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Environmental Research Laboratories

Exploration Methods for the Continental Shelf: Geology, Geophysics, Geochemistry

PETER A. RONA

BOULDER, COLO.
JUNE 1972

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EXPLORATION METHODS FOR THE CONTINENTAL SHELF: GEOLOGY, GEOPHYSICS, GEOCHEMISTRY*

Peter A. Rona

The continental shelf is an extension of the continent into the ocean. This fact determines both the occurrence of mineral deposits and methods used to seek these deposits.

1. INTRODUCTION

The problem of mineral exploration is the proverbial one of searching for a needle in a haystack. Just as the needle is a small object in the large haystack, economic concentrations of mineral deposits, including oil, occupy a minute fraction of the earth's crust. Exploration methods aim to delineate anomalous quantities, that is, abnormal concentrations of the mineral being sought. Just as the needle is different from the hay, the mineral deposits are different from the surrounding crust. Their presence must be detected by measuring the distinctive physical properties such as size, shape, density, sound velocity, magnetism, electrical and heat conductivity, or the chemical properties such as composition, that reside in or are associated with the deposits. In the case of the needle, a method might be employed to detect its magnetic properties; likewise, exploration methods are matched to detect the distinctive properties of different types of mineral deposits.

The exploration method employed must have adequate resolution and penetration to detect the size and depth of burial of the deposit being sought. By "resolution" is meant the minimum size deposit that the particular method is capable of detecting. "Penetration" refers to the maximum vertical distance beneath the sea bottom that a particular method can detect a deposit. The resolution of a particular method decreases as its penetration increases so that deeply buried deposits may be unresolvable. For example, the magnetic method used to search for the needle must be capable of penetrating through the haystack and resolving the tiny needle.

In addition to resolution and penetration, the capability of discriminating the deposit sought from its surroundings depends on the ratio of signal-to-noise of the method employed, which specifies the clarity with which the measured properties of the deposit stand out from extraneous effects. The results may be so noisy that the detecting signal is obscured. Techniques of amplifying, filtering, and signal processing are designed to enhance the signal and suppress the noise.

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*Adapted from a paper presented in 1971 at the United Nations Interregional Seminar on the Development of Mineral Resources of the Continental Shelf.

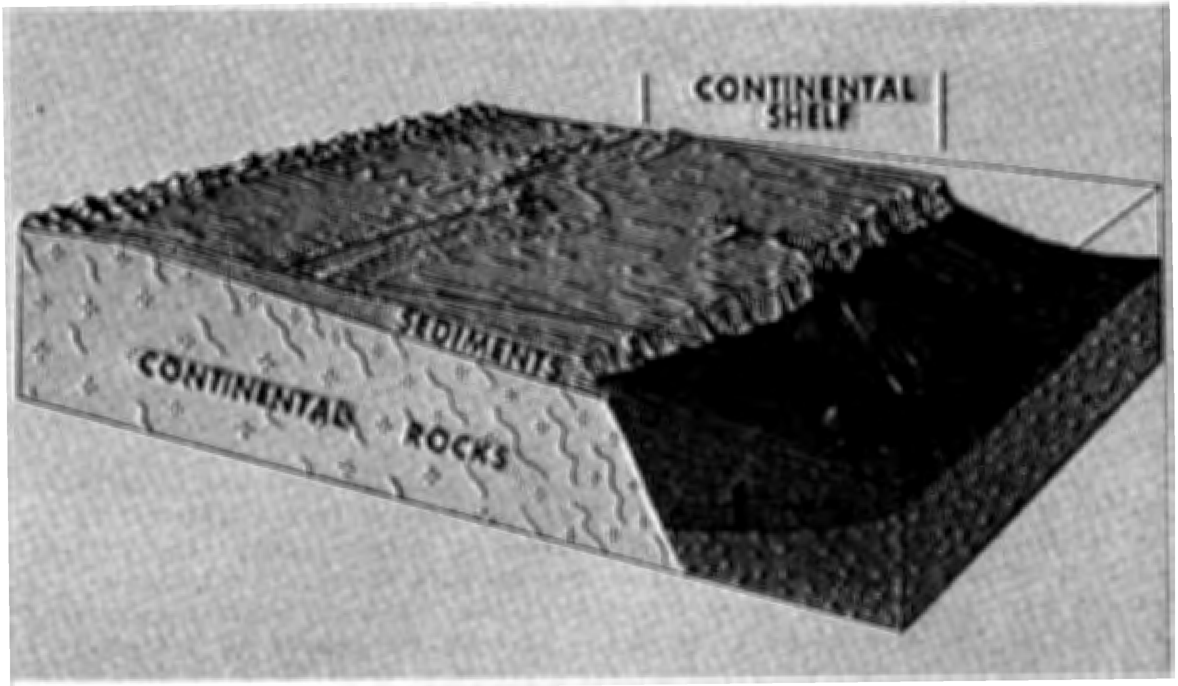

Figure 1. The continental shelf is an extension of the continent into the ocean. Rocks of the continent extend beneath the continental shelf where they may be covered by sediment several kilometers thick (Courtesy of Robert S. Dietz and John C. Holden).

Exploration methods usually obtain a two-dimensional profile of the quantity being measured along a line run across a region where the mineral deposits are thought to occur. A pattern of profiles along straight lines both parallel and perpendicular to the known or presumed orientation of the deposit being sought provides measurements to construct a three-dimensional picture. The measurements are conveniently presented on a contour map which joins points of equal values and thereby outlines areas of high and low values. The distance between profiles will determine the minimum lateral dimensions of a deposit that can be detected, just as the size of openings in a fishing net will determine the smallest fish that can be caught. An optimum line spacing must be chosen for the type of mineral occurrence being sought.

The interpretation of the information obtained from mineral exploration begins with a geological understanding of the mineral occurrence. The method selected and the measurements made must be thoughtfully tailored to obtain the information critical to detecting a particular type of deposit. The measurements obtained must be interpreted by competent geologists and geophysicists. An important discovery can be overlooked for lack of good interpretation.

2. OCCURRENCE OF CONTINENTAL SHELF MINERAL DEPOSITS

The occurrence of the mineral deposit being sought must be considered in advance of the actual exploration because the method employed must be selected for the specific occurrence anticipated. Rocks of the continent underlie the continental shelf so that mineral deposits of the continental shelf would be expected to be similar to those of the adjacent portion of the continent with the addition of certain deposits peculiar to the marine environment (fig. 1). For purposes of exploration, mineral deposits of the continental shelf can be divided into consolidated and unconsolidated, depending on whether hard or soft, as well as bottom and sub-bottom, depending on whether they lie on or beneath the sea floor (table 1). Consolidated mineral deposits include coal, limestone, common salt, sulphur, certain iron ores, and metal-bearing hardrock deposits. Unconsolidated deposits include diamond-bearing gravels, barite, glauconite sands, manganese and phosphorite nodules, sea shells, and petroleum. The unconsolidated deposits may occur either as bottom or sub-bottom deposits. The consolidated deposits may be buried beneath thicknesses up to several kilometers of unconsolidated materials. Rocks are consolidated materials, and sediments like sand, silt, and clay, are unconsolidated materials. In addition to sea-floor deposits, a number of useful minerals may be extracted from seawater including borax, bromine, magnesium, potash, common salt, sulphur, and fresh water. The methods used to explore the continental shelf are adapted from methods developed to explore the continent (table 2).

*Table 1. Occurrence of Continental Shelf Mineral Deposits**

Unconsolidated		Consolidated		Dissolved
Bottom	Sub-bottom	Bottom	Sub-bottom	Seawater
Shallow beach or offshore placers:	Buried beach and river placers:	Exposed stratified deposits:	Disseminated massive, vein or tabular deposits:	Metals and salts:
Heavy mineral sands	Diamonds	Ironstone	Coal	Magnesium
Iron sands	Gold	Limestone	Iron	Sodium
Silica sands	Platinum		Tin	Calcium
Lime sands	Tin	Chemical deposits:	Gold	Bromine
Sand and gravel		Manganese oxide	Sulphur	Potassium
	Heavy minerals:	Associated Co, Ni, Cu	Metallic sulfides	Sulphur
Chemical deposits:	Magnetite	Phosphorite	Metallic salts	Strontium
Manganese nodules (Co, Ni, Cu, Mn)	Ilmenite			Boron
Phosphorite nodules	Rutile	Hydrocarbons:		Uranium
Phosphorite sands	Zircon	Coal		Fresh water
Glauconite sands	Leucoxene			
	Monazite			
	Chromite			
	Scheelite			
	Wolframite			
	Hydrocarbons:			
	Oil			
	Gas			

**Modified from Cruickshank, 1970*

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Iron sands	Gold	Limestone	Iron	Sodium
Silica sands	Platinum		Tin	Calcium
Lime sands	Tin	Chemical deposits:	Gold	Bromine
Sand and gravel		Manganese oxide	Sulphur	Potassium
	Heavy minerals:	Associated Co, Ni, Cu	Metallic sulfides	Sulphur
Chemical deposits:	Magnetite	Phosphorite	Metallic salts	Strontium
Manganese nodules (Co, Ni, Cu, Mn)	Ilmenite			Boron
Phosphorite nodules	Rutile	Hydrocarbons:		Uranium
Phosphorite sands	Zircon	Coal		Fresh water
Glauconite sands	Leucoxene			
	Monazite			
	Chromite			
	Scheelite			
	Wolframite			
	Hydrocarbons:			
	Oil			
	Gas			

**Modified from Cruickshank, 1970*

Table 2. Application of Marine Geological, Geophysical, and Geochemical Exploration Methods

	GEOLOGICAL METHODS				GEOPHYSICAL METHODS		
	BATHYMETRY AND SIDE-LOOKING SONAR	BOTTOM PHOTOGRAPHY		BOTTOM SAMPLING	SEISMIC REFLECTION	SEISMIC REFRACTION	MAGNETIC
INSTRUMENTS	Vertical echo-sounder Horizontal echo-sounder	Underwater still and television cameras	Satellite camera	Core, dredge, drill	Hydrophone, amplifier, recorder	Hydrophone, amplifier, recorder	Magnetometer
MOVING OR STATIONARY	Moving	Stationary	Moving	Stationary	Moving	Moving	Moving
RECONNAISSANCE OR DETAIL	Either	Detail	Reconnaissance	Detail	Either	Either	Reconnaissance
QUANTITY DIRECTLY MEASURED	Travel time of reflected sound wave between ocean surface and bottom	Picture of small area (tens of square meters) of ocean bottom	Picture of large area (thousands of square kilometers) of ocean bottom	Sample of bottom material	Travel time of reflected sound wave between ocean surface and sub-bottom reflecting interfaces	Travel time of refracted sound wave between ocean surface and sub-bottom refracting layers.	Variations in intensity of magnetic field
QUANTITY INDIRECTLY DETERMINED FROM MEASUREMENTS	Depth and shape of ocean bottom	Shape and texture of ocean bottom	Overall shape, dimensions, and inhomogeneities	Detailed composition and engineering properties	Dip of beds Depth to distinct reflecting interfaces	Depth to refracting horizons, horizontal speeds of seismic waves	Depth or susceptibility of rocks with magnetic properties or magnetic ore bodies
TYPES OF STRUCTURES MOST OFTEN LOCATED	Submerged features such as beaches, channels, and exposures of bedrock	Small scale features such as ripple marks, shells, nodules, and exposures of bedrock	Large features such as channels, bars, and deltas	Chemical, placer, massive vein, and tabular deposits	Faults, anticlines, synclines, monoclines, unconformities, ore deposits buried in sediments	Faults, salt domes, basement configuration, anticlines	Anticlines, synclines, faults, igneous intrusive rocks, iron bearing deposits

	GEOPHYSICAL METHODS (continued)				GEOCHEMICAL METHODS
	GRAVITY	ELECTRICAL	HEAT FLOW	RADIOACTIVE	CHEMICAL ANALYSIS
INSTRUMENTS	Gravimeter	Electrodes, milliammeter, potentiometer	Thermograd	Geiger counter Scintillation counter	Emission and flame spectrometer, x-ray spectrometer, radiometer, wet laboratory
MOVING OR STATIONARY	Moving and stationary	Moving and stationary	Stationary	Moving	Moving and stationary
RECONNAISSANCE OR DETAIL	Reconnaissance	Either	Detail	Either	Either
QUANTITY DIRECTLY MEASURED	Variations in force of gravity	Current transmitted through earth between electrodes and resulting potential	Temperature gradient beneath ocean bottom	Natural and artificially induced gamma radiation	Composition of rock and water samples, identity and amounts of elements present
QUANTITY INDIRECTLY DETERMINED FROM MEASUREMENTS	Density of rocks and depths to anomalous rock bodies	Depth to interfaces, resistivities of rock bodies	Amount of heat flowing through the ocean bottom	Presence of radioactive elements	Proximity to mineral concentrations
TYPES OF STRUCTURES MOST OFTEN LOCATED	Buried mountains, salt domes, faults	Metallic ore bodies	Salt domes and metallic ore bodies	The presence of radioactive minerals and certain rock types	Chemical, hydrocarbon, placer, massive, vein or tabular ore deposits

3. GEOLOGICAL METHODS

Geological methods provide the most direct, unambiguous information about depth below sea level, shape, and composition of the continental shelf.

3.1 Bathymetry and Side-looking Sonar

Bathymetry is the measurement of ocean depth and is the single most routine and useful measurement made at sea. Sound travels much better through water than air and so is extensively applied in bathymetric and seismic methods. Bathymetric techniques are based on the principle of acoustic reflection, according to which a pulse of high frequency sound will be reflected by the ocean bottom at an angle equal to its angle of incidence, like a ball bouncing off the ground or a ray of light reflected from a mirror.

Depth is measured with an echo-sounding system which comprises a combined sound-source/receiver (high frequency piezo-electric transducer), usually mounted on the hull of a ship, and a graphic recorder (fig. 2) (Shepard, 1963). As the ship moves along, short pulses of sound are repeatedly projected at the bottom and the round-trip travel time of the bottom-reflected pulse is continuously displayed as depth below sea level on the graphic recorder which is calibrated for the known speed of sound through seawater. Each record provides a profile of the ocean bottom along the ship's track (fig. 3). When many profiles have been obtained over an area they are compiled into a bottom contour map which depicts the shape of the ocean bottom by drawing lines to join points of equal depth (isobaths) (fig. 4) (Johnson and Jugel, 1968).

Side-looking sonar systems are similar to standard echo-sounders, except that the sound transducer is mounted to give a side-looking instead of vertical beam, in order to obtain a sonar display of the sea floor analogous to an oblique aerial photograph on land (fig. 5). Fan-shaped beams of sound that are narrow in a horizontal plane and wide in a vertical plane are projected to either side of the moving ship's track. The geographical location and shape of ocean bottom features are determined along a swath bisected by the ship's track. The minimum size bottom feature that the system can resolve is limited by the horizontal beam width, the dynamic range, and the number of reflected sound pulses received from that feature. In short-range side-looking sonar, the sound transducer is towed some tens of meters above the ocean bottom and ensonifies a swath about one kilometer wide with a resolution of about 5 meters (Chesterman et al., 1958; Clay et al., 1964). In long-range side-looking sonar, the sound transducer is towed near the sea surface and projects sound to a lateral distance of about 20 km with resolution of about 1 km (Rusby, 1970). Many overlapping side-looking sonar records may be combined into a mosaid of the ocean bottom comparable to an air photo-mosaic on land.

Figure 2. The components of a bathymetric system comprise a combined sound source-receiver (center) mounted either on a ship's hull or towed, and a graphic recorder (left). Bathymetric profiles (right) are compiled to construct bathymetric charts (on wall at left of center).

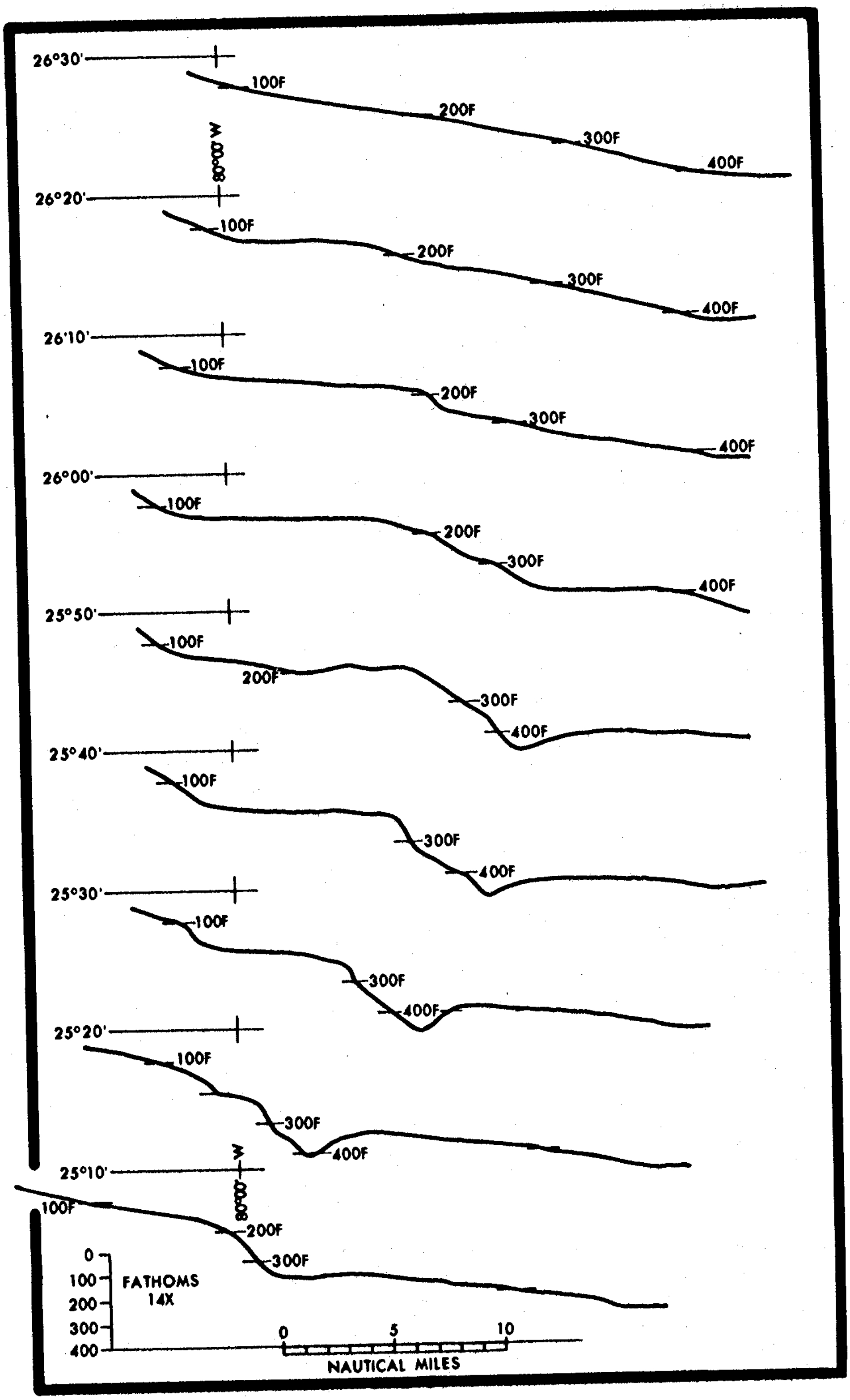


Figure 3. Bathymetric profiles across the continental shelf off Miami, Florida, (from Kofoed and Malloy, 1965, fig.2).

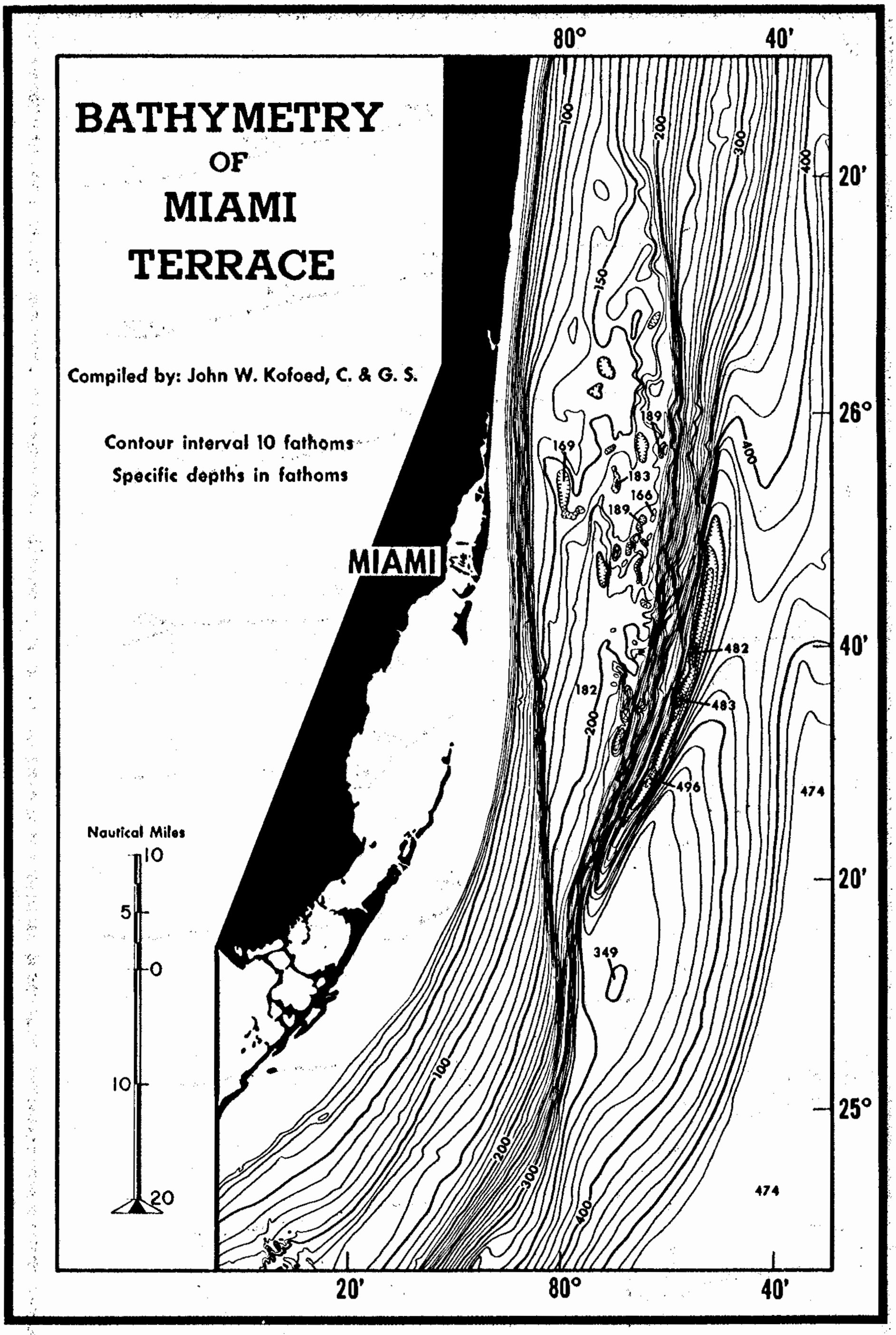


Figure 4. A bathymetric map depicting the depth and shape of the continental shelf off Miami, Florida, constructed from many individual bathymetric profiles, such as those shown in figure 3, by connecting points of equal depth with contour lines (isobaths). From Kofoed and Malloy, 1965, fig. 1.

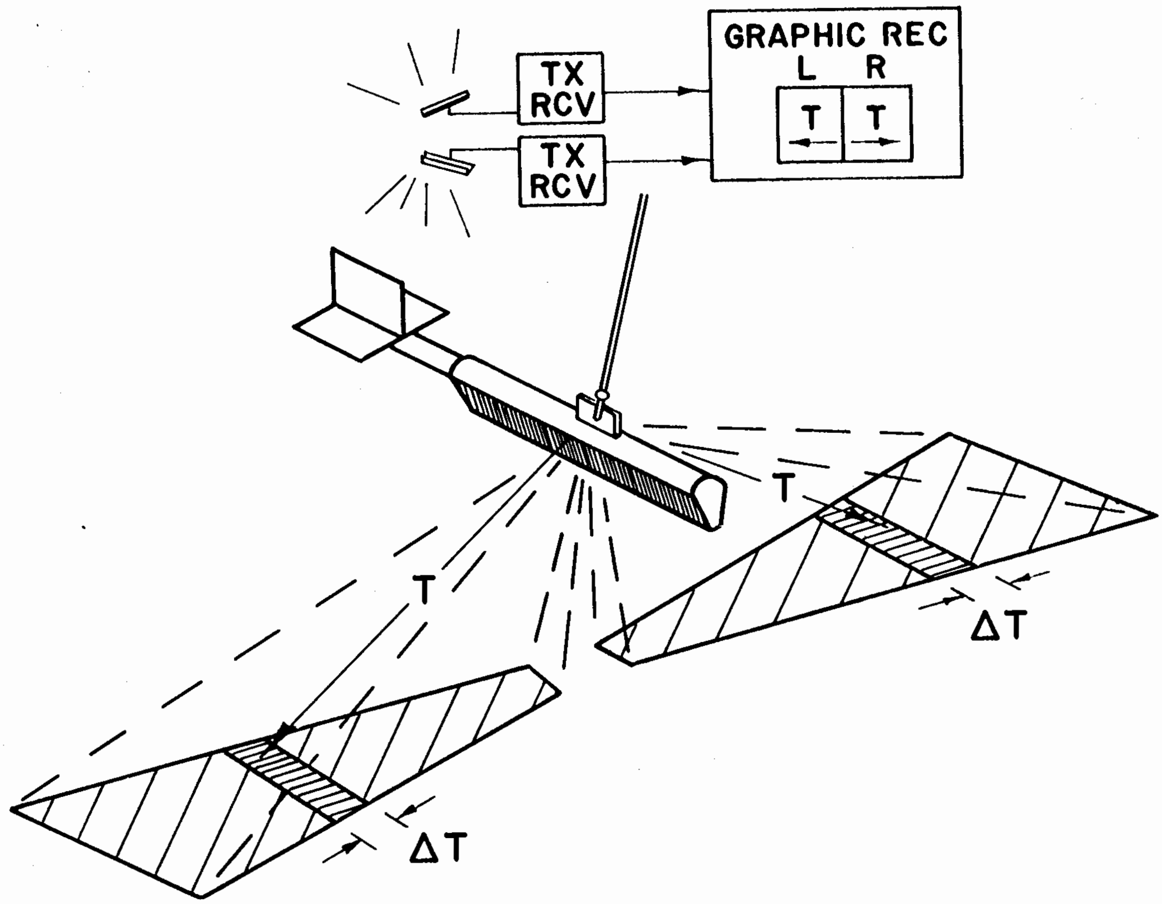


Figure 5. A side-looking sonar system in which sound sources are mounted to project sound laterally from a vehicle towed by a ship to obtain a sonar display of the ocean bottom analogous to an oblique aerial photograph (From Clay et al., 1964, fig. 1).

3.2 Photography

The ocean constitutes an effective cover over the continental shelf because light is rapidly attenuated by passage through water and scattered by suspended matter. The amount of light at 100 meters below sea level is a small fraction of that at the sea surface. The continental shelf can be photographed either at extremely close or far ranges but not at intermediate range. Deep-sea cameras operate by illuminating small areas from two to ten square meters of the ocean bottom and sequentially taking pictures as they are towed within about 5 meters of the bottom (figs. 6 and 7) (Hersey, 1967). Cameras mounted in airplanes and satellites flying at elevations of hundreds of meters to hundreds of kilometers above sea level photograph areas encompassing thousands of square kilometers revealing major features of continental shelves such as submerged river deltas, islands, channels, and sand bars. Films sensitive to different portions of light spectrum reveal different features such as color variations and areas of abnormal heat on the continental shelf and in the overlying seawater.

3.3 Bottom Sampling

The only exploration method that proves the presence of a particular mineral deposit is sampling. Information obtained by sampling is limited to the precise spot sampled. For sampling to be effective, the sampling location must be closely delineated by the exploration methods or a sampling pattern employed suited to the anticipated size and subbottom depth of the deposit being sought.

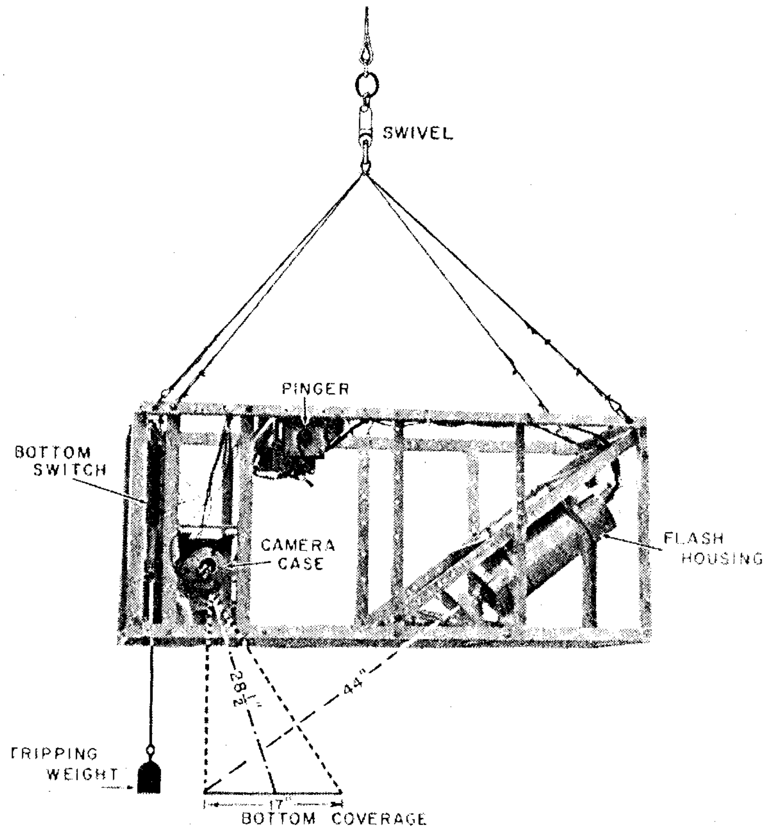


Figure 6. A deep-sea camera system consisting of a camera, stroboscopic flash, and triggering device designed to take photographs of small areas of the ocean bottom (From Owen, 1967, figs. 8-4).

In the technique of coring, a core barrel consisting of a tube several centimeters in diameter up to about 20 meters in length penetrates into the sediments of the ocean bottom either by gravitational impact or mechanical vibration (fig. 8). The core barrel recovers a sample in the form of a vertical column through the ocean bottom (Shepard, 1963). Several cores can be collected in an hour on the continental shelf using a power operated winch to lower and retrieve the coring device on a cable. Standard coring devices are not suitable for penetrating rocks.

Dredging is a technique to gather fragments of rocks exposed on the sea floor that are too hard and large to recover by coring. A chain basket or pipe suspended from the ship on a cable is dragged along the bottom in areas where echo sounding records and bottom photographs indicate rock ledges or loose nodules and rock fragments (fig. 9). Information from coring and dredging may be portrayed as a map of the distribution of sediment and rock types (fig. 10).

Drilling techniques are employed to recover samples of rock or of sediments beyond the penetration of conventional coring techniques. Ship mounted rotary, percussive, and vibratory drills of various sizes are capable of different penetrations. Drilling for oil is done by rotary drills mounted on floating barges or on fixed platforms capable

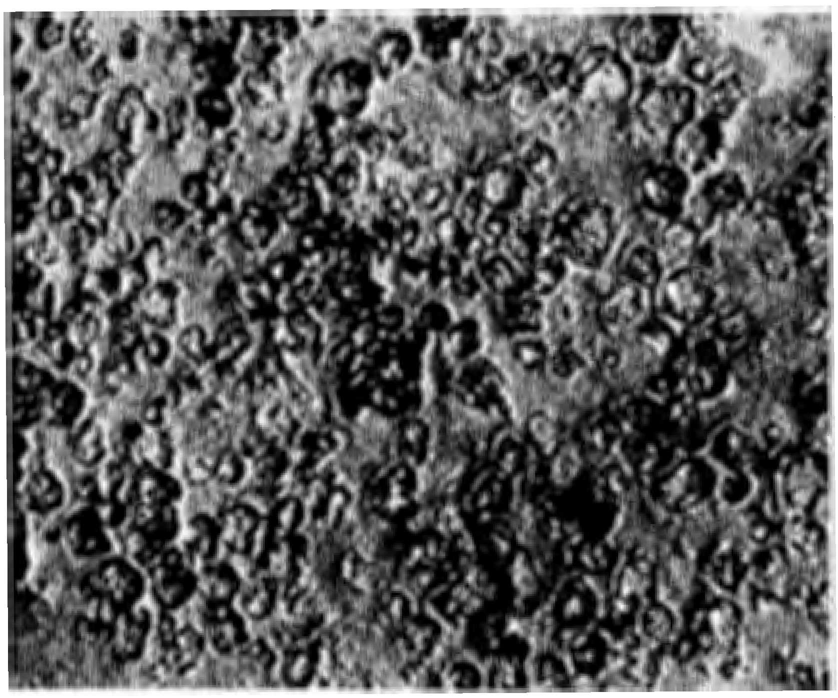
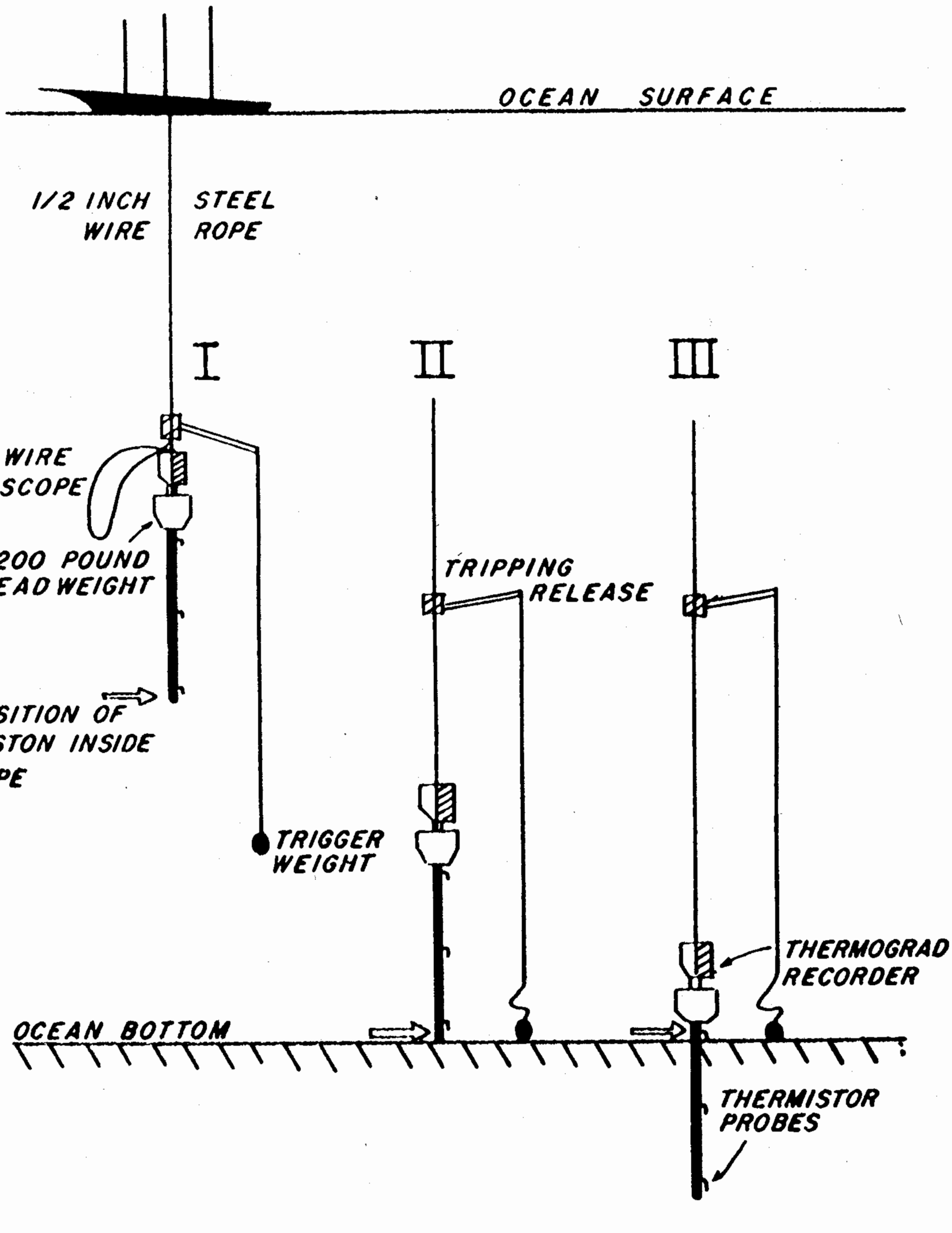


Figure 7. A deep-sea photograph showing about one square meter of the ocean bottom covered with manganese nodules. The individual manganese nodules are about the size of tennis balls (7 to 10 cm in diameter). (Photograph by R. M. Pratt and Woods Hole Oceanographic Institution).



OPERATION OF PISTON CORING DEVICE AND THERMOGRAD

Figure 8. A coring device shown while being lowered, at the instant of the hit, and while in the sediment (from Talwani, 1964, fig. 9a). Thermister probes mounted along the core barrel measure the temperature gradient in the ocean bottom to determine heat flow (Gerard et al., 1962).

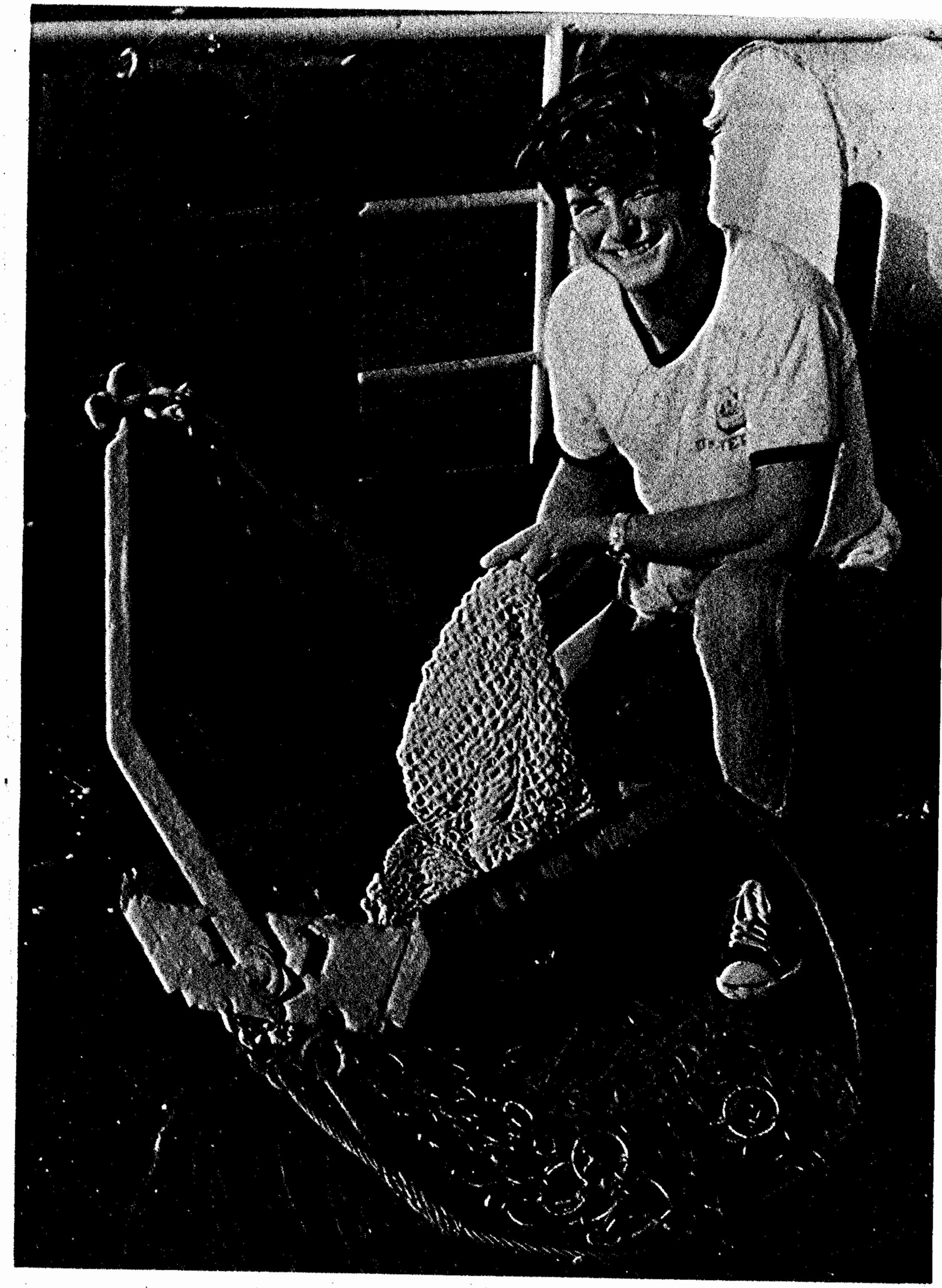


Figure 9. A dredge which is dragged along the bottom on a cable from a ship to recover loose rocks.

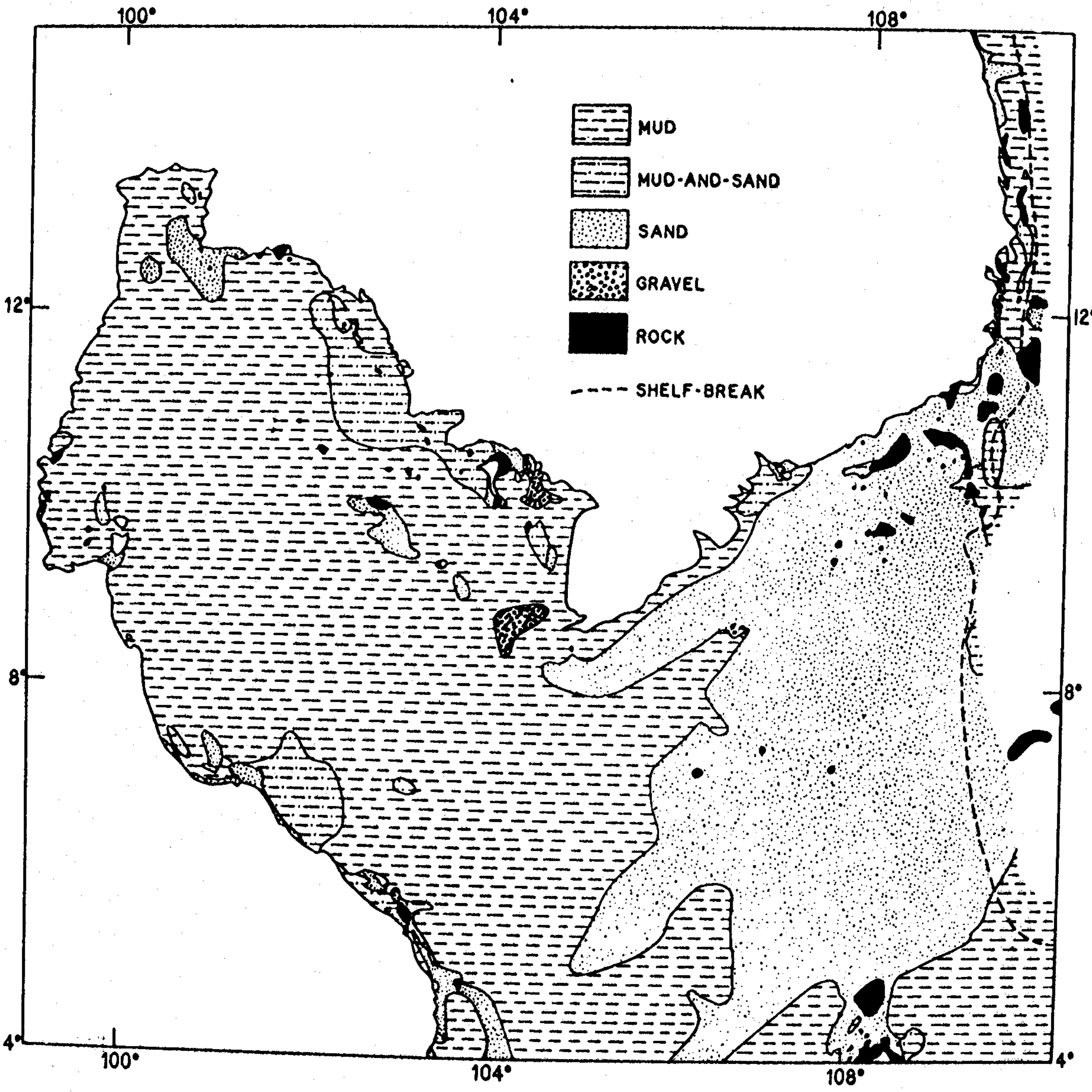


Figure 10. A map of the distribution of sediment types and rock in the Gulf of Thailand compiled from bottom samples (Shepard et al., 1949).

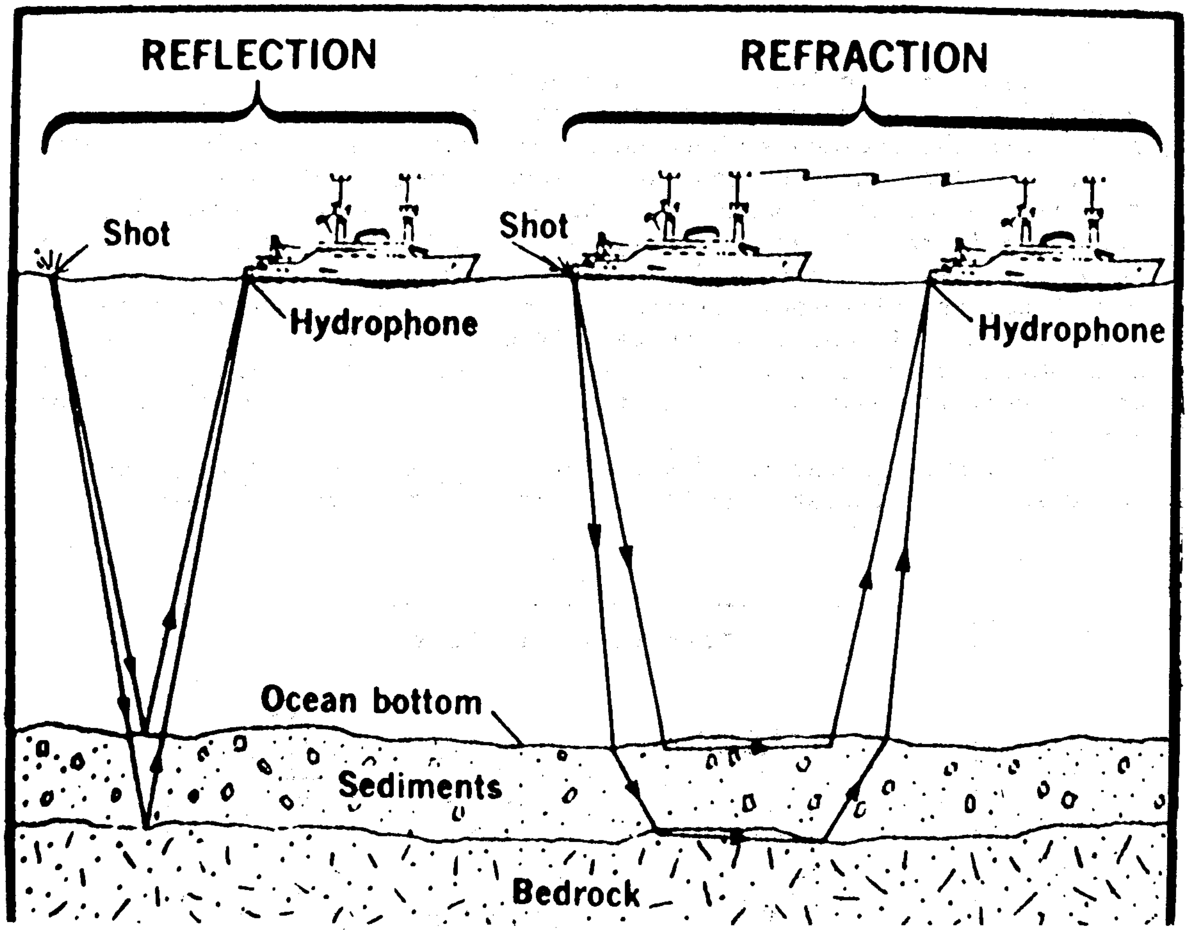


Figure 11. In the seismic reflection technique sound waves from a source at a ship bounce directly back to the ship from sediment and rock layers. In the seismic refraction technique the sound waves from a "shooting" ship travel along the sediment and rock layers before propagating back to a "receiving" ship.

of penetrating over 5 kilometers through sediments (Petroleum Engineer Publishing Co.). Drilling in moderate water depths is so expensive that it is generally limited to targets identified by other methods rather than as an exploration tool.

4. GEOPHYSICAL METHODS

Geophysical methods provide indirect quantitative measurements of physical properties of sediments and rocks and are subject to varying degrees of ambiguity in their interpretation.

4.1 Seismic Reflection

Seismic reflection is the most useful method to delineate structures favorable to the occurrence of oil and other mineral deposits buried in or beneath the sediments which cover most continental shelves. Seismic methods utilize the fact that sound waves travel with different velocities (expressed as kilometers per second) in different materials. The principle is to initiate sound waves at a point and determine at another point the time of arrival of the energy that is reflected by discontinuities between different materials (fig. 11). The discontinuities result from differences in the density of the materials and the velocity with which sound waves travel in the materials. The seismic reflection method unambiguously determines the relative positions of such discontinuities.

The basic components of a seismic reflection system comprise a sound source, receiver, amplifier, filters, and recorder (fig. 12).

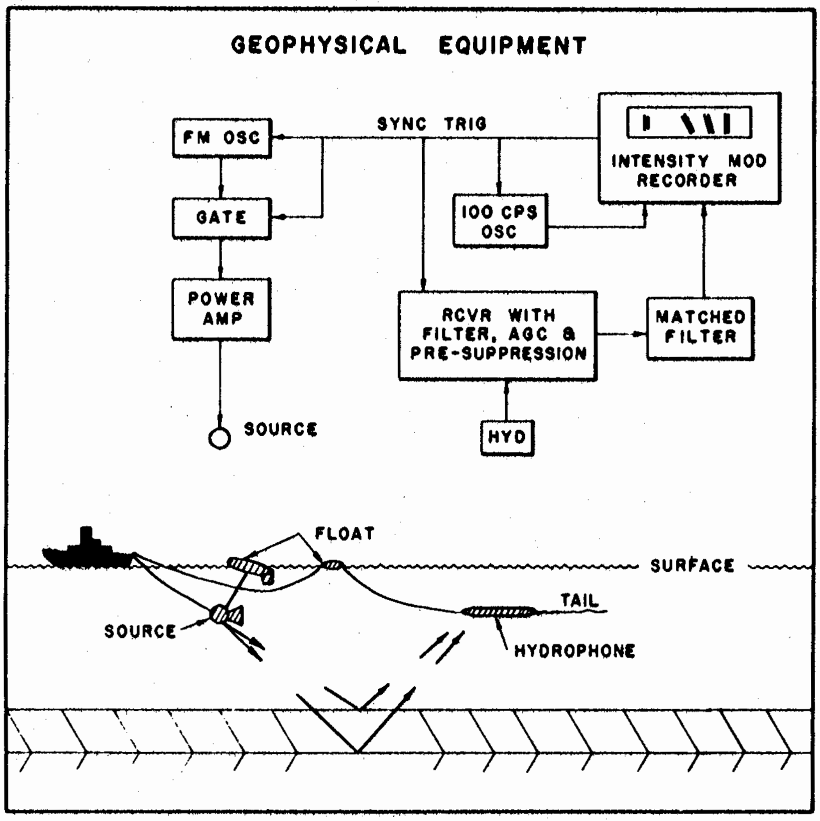


Figure 12. A seismic reflection profiling system including a repeating sound source, hydrophones to receive the sound reflected from sediment and rock layers, and amplifiers, filters, and a graphic recorder to display the reflection (From Clay and Liang, 1962, fig. 1).

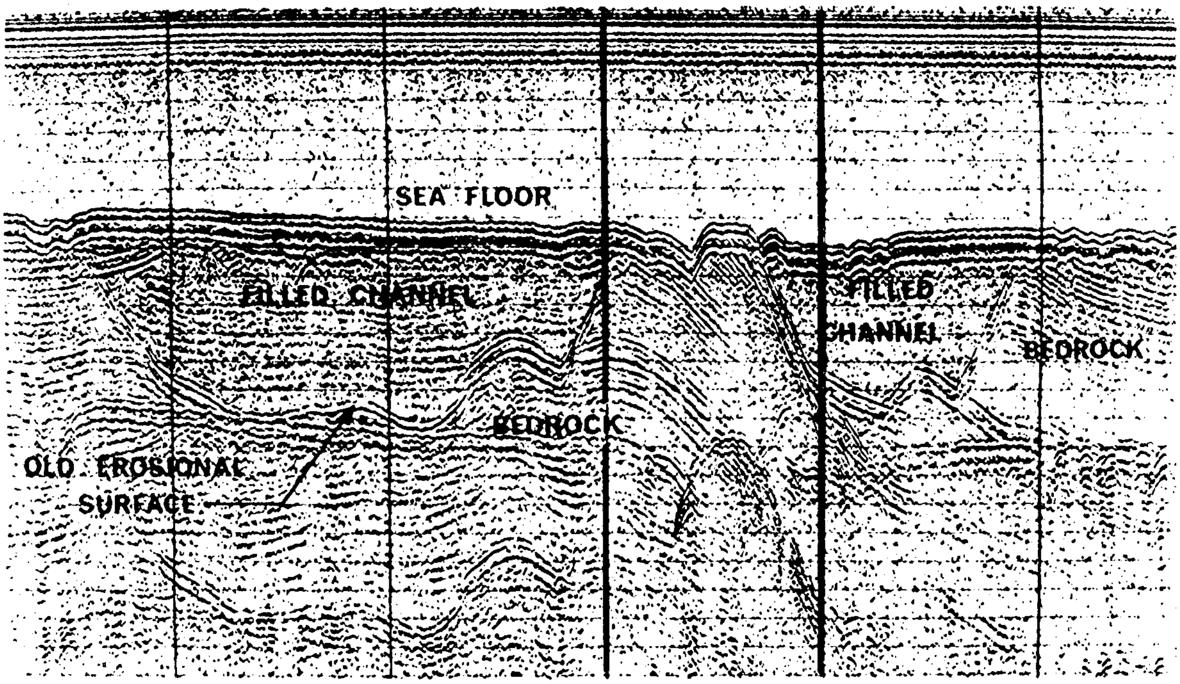


Figure 13. A high resolution, shallow penetration (0.5 kilometers) seismic reflection profile shows sediment-filled river channels cut in bedrock beneath the surface of a continental shelf.

Penetration by different systems varies between about 1 meter and 10 kilometers beneath the ocean bottom. Penetration is primarily determined by the amount of energy transmitted by the sound source in the low frequency range (less than 100 Hertz, i.e., cycles per second) because low frequencies of sound undergo less absorption in travel through sediment and rock layers than higher frequencies. The resolution of different seismic reflection systems varies between about one meter and hundreds of meters. Resolution is related to the duration, peak frequency, and frequency content (bandwidth) of the acoustic signal transmitted. In general, the shorter the duration, or the higher the peak frequency, or the wider the bandwidth, the thinner the layer that can be resolved (Brillouin, 1956). Shortening of the signal duration limits the amount of energy transmitted resulting in decreased penetration. Raising the peak frequency (greater than 100 Hertz) also limits the penetration by increasing absorption losses. Widening the signal bandwidth does not restrict the amount of energy that can be transmitted and is being developed as the most promising direction to achieve relatively deep penetration with high resolution.

The state-of-the-art forces the user to choose between systems which achieve either high resolution or deep penetration. The choice depends on whether the objective is to find a relatively thin deposit in the upper several hundred meters sub-bottom (fig. 13) or a more deeply buried thick deposit (fig. 14). Thin deposits that are deeply buried cannot be resolved by present systems. In either case, the deposit sought must be associated with density and sound velocity discontinuities in order to be detected by seismic reflection.

A variety of sound sources exists differing in their acoustic characteristics (Kramer et al., 1968; Ocean Industry, 1968). The low frequency energy component of explosive sources such as TNT, Nitromon, and Geofex (du Pont Blasters Handbook) can achieve penetration of several tens of kilometers at the expense of resolution. Explosive charges from about 250 grams up to thousands of kilograms are generally prepared and thrown over-the-side manually, which limits the repetition rate. Other types of sources repeat automatically at faster repetition rates providing more sampling points to delineate reflecting interfaces which can change markedly over distances of one kilometer. Gas mixture sources generate explosions within long rubber hoses producing low peak frequency (less than 10 Hertz), broad bandwidth signals with intermediate resolution up to about 6 kilometers penetration in unconsolidated rocks. The Vibroseis source hydraulically drives metal plates to produce low frequency (less than 100 Hertz), broad bandwidth signals which can be shaped and programmed to yield deep penetration with fair resolution. The pneumatic source or air gun suddenly injects a bubble of high pressure air (about 2000 pounds per square inch or 140 kilograms per square centimeter) into the water which commences to oscillate generating subsidiary

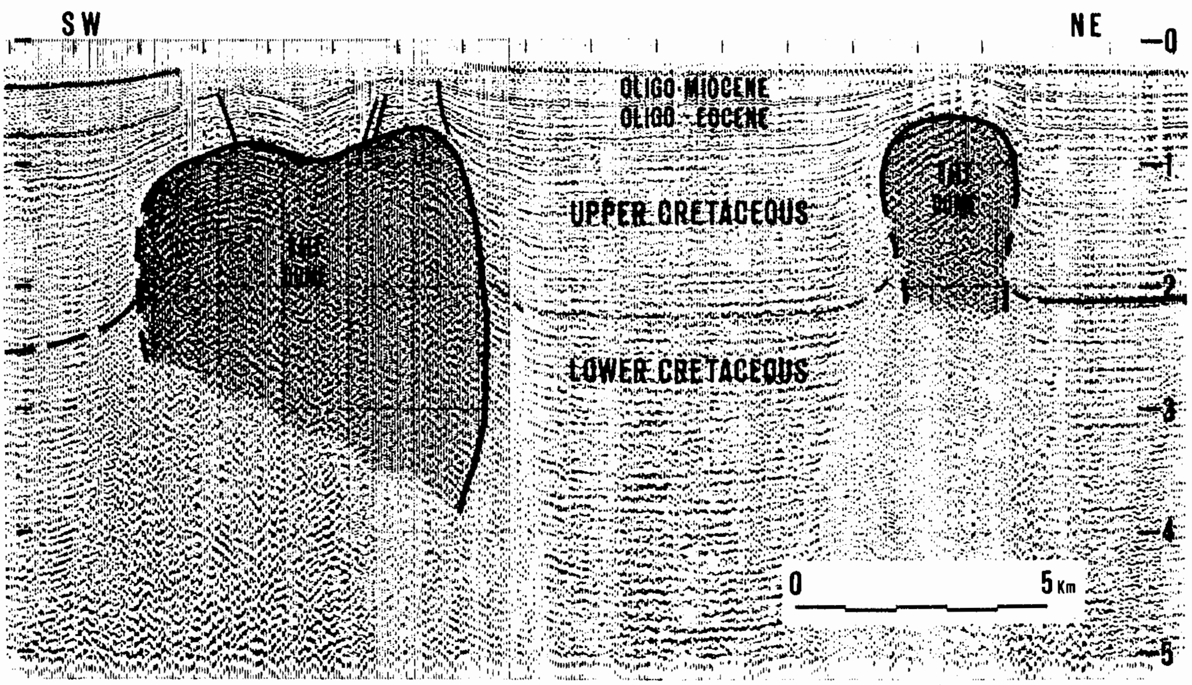


Figure 14. A low resolution, deep penetration (5 kilometers) seismic reflection profile shows salt domes (shaded) beneath the continental shelf off West Africa (From Templeton, 1970, fig. 7).

signals; the fundamental frequency and energy output is controlled by the volume of air which may be adjusted from 1 cubic inch or 16 cubic centimeters (about 50 Hertz) for shallow penetration to 2000 cubic inches or 32,800 cubic centimeters (about 5 Hertz) for deep penetration (fig. 15). Electric spark discharge sources generate an explosion by suddenly breaking water into its component gases which produces a broad bandwidth low-to-intermediate frequency (50-500 Hertz) signal achieving penetration to several kilometers depending on the electric energy used (100-120,000 Joules). The boomer is an electromechanical source consisting of two metal plates spring loaded against a coil which are suddenly separated by turning on and off a high voltage in the coil; the signal is of broad-bandwidth and intermediate frequency (500-2500 Hertz) capable of several hundred meters penetration. Piezo-electric and magnetostrictive sources transmit high frequency (hundreds to thousands of Hertz) signals of short duration to achieve high resolution and penetration of a few hundred meters. Sources can be used in concert to obtain mutual characteristics if the shipboard handling problems do not become too difficult.

In the operation of seismic profiling, a sound source and a receiver consisting of an array of pressure sensitive elements mounted inside an oil filled hose (fig. 15) are towed from the stern of a ship at speeds limited to about 20 kilometers per hour to reduce flow noise. The signals reflected from the ocean bottom and sub-bottom interfaces are received by the hydrophones, amplified, filtered, and continuously displayed on a graphic recorder (fig. 12). The reflected signals may also be recorded on magnetic tape to allow replaying and signal processing. The objective of signal processing is to increase the ratio of signal-to-noise by suppressing the noise and enforcing the signal (Silverman, 1967;

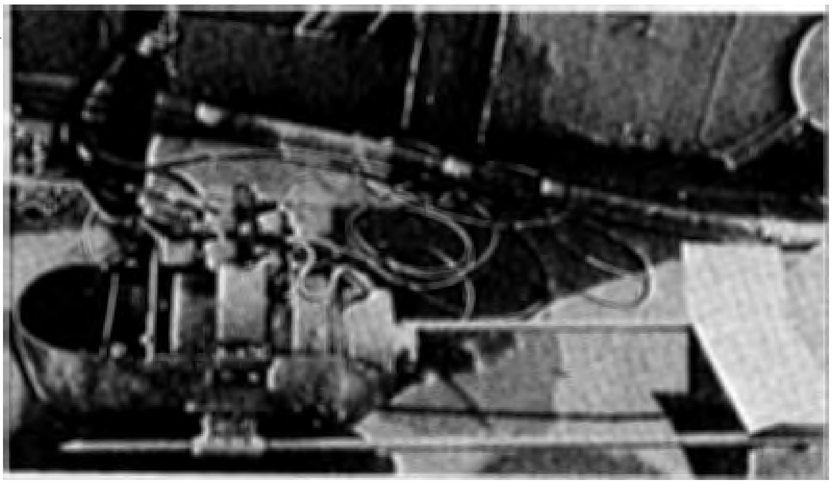


Figure 15. An air gun (30 cubic inch or 500 cubic centimeter capacity) mounted in a hydrodynamically stable towing vehicle about 1.5 meters long (foreground) is one type of sound source used in seismic reflection profiling. An array of hydrophones is mounted in an oil-filled clear plastic hose (background).

Neidell, 1968). Seismic signal processing has reached its most advanced development in the petroleum industry and has been neglected outside of industry owing to cost considerations (Schneider, 1971).

Reflection records are generally expressed in seconds of round-trip travel time to the reflector and back. The velocity of sound in the particular rock interval penetrated must be known in order to convert the travel time into thickness. Interval velocities are computed from information on the change in travel time with increase in distance between source and receiver utilizing a buoy-mounted hydrophone and radio transmitter (sonobuoy) to receive and transmit the reflected signal to the ship (Clay and Rona, 1967).

4.2 Seismic Refraction

Seismic refraction complements seismic reflection in providing a more generalized picture of the structures beneath the ocean bottom, deeper penetration, and a determination of sound velocities in major sediment and rock layers (fig. 16). Like seismic reflection, seismic refraction utilizes the fact that sound waves travel with different velocities in different materials. As in seismic reflection, the principle is to initiate such waves at a point and determine at another point the time of arrival of the energy. In refraction the sound wave is deflected from a straight line in passing obliquely from one sediment or rock layer into another of different velocity (fig. 11). In entering a layer of higher velocity the sound wave bends away from the higher velocity zone toward the zone of lower velocity by an amount proportional to the velocity difference between the zones, in a pattern that can be described according to principles of geometrical optics. Optical examples of refraction are the distortion of objects as seen through hot air or through the surface of water. From the measurements of the travel time of the sound wave from the sound source, through the water and rocks, and back to a receiver, the travel path can be reconstructed, and the position of boundaries between layers and sound velocities in the layers can be deduced (fig. 17).

The performance of seismic refraction involves the same basic components as reflection: 1) sound source, 2) receiver, 3) amplifiers and filters, 4) recorder. The major difference is in the configuration of source and receiver which must be separated at least several times the distance of the desired penetration in order to be in the path of the refraction returns (fig. 11). To accomplish this separation requires either two ships, a "shooting" and a "receiving" ship, or a sonobuoy which performs the listening function of the receiving ship (Hill, 1963). As the travel paths of the sound waves are much longer than in reflection the higher energy sources such as explosives or large air guns must be used. Various arrangements involving more than one receiver may be used in order to gain more information from different travel paths of each shot.

The practice of seismic refraction is limited to situations where each layer has a sound velocity higher than the layer immediately above

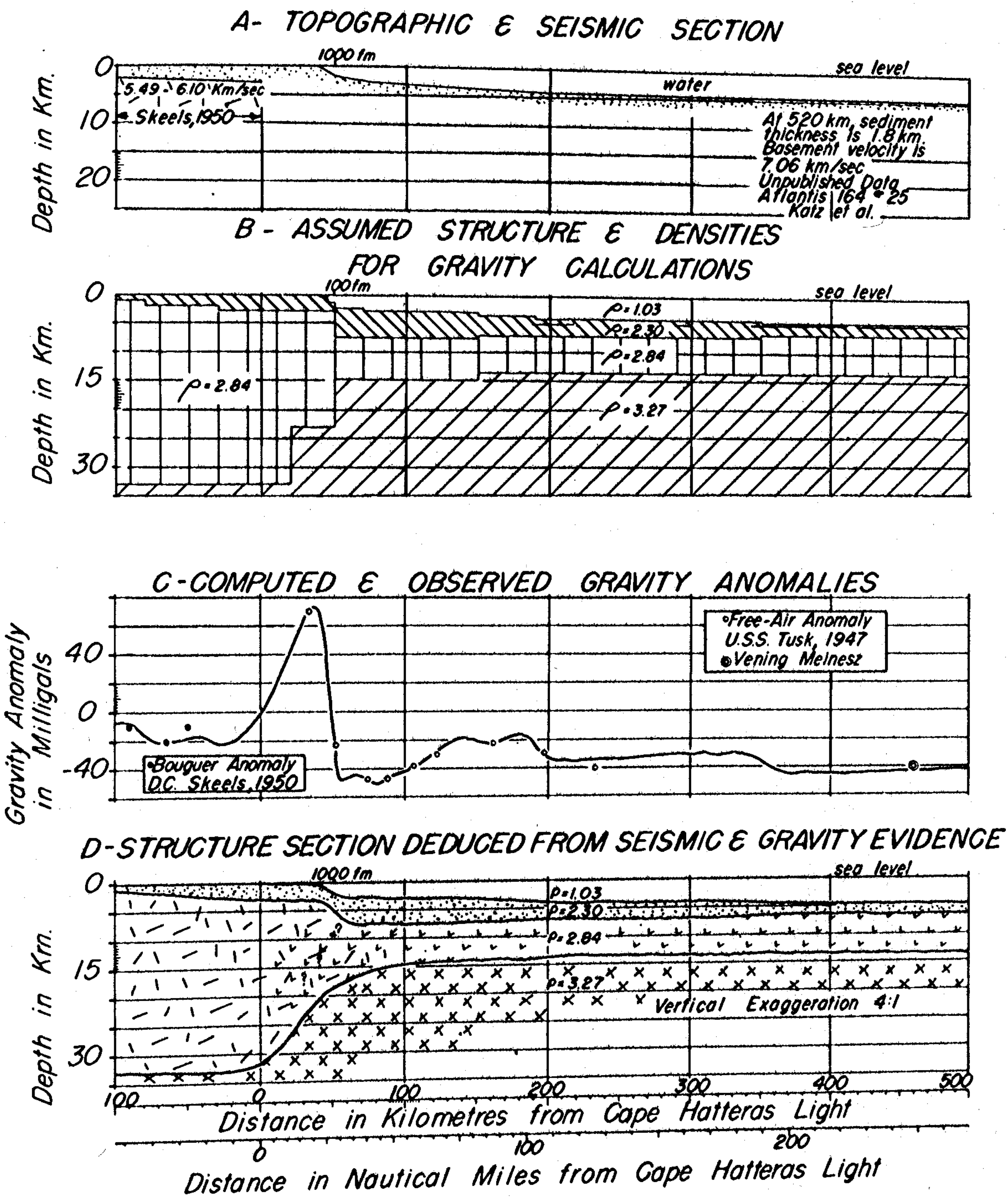


Figure 16. Seismic refraction profiles provide a generalized picture of major sediment and rock layers down to about 30 kilometers beneath the ocean bottom as in this example off Cape Hatteras, U.S.A. (From Worzel and Shurbet, 1955, fig. 8).

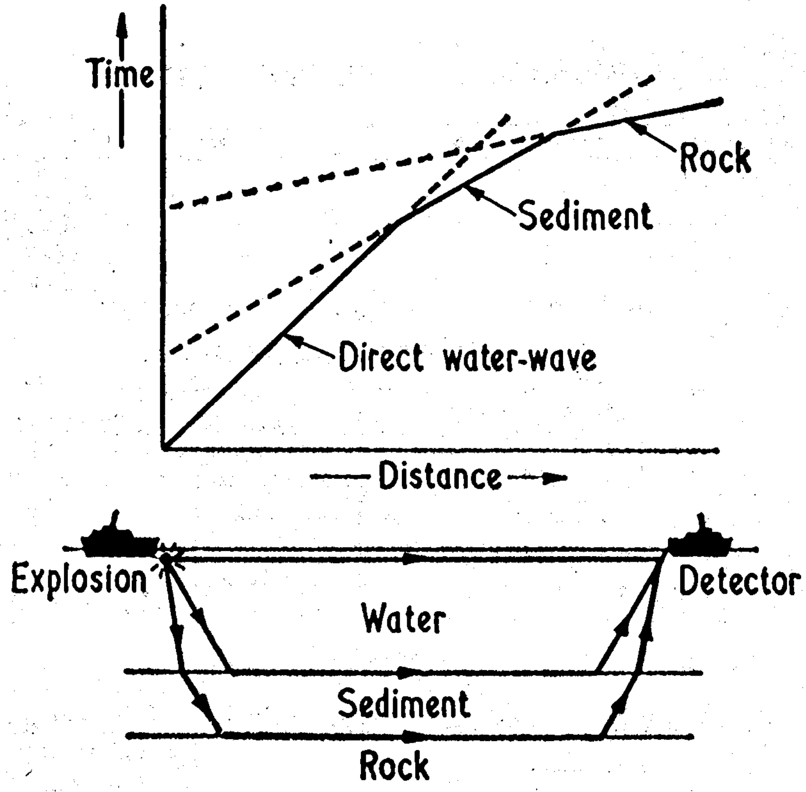


Figure 17. The travel times of sound waves refracted through water, sediment and rock layers are plotted on a time-distance graph. The sound velocities through the different materials are derived from the slopes of the corresponding segments of the time-distance curve and the thicknesses of the layers from their intercepts on the time axis (From Smith, 1968, fig. 2).

it, and where the velocity contrast between layers is sufficiently great to refract the energy. This means that the refraction method is blind to a lower velocity layer underlying higher velocity layers such as sediments underlying rocks.

4.3 Magnetic Method

The magnetic method is used to delineate geological structures associated with petroleum, to measure thickness of sediment above magnetic basement rocks, and to locate concentrations of magnetic (iron-bearing) minerals on or beneath the sea floor. The magnetic method depends on accurately measuring anomalies of the local geomagnetic field produced by variations in the intensity of magnetization residing in magnetized sediments and rocks. The magnetization is due partly to induction in the earth's magnetic field and partly to permanent (remanent) magnetization. The induced intensity depends primarily upon the magnetic susceptibility of the materials and the present magnetizing field. The susceptibility is almost entirely controlled by the quantity

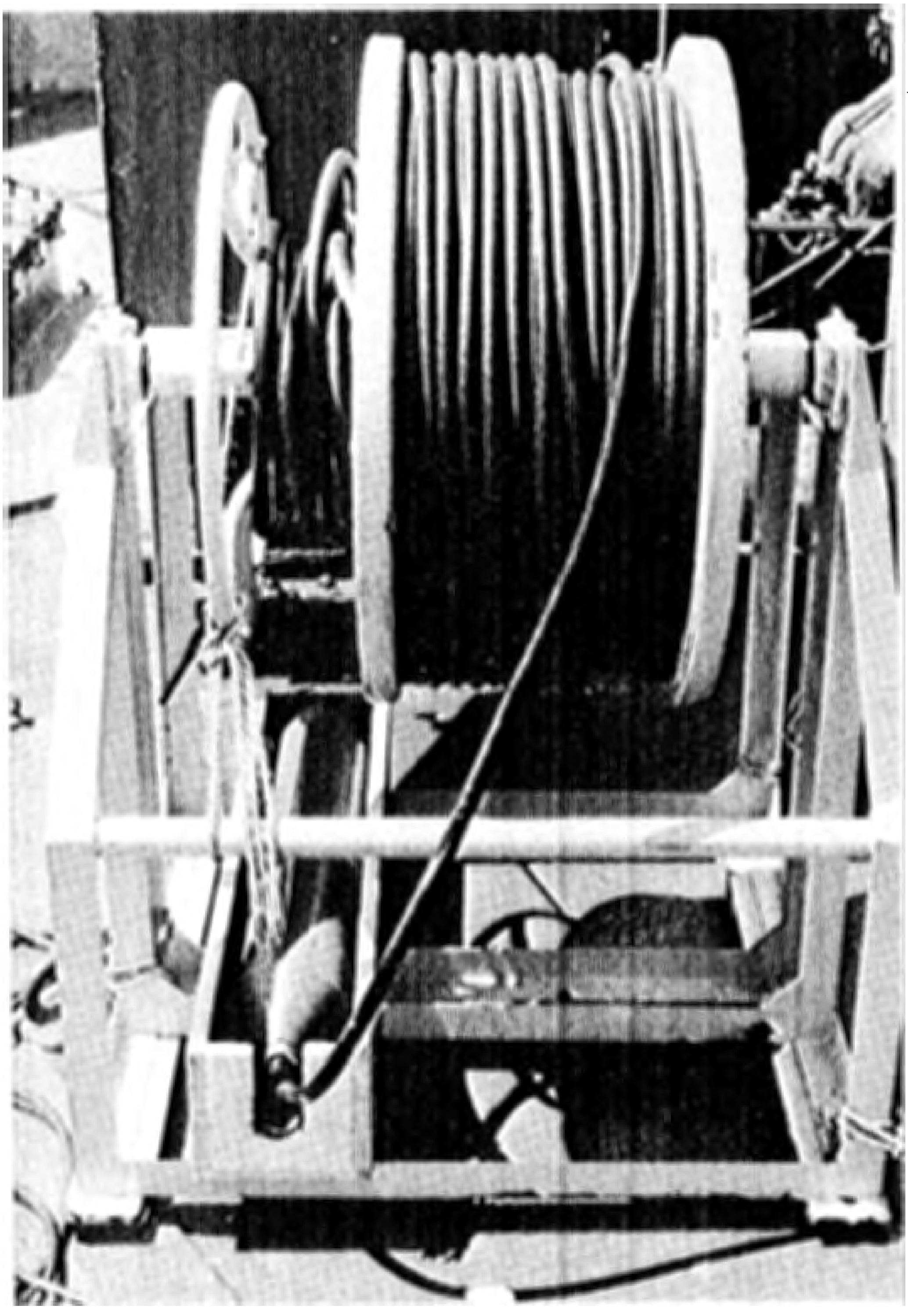


Figure 18. The sensor of the proton free-precession magnetometer is affixed to electrical cable by which it is towed behind a moving ship.

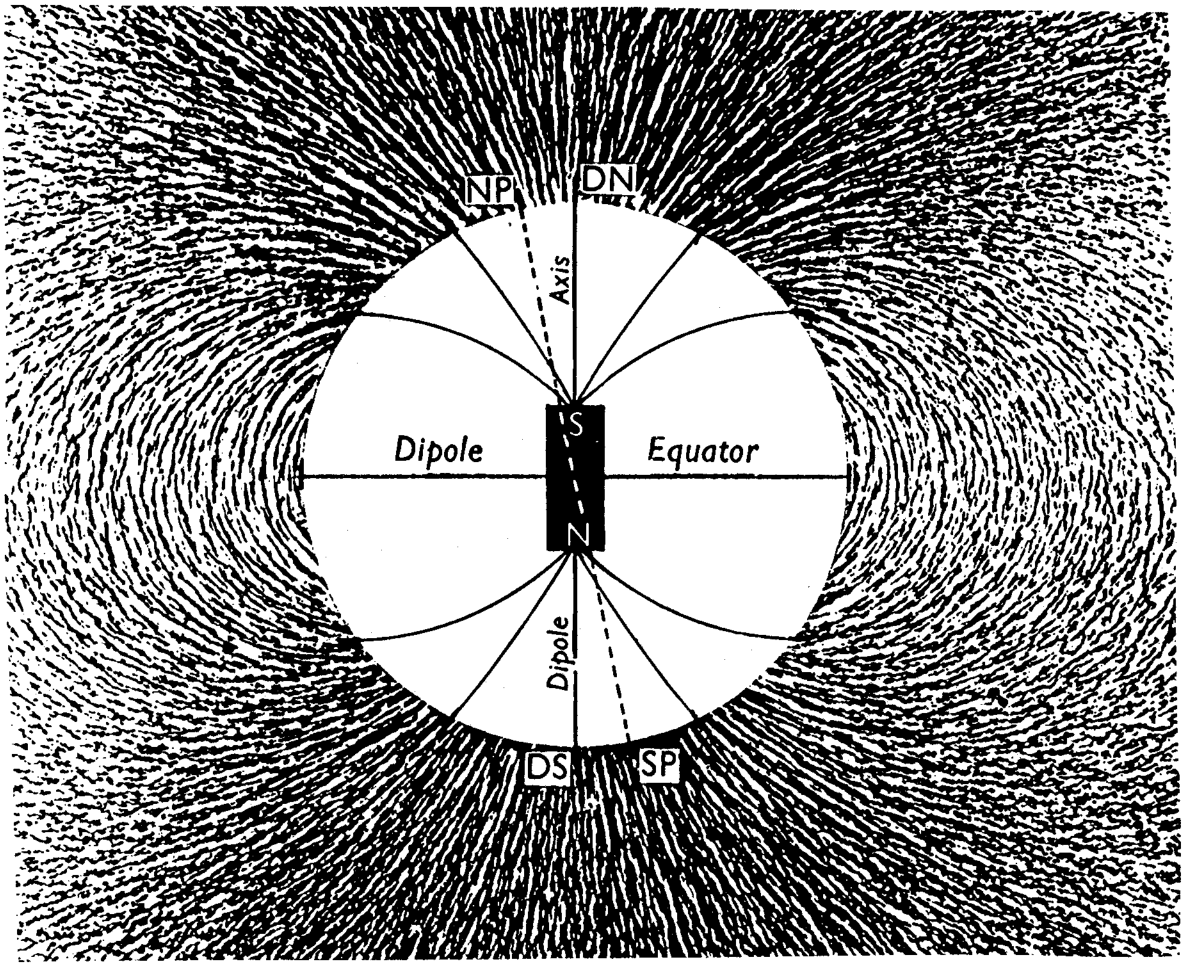


Figure 19. Lines of force of the earth's magnetic field are aligned as if generated by an internal bar magnet. DN and DS are the north and south geomagnetic poles; NP and SP are the geographical north and south poles. (Arthur Holmes, PRINCIPLES OF PHYSICAL GEOLOGY, Second Edition, The Ronald Press Company, New York, fig. 726. Copyright 1965).

of iron-rich minerals with magnetic properties, especially the mineral magnetite present in many volcanic rocks. Quartz, limestone, rock salt, and most sediments have very low magnetic susceptibilities. The permanent intensity is recorded in the materials from exposure to previous magnetic fields which have varied in the past.

Magnetic intensity measurements of the continental shelf are made with a magnetometer towed either by a ship or an airplane. The components of a magnetometer are the sensing element towed on an electrical cable, electronic components to convert the output of the sensor into units corresponding to magnetic intensity (gammas; 1 gamma = 10^{-5} gauss), and a recorder to display the values. Two types of magnetometers in common usage are the fluxgate and the proton free-precession (fig. 18).

Fluxgate magnetometers operate by sensing flux densities induced by the external magnetic field in certain materials of high electrical permeability. The fluxgate magnetometer measures relative magnetic intensity. Proton free-precession magnetometers (Hill, 1959) utilize the phenomenon of magnetic resonance of elementary particles. The proton free-precession magnetometer measures the magnitude of the total magnetic field consisting of the earth's regional field (fig. 19) plus the magnetic anomaly related to the materials of the ocean bottom (fig. 20). The earth's regional or reference field, known at all points (I.A.G.A., 1969), is subtracted from the total field leaving the residual field, which reveals anomalies associated with the sediments and rocks of the ocean bottom. The total field is measured along a set of tracks spaced for adequate coverage and residual values are plotted and contoured to delineate the magnetic anomalies (fig. 21).

Computer techniques have been developed to obtain the residual field from the total field (Cain and others, 1964) and to calculate models of crustal structure from the magnetic anomalies (Talwani and Heirtzler, 1964). Thicknesses of sediments and depth of burial and shape of rocks with magnetic properties can be deduced from the

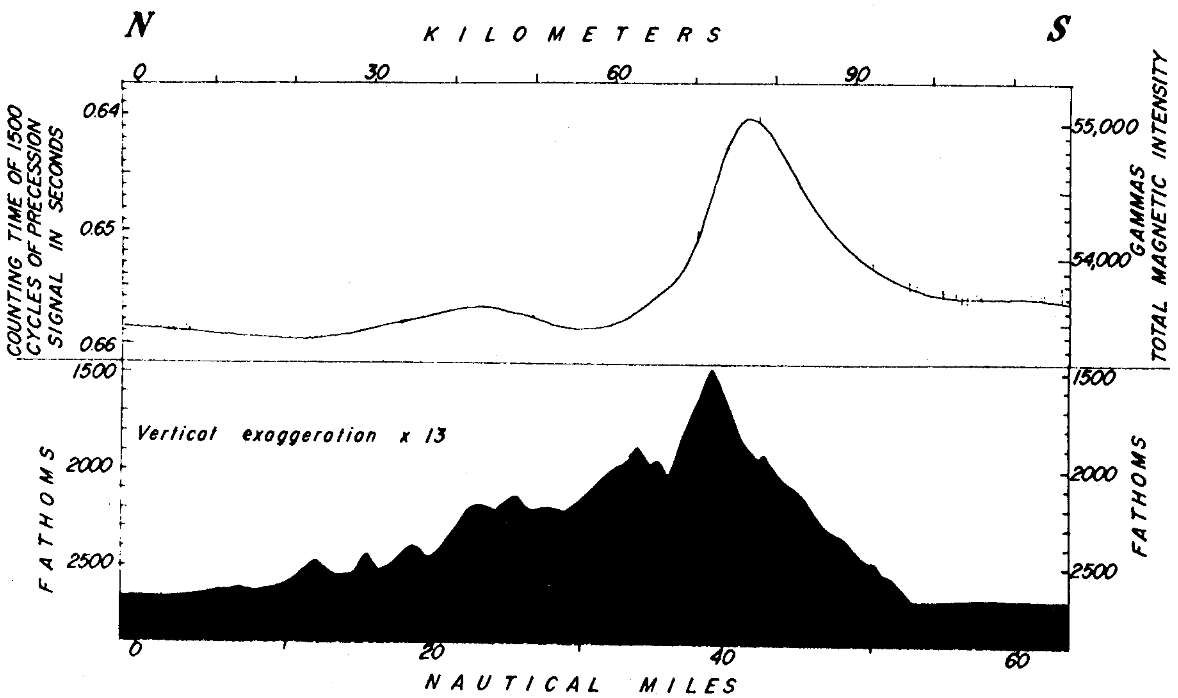


Figure 20. Profile of total magnetic intensity (top) made by a shipborne proton free-precession magnetometer over a seamount (bottom) (From Talwani, 1964, fig. 6).

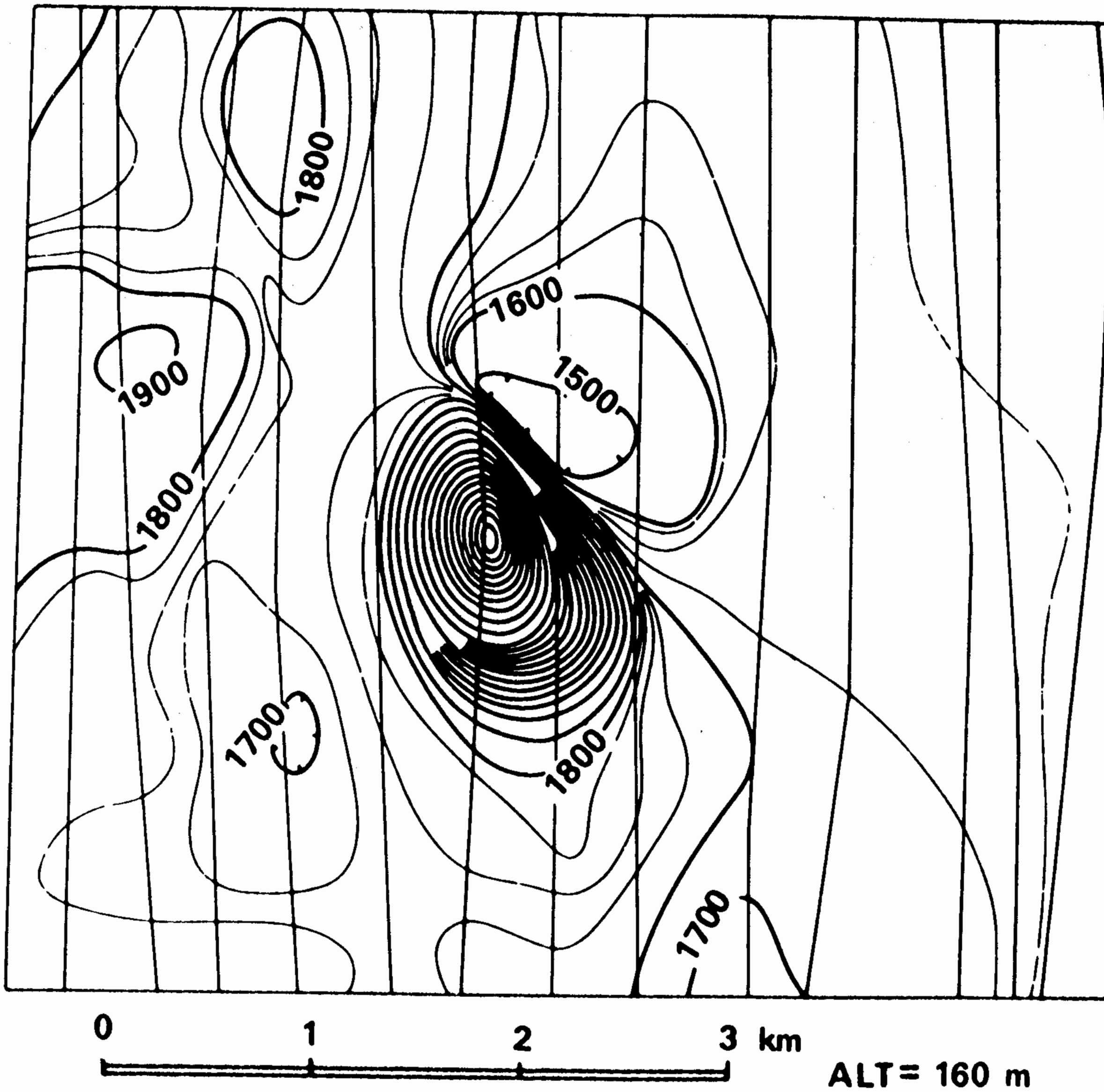


Figure 21. A residual intensity magnetic contour map (gammas) constructed from aeromagnetic profiles flown along north-south lines. An anomalous magnetic "high" (center) is associated with an iron-bearing deposit.

associated magnetic field. The interpretation of magnetic measurements is usually ambiguous. Many possible depths and shapes of magnetic source materials may account for the observed magnetic field (fig. 22). If either the depth or dimensions of the magnetic source materials is determined by seismic methods, then the other unknown quantity can be calculated from the associated magnetic field. Alternatively, the depths and dimensions of magnetic basement rocks can be determined empirically by comparing magnetic anomalies at locations where the basement rocks are known from drilling with anomalies over unknown sites in the same region.

4.4 Gravity

The gravity method, in common with the magnetic method, measures a field associated with the earth as a whole and influenced by local fluctuations. The local fluctuations in gravity relate to variations in the density of materials, in turn related to geologic features such as intrusions of light material like salt, or heavy material like basalt, or displacements of materials with contrasting densities in faults or folds.

Newton's law of gravitation states that the force of attraction between two objects is directly proportional to the product of their masses and is inversely proportional to the distance between them. Gravity measurements are expressed in milligals. One milligal is one thousandth of a gal, which is a unit of acceleration (1 centimeter/second^2) named after Galileo, and is roughly equal to one millionth of the total value of gravitational attraction exerted by the earth. The force of gravitational attraction exerted by the earth on an object of unit mass on its surface is not constant, but varies from place to place.

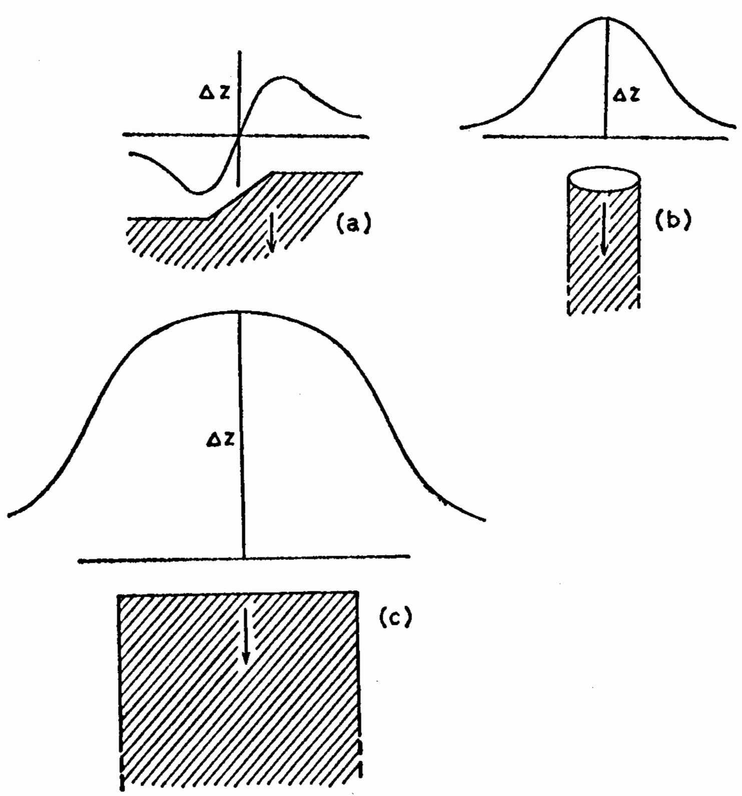


Figure 22. Curves of magnetic intensity and one of the many possible distributions of magnetic materials which could account for each of the curves (From Parasnis, 1962, fig. 6).

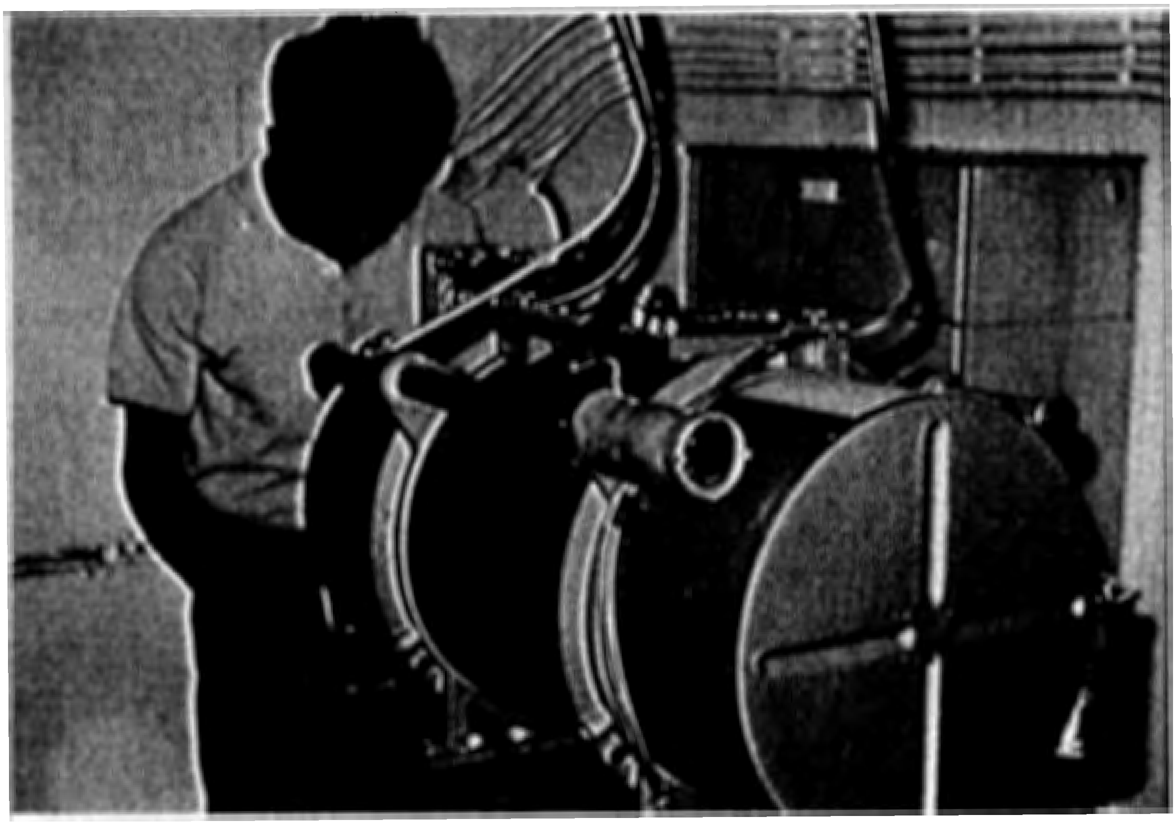


Figure 23. A scientist adjusting a Graf-Askania shipborne gravimeter (Courtesy of B. P. Dash).

A major part of this variation is related to the shape of the earth which is not a perfect sphere but is wider at the equator than at the poles and to the centrifugal force of a spinning earth. Superimposed on this gradual variation of the gravitational field are small variations caused by the density inhomogeneities in the earth's crust. The object of gravity measurements is to detect these small variations and relate them to geological structures.

Gravity measurements at sea are made with gravimeters installed on ships (fig. 23). The LaCoste-Romberg and the Gräf-Askania are two types of gravimeters in common usage in which changes in the force of gravity are measured by its effect on a weight at the end of a spring; the former type of gravimeter measures the force displacing the weight from an equilibrium position and the latter type measures the force necessary to restore the weight to an equilibrium position (fig. 24). In order to cancel the effects of horizontal and vertical accelerations of ship motion, the Graf-Askania gravimeter is mounted on a gyro-stabilized platform and the LaCoste-Romberg may be gimbal mounted with an auxiliary pendulum to establish true vertical. Observations are fed to a computer which eliminates extraneous accelerations and produces the corrected observations due to gravity. The vibrating string is another type of shipborne gravimeter which measures a change in frequency of vibration which is proportional to the acceleration of gravity (Wing, 1969). Ships larger than several thousand tons displacement are favored as platforms for making gravity measurements because of their stability. The problem of extraneous accelerations is averted and the highest accuracy is achieved in the sea-floor gravimeter which is encased in a water-tight chamber, placed on the ocean bottom, and operated by remote control through an electrical cable to the surface ship. Accuracy of navigation during gravity measurements is essential because the Eötvös correction arising from the Coriolis force experienced by moving bodies on a rotating earth varies significantly with ship's speed, course, and position (Worzel and Harrison, 1963).

The observed value of gravity minus the value predicted by the international formula for the earth's field gives the free-air anomaly (fig. 25). Bouguer anomalies are computed from the free-air anomalies after an allowance is made for the density deficit of water with respect to crustal materials and directly represent density variations below the sea floor. The corrected gravity measurements can be contoured to delineate gravity "highs" and "lows" if enough measurements over an area are available (fig. 26). Hypothetical reconstructions of buried geological structures can be computed from individual profiles. As in the magnetic method, the interpretation of gravity measurements is ambiguous

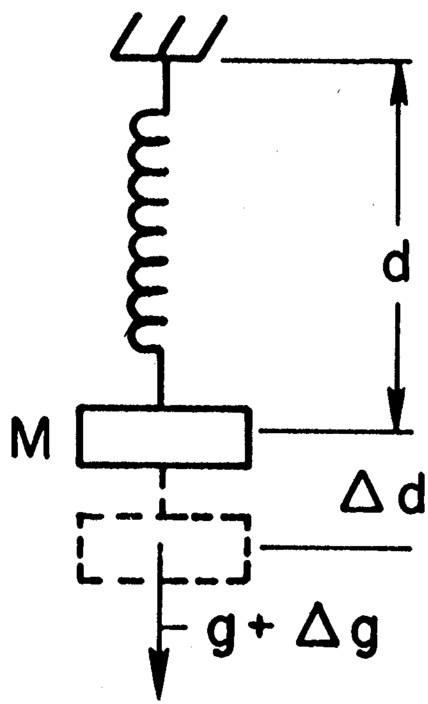


Figure 24. The Graf-Askania and La Coste-Romberg gravimeters measure the force of gravity (g) by its effect in displacing a weight (Δd) balanced by a spring (From Nettleton, 1971, fig. 6).

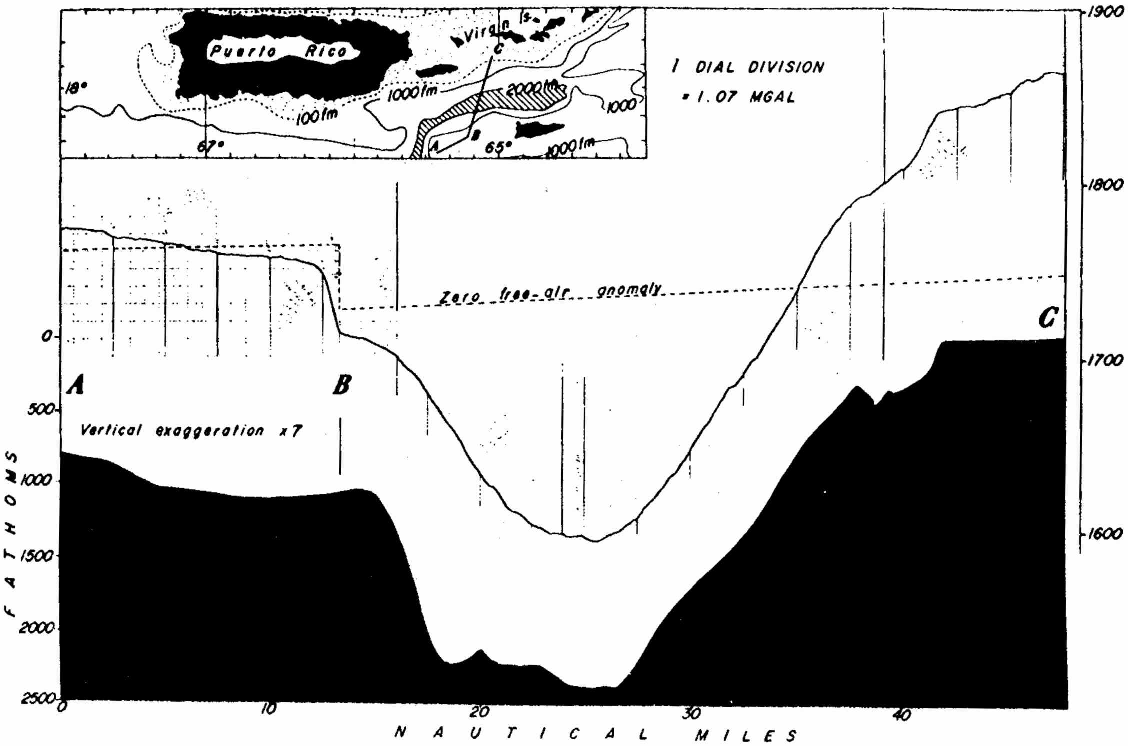


Figure 25. Profile made by a Graf-Askania shipborne gravimeter across a trough-shaped depression in the ocean bottom (shaded). The difference between the earth's gravity field (dashed line) and the observed value of gravity (solid line) is the free-air anomaly which closely corresponds to the shape of the ocean bottom (From Talwani, 1964, fig. 1). The slope of the zero free-air anomaly reflects the change of gravity with latitude and the step at B is caused by a change of Eötvös correction due to change in the heading of the ship.

because any gravitational field observed at the surface can be caused by an infinite number of different mass distributions, although every configuration of masses gives rise to a unique gravitational field (fig. 27). Gravity can only be interpreted if the number of possible solutions can be constrained by information on the size and depth of source materials obtained from seismic methods (fig. 16).

4.5 Electrical Methods

Electrical methods utilize natural electric fields flowing through the earth (self-potential and telluric), applied direct-current fields (resistivity and equipotential), and applied alternating fields (induced polarization and induction), to locate small scale features such as electrically conductive ore bodies. Voltages due either to natural or artificial electrical currents flowing through the earth are measured between two electrodes inserted in the ocean bottom. Differences in electrical response between pairs of electrodes evidence differences in the resistivity of the intervening rocks. Electrical methods are commonly used on land and their application to the ocean bottom is presently in the stage of research and development.

The self-potential method involves placing electrodes into the ocean bottom and measuring naturally occurring anomalous potentials between them with a millivoltmeter or potentiometer. Anomalously high potentials result from electric currents flowing through sulfide and graphite ore bodies caused by associated naturally occurring electrochemical reactions. Self-potential anomalies have been observed associated with sulfide ore bodies beneath the continental shelf (Corwin et al., 1970).

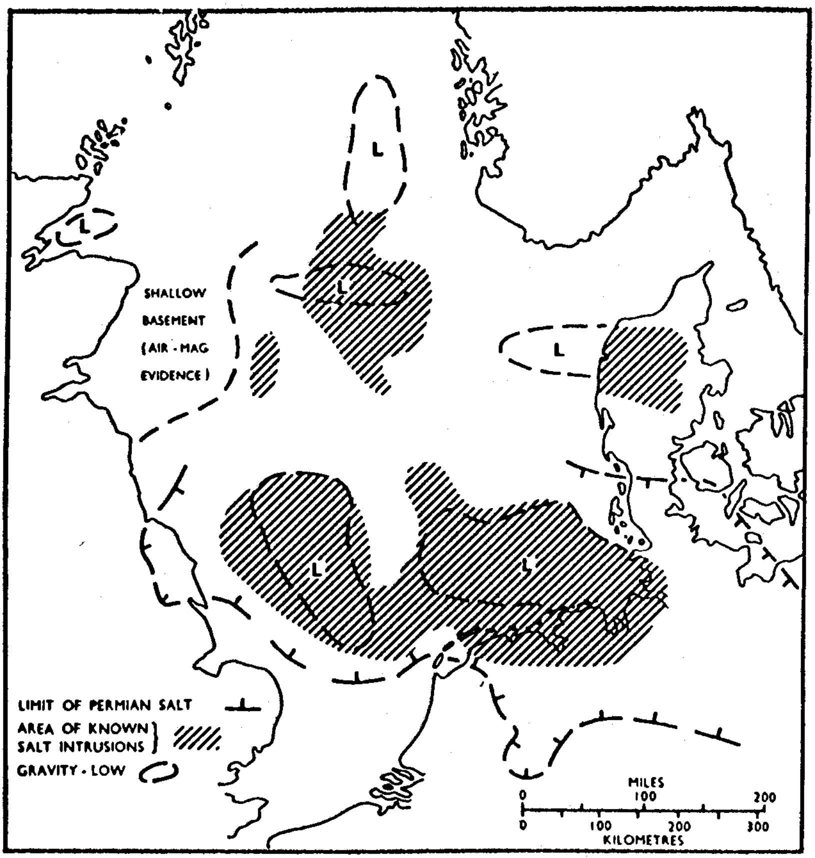


Figure 26. Gravity "lows" on a gravity map of the North Sea are associated with salt domes of lower density than surrounding materials (From Smith, 1968, fig. 6).

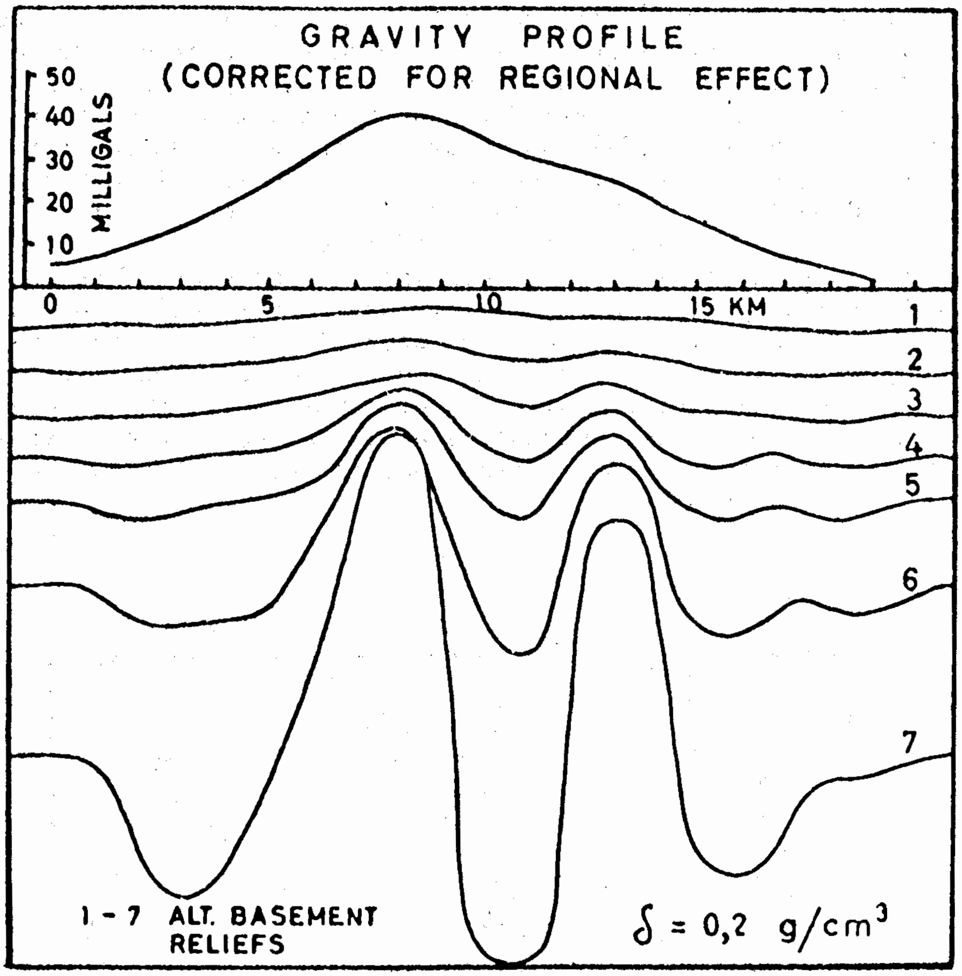


Figure 27. A given gravity anomaly (top) may be explained by each of the mass distributions shown below (From Parasnis, 1962, fig. 18).

Telluric currents are electric currents flowing naturally through the earth on a broad scale that can be detected with pairs of properly spaced electrodes. The telluric method has been used to detect large scale anomalies in conductivity such as salt domes.

Resistivity and equipotential methods consist of putting an electric current into the bottom with two electrodes and measuring the potential differences with two other electrodes. The results indicate the resistivity of a layer in the earth whose depth is proportional to the electrode spacing and whose dimensions are related to the symmetry of the lines along which the current flows.

In induced polarization a voltage is applied across two electrodes put into the bottom and shut off. The nature of the intervening material is inferred from the decay rate of the resulting current. Induced polarization and resistivity are generally limited in depth of penetration to twice the minimum dimension of the ore body sought.

In electromagnetic or induction methods an alternating current is set up in a wire loop. If a conducting body is present such a body of metallic ore, currents will flow in the body and can be detected with search coils. Electromagnetic methods have not yet been applied successfully at sea because of the high conductivity of sea water (Tooms et al., 1965).

4.6 Heat Flow

Heat is constantly being dissipated through the ocean bottom generated from the decay of radioactive elements within the earth. Hot spots may occur at sites of submarine volcanism, and very subtle temperature changes may be related to the heat conducting properties of local bodies of rock. For example, higher rates of heat dissipation would be expec-

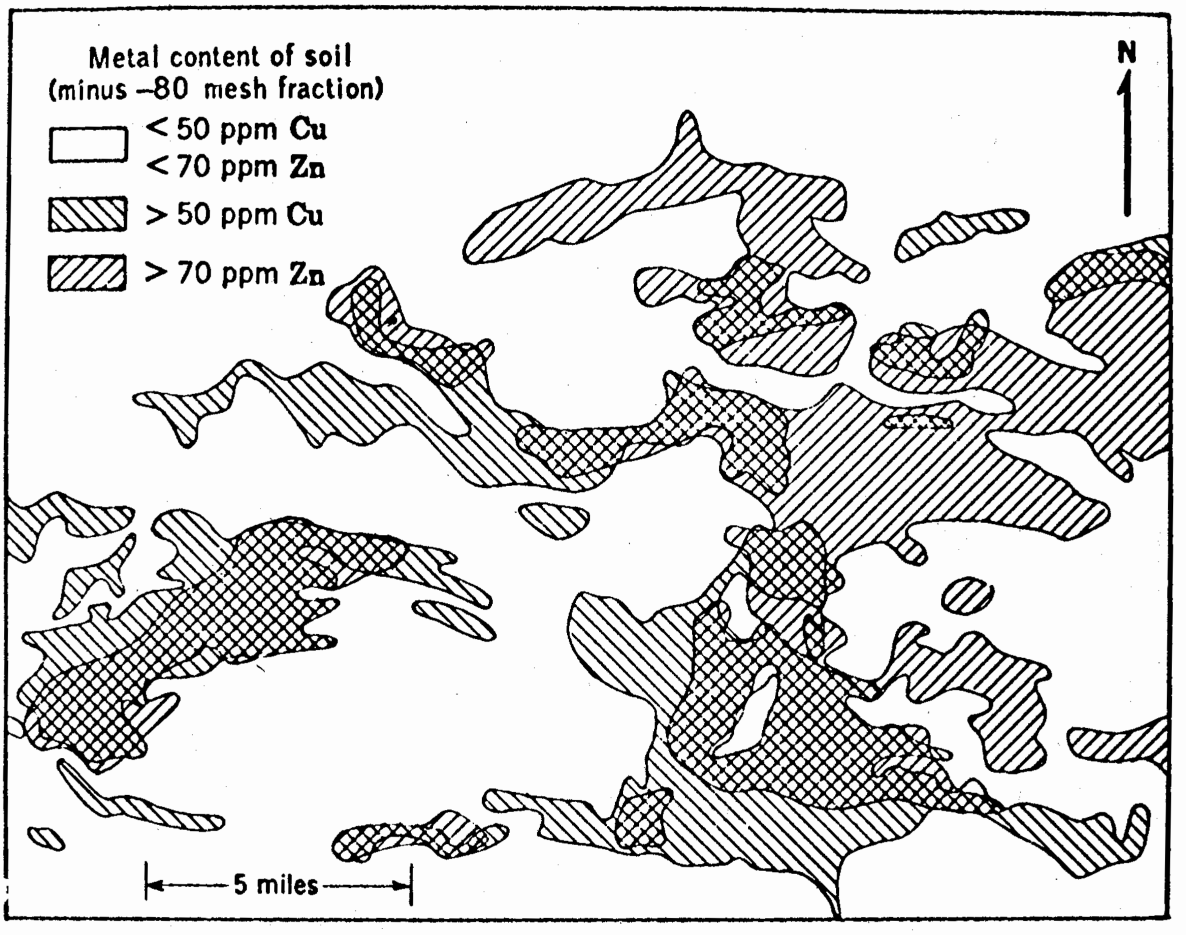


Figure 28. A geochemical map showing anomalous concentrations of copper and zinc measured in soil samples directly overlying buried ore bodies (Hawkes and Webb, GEOCHEMISTRY IN MINERAL EXPLORATION, Harper & Row Publishers, 1962. Data for this figure were supplied by Chartered Exploration Ltd.).

ted over metallic ore bodies of high conductivity than over salt domes of relatively low conductivity.

Measurements of the amount of heat flowing through the ocean bottom are made with a heat probe called a "thermograd", an instrument consisting of several heat sensors (thermistors) mounted at equal intervals along a cylindrical probe or along the barrel of a sediment coring device, which is vertically inserted into the sediments of the ocean bottom (fig. 8). The vertically spaced thermistors measure electrical

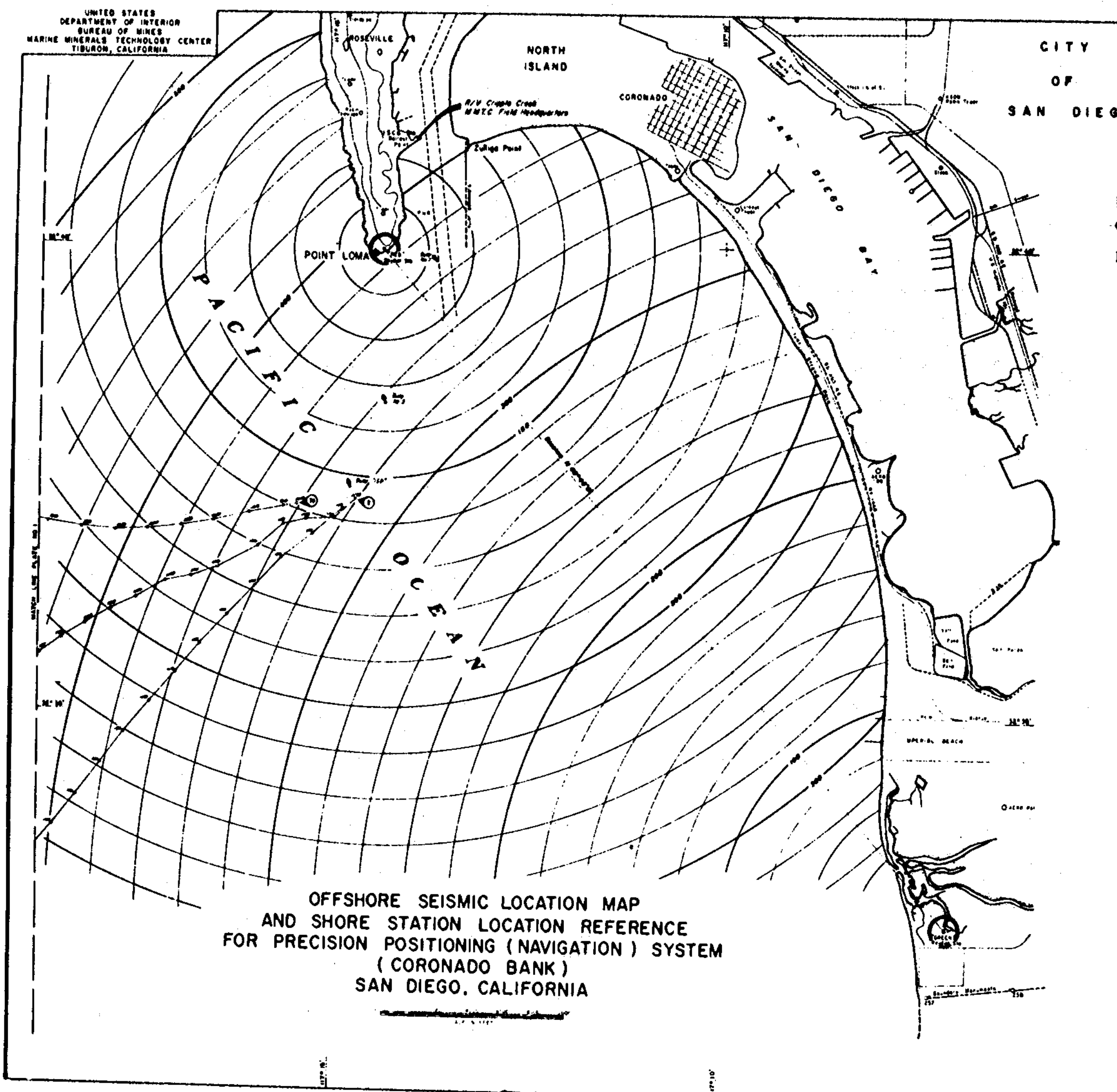


Figure 29. A range-range electronic navigation system in which a ship's position is at the intersection of two circles concentric about shore-based transmitting stations (From Barnes, 1970, plate 3). Each circle is the locus of all points equidistant from a transmitting station.

resistance which registers on an accompanying recorder calibrated to convert the resistances to temperature differences which may amount to several tenths of a degree Centigrade or more over a 10-meter vertical separation (Bullard, 1963; Gerard et al., 1962; Langseth, 1965). To obtain heatflow, the measured temperature gradients are multiplied by the value of the average thermal conductivity of the sediments between the thermistors. The thermal conductivity is routinely measured on-board ship in the simultaneously recovered sediment core (Von Herzen and Maxwell, 1959). The quantity determined is the amount of heat emerging through a unit area of the ocean bottom in a given time expressed as microcalories per second per square centimeter.

A spectacular association between submarine heat flow and valuable metallic ore bodies is described from the central rift of the Red Sea (Degans and Ross, 1969), where the temperature of bottom water is about 10°C higher than that of surface water. Heat flow is not presently used as a standard exploration method at sea largely because of the great

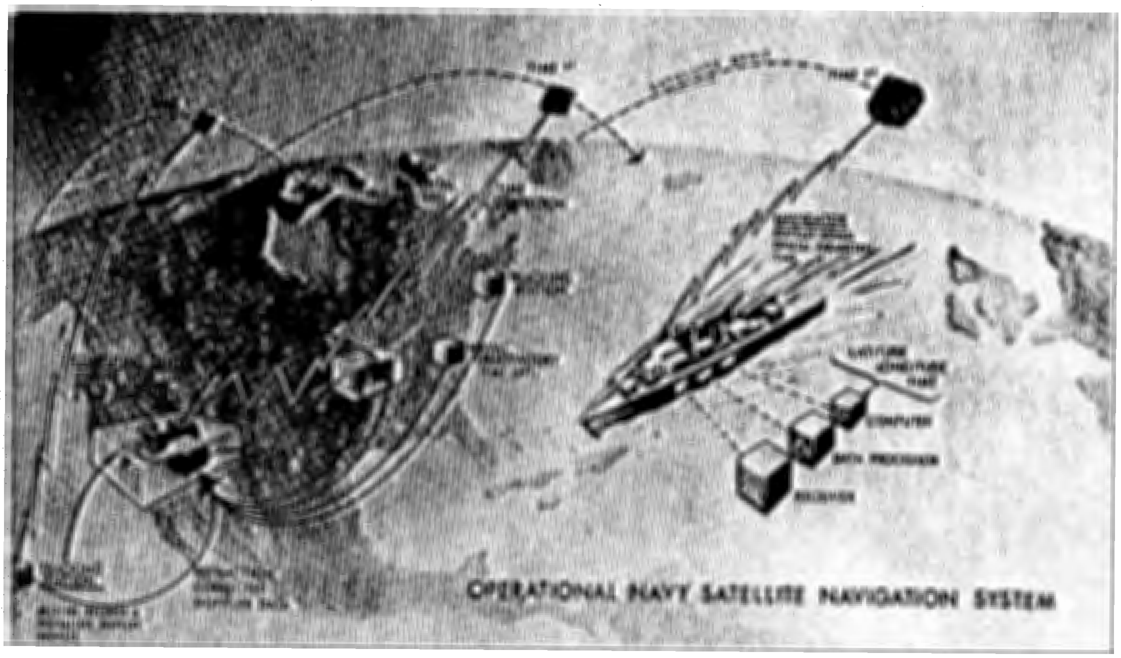


Figure 30. The satellite's signal is picked up by a tracking station (time^1) which is relayed to the Computer Center. After computing future orbital parameters and a time correction, these are then relayed to an injection station which in turn transmits them to the satellite (time^2). The satellite stores the information and transmits it to earth intermittently (time^3). Shipboard systems with receiver-computer equipment combines position information of the satellite with information on the position of the ship relative to the satellite to determine the ship's position on earth (from Thomas, 1966, fig. 15.).

variation in values observed within small areas and the large changes in water temperature over continental shelves. Statistical analysis of many closely-spaced measurements at depth beneath the surface of the continental shelf is needed to accurately define anomalies.

4.7 Radioactive Methods

Radioactive methods are principally used to search for ores that are naturally radioactive or that are associated with radioactive minerals. They may also be used to locate minerals that emit characteristic radiation when artifically stimulated (see radiometric methods under Geochemical Methods).

Natural radioactivity occurs when certain atoms disintegrate, spontaneously emitting alpha particles (helium nuclei), beta particles (electrons and positrons), and gamma electromagnetic radiation. This phenomenon is confined principally to four radioactive series including the elements neptunium, thorium, and two types of uranium. The alpha and beta particles lose their energy in passing through matter and are not detectable under even a thin cover of sediments. The gamma rays can be detected through considerable thicknesses of material depending on the sensitivity of the instruments and the background effects due to

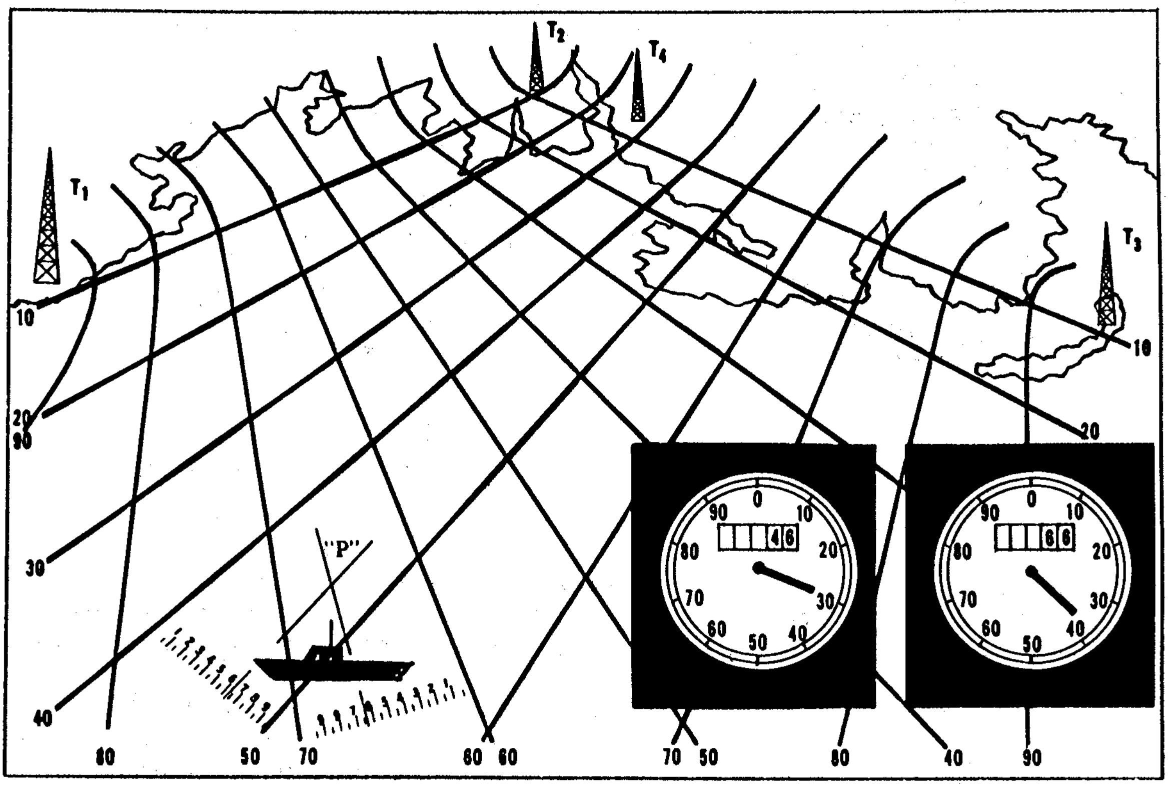


Figure 31. Hyperbolic electronic navigation system in which a ship's position "P" is at the intersection of two hyperbolae with foci at shore-based transmitting stations.

cosmic radiation. Characteristic gamma radiation may be stimulated when non-radioactive minerals are bombarded by neutrons from a radioactive source such as californium 252 in the method of neutron activation analysis.

Natural or stimulated radiation emanating from rocks is detected by Geiger and scintillation counters. Geiger counters detect gamma rays by their effect of ionizing gas contained in the instrument to produce an electric current. Scintillation counters detect gamma rays by their effect of causing certain substances to emit radiation. The radiation intensities may be recorded as counts-per-minute or millirontgens-per-hour.

Radioactive methods are used on land and have not yet been extensively applied to marine work. The Geiger or scintillation counter can be encased and towed near the sea floor, as has been done in exploration for submarine phosphorite nodules enriched in uranium (Tooms, 1969). A neutron activation analysis system designed for towing near the sea floor has been used experimentally to identify ore samples planted on the continental shelf (Ocean Industry, 1970; Noakes and Harding, 1971). Alternatively, shipboard measurements can be made on seawater, sediment, and rock samples.

5. GEOCHEMICAL METHODS

In geochemical prospecting the constituents in sediments and rocks and seawater are analyzed for indications of the presence of ore bodies and petroleum. The chemical property measured is usually the content of some element that occurs in minute "trace" quantities relative to other elements. The purpose of the measurement is the discovery of abnormal chemical patterns, or geochemical anomalies, related to mineralization. Geochemical prospecting is especially important in the search for minerals that occur in quantities too small to be resolved by most geophysical methods, as occurrences of such industrially important metals as molybdenum, tungsten, and vanadium.

Chemical indicators of the presence of a mineral deposit may disperse hundreds to thousands of meters away from the deposit. The indicators may disperse in solid, liquid, or gaseous phases. The concentration of the indicator will decrease away from the source giving rise to a concentration gradient that leads back toward the source. For example, hydrocarbon gases like methane, ethane, and propane, as well as brines from salt domes, may diffuse from petroleum deposits through overlying materials, to the ocean bottom (Kartsev and others, 1959). Metal ions in solution can migrate through the agencies of weathering, leaching, and transport in ocean currents resulting in dispersion halos around the parent ore body (Ginsburg, 1960). Dispersion patterns can be identified by the chemical analysis of samples systematically obtained on and beneath the ocean bottom and from the adjacent seawater.

Qualitative and semi-quantitative chemical methods are used to identify and estimate concentrations of the principal and indicator elements in samples. The reliability of geochemical prospecting depends on the sensitivity and precision of these measurements, which can vary depending on the method, the presence of impurities, and the competence of the geochemist. The analytical methods in most common use are summarized in table 3.

The results of sample analyses can be usefully portrayed by maps on which concentrations of different elements are contoured to delineate geochemical anomalies (fig. 28). The maps may reveal trends and gradients in concentrations of indicator elements, which may converge toward a source mineral deposit.

6. THE MARINE ENVIRONMENT

The continental shelf is covered by a layer of salt water up to about 200 meters thick. This means that a ship must be used as a stable platform for the execution of most exploration methods with the exception of magnetics, long-range photography, and certain electromagnetic techniques which can be flown (Powell, 1969; Undersea Technology, 1970, Oceanographic Ships and Submersibles of the World, Section E, p. 1-36). This also means that instruments immersed in sea water must be specially packaged against water, corrosion, and the pressure of submergence.

The progress of a ship over the sea or a submersible vehicle through the sea is less hampered by physical obstacles and, therefore, faster than that of a vehicle over most terrains on land. Sound energy transmitted to probe the earth is more effectively coupled through water than through soil zones on land. The ocean bottom is less contaminated by mechanical and electromagnetic noise than is the land, generally resulting in better signal-to-noise ratios in geophysical measurements at sea. Alternatively, operations at sea are even more weather sensitive than those on land because as soon as waves start building, the ship becomes unstable and the efficiency of men and instruments rapidly declines. Operations at sea frequently must be curtailed due to rough seas. The percentage of unfavorable weather conditions varies with region and time of year and can be approximately predicted from consideration of synoptic weather maps compiled from prior years.

The efficiency of shipborne seismic, magnetic, and gravity coverage generally results in cost savings over the application of corresponding methods on land. However, the cost of exploration drilling at sea is considerably greater than on land. The rapid rate of development of ocean exploration techniques acts to increase the prices of equipment and services (Luehrmann, 1971). Airborne exploration offers the most rapid and inexpensive way to gather certain information over a large area at sea, but is limited in methods, resolution, and positional accuracy.

Table 3. Analytical Methods in Geochemistry *

FLAME SPECTROMETRY: Many elements emit characteristic radiation when vaporized in the heat of a flame. The elements are identified by the wavelength of the spectral lines and their quantity estimated by the intensity of the lines.

EMISSION SPECTROMETRY: Almost all elements emit radiation of characteristic wavelengths when vaporized and ionized in the intense heat of an electric discharge. As with flame spectrometry, the element is identified by the wavelength and the quantity present is determined by the intensity of the spectral line. Flame and emission spectrometry are the basic tools of geochemical prospecting because of their capacity to conveniently determine whole series of chemical elements.

GRAVIMETRY: Gravimetric methods involve weighing the separated constituent.

COLORIMETRY: A trace element is made to form a compound that, when dissolved or suspended in a suitable liquid medium, absorbs or scatters light of characteristic wavelengths.

TURBIDITY AND NEPHELOMETRY: These methods involve, respectively, the unselective absorption and the scattering of light of all wavelengths by suspended particles of a precipitate containing the element to be determined.

SPOT TESTS: Some trace elements may be made to form colored compounds that can be displayed on paper.

PAPER CHROMATOGRAPHY: Ions may be separated by their differential rates of movement in a solvent as it flows along a strip of filter paper and dries in different colored bands. The element is identified by color and the amount by width and color intensity of the band.

VISIBLE FLUORESCENCE: Samples containing uranium emit a visible luminescence under ultraviolet light when fused and cooled.

X-RAY SPECTROMETRY: The inner orbital electrons of atoms may be activated by x-rays in such a way that they re-emit x-rays of a wavelength that identifies the activated element.

RADIOMETRIC METHODS: Uranium, thorium and potassium are naturally radioactive. Non-radioactive elements may be made radioactive by exposure to neutrons generated in an atomic reactor. Both natural and artificial radioactive elements give off gamma radiation of characteristic energy. The element is identified from the gamma ray energy and the quantity is measured from the intensity.

ELECTRICAL MEASUREMENTS - Polarography: A number of analytical methods depend on instrumental determination of the electrical properties of solutions as a measure of the kind and concentration of ions dissolved in the solution.

**After Hawkes and Webb, 1962*

7. NAVIGATION

Exploration and navigation go hand in hand because geological, geophysical, and geochemical information must be accurately located to be useful. The ship performing the exploration must be equipped with a position-keeping system capable of sufficient accuracy, repeatability, and range, to fulfill the requirements of a particular exploration problem.

Positions at sea are determined relative to known locations using visual and electronic instruments with accuracies varying from 1 meter to many kilometers depending on the method and the conditions of its use. Accuracies quoted by manufacturers of navigational systems are based on optimum conditions, and may be greater than accuracies achieved in actual operations.

The traditional methods of visual and celestial navigation are seldom adequate as primary navigation but are useful as verification and backup for more efficient electronic methods which utilize radio waves. Most electronic methods work by determining ranges from the ship to known locations, or the position of the ship on hyperbolic curves (Thomas, 1966; Chernof, 1971). The range methods utilize travel time or phase differences of electromagnetic signals transmitted between the ship and two radio transmitters at two different known locations to measure two ranges; the maximum operational distance is generally line-of-sight. The two ranges determine the radii of two circles, and one of the intersections of the circles is the position of the ship (fig. 29). Radar determines range and bearing relative to an object such as an anchored buoy or landmark which reflects electromagnetic signals. Satellite navigation systems determine the position of the ship relative to the known position of the satellite from information transmitted via radio from the satellite to a shipboard receiver and computer (fig. 30).

Hyperbolic methods utilize two pairs of transmitting stations at known locations and a receiver onboard the ship (fig. 31). The difference in arrival time or phase of electromagnetic signals received at the ship determines the position of the ship along a hyperbola, defined as the locus of all points along which the difference in distance to two foci (land-based transmitters) is equal. The ship's position is determined by the intersection of two hyperbolae.

Electronic navigational systems utilizing other than radio waves include doppler sonar and inertial. Doppler sonar systems utilize the reflection of sound waves from the ocean bottom in depths up to about 300 m (Buford, 1969). As the ship moves relative to the ocean bottom a hull-mounted sonar transducer continuously emits sound waves at a frequency which is shifted by a value proportional to the ships velocity (Doppler shift). This information is displayed as a velocity and direction and is integrated by a computer to provide distance and course from an independently known starting point. Inertial systems utilize a gyroscope to sense accelerations from which ships speed and direction are derived and integrated by a computer to provide distance and course from an independently known starting point; the high cost of inertial navigation systems limits their application to exploration.

At present the only electronic navigational systems with worldwide coverage are satellite and Omega (hyperbolic). Several other hyperbolic systems have permanent installations but are limited in range up to about 2000 kilometers. Shorter range systems can be commercially obtained to suit specific tasks.

8. COMPOSITE EXPLORATION METHODS

The choice of an exploration method is guided by pure and practical considerations. The pure considerations emphasize the objective of the investigation and the type of information needed to fulfill the objective, including the geology of the region to be investigated and the anticipated mode of occurrence of the mineral deposit being sought (Table 1). Cost, anticipated economic return, the availability of funding, competent manpower, instrumentation, ships, navigational control, and the conditions of work (accessibility, weather, etc.) in a given region are important practical considerations.

An exploration campaign should employ several exploration methods both concurrently and sequentially (table 2). For example, bathymetric, seismic reflection, magnetic, and gravity methods can be run concurrently from a single moving ship to provide complementary information about the ocean bottom (Robinson, 1971). The aeromagnetic method can provide rapid regional reconnaissance. Shipborne geophysical methods can provide more information on selected areas and serve to guide geological and geochemical sampling. Estimates of additional field costs to obtain shipboard gravity, magnetic, and seismic refraction information in combination with seismic reflection data range as low as 10 percent (Dean and Kologinczak, 1970). The information gained from such a composite investigation reduces the uncertainties in interpretation and increases the probability of discovery.

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