic, and biogenous

Note: Materials not shown here consist of manganese or phosphate nodules, volcanic ash and lava flows.

GENERALIZED SEA FLOOR SEDIMENT DISTRIBUTION

Between Latitudes 40°N and 40°S.

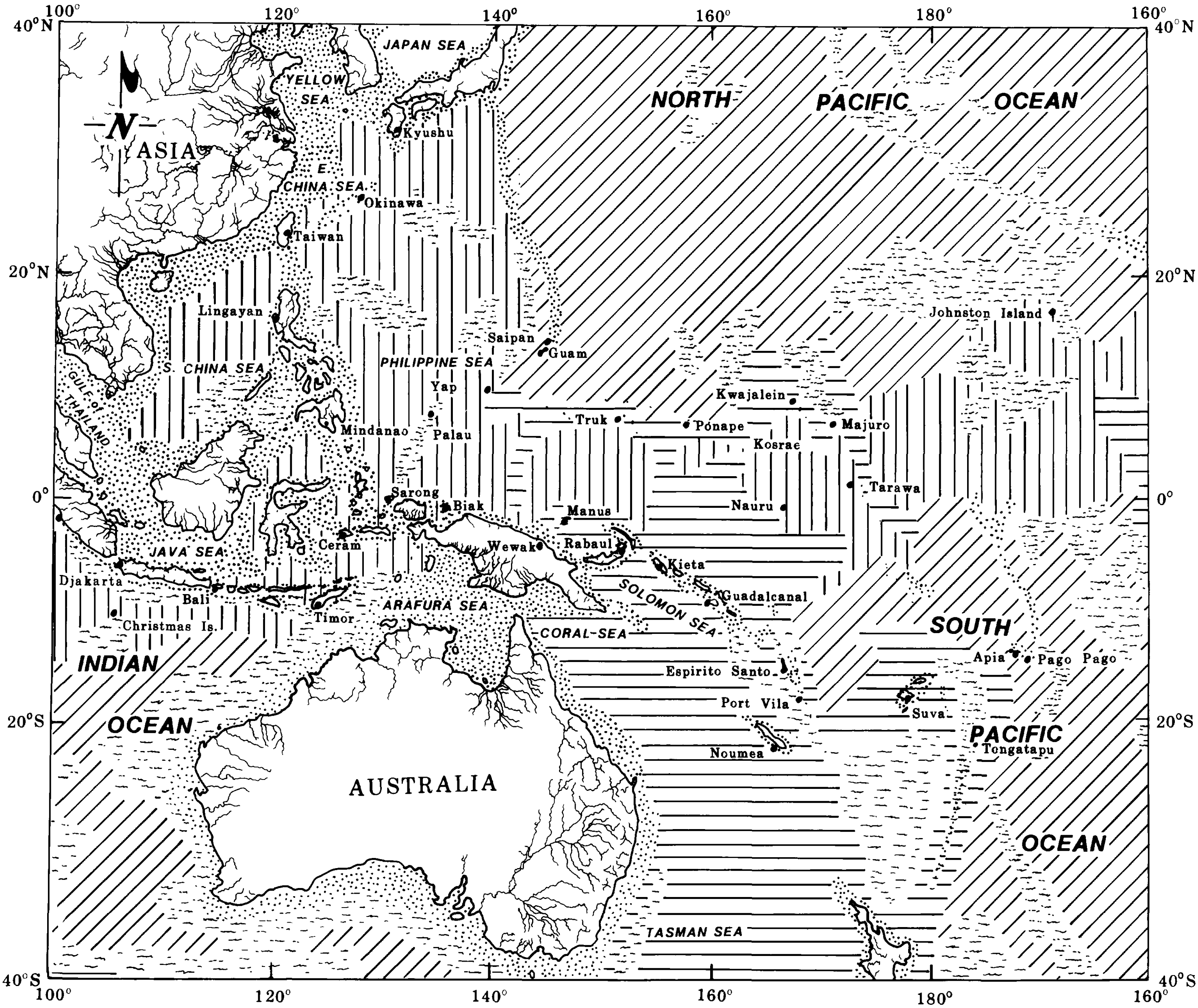
Figure 9A



GENERALIZED SEA FLOOR SEDIMENT DISTRIBUTION

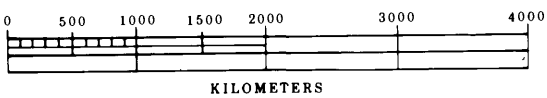
Between Latitudes 40°N and 40°S.

Figure 9B



WESTERN PACIFIC OCEAN

SCALE



Mercator Projection

LEGEND

BIOGENIC OOZE

Skeletal remains greater than 30%

- Carbonate Ooze
- Siliceous Ooze

DEEP-SEA CLAY

- Authigenic Clay/Mud
  From erosional or chemical activity
- Pelagic Clay
  Skeletal remains less than 30%.

CONTINENTAL MARGIN/ISLAND

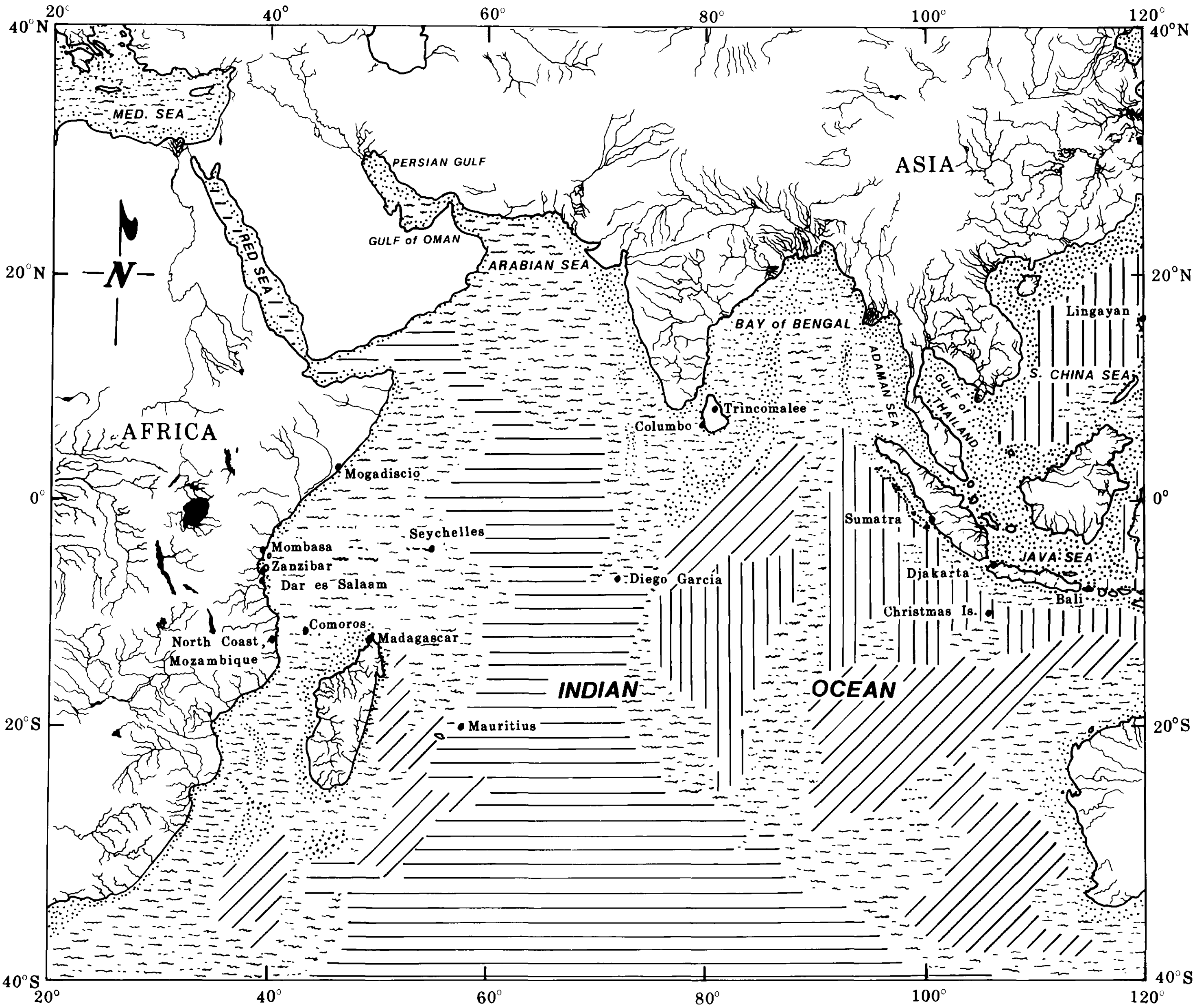
- Combinations of Sand, Silt, Mud, Clay. Terrigenous, volcanogenic, and biogenous

Note: Materials not shown here consist of manganese or phosphate nodules, volcanic ash and lava flows.

GENERALIZED SEA FLOOR SEDIMENT DISTRIBUTION

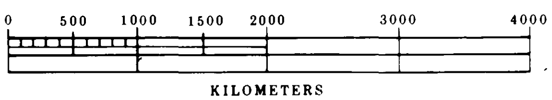
Between Latitudes 40°N and 40°S.

Figure 9C



INDIAN OCEAN

SCALE



Mercator Projection

LEGEND

BIOGENIC OOZE

Skeletal remains greater than 30%

- Carbonate Ooze
- Siliceous Ooze

DEEP-SEA CLAY

- Authigenic Clay/Mud
  From erosional or chemical activity
- Pelagic Clay
  Skeletal remains less than 30%.

CONTINENTAL MARGIN/ISLAND

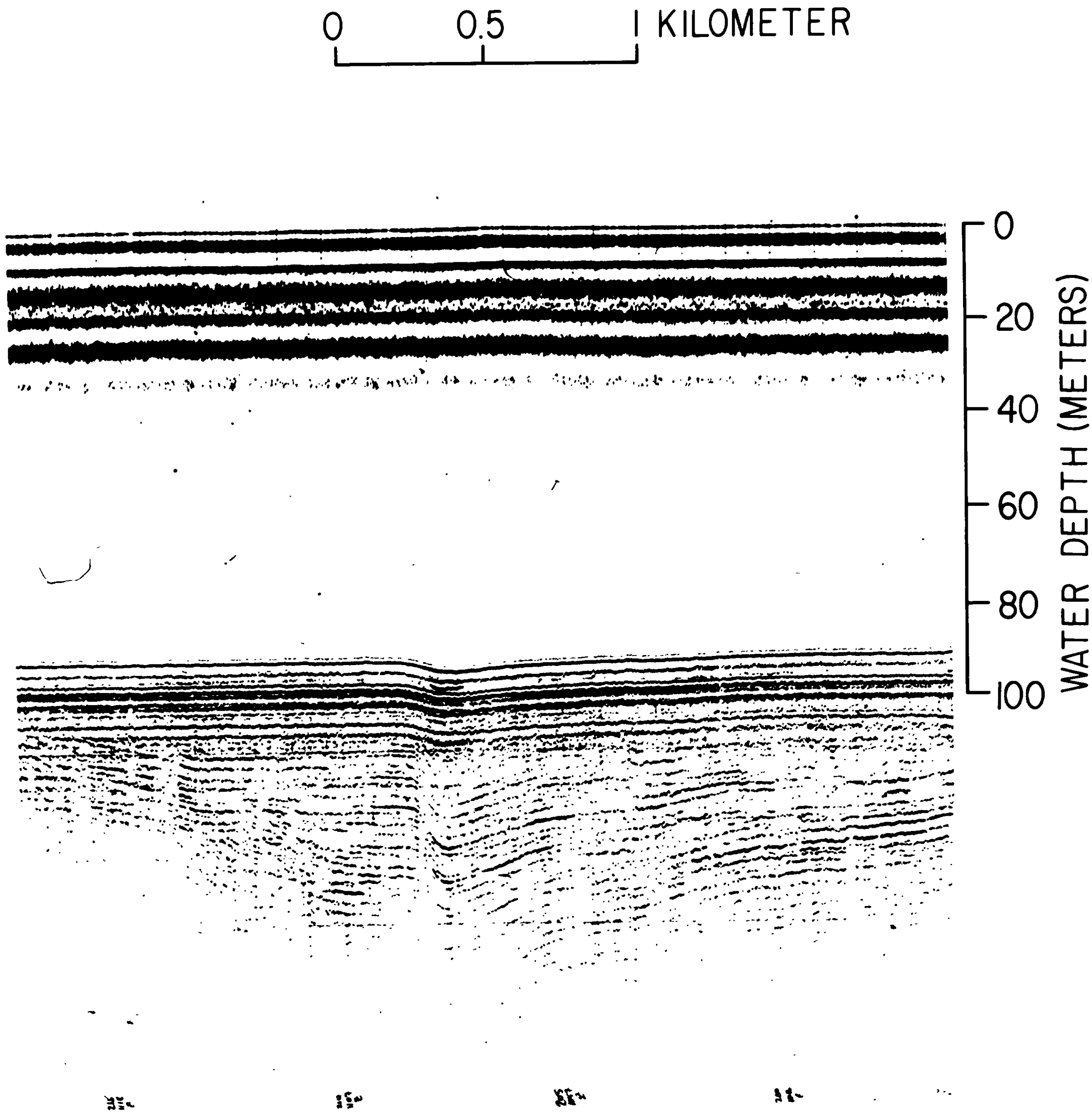
- Combinations of Sand, Silt, Mud, Clay. Terrigenous, volcanogenic, and biogenous

Note: Materials not shown here consist of manganese or phosphate nodules, volcanic ash and lava flows.

GENERALIZED SEA FLOOR SEDIMENT DISTRIBUTION

Between Latitudes 40°N and 40°S.

Figure 9D


0
0.5
1 KILOMETER
0
20
40
60
80
100
WATER DEPTH (METERS)

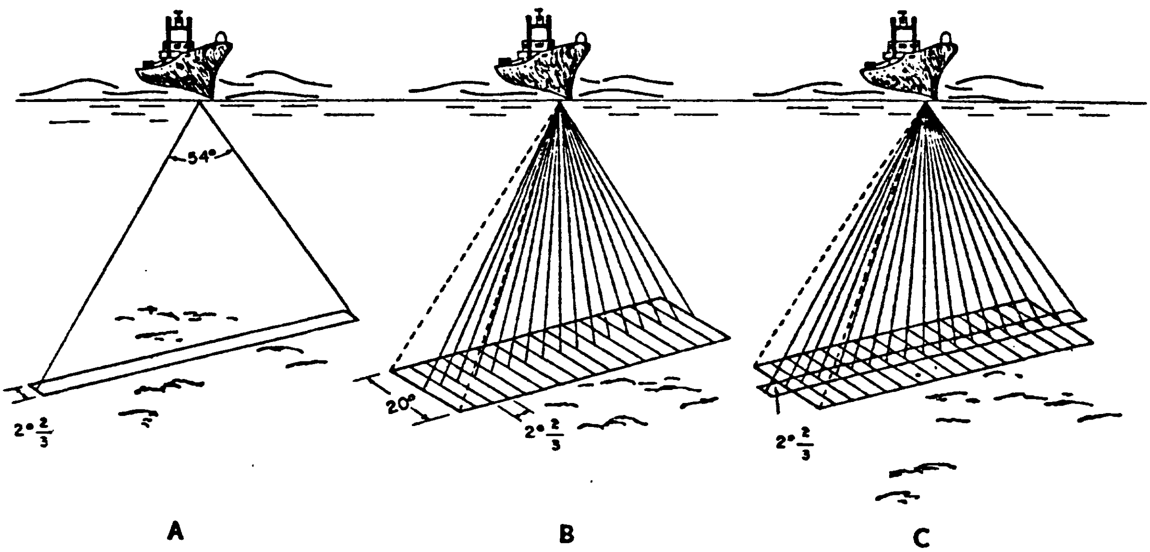


Figure 11

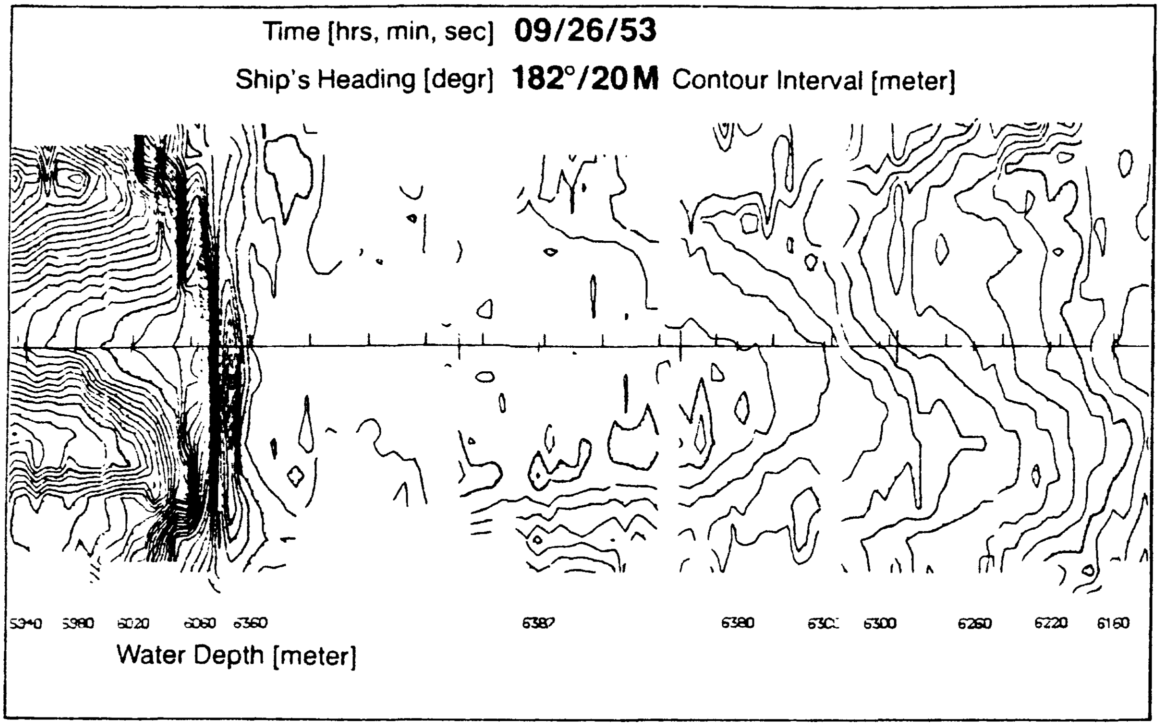

Time [hrs, min, sec] 09/26/53
Ship's Heading [degr] 182°/20 M Contour Interval [meter]
5340 5980 6020 6060 6360
6387
6380
6300
6260
6220
6160
Water Depth [meter]

Figure 12

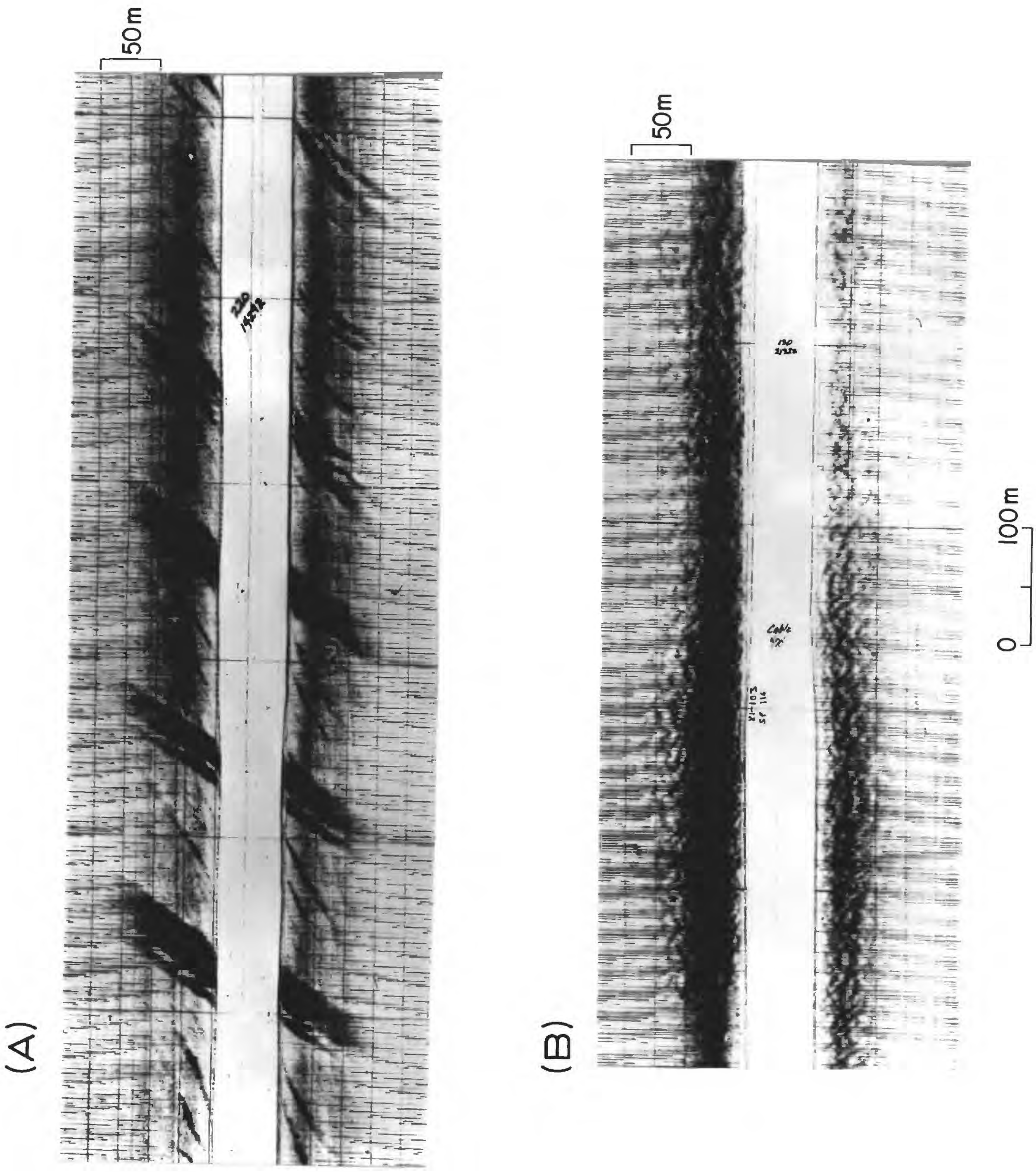


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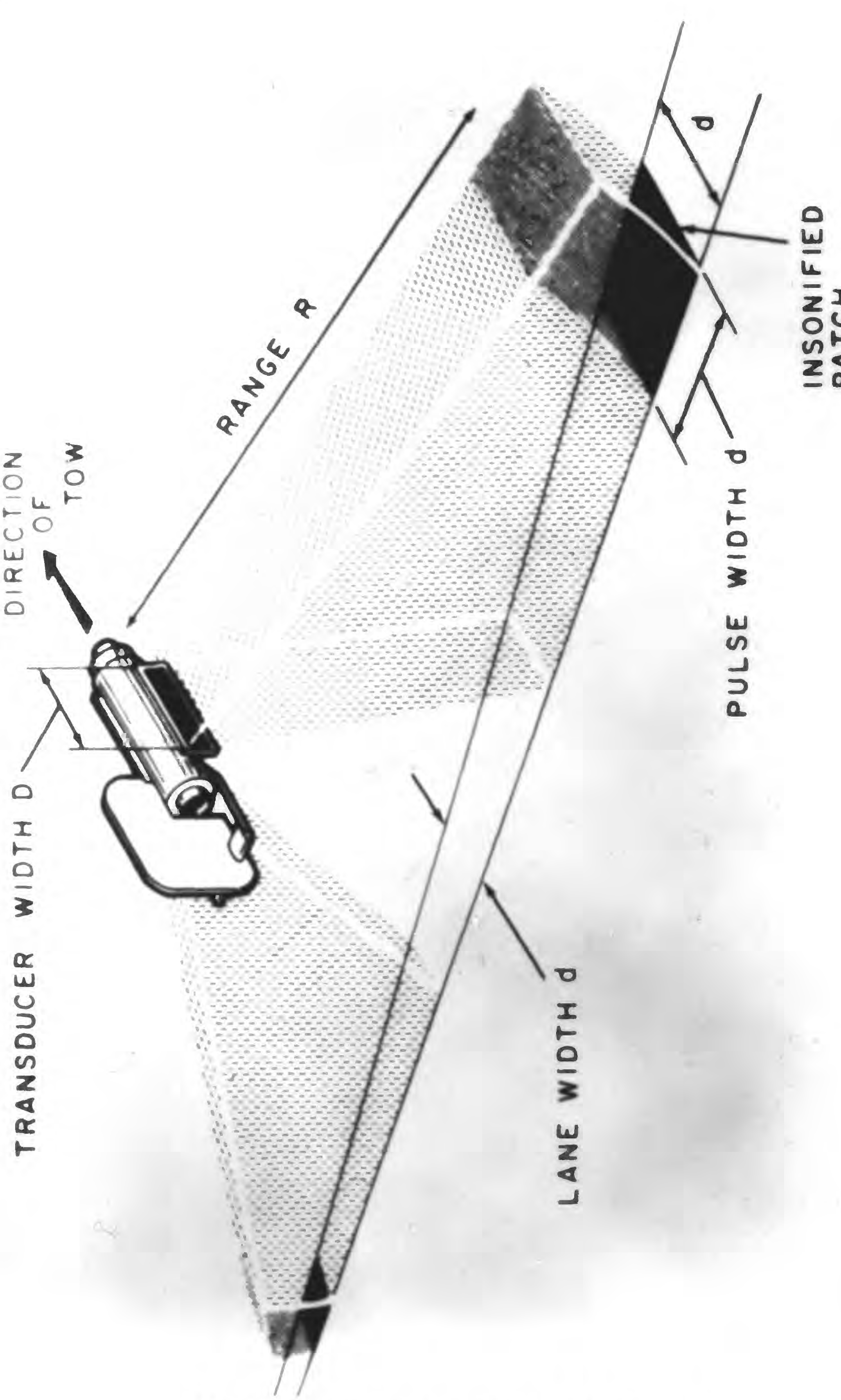
Figure 13



Made from best available copy

Figure 14

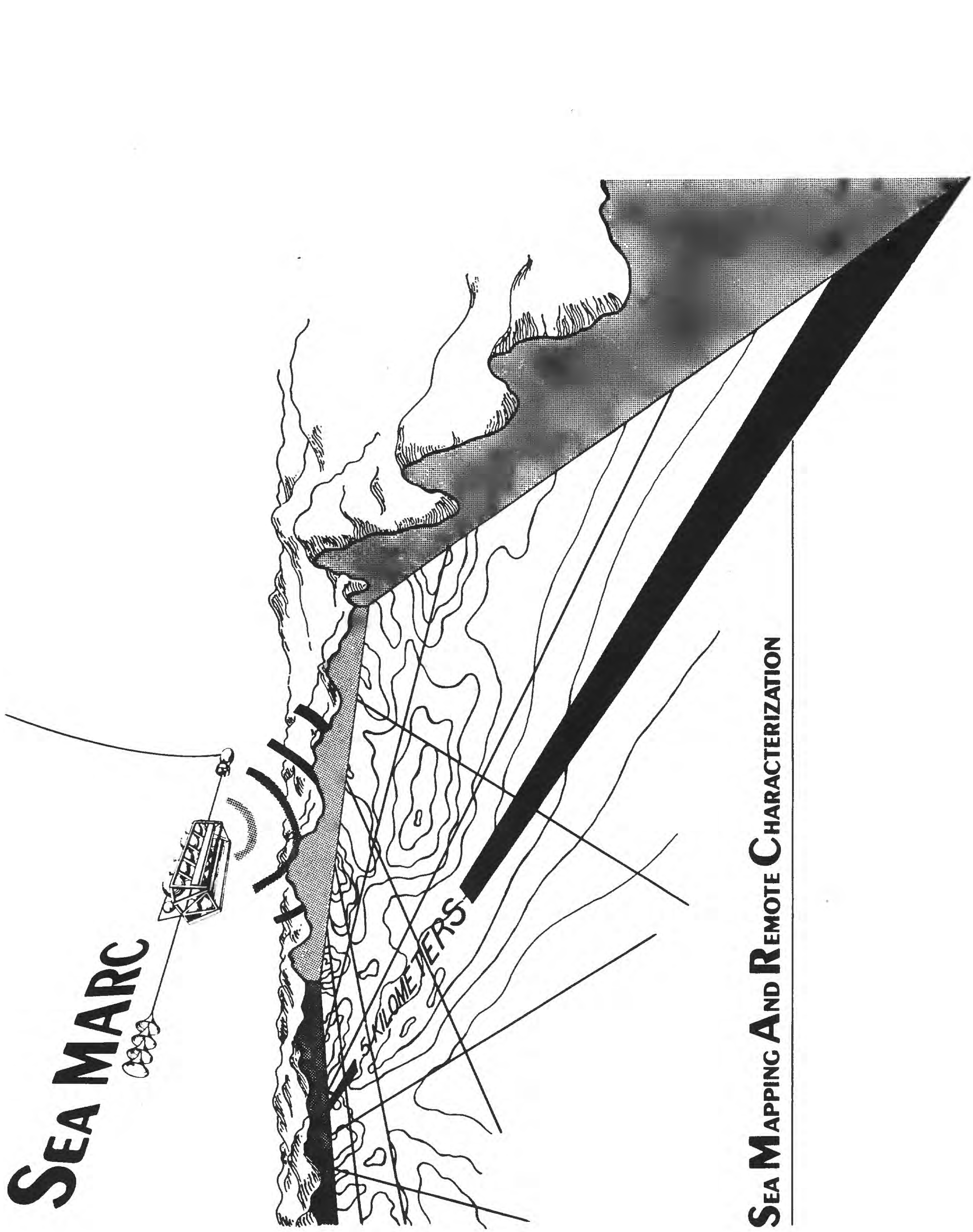

SEA MARC
5 KILOMETERS
SEA MAPPING AND REMOTE CHARACTERIZATION

Figure 15

Figure 16

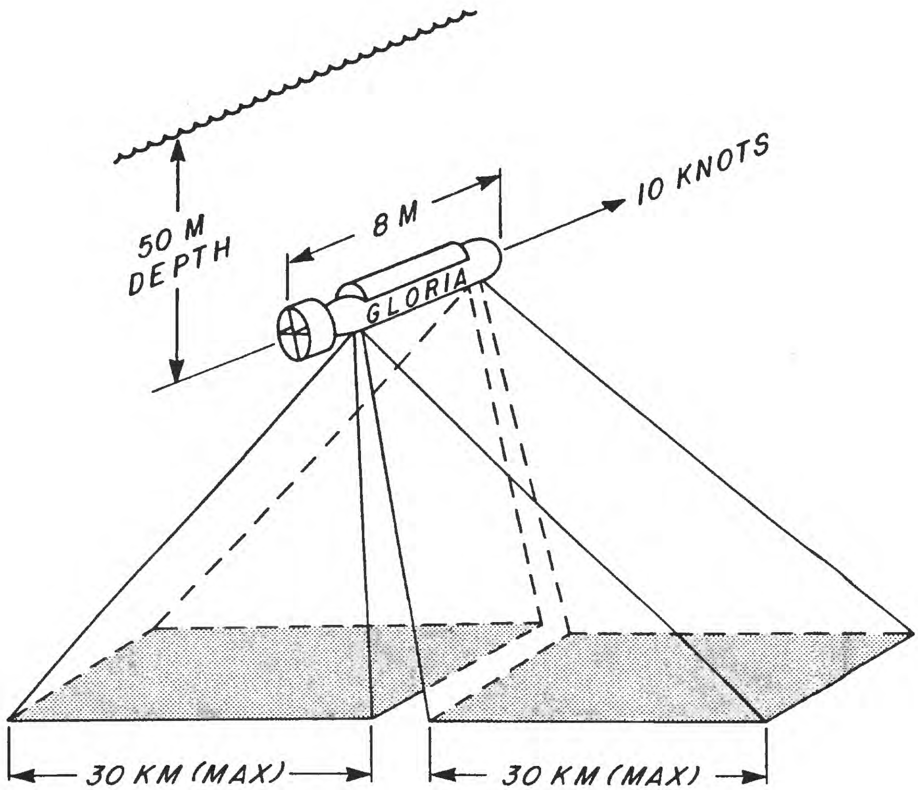


Figure 17

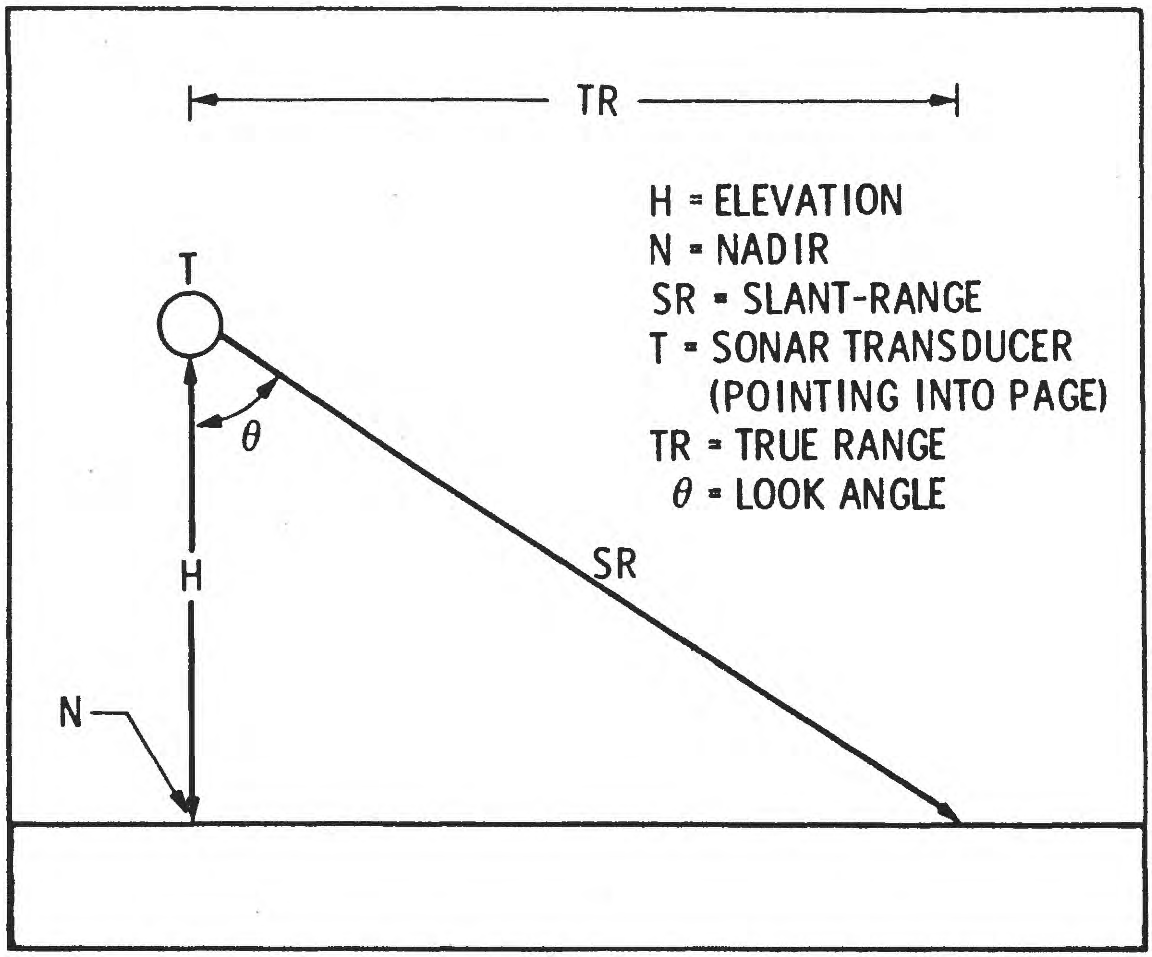

TR
H = ELEVATION
N = NADIR
SR = SLANT-RANGE
T = SONAR TRANSDUCER
(POINTING INTO PAGE)
TR = TRUE RANGE
θ = LOOK ANGLE
T
θ
H
SR
N

Figure 18

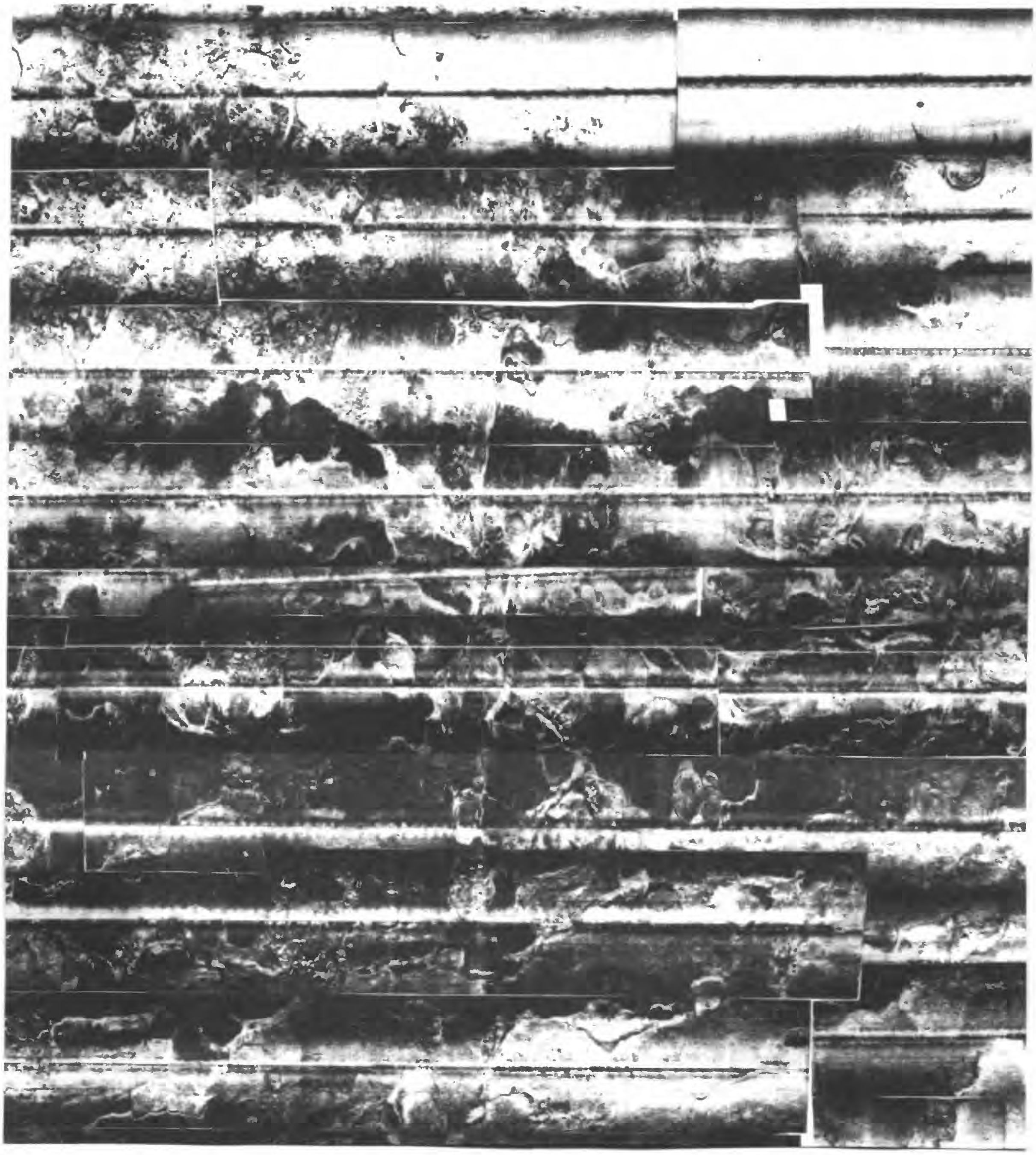


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Figure 19

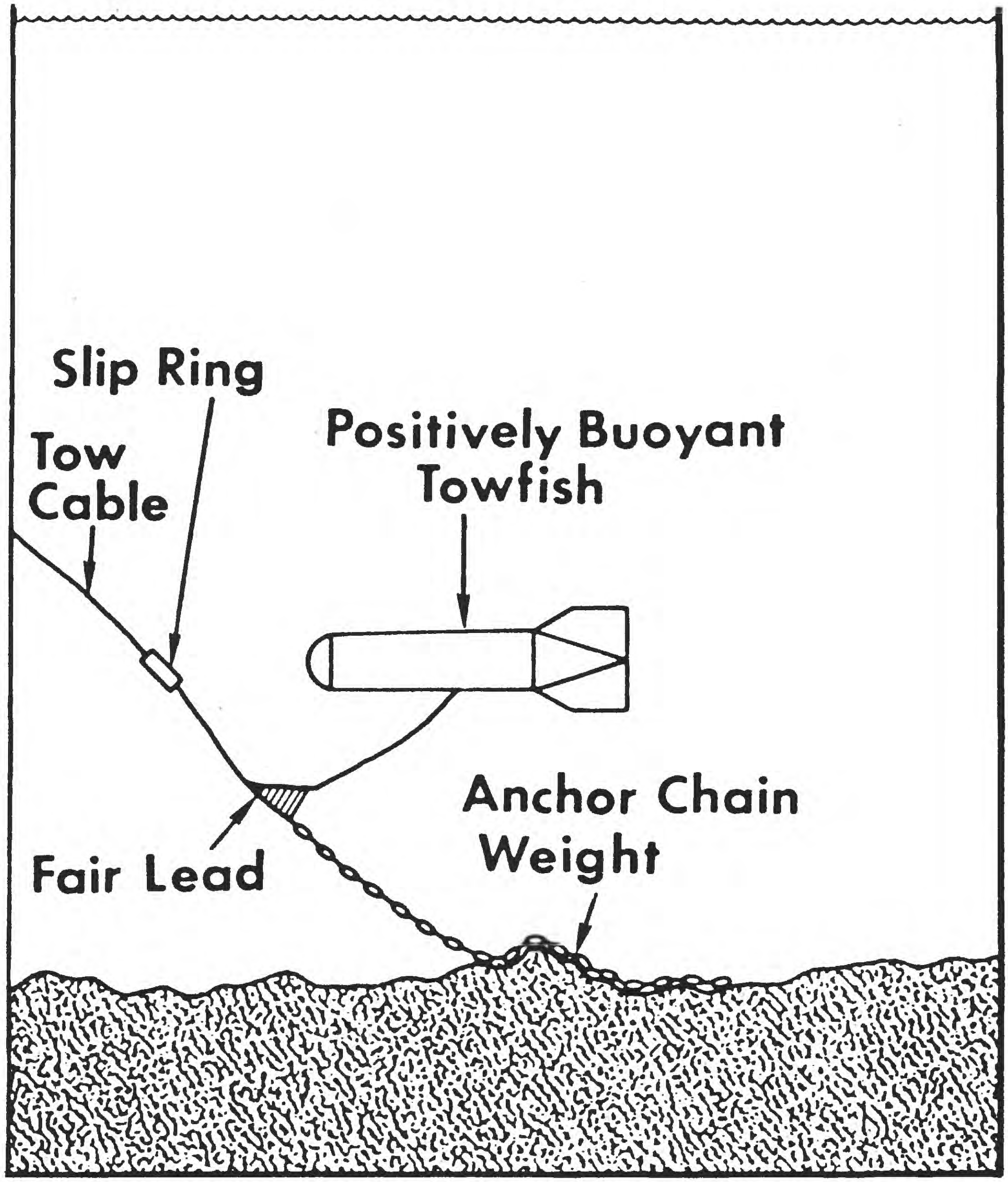
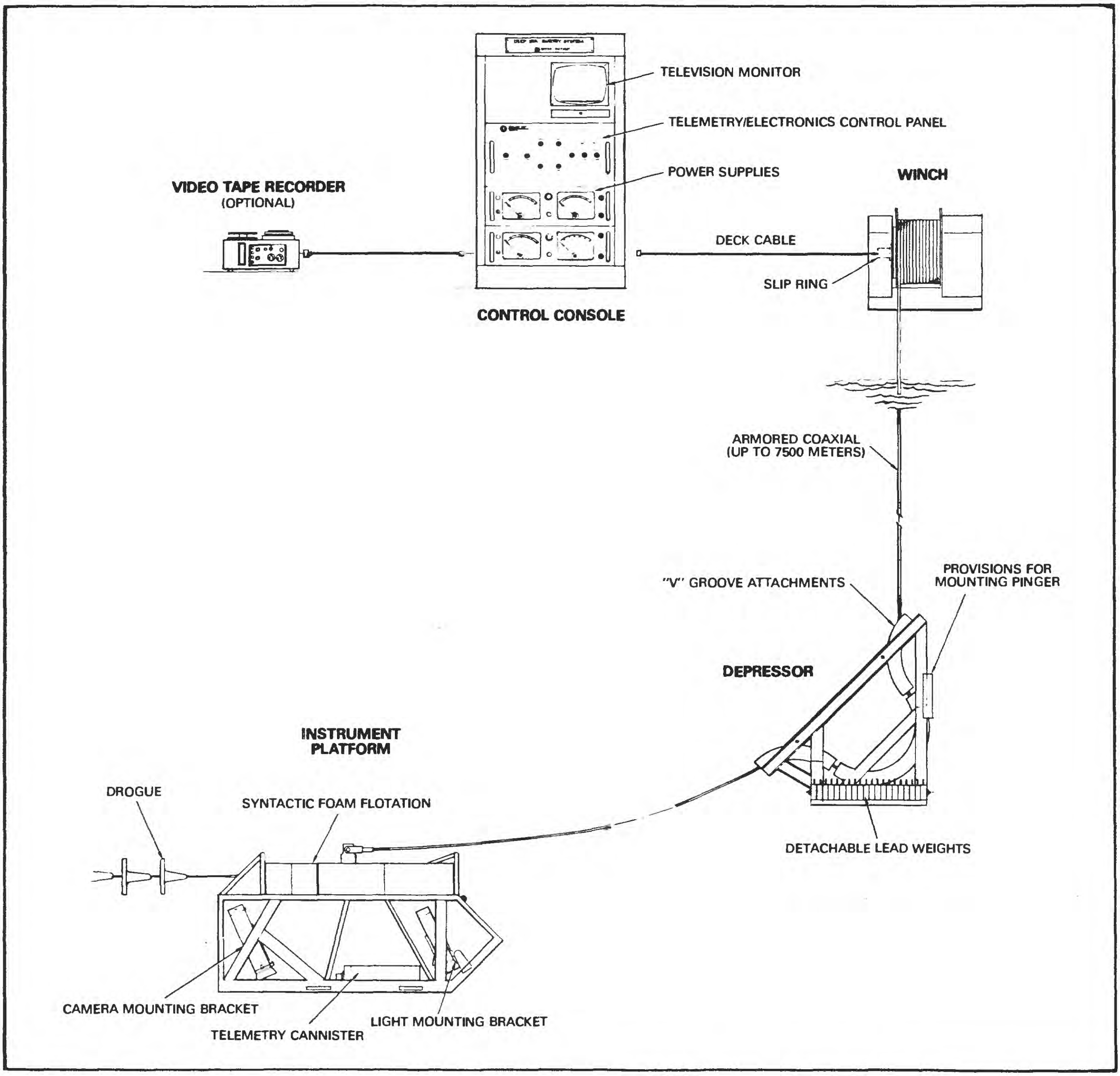

Slip Ring
Tow
Cable
Positively Buoyant
Towfish
Anchor Chain
Weight
Fair Lead

Figure 20

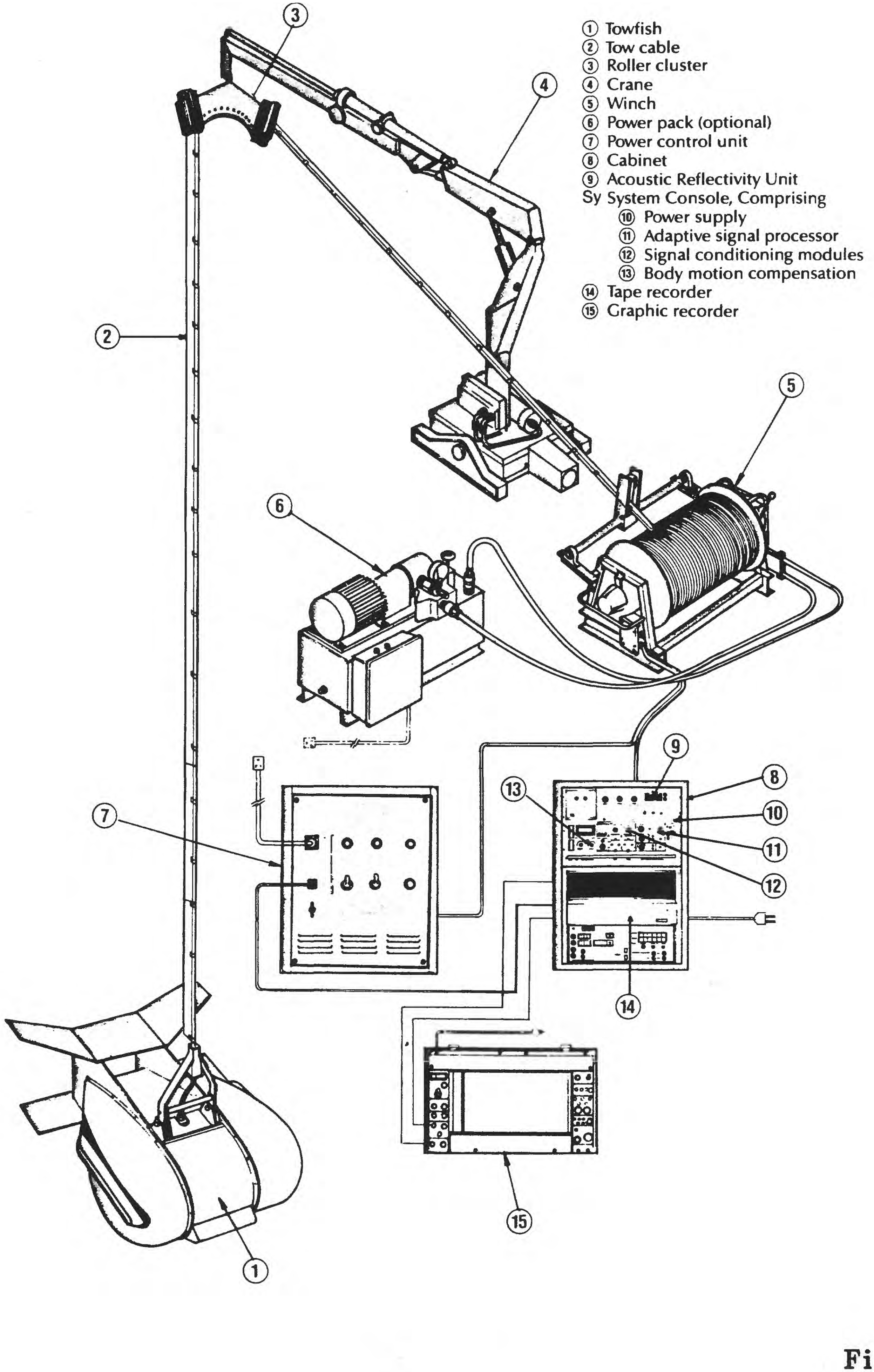


TELEVISION MONITOR
TELEMETRY/ELECTRONICS CONTROL PANEL
POWER SUPPLIES
WINCH
VIDEO TAPE RECORDER
(OPTIONAL)
DECK CABLE
SLIP RING
CONTROL CONSOLE
ARMORED COAXIAL
(UP TO 7500 METERS)
"V" GROOVE ATTACHMENTS
PROVISIONS FOR
MOUNTING PINGER
DEPRESSOR
INSTRUMENT
PLATFORM
DROGUE
SYNTACTIC FOAM FLOTATION
DETACHABLE LEAD WEIGHTS
CAMERA MOUNTING BRACKET
LIGHT MOUNTING BRACKET
TELEMETRY CANNISTER

Figure 21

Figure 22

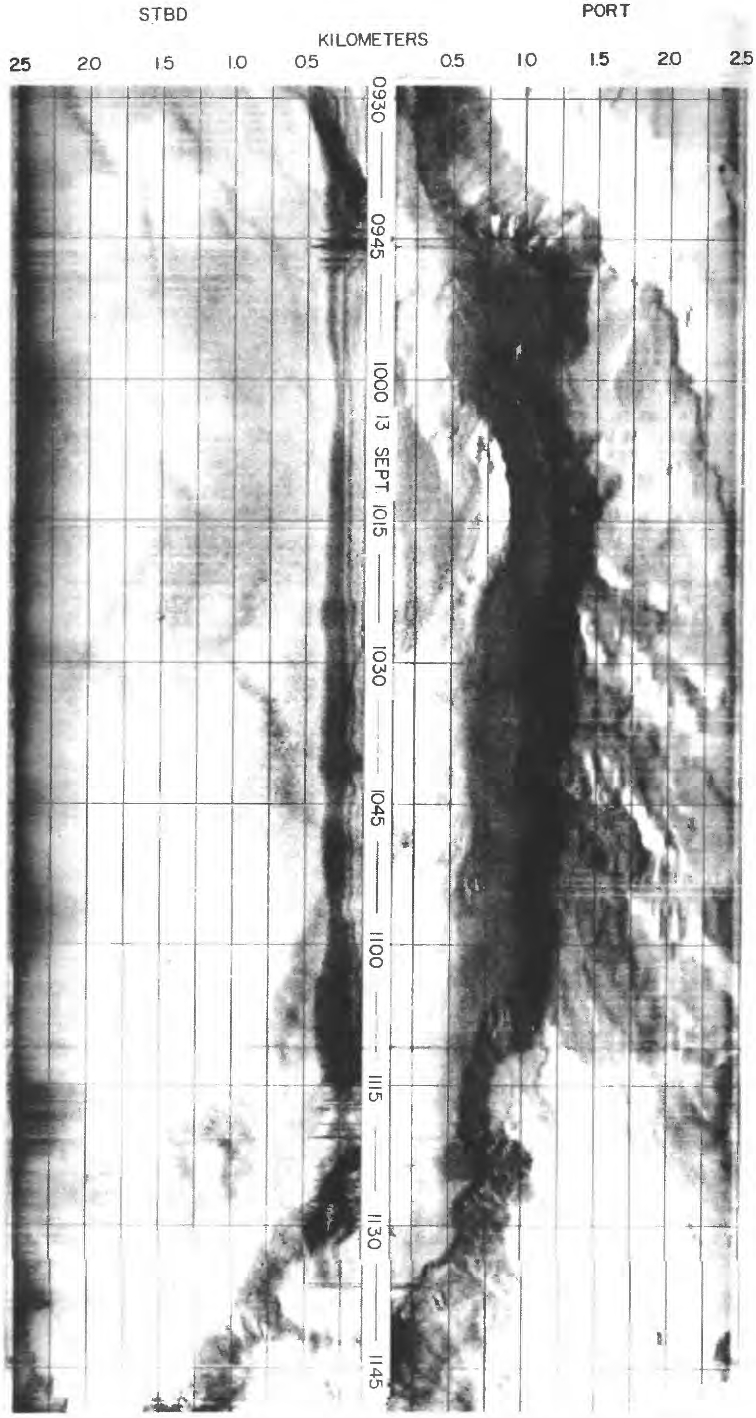
Figure 23



① Towfish
② Tow cable
③ Roller cluster
④ Crane
⑤ Winch
⑥ Power pack (optional)
⑦ Power control unit
⑧ Cabinet
⑨ Acoustic Reflectivity Unit
Sy System Console, Comprising
⑩ Power supply
⑪ Adaptive signal processor
⑫ Signal conditioning modules
⑬ Body motion compensation
⑭ Tape recorder
⑮ Graphic recorder

Figure 24

Figure 25



Made from best available copy

Figure 26

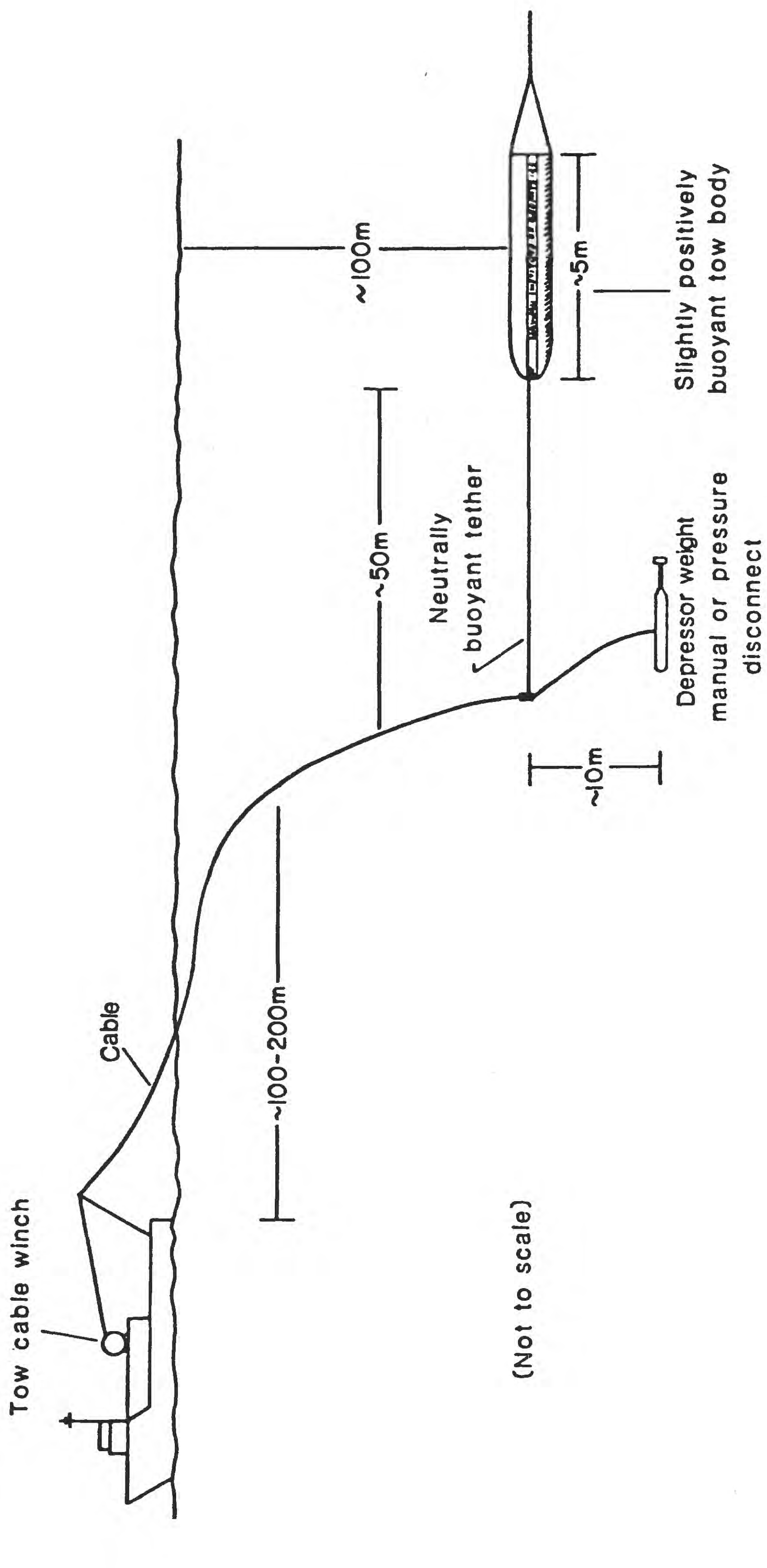

Tow cable winch
Cable
~100-200m
(Not to scale)
~50m
~100m
Neutrally buoyant tether
Depressor weight manual or pressure disconnect
~10m
~5m
Slightly positively buoyant tow body

Figure 27

Figure 28

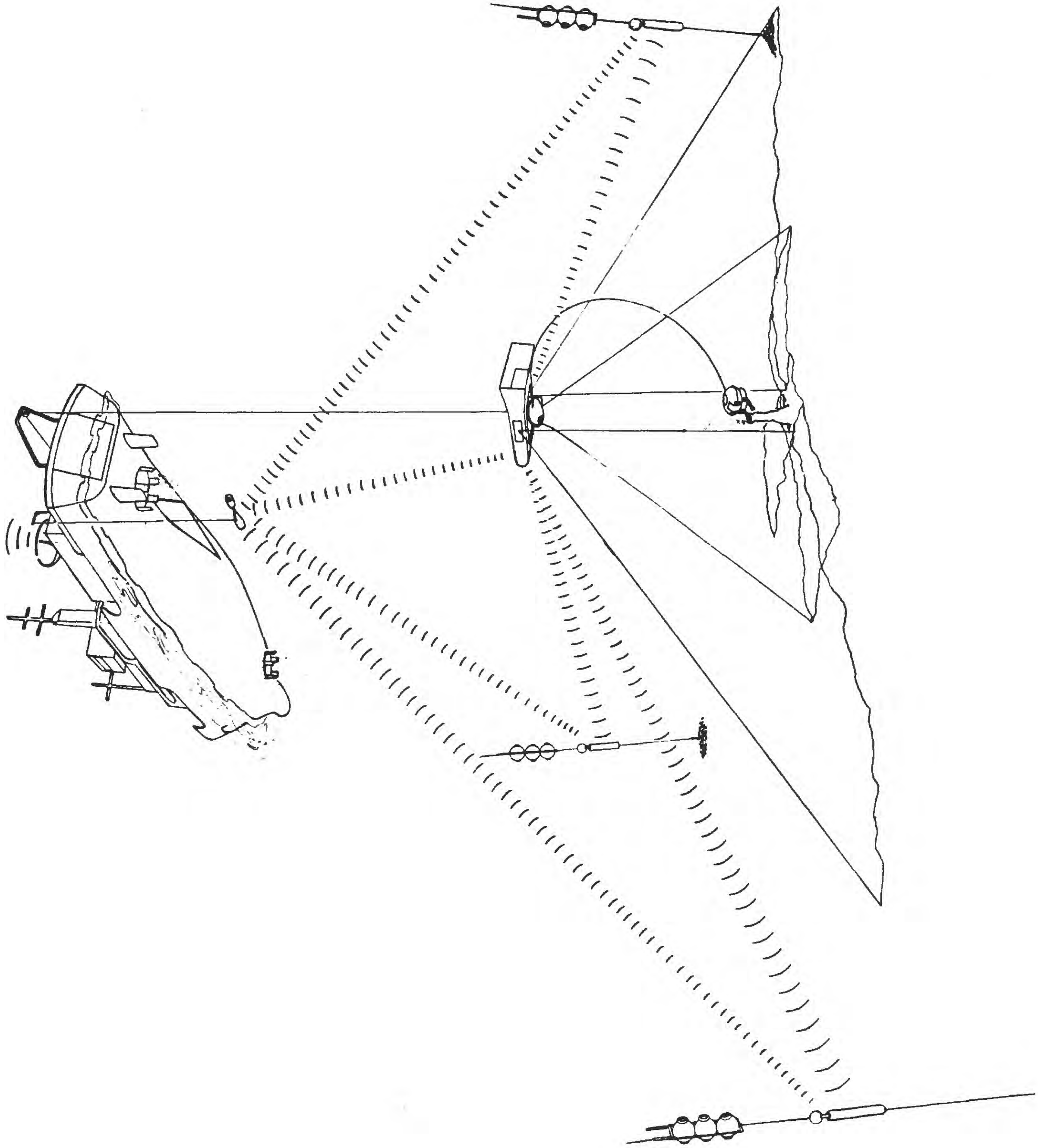
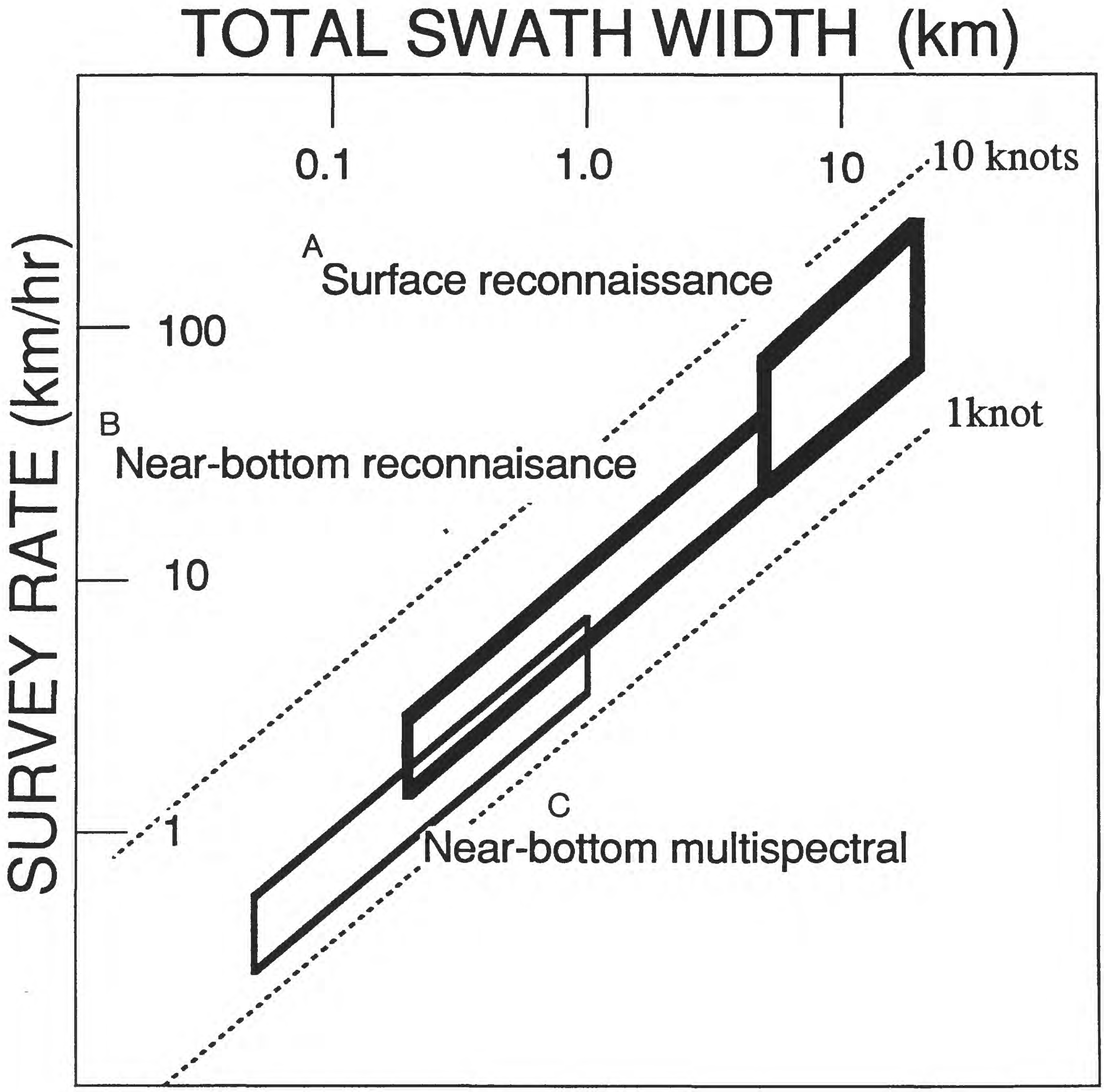


Figure 29

Figure 30



A) GLORIA, SeaMARC II, high-resolution seismic-reflection

B) SeaMARC I, high-resolution side-scan

C) ARGO, ANGUS, submersible

Figure 31

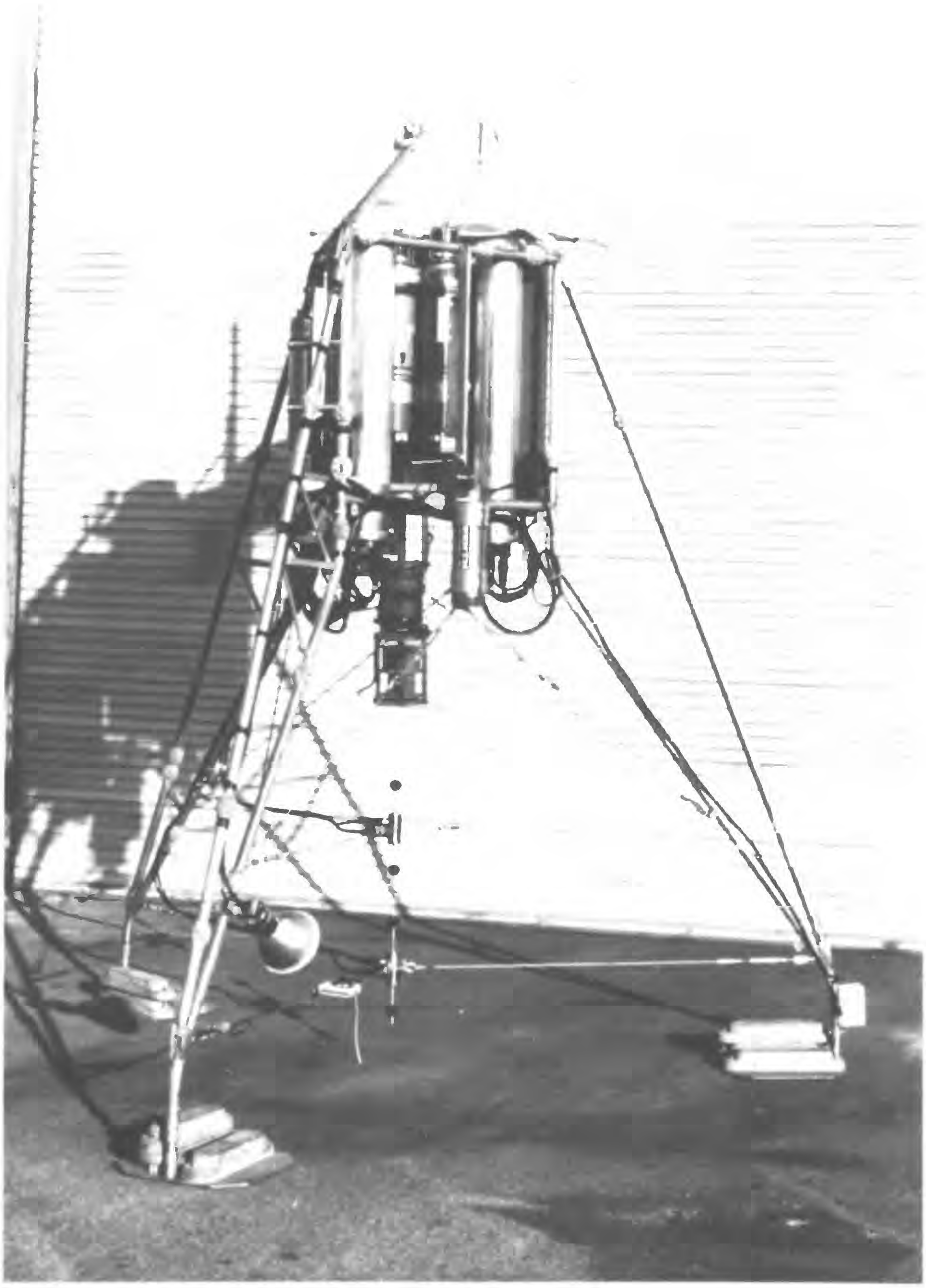


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Figure 32