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PART ONE: MINERAL RESOURCES OF THE SEA BEYOND THE CONTINENTAL SHELF

Report of the Secretary-General

ADDENDUM

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I. MARINE MINERAL RESOURCES BEYOND THE CONTINENTAL SHELF

In discussing marine mineral resources beyond the continental shelf, that is to say, on and underlying the sea bed for all the regions currently called the continental slope and the abyssal ocean floor, it is at the outset desirable to define these terms more specifically.

The continental shelf is defined as that area of the sea or ocean floor between the mean low water line and that sharp change in the inclination of the floor that marks the beginning of the continental slope. The sharp change in inclination, from about one eighth of one degree to more than three degrees, occurs at various depths but usually between about 130 and 200 metres. The width of the shelf ranges from less than one mile up to 800 miles.

The continental slope, usually from ten to twenty miles wide, extends from the outer edge of the continental shelf to the abyssal ocean floor. The inclination of the slope varies widely from as little as 3° to over 45°: slopes of 25° are common.

The abyss or ocean floor appears to be a rolling plain from 3,300 to about 5,500 metres below the surface of the sea: it is scarred by deep gorges called trenches and studded with sea mounts and guyots.[1/] The mean depth of the superjacent waters is 3,800 metres. More than 75 per cent of the ocean floor lies at a depth of less than 5,000 metres.

There are difficulties in defining the boundary line between the continental shelf and the continental slope, largely because the continental margins [2/] (shelves and slopes) may have different origins and consequently different structures. Various parameters and criteria have been proposed for more specific definition; discussion of these do not however come within the scope of the present report.

A. Brief survey of marine minerals

There are many marked and fundamental differences in the types of deposits occurring in the continental shelves, continental slopes and the deep sea floor

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1/ Guyots are flat-topped sea mounts.

2/ Also called the continental terrace.

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beyond. A primary division depends on whether the deposits are associated with bedrock, that is, with pre-existing geological formations now buried under the sea; are surficial and more or less of contemporaneous origin, forming or having been formed in the ocean environment; or are contained in solution within the waters of the sea.

Mineral deposits within bedrock

A two-fold division may be based on two fundamentally different geological environments. The first applies to those geological formations of the continents which generally do not extend beyond the base of the continental slope, and are contained within the so-called 'sialic layer'[3/] of the earth's crust. These include the bedded sedimentary rocks within which oil, gas, coal and other deposits are to be found, as well as the less dense crystalline rocks such as granites with which associated metallic minerals may occur as vein deposits and disseminations. Generally speaking, such deposits are not to be expected in the abyssal depths of the oceans, in which environment only those minerals that are genetically associated with oceanic types of basic and ultrabasic magmatic rocks - for example chromite, nickel and platinum - are likely to be found in the simatic layer of the earth's crust.

Subsurface deposits associated with pre-existing bedrock formations and found at various depths below the ocean floor include petroleum and gas, sulphur, coal, bedded salt and potash deposits, certain iron ores and various metallic minerals in veins etc. In many areas, offshore petroliferous sedimentary basins extend from the shelf to the continental slope, the bottom of which, at the ocean rise, is generally taken as marking the outside limit for such occurrences.[4/] Although

3/ Of the earth's two major crustal layers, only the simatic layer - the lower one made up of basic magmatic rocks - is earth-encircling and found beneath both the continents and the oceans. The overlying sialic layer, which constitutes the bulk of the continents is generally confined to the continental margins (shelf plus slope). The origin and age of the ocean basins and the distribution of sediments being formed within them is under very active study; sediments as old as lower Cretaceous are recorded in the Atlantic.

4/ Oil seeps have been found in waters as deep as 1,000 fathoms in the Sigsbee Deep of the Gulf of Mexico.

the continental slopes may not everywhere be as favourable as the shelves, they no doubt contain large quantities of petroleum which will eventually become available when deep water technology permits economic exploitation.

In the Gulf of Mexico off the coasts of the United States of America and Mexico, there are as many salt dome structures in the continental slope as in the shelf areas. Geological evidence indicate that some of these structures are similar to the sulphur-bearing domes of the inner shelf and may possibly contain commercial quantities of sulphur. Although salt dome structures are known to exist in other saline sedimentary basins in the shelves, as for example in the Persian Gulf, the Frasch sulphur (dome-type sulphur) of the Gulf of Mexico has not been found elsewhere in the world except for a few areas on land.

The bedded salt deposits, which often include potash layers, may exist in some offshore saline sedimentary basins, a number of which are known to occur in the shelf and slope areas of Africa, the Middle East, Europe and the Gulf of Mexico. Recent petroleum exploration in the North Sea has demonstrated the undersea extension of the Upper Permian potash-bearing evaporite sequence, which has been mined for salt and potash for many years in Germany and the United Kingdom (Dunham, 1967). Similarly, salt beds probably extend under the Irish Sea off the north Irish Coast - salt has in fact been mined in the Isle of Man. In the Union of Soviet Socialist Republics potash deposits found along the northern shore of the Caspian Sea appear to extend offshore.

Coal is another economically important bedded deposit which may extend offshore for long distances, theoretically as far as the bottom of the continental slope. The subsea coal seams being exploited are generally the extensions of known onshore deposits. Iron and other metallic minerals are also likely to exist in the shelf and slope areas. Before its recent closure, underground mining operations in a subsea iron mine off Newfoundland were taking place far offshore, under 400 ft of water.

Beyond the base of the continental slope the prospects of finding metallic lode and vein deposits in the deep sea floor are likely to be restricted to a few specific minerals such as chromite, platinum, nickel and cobalt which are genetically associated with the basic and ultra-basic magmatic rocks. Pure chromite has recently been discovered by oceanographers of the Soviet Union in sea-floor rifts in the Indian Ocean. It cannot be expected that the deep-sea floor

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will contain those primary ore deposits that are associated with the granitic magmas of the continents. Furthermore, geological history indicates that secondary enrichment by weathering and other land based geological processes has not taken place to any appreciable extent on the sea floor below about seventy-five fathoms of water. On land and in shallow shelf areas these secondary enrichment processes have been highly important, the long exposure to weathering and erosion being often responsible for changing a low grade deposit to one of mineable grade.

Surficial deposits

Placer deposits could also be included within this category. They include tin, gold, diamonds, platinum, chromite, iron sands, titanium minerals, zircon, monazite, glass and foundry sands, and other resistant or heavy minerals which may have importance in the continental shelf areas where rivers empty or once emptied into the sea. Placer deposits of potential economic importance are likely to be restricted to the inner edge of the shelf, where the high unit-value minerals such as tin, gold and diamonds generally occur as irregular and localized concentrations whose distribution is controlled to a large extent by topographic considerations. Although the continental slope areas may be well supplied with important construction materials such as sand, gravel and lime shells, there appears little need to investigate them as long as the shallow water supplies now being exploited remain plentiful.

The most important surficial deposits are however the chemical precipitates - for example, phosphorite being deposited on the shelf, slope and ocean floor, and the manganese nodules found mostly on the abyssal sea floor.

Phosphorite occurs on the sea floor in the form of blankets of nodules, flat slabs, sand-sized pellets and rock-coatings. Although known in very deep water, phosphorite is more commonly confined to water depths of twenty to 200 fathoms in the slow depositional environment on the outer continental shelves, upper portions of continental slopes and tops of submarine banks. Phosphatic strata contained in bedrock similar to the deposits of Tertiary Age being mined onshore, may also crop out on the sea floor of the shelf or slope. In view of the potential importance of the widespread phosphorite deposits, they will be discussed later in more detail.

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The known deep-sea (pelagic) mineral-bearing materials of potential economic importance are also surficial sediments or nodules, such as manganese nodules and crusts, red clay, siliceous ooze, calcareous ooze etc. They are formed by the prevailing pelagic processes in various depth zones and regions of the deep sea environment.

Probably the most interesting, especially from an economic standpoint, are the manganese nodules widely distributed in the Pacific, Atlantic, and Indian Oceans. They are black to brown coloured hydrous manganese dioxide concretions containing small amounts of copper, nickel, cobalt, molybdenum, vanadium, zinc, and many other metallic elements. Manganese nodules occur abundantly on the abyssal sea floor and also on the lower portions of the continental slope, mostly in water depths from 200 to 4,000 fathoms. They are thought to be formed by colloidal precipitation of manganese from sea water in areas of extremely slow deposition, thus they are not commonly found in shallow water areas. They will also be treated later in greater detail.

Unconsolidated surficial sediments on the ocean floor, such as red clays, calcareous oozes, and siliceous oozes, all contain some potentially useful constituents, but are not today considered as economic deposits. The red clays are very fine grained pelagic sediments, covering about 100 million sq. km. of the ocean floor. Typically they contain about 20 per cent Al_2O_3, 13 per cent Fe_2O_3, 1 to 3 per cent Mn, 0.2 per cent Cu, and minor amounts of cobalt, nickel, lead, molybdenum, vanadium, zirconium, and other rare earth elements. They occur at an average water depth of about 2,920 fathoms but exist in their purest form at depths below 4,500 fathoms. It is estimated that about 10,000 million million tons of red clays exist in the world's oceans (Mero, 1967). In the Pacific, red clays are distributed over one half of the abyssal ocean floor.

Calcareous oozes are composed mainly of minute calcareous skeletons of Protozoa, covering some 128 million sq. km of the ocean floor. They occur most commonly in water less than 2,000 fathoms, and rarely at depth exceeding 3,300 fathoms. In some areas they contain as much as 95 per cent $CaCO_3$ and are similar in composition to certain limestones being mined on land. It is estimated that about 10,000 million million tons of calcareous oozes exist on the ocean floor.

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Siliceous oozes, consisting largely of skeletal remains of diatoms (planktonic plant life) and Radiolaria (planktonic animal life), cover some 38 million sq. km of the ocean floor at average depth of about 2,000 to 2,900 fathoms. It is estimated that about 10,000 million million tons of these oozes can be found in the oceans (Mero, 1967). One type of siliceous ooze - diatom ooze - occurs most abundantly in the two wide belts in the far northern and far southern Pacific Ocean at about 50° N and 50° S. In its purer forms, the diatom ooze is white or cream coloured, with characteristics comparable to the diatomaceous earth now exploited on land and used for heat and sound insulators, filtering and dusting products, light-weight concretes and other industrial applications.

Glauconite or "green sand" is a hydrous potassium-iron-silicate mineral with potash content varying from 2.5 to 8.5 per cent, which occurs in both ancient and recent marine sediments. Glauconite mined from land areas has supplied for more than a hundred years the market for water softeners and soil conditioners. In the marine environment, the mineral forms most abundantly in areas of slow detrital deposition in the outer continental shelf and upper portions of continental slope, occasionally also near-shore. Glauconite-rich samples have been taken from many sea-floor locations off the coasts of North America, South America, Africa, Australia, New Zealand, Scotland, Portugal, Japan, the Philippines etc. Most of the marine glauconite deposits lie in waters between 100 to 400 fathoms, although deeper water occurrences are not uncommon.

Another type of surficial material is barite, a barium sulphate mineral, which occurs as nodular concretions at scattered locations on the continental shelf and slope. Barite concretions have been dredged off the coasts of Ceylon and southern California and off the Kai Islands in Indonesia. Their concentration and grade do not however match those of land deposits which have been mined for use as drilling mud additives, in manufacture of barium chemicals and in the processing of sugar. It appears unlikely that extensive deposits of barite will be found on the ocean floor.

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Mineral concentration within the water of the sea

It is not proposed to deal here with those resources such as salt, magnesium, bromine, and fresh water itself which are extracted economically from sea water near to shore in certain parts of the world and unlikely to be exploited beyond the continental shelf. Attention must however be drawn to the possibility of local metal concentrations in the ocean environment which may have economic importance in the future. Apparently a method of extracting uranium from sea water has been developed[6/] which could be competitive with low grade uranium ores, while gold concentrations in sea water have been analysed as high as almost 60 mg per ton,[7/] which would constitute a relatively high grade gold prospect if contained in a sufficient body of water. More recently attention has been focused on the "hot spots" located at the bottom of the Red Sea, where bodies of stagnant or semi-stagnant waters have been found to contain zinc, copper, and other mineral constituents in concentrations ranging from 1,000 to 50,000 times that of normal sea water. The location, blocking out and developing exploitation techniques for such sea water "deposits" may be of importance in the years ahead.

B. Deep-water petroleum resources

Oil and gas dominate the history of profitable mineral development on the continental shelf off the coasts of many countries, and the list of successes has been growing rapidly with new offshore petroleum discoveries being made every year. Recently there have been potentially important discoveries from the shelves off the United States of America, Mexico, Venezuela, Peru, Chile, Trinidad, Brazil, Nigeria, Gabon, Cabinda, United Arab Republic, Libya, Iran, Saudi Arabia, the United Kingdom, Italy, the Union of Soviet Socialist Republics, Japan, Brunei, Australia, and other countries (Hedberg, 1967). Although offshore petroleum is still in an early stage of development, 16 per cent of the world's

6/ By the National Physical Laboratory of Great Britain.

7/ Average gold content in sea water has been estimated at about 0.04 mg per ton (F. Haber, 1927).

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total oil production (over 5 million barrels per day) and 6 per cent of the world's natural gas production come from offshore wells.8/

Origin of offshore petroleum

The origin of offshore petroleum and the factors controlling its distribution in sedimentary basins in the shelf and the slope are no different from those applying to sedimentary basins on land.9/

From the viewpoint of genesis and accumulation of hydrocarbons, the most important aspects are petroleum source beds with abundant organic matter, reservoir rocks, structural and stratigraphic traps, and geological history, particularly sedimentation and structural development. Organic matter growing near the ocean surface is partially transformed through ingestion by small and large marine organisms in the complex food webs of the sea. After death, the organic remains are transformed by bacteria and eventually buried deep beneath detrital and biogenic sediments where hydrocarbons are generated by further diagenesis of the organic matter.

Under suitable geological conditions, these petroleum hydrocarbons migrate into structural or stratigraphic traps from which oil and gas may be released to the earth's surface through natural seepages or commercial exploitation by drilling

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8/ About two thirds of current offshore production comes from Venezuela, the Persian Gulf and the Gulf of Mexico. The remainder is from widely scattered shelf areas in Africa, Asia, South and Central America and the western coast of the United States of America (California and Alaska). Over 240,000 barrels per day are produced from the Caspian Sea in the Union of Soviet Socialist Republics. In the Gulf of Mexico, more than 220 oil and gas fields have already been discovered in the shelf area off Louisiana and Texas, and more than $7 billion worth of petroleum has already been produced.

9/ Of the many types of oil-bearing sedimentary basin, the richest petroleum accumulations occur only in those mobile geosynclines and stable basins that were characterized by rapid subsidence and rapid deposition during the geologic past, resulting in great thickness of sediments being formed. Some of the richest deposits, now partially under water are located in semi-closed basins developed at the continental margins by geosynclinal subsidence (e.g. the Persian Gulf and Venezuela's Lake Maracaibo) or by block faulting, (Gulf of Suez, Red Sea, and the basins of Southern California (Weeks, 1948)). A number of the open-sea basins developed in the mobile belts at continental margins are also very rich in petroleum (the Gulf Coasts of the United States of America and Mexico and the Nigeria delta province).

of wells. Occasionally, under special conditions, biochemical alteration of the organic matter also causes the dissolved sulphates in the associates brines to be concerted into elemental sulphur and deposited in economic quantities at the tops of salt domes.

The geological and geophysical investigation of continental margins is still in its earliest stage with efforts to date mostly concentrated in a few areas off southern California, the Gulf and Atlantic coasts of the United States of America, and Western Europe. As a whole, the geology of the continental shelves of the world has been little investigated and is poorly understood. The state of knowledge is even more meagre on the continental slopes and the continental rises which constitute a zone of transition between the continents and the ocean basins. Hence the petroleum potential of these deep-water regions can only be evaluated tentatively on the basis of the factors governing petroleum genesis.

Petroleum possibilities in the continental shelf

Most offshore production to date is from the seaward extensions of known onshore petroleum areas such as Lake Maracaibo, southern California, and the Persian Gulf. Some reservoirs are partly beneath the water and partly under land. Another group of petroleum accumulations in the shelf are in structural and stratigraphic traps which are separate from but have a distribution pattern related to similar structures previously discovered on land (Emery, 1965).[10/]

Preliminary geological investigation indicates that in many cases potentially favourable sedimentary basins extend from the inner shelf to the shelf edge and beyond, and that the stratigraphic and structural features present in the outer shelf are essentially the same as those nearshore. The next step in exploration will probably therefore be to seek the deep-water extensions of known producing structures on the inner shelf and adjacent land, and identify structural conditions and features such as salt domes which are known to be favourable in similar structures previously discovered on or nearer land. Such outer shelf (and upper

10/ For example, the East Wilmington Field, a single giant reservoir along and off the coast of Los Angeles, California, still holds 1,20C million barrels after having produced more than 350 million barrels. Examples are the oil-bearing salt domes off Louisiana and Texas and numerous unknown structures that have been identified in the slope and beyond as possible salt domes (Ewing and Antoine, 1966, and Murray, 1966).

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slope) areas probably contain as large quantities of petroleum resources as the near shore fields. In addition, types of folding and faulting known to occur in the outer shelf and upper slope, raise the possibility of petroleum accumulation in traps which are unique to this environment (Emery, 1965). However, the petroleum potential of the outer shelf has been little investigated, except off southern and central California, Oregon in the United States of America, Nigeria and in the Gulf of Mexico. The deep-water regions have so far received scant attention from the petroleum industry, because of technological and economic limitations and lack of geological knowledge but it must be expected that with technological advances the exploration possibilities of the outer shelf and upper slope will assume greater importance.

Petroleum possibilities in the continental slope

Unlike the continental shelf and its outer edge, the petroleum possibilities of the slope are almost completely unknown. In a geological sense, the slope is unique in that it marks the rather abrupt transition from continental or sialic crust to oceanic or simatic crust. The known geological conditions of the outer shelf and shelf edge cannot therefore be extended hypothetically to this deep water regime.

Nevertheless, it is well recognized that petroleum accumulations often occur along more than one side of a petroliferous sedimentary basin, and these basin margins are considered to be most favourable prospecting areas. When petroleum accumulations are located at one edge of such a basin in the inner shelf or adjacent land, the geology and petroleum possibilities of the other (unknown) edge(s) of the basin further offshore in deeper water obviously merit investigation (Hedberg, 1967). There is some evidence to indicate that the outer portions of many "open-sea type" sedimentary basins, particularly coastal Tertiary basins such as those along and off the Gulf coast of the United States of America and Mexico, and the Nigeria delta province, are in fact not unfavourable for petroleum accumulation.

The occurrence of petroleum source beds in the slope appears very likely. The sediments in the slope are finer grained and contain more organic matter than those of the shelf and their organic content commonly reaches a peak because of slow detrital deposition and the oxygen-deficient bottom waters favouring organic preservation (Emery, 1965).

Since 1965, petroleum companies have initiated co-operative projects of a limited nature for geophysical reconnaissance and drilling of shallow core-holes in the shelf edge and the slope off the Atlantic and Gulf coasts of the United States of America, in waters as deep as 1,500 metres. Although preliminary results indicate that there might be less reservoir beds in the slope, it is known that turbidite sands (mostly coarse-grained well sorted arkosic or calcareous sands), which could be favourable, are widely distributed by turbidity currents in slope areas and beyond. Structural highs which might provide traps are commonly present in the upper slope (Hedberg, 1967). Moreover, the sedimentary strata commonly thicken just below the shelf edge and the upper slope, becoming gradually thinner again further down slope. This situation increases the likelihood of stratigraphic traps being developed in the slope. If suitable reservoir beds and structural or stratigraphic traps exist under the slope, petroleum accumulations seem assured (Hedberg, 1967).

The kinds of structures found in the shelf areas may also be expected beneath the slope (Emery, 1965).[11/] It has been suggested that the permeable layers in oceanward-inclined sedimentary strata might constitute ideal conduits for the updip migration of hydrocarbons to suitable traps in the slope and shelf, that might have been developed by structural movements and sedimentary processes (Hedberg, 1967). Furthermore, the petroleum possibilities are supported by many favourable indications, such as the oil seeps found in the slope areas (Pepper, 1958) and numerous structures suggestive of salt domes occurring in these regions (Ewing and Antoine, 1966).

The slope sediments and their organic content are of deeper water origin than those of most known petroliferous areas in the shelves and their content of terrigenous organic matter must in general be smaller. Whether or not these differences have effected the generation of petroleum is unknown and needs extensive study. However, if organic matter in the slope sediments is derived mainly from marine planktons, the source beds might not differ greatly in character from those of the shelf (Hedberg, 1967).

11/ Some of the folds, faults, unconformities and lenses developed contemporaneously with the deposition of wedges of sediment are judged as more favourable than those developed after the deposition.

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Of the sedimentary areas now under deep water, at least a few types of continental-margin basins that were downfolded or down-faulted from pre-existing shelves by major tectonic disturbance, appear to have good petroleum potential.12/ Large-scale geological and geophysical investigations during the next two or three decades will furnish more precise knowledge on the petroleum potentials in the slopes.13/ As on land, prospecting on the sea floor, will be most effective when it can be based on an adequate understanding of the geology for which accurate geological maps are necessary.

More detailed geological and geophysical investigations are a major task facing the petroleum industry. It has been estimated that only 7 per cent of the world's prospecting shelf areas have been adequately covered by detailed seismic surveys.

Knowledge of the configuration of the ocean floor has greatly increased in the past two decades, yet the cartography of the oceans has not reached the stage of that of the land 200 years ago (Weeks, 1967). Even at a chart scale of 1:1,000,000, only 2 to 20 per cent of the sea area is adequately covered. Availability of more detailed bathymetric charts is a prerequisite of efficient offshore geological mapping and mineral prospecting.14/

12/ The petroliferous basins off southern California are a good example of a relatively deep-water region complexly broken by block-faulting and strike-slip faulting. Geological and geophysical investigations of the deep-water areas off California and Oregon have been continued for several years, and preliminary drilling in more than 182 metres (600 ft.) of water will soon begin.

13/ A long-term programme is now being initiated by the United States Geological survey for systematic geological and geophysical mapping of the continental margins of the United States of America, initially at scale 1:1,000,000 and later at scales of 1:250,000 and 1:125,000. This will extend the traditional map-making function of governmental agencies from land to the shelf and slope areas and beyond. The information will be made available to industrial corporations in order to encourage their intensive exploration and investment of marine resources.

14/ The United States Coast and Geodetic Survey has recently completed a series of detailed charts at the scale of 1:125,000 covering the region off the north-eastern United States. Bathymetric surveys of other shelf and slope areas are in progress.

Petroleum possibilities in the continental rise

A feature of great interest to petroleum geologists is the "continental rise", that apron of clastic sediments which, wherever deep sea trenches are absent, slopes gently oceanward from the base of the continental slope, usually in 2,000 to 5,000 metres of water. Typically, it is a broad uniform, gently sloping and smooth-surfaced wedge of sediments, from 100 to 1,000 km wide and up to 10 km thick (Heezen, 1966). Continental rises are particularly strongly developed adjacent to large deltas such as those of the Indus, Brahmaputra-Ganges, Amazon, Zambezi, Congo, and Mississippi (Smith and Menard, 1966). The surficial sediments of the rise are commonly low in organic content because of the oxidation conditions in the very slowly deposited hemipelagic sediments (Emery, 1965). However, organic rich sediments from the bottom portions of the slope may periodically slide down to form long scars and lobes near to the top of the rise (Emery, 1965). Speculation is that these slides might constitute source beds and that reservoir sands, possibly deposited by turbidity currents, might under favourable conditions form stratigraphic traps (Hedberg, 1967). It is theoretically conceivable that diagenesis of organic matter in the rise, as elsewhere, may release hydrocarbons (Emery, 1965), but the question of their generation, preservation and concentration in the rise requires and warrants intensive study. It is not possible at present to say that the rise does not contain petroleum accumulations. However, one unfavourable factor is the probable lack of drive for migration and entrapment of hydrocarbons (McKelvey, 1966). Most continental rises are located in tectonically stable belts, although recent geophysical reconnaissance has indicated in them some features which may be folds.

C. Submarine phosphorite

Phosphorite, a complex calcium phosphate rock, has long been used as a source of phosphate for fertilizer and chemicals. The principal mineral constituent is carbonate fluorapatite, which contains some fluorine and minute but important quantities of uranium and rare earth elements bound up in the crystal lattice. On land, high grade phosphate deposits are not widely distributed and it is estimated that approximately two thirds of the world total production comes from Florida, the United States of America and the North African deposits in Tunisia, Algeria, and Morocco. The remainder is produced in the Middle Eastern countries of the United Arab Republic, Jordan and Israel, from newly developed deposits in Senegal, Togo and South Africa, from the guano deposits of the Ocean Islands (Makatea, Nauru) in the Pacific and Christmas Island in the Indian Ocean, from the western United States of America (Idaho) and a few small deposits in the Union of Soviet Socialist Republics and Brazil (Sweeney et al., 1963).

Submarine phosphorite was first discovered in samples dredged from the Agulhas Bank off South Africa by the Challenger Expedition in 1873. A sample taken still earlier in 1863 off the coast of Morocco awaited sixty years before being identified as phosphorite (Murray et al., 1924). In 1937 phosphorite nodules were found in samples from the tops of submarine banks off southern California. Subsequently, oceanographic expeditions have dredged phosphorite nodules from many scattered localities, mostly in the outer shelf and upper slope areas characterized by non-depositional environment, and on the tops and sides of submarine banks. However, all the earlier studies were mainly scientific in nature, with intensive exploration for submarine phosphorite deposits beginning much later. Only in the last few years has some preliminary prospecting work been started in areas off the coast of Baja California in Mexico, off southern California, and off Australia. To date there has been no commercial phosphorite production from the ocean floor.

Phosphorite found on the ocean floor is of four major types: phosphorite nodules, phosphatic sands, pelletal phosphatic muds, and consolidated phosphatic beds of Tertiary Age. Although in general the deposits are low-grade when compared with those now mined on land, submarine phosphorite and certain placers in the shelf areas have in the last few years attracted more attention from the mineral industry and are considered most promising possibilities for exploitation. Whether or not submarine phosphorite can now be mined economically in competition with land deposits may be debatable, but for certain coastal countries that do not have land deposits, those offshore should prove valuable. Chile and India, as examples, apparently have rather poor prospects for land deposits but good hopes of submarine phosphorite deposits. Even in the case of a high-grade phosphate deposit located remotely inland in a developing country, exploitation may not be economically justified because of the investment necessary for construction of roads and other facilities. History points out clearly that nations develop first along their sea coasts and river systems.

Phosphorite deposition by upwelling

Deposition of phosphorite on the sea floor depends on the rapid precipitation of phosphate from sea water without much dilution by detrital sediments. Phosphorite commonly forms in regions where deep cold waters rich in dissolved phosphate and other nutrient salts are brought in large volumes to shallow depth by vigorous upwelling (Kazakov, 1937; McKelvey, 1963, 1966; Sheldon, 1964). The ensuing precipitation of phosphorite, probably inorganically or biochemically, on the submarine banks and shallow shelf areas is due to the release of dissolved carbon dioxide and increasing pH of the water, which are caused by decrease in depth and pressure, increase in temperature and/or mixing with warm surface waters. Waters at intermediate depth, from 100 to 500 metres, generally have the highest concentration of dissolved phosphate, as much as 300 to 600 mg P_2O_5 per cubic metre. These waters are low in oxygen and rich in fluorine, calcium, and carbon dioxide. Besides that in rivers that empty into oceans, dissolved phosphate and associated constituents are derived from decay of animal and plant remains and from sediments on the sea floor.

The cold phosphate-rich waters are brought to the surface in four ways: upwelling caused by divergence, dynamically-caused upwelling, turbulent mixing of two currents, and mixing as a result of winter cooling (McKelvey, 1965).

Nearly all the known phosphorite on the present sea floor lies in areas of divergent upwelling, where a current diverges from a coast and the seaward movement of coastal waters brings up phosphate-rich subsurface waters to replace it.

Strong upwelling caused by current divergence generally occurs in places off the west coasts of continents in the trade-wind belt, at latitudes below about 40° N. The upwelling appears to be associated with eastern boundary currents, flowing towards the equator, but sometimes it also occurs in divergencies of the equatorial current system (Van Andel, 1965). It may also take place off the north coasts of continents in the northern hemisphere, and off the south coasts of continents in the southern hemisphere (McKelvey et al., 1953).

The presence of cold upwelling waters often produces coastal fogs and humid air deserts, with some hygrophytic vegetation but little or no rain. The Peruvian and southwest African deserts are examples. In these conditions, characteristic low rainfall and absence of large rivers on adjacent land favours the deposition of phosphorite because the rate of sedimentation is not great. Further decrease in the rate of detrital sedimentation is caused by topographic isolation from sediment sources by offshore banks, as for example off southern California. The nutrient-rich upwelling waters support tremendous quantities of organisms, with phytoplanktons at one end of the food chain, and fish, whales and fish-eating sea-fowl at the other. Such abundance of organic matter and reducing conditions in the bottom sediments are often associated with phosphorite deposition.

Dynamically-caused upwelling or forcible upwelling takes place when a subsurface water current is forced up over a very shallow shelf area; this usually occurs off the east coasts of continents along the edge of poleward moving warm currents. The phosphorite deposits related to dynamic upwelling are generally of lower grade than those associated with divergent upwelling, and they are not associated with organic or siliceous sediments. Although large deposits of this type were formed in the ancient oceans - the phosphate deposits of Miocene age in the south-eastern United States of America and Recife, Brazil, for example - they are not widespread on the present ocean floor.

Nutrient-rich waters are sometimes brought to surface by turbulent mixing at the boundary between two distinct water masses, or by mixing as a result of winter-cooling, particularly in high latitudes where highly saline waters coming from the tropics tend to sink. These occurrences are on smaller scales and therefore not as important in phosphorite deposition as divergent upwelling.

Knowledge of phosphorite deposition, the related processes involved in its origin and the types of associated sediments, applied successfully to the search for phosphate on land in several developing countries (Sheldon, 1964b), are now being used in marine prospecting off Australia and off Baja California in Mexico. Areas of strong upwelling, particularly those off the west coasts of the continents, are apparently the best prospecting targets, whether or not phosphorite has previously been found on the sea floor.

Although most of the prominent upwelling areas have probably already been identified, more oceanographic research is needed to obtain detailed knowledge of water circulation and associated physical, chemical, and biological processes, all of which will be particularly useful in the early phases of marine phosphate exploration.

Regional distribution of phosphorite nodules

Nodular phosphorite, the most common form found on the ocean floor, includes nodules, flat slabs, irregular masses, and coatings on rocks, which occur either scattered or as extensive blankets. The nodules are hard, dense (specific gravity 2.62), vary in colour from light brown to black with smooth glazed surfaces and black manganese coatings, and range in size from small pebbles to more than 80 cm in length and 75 kg in weight. The smaller nodules are usually pure phosphorite; larger ones may be conglomeratic and include rock fragments of smaller phosphorite nodules. Nodules from a particular area generally have similar characteristics, especially in colour and size.

Water depth appears to exert little, if any, control on nodule formation. Although occurrences in water as deep as 1,900 fathoms are known, water depths of 20 to 200 fathoms in the slow depositional environment of the outer continental shelves, upper continental slopes, and tops of submarine banks and ridges are more common.

Off southern California (United States of America) and Baja California (Mexico), upwelling occurs in many areas during the spring and summer, nodules have been found from within a km from land up to 375 km out into the Pacific Ocean, mostly in waters less than 300 fathoms, with the deepest sample from 1,400 fathoms at the base of the continental slope. In the northern portion of the continental margin off southern California, scientific investigations related to phosphorite have been in progress for thirty years and it is estimated that nodules probably cover about 10 per cent of the total area of 93,000 sq. km (36,000 square miles), with more than ten areas of phosphorite occurrences being

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suggested as prospecting targets.[15/] Although appreciable accumulations of phosphorite nodule are found in topographic depressions on submarine banks, their exact thickness cannot fully be determined by the methods of dredging and underwater photography currently used. Better techniques must therefore be developed for delineation of the deposits and estimation of reserves. A tentative estimate of about 1,000 million tons of nodules has been made, of which not more than 100 million tons will possibly be of economic grade (Mero, 1967). Other studies indicate that probably not more than 50 million tons of nodules in several selected areas would deserve further investigations. In any event, present recovery costs will favour investigations in not more than 50 fathoms of water, at least for the immediate future.

Most of the selected better nodules dredged off California contain about 22 to 29 per cent P_2O_5 but the average agglomerated impure nodules are of much lower grade. By comparison, the P_2O_5 content of most of the phosphate deposits being mined on land is 31 to 36 per cent.[16/] Assuming that most of the other constituents can be separated by some conventional method of beneficiation and the phosphate can be further upgraded by calcination, the finished product grade after processing would still probably average only 31 to 33 per cent P_2O_5, which is a low grade product.[17/] The implication is that all submarine phosphorite

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15/ The occurrence of phosphorite nodules was first discovered in 1937 off the coast of southern California. Since then they have been dredged in more than 200 locations along 2,000 km of coastline extending from Point Reyes, just north of San Francisco, to the southern end of Baja California. In the last few years, the ocean mining industry has been paying more attention to a few specific targets, particularly the Coronado Bank (about 16 km west of San Diego in 10 to 200 fathoms of water) and the Thirty Mile Bank and Forty Mile Bank (about 50 to 60 km west of San Diego in 50 to 250 fathoms of water). Phosphorite nodules have been found on submarine banks off Baja California, such as the Ranger Bank and others between 28° S and 29° S, where phosphatic sands are of more common occurrence.

16/ This somewhat higher P_2O_5 content of many land deposits generally seems to be due to enrichment by prolonged weathering and other geological processes. It appears that the best submarine nodular phosphorite will not be much higher than 30 per cent P_2O_5, which apparently corresponds to the "proto-ore" of land phosphate deposits before enrichment by weathering.

17/ The high ratio of metallic impurities to P_2O_5 is another factor making California submarine phosphorite poorer in quality than competitive phosphate rocks from land sources.

nodules off California, and elsewhere in the world, will probably require considerably more chemical upgrading and beneficiation to become competitive. The California submarine phosphorite deposits appear neither sufficiently concentrated nor sufficiently high in grade to warrant commercial exploitation at the present.[18/]

Phosphorite nodules have been found in many surface samples from the continental slope adjacent to the Atlantic coast of the United States of America (Emery, 1965). They occur most commonly east of Florida at depths of 200 to 500 metres on the slope leading down to the Blake Plateau. On the upper slope areas extending from the Blake Plateau northward to about 40° N (vicinity of New York City), phosphorite nodules are present but probably less abundant. Further to the northeast occurrences become very rare.

The nodules are mostly brown coloured, range up to 8 cm in diameter and are associated with glauconite and other impurities. The phosphate content of samples from the Blake Plateau is less than 20 per cent P_2O_5 (Agassiz, 1888), and many impure nodules contain not more than 13.5 per cent P_2O_5 (Trumbell, 1958). Preliminary work indicates a probable residual origin, derived from erosion of

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18/ Nevertheless, continued research has been undertaken in upgrading the low grade rocks for fertilizer manufacture. Future technological breakthroughs in beneficiation processes and efficient sea floor recovery systems would, no doubt, improve the economic potential. An important potential advantage is that exploitation to supply the local fertilizer market of the Pacific coast would not involve any expensive transportation. Shipping phosphate rock from Florida to California costs about $4.50 per ton; rail transportation of phosphate rock from Idaho is much higher, exceeding the value of ore at the mine.

Geological studies of samples dredged off California, including radioactive dating, indicate that some of the phosphorite nodules were formed in place during recent times, but the majority were probably derived from underlying phosphatic bedrock of Miocene age, mainly low-grade phosphatic shales which are sometimes found as rock outcrops on the sea floor. When eroded and broken loose, these phosphatic rock fragments may have served as nuclei for intermittent addition of phosphatic coatings (often with manganese oxide coatings). The phosphatic bedrock on the ocean floor appears to have no economic potential at present, even if deposits of sufficient grade and quantity could be found. The mining costs of consolidated rock are higher than those of unconsolidated material, even on land.

sea-floor outcrops of phosphatic strata that are probably similar to the Miocene and Pliocene phosphatic rocks being mined onshore.19/

Although low grade and the great water depth of phosphorite occurrences off the Atlantic coast are unfavourable factors, further exploration should be undertaken to determine quantity and quality of the phosphorite nodules and phosphatic strata, with the prospect of locating similar occurrences in shallower water.

There are several regions off the west coasts of South America, from about 5° to 40°S Lat., in which divergent upwelling is intense. Phosphorite nodules are known to occur on the sea floor off the coasts of Peru, northern Chile and in the region of the Galapagos Islands, but only a few occurrences have been recorded because few bottom samples have been taken. All evidence points to the regions off Peru, Chile, and between Ecuador and the Galapagos Islands being the most favourable sites within the Pacific for possible extensive deposits. This is particularly important to Chile, where the prospects of finding important phosphate deposits on land are not great. An exploration programme over the entire region may well reveal one of the most promising sources of low-grade phosphate for the future.

During the Challenger expedition, phosphorite nodules were dredged off the south-east coast of South America from two widely separated localities, one from the continental slope near the Falkland Islands and the other from the slope off Rio de la Plata, about 36° to 38°S Lat. Dynamically-caused upwelling takes place off the coast of Salvador province in Brazil (McKelvey, 1963), and upwelling waters in several other areas of the south-west Atlantic have been known for a long time. The shelf and slope areas off the south-east coast of Brazil, Uruguay, and Argentina appear to be the only ones in this region offering possibilities of submarine phosphorite.

Several phosphorite nodules containing 20 to 23 per cent P_2O_5 were dredged by the Challenger Expedition from the Agulhas Bank off South Africa, in depths of 150 to 1,900 fathoms. Later, the German Gazelle expedition and Valdivia expedition also recovered phosphorite nodules. The work of the oceanographic vessel Ob of the Union of Soviet Socialist Republics apparently produced results

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19/ Phosphorite nodules have also been taken from the Pourtalés Plateau in the Strait of Florida. The recovery of index fossils, combined with other evidence, indicates that the phosphorite nodules probably represent fragments eroded from outcrops of Miocene phosphatic strata. It appears very likely that little or no phosphorite is being deposited under the ocean conditions now prevailing in the area.

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not too encouraging for phosphate potential - P_2O_5 content was noted as less than 25 per cent in all the samples, the phosphorite occurring mixed with glauconite sands and limited to a small area on the upper slope of the bank. Despite all that has been written about the Agulhas Bank, long known for its phosphorite nodules and as an area of upwelling and high organic productivity, the possibility of extensive commercial-grade phosphorite has not yet been established. Nevertheless, the oceanographic conditions of the area satisfy the environmental criteria for phosphorite deposition. More systematic investigations are needed.

Phosphorite nodules are known in certain continental slope areas off North-west Africa and Equatorial West Africa. Occurrences have been recorded off the Morocco coast and the Guinea coast, but they are few because the region has not been sampled extensively. In general, oceanographic conditions along the entire coast appear favourable with intense upwelling, high phosphate content and high organic productivity in the water off the Guinea coast long being recognized. Divergent upwelling also occurs off the coast of Ghana, at approximately 5° N. Less is known of the waters off north-west Africa, but preliminary data suggests that upwelling should occur at places along the coast from the Straits of Gibraltar to Senegal, and particularly off Morocco.

In addition, the shelf areas off the mouths of several large rivers such as the Niger and the Congo, and many smaller rivers which enter the sea on the west coast of Equatorial Africa may have possibilities for phosphatic muds. These rivers drain large areas covered by phosphate - rich lateritic soils and characterized by high rainfall - conditions always associated with offshore phosphatic mud deposits.

Although the submarine possibilities in this region are very good, there appears to be no immediate need to explore them because of the very large reserves of high-grade phosphate ore available in adjacent land areas.

Upwelling is known off the coasts of East Africa in the Indian Ocean along the Somalia Coast (Sverdrup *et al.*, 1942), off Cape Guardafui at the eastern tip of the Horn of Africa and eastwards along the coast of Arabia (Bobzin, 1921). Within the Red Sea, dynamically caused upwelling is very active during the summer and winter (Thompson, 1939). Although submarine phosphorite has never been reported from either the Red Sea or the Indian Ocean coast, the bottom sediment

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characteristics of the outer shelf and slope areas have not been fully investigated and it is not unexpected that occurrences will come to light during future investigations.

Upwelling occurs over several wide areas of the continental shelf and slope off northern and north-western Australia. It has been noted in the Timor Sea between Australia and Timor and in the eastern Arafura Sea, extending from the Aroe Islands off New Guinea to the Gulf of Carpentaria. A minor zone of upwelling occurs along the south coast of Papua, and possibly in the Coral Sea and the Tasman Sea. Western Australia is another area in which upwelling is known to take place.

A few phosphorite nodules have been recovered from the shelf off the northern coast of New South Wales, but they are ferruginous and of low grade. Bottom sediments containing anomalous phosphate content have also been found at localities along the coast of New South Wales, on the west coast north of 25° S, and on the Arafura shelf. However, most of the shelf and slope areas are unsampled, and submarine phosphorite potential cannot therefore be assessed. Preliminary data suggest that prospecting for submarine phosphorite is justified on the shelf and slope areas all around the continent, except possibly off southern Australia. Over the last few years, vast areas of the Australian shelf have in fact been taken up in exploration concessions for phosphorite and placer minerals. The most favourable prospecting targets include the banks off north-western Australia, the banks in the south west Pacific near the Solomon and Bismarck Islands, and the banks and platforms on the seaward side of the Great Barrier Reef and in the Coral Sea (Van Andel, 1965).

Phosphate-rich waters are known to exist off the Japanese coasts, over the upper continental slope near Tokyo (Graham et al., 1944). They extend to the south-west of the Japanese Islands in an area dominated by a series of submarine banks and ridges, some of which are similar to those off southern California. It is probable that phosphorite nodules will be found on these banks, with the likelihood of contamination by basaltic, andesitic and other volcanic rock material characterizing the region.

Other potential areas may also be mentioned. Upwelling waters off Vancouver Island, on Canada's Pacific coast have long been known as being rich in phosphate (Tully, 1937). Other areas of upwelling are reported in the Irish Sea off the

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southeastern coast of Ireland (Cooper, 1960), and off the coast of Venezuela. Upwelling may also occur in the Banda Sea (eastern part of the Indonesian archipelago) and in the Indian Ocean off the Java coast. Although submarine phosphorite has never been reported from any of the above, the sea floor has been little sampled and there are good possibilities that phosphorite will be found in some of these areas. Phosphorite nodules have recently been found off North Andaman Island in the Indian Ocean; distribution in this area and possibly around other islands in the Indian Ocean has not been fully investigated.

Phosphatic sand occurrences

The phosphorite nodules found on the tops of submarine banks west of Baja California, Mexico, are essentially identical in composition to those occurring off southern California (Imery and Dietz, 1950); there has therefore been little interest in their exploration and possible exploitation. However, unconsolidated fine-grained deposits of phosphatic sands occur widely in the shelf areas and they have been investigated in recent years by both oceanographic institutions and mining companies. Shallow water depth, unconsolidated nature and virtually no overburden, are factors favouring exploitation.[20/] The P_2O_5 content of these phosphatic sands varies from a few per cent to more than 10 per cent.[21/]

Sea-floor phosphatic sands of somewhat higher grade cover an area about 24 by 32 km in the vicinity of 26° N Lat. and 112°30' W Long., some 24 km off the coast of southern Baja California. Generally occurring in 50 to 130 metres of

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20/ In 1966, a newly organized company, obtained an exploration concession covering about 70,000 square kilometres of the sea floor along the entire west coast of Baja California and around its southern tip up to about La Paz on the eastern side of the peninsula.

21/ The phosphate material is dominantly contained in sand-sized pellets and oolites, mostly about 0.1 to 0.3 mm in diameter, possibly including some phosphatized foraminifera tests, shell fragments and fecal pellets. The non-phosphatic constituents are largely clay-sized and silt-sized sediments and calcium carbonate material. Most of the phosphatic oolites and pellets were probably formed in the warm, saline, phosphate-rich shallow waters by intermittent precipitation of phosphate around sand nuclei being continuously reworked by currents and waves. Some of the phosphatic sand grains could also have been eroded from the Miocene phosphatic beds exposed on the sea floor.

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water, these sands contain 15 to 40 per cent apatite grains (d'Angeljan, 1964), equivalent to about 4.5 to 12 per cent P_2O_5. It has been estimated that about 2,000 million tons of phosphate material may be contained in this deposit (Mero, 1967) but it has not been determined which patches, if any, may have immediate economic potential.22/ In general, there is some doubt that these and other similar deposits can be exploited economically in open competition with land sources. Future breakthrough in beneficiation processes is also likely to bring vast low-grade deposits on land into competition with submarine phosphate sources. Nevertheless, the exploitation of submarine phosphorite will most likely be a sound economic venture for those seaboard nations, such as Chile, India and Mexico, whose domestic phosphate sources are insufficient or lacking.

In addition to offshore phosphatic sands, low-grade phosphatic sands also occur abundantly as thin beds in the beach and backshore sediments along the Baja California coast, particularly in the vicinity of the Santo Domingo lagoons. The sands generally contain 1 to 6 per cent P_2O_5 with an average about 3.6 per cent P_2O_5, and occasionally up to 12 per cent P_2O_5 in certain rich layers. It appears likely that the onshore sands contain as large a quantity of phosphate material as the offshore deposits, but beneficiation and processing may be even more difficult, because the onshore phosphatic oolites and pellets contain more quartz and other mineral inclusions than the offshore material.

In 1966, phosphatic sands were found to occur in the shallow shelf area off Cape Fear, North Carolina, United States of America (Pilkey et al., 1966), where a relatively high phosphate concentration (1 to 8 per cent P_2O_5) occupies an elongate area about 16 km long and 5 km wide below 20 to 30 metres of water. The phosphate sand grains are usually smaller than the accompanying non-phosphatic minerals and shell fragments. Whereas the Baja California phosphatic pellets and

22/ At present, the possibility of profitable exploitation depends upon the costs of ocean-floor dredging, and of beneficiation and processing. While the associated silt and clay-sized impurities can readily be separate, the quartz and other mineral inclusions within the phosphatic pellets and oolites present a difficult beneficiation problem. Sands with considerable amounts of carbonate minerals may not be easy to separate. Research on new beneficiation processes is continuing and if some of the phosphatic sands prove to be economically exploitable, this material could easily dominate the local market in Mexico. A major advantage is lower transportation costs which facilitate competition with world sources in the local market. Today Mexico's fertilizer needs depend largely on phosphatic rocks and other products imported from Florida. Even for trans-Pacific shipping to Japan, the Baja California material would have a $2.50 per ton freight advantage over Florida supplies.

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oolites are of mechanical agglomeration origin, the North Carolina sands are probably derived as a weathering concentrate from sea-floor outcrops of phosphatic limestone, apparently somewhat similar to the thick sequences of phosphatic sands being mined in adjacent land areas and beneath the Pamlico River estuary. As the latter contain 8 to 31 per cent P_2O_5, the submarine phosphatic sands off North Carolina are probably uneconomical.

Phosphatic mud occurrences

Phosphatic mudbanks are known in shallow waters off the south-west coast (Malabar) of India. Between monsoons, the mudbanks contain significant amounts of phosphate (Seshappa, 1953), with a few patches assaying 1 to 5 per cent P_2O_5 on a dry basis, together with some amounts of nitrate and potash; a composition comparable with certain fertilizer mixtures now in use. The highest P_2O_5 content sampled is 18 per cent. During the monsoon season, the bottom material is disturbed and the phosphate stirred up into the water.

These phosphatic mudbanks are probably related to the phosphate-rich lateritic soils on adjacent land areas characterized by high rainfall, where the soils are continuously being eroded and carried by rivers to the sea. Moderate upwelling takes place off the coast in the periods between monsoons and may be a contributory factor, but seaward transport of lateritic soils appears to predominate in the accumulation of these phosphatic muds. The presence of many rivers and a fairly rapid rate of detrital sedimentation make it probable that the inner and middle protions of the shelf have little or no phosphorite nodules, although these may form on the outer shelf and upper slope. Upwelling is also known off the south-east coast of India, but the muds there have a lower phosphate content than those off Malabar. Exploitation of the phosphatic muds is favoured by proximity to shore, shallow water occurrence, and the finely divided nature of the material which would facilitate pumping.23/

23/ The possibility of direct application of the raw phosphate material and its relative insolubility may be particularly advantageous in improving the local acid soils. A floating plant to prepare raw phosphate for direct application to the soil can be built with a small capital investment, and production could be fairly high or as low as a few tens of thousands of tons per year.

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Significant amounts of phosphate off the coast of south-east Australia were noted in a few bottom samples from the Bass Strait and in the estuaries of several rivers, such as the Tweed, Richmond, and Clarence (Rochfold, 1958) which drain a region covered by phosphate-rich soils. This may indicate the possibility of finding phosphate mudbanks in shallow water areas off the coast of south-east Australia. Upwelling may occur at times off this coast, from the eastern end of the Bass Strait to Sydney, and the occurrence of phosphorite nodules is also suspected, particularly in the eastern part of the Bass Strait.

D. Manganese nodules and crusts

World annual production of high-grade manganese ores for metallurgical and other uses is approximately 10 million metric tons, with a value of more than $400 million. The total known land reserves of commercial-grade manganese ore are estimated to be at least 1,000 million tons, with inferred figures several times higher. Most of the known reserves are in South Africa and the Union of Soviet Socialist Republics; however, Gabon, Ghana, Ivory Coast, Australia, Brazil, India, and China (mainland) also have large quantities of commercial manganese ore.

While the producing countries appear to have adequate reserves and capacity to take care of world demand well into the future, it may be noted that a few of the developed countries are almost totally deficient in manganese, as well as in nickel and cobalt. The United States of America, as an example, consumes more than 20 per cent of the world's total production of manganese ore, yet its domestic output is less than 1 per cent of the world's total. It is, moreover, possible that countries which are now developing industrially, may eventually require all of their domestic manganese production for local needs, in their own steel mills for example. Thus there are incentives for certain developed countries to consider the oceans as possible sources of manganese and other strategic materials.

The occurrence of manganese nodules on the deep sea floor was first reported by the Challenger Expedition of 1872-1876. Since then, more than 500 locations on the ocean floor have been recorded, not counting the additional hundreds of occurrences investigated in the last few years by the ocean mining companies.

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Although the nodules are known to exist in less than 200 fathoms of water, they occur most abundantly on the abyssal ocean floor and submarine ridges, and sometimes on lower parts of continental slopes, generally at depths from 400 to more than 3,500 fathoms. Those found at depths below 1,000 fathoms are comparatively low in manganese content but high in copper, cobalt, nickel and other metals, while the nodules in relatively shallow waters are somewhat higher in manganese but low in other constituents.

Physical and chemical characteristics

Most manganese nodules on the ocean floor are round, reniform, or spherical-shaped, with either smooth or knobby exteriors. They range in size from less than 1 cm to 20 cm, with an over-all average of about 5 cm. Occasionally, an agglomerate slab of manganese nodules may be as long as a metre; one of the largest recovered weighed some 750 kg. The nodules are generally light brown to earthy black in colour, friable, fairly soft, mostly porous, and have a specific gravity of 2.1 to 3.1. Internally, they usually show concentric growth layers, frequently around a nucleus such as a shark's tooth, whale's earbone, micrometeorite, red clay, grain of detrital minerals or fragment of pumice, basalt, or other rock.

Besides the nodules, other forms of manganese dioxide occurring on the ocean floor include grains or "micronodules", coatings on rocks and impregnations of porous materials. Small manganese dioxide sand grains, about 0.5 mm in diameter, are a common constituent of ocean bottom red clays and organic deep-sea oozes. The manganese encrustations on bedrock of sea mounts are usually about 2 cm thick but occasionally reach 10 cm or more.

The mineralogical composition of manganese nodules is usually a mixture of manganese-oxide minerals, goethite (amorphous iron hydroxide), clay minerals and minute amounts of other detrital minerals. The dominant manganese minerals in the nodules are identified as "delta-MnO_2" (birnessite) and todorokite, a hydrous manganese oxide. At least two other manganese dioxide minerals of major importance have been recognized which are not similar to any previously known mineral of this element. Various elements such as Na, Ca, Sr, Cu, Cd, Co, Ni, and Mo can substitute for Mn or Fe in the crystal structures of these manganese minerals.

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Chemical composition as well as physical characteristics of nodules vary considerably, not only from one location to another, but within a single nodule. Analyses of fifty-four nodules taken from the Pacific show that they contain 8.2 to 41.1 per cent Mn, 2.4 to 26.6 per cent Fe, 0.01 to 2.3 per cent Co, 0.1 to 2.0 per cent Ni, and 0.03 to 1.6 per cent Cu (Mero, 1965). The maximum assayed value of these, 41 per cent Mn, is less than that of the ferro-grade and battery-grade manganese ores from land sources. Nevertheless, manganese nodules have received considerable attention during recent years, and are being investigated by the mining industry from the viewpoint of low-grade ores of copper, cobalt, nickel and manganese, rather than for manganese alone.

Origin of manganese nodules

Like the other authigenic minerals, manganese nodules occur in areas of extremely slow deposition, in this case the abyssal depths of the oceans under oxidizing conditions. It is generally believed that the nodules are formed and continuously enlarged by precipitation of elements from solution, most likely in a colloidal form, and by a process of particle agglomeration. Goldberg and Arrhenius (1958) suggest that the ocean is saturated with respect to manganese and iron and that the addition of these two elements by river runoff causes precipitation of hydrated oxides in colloidal form. The colloidal particles are electrically charged and tend to act as scavengers and remove cobalt, nickel, copper, molybdenum, zinc, lead, and other metals from the sea water. Small particles of detrital minerals and organic debris settling through the water could act as centres of accretion, effective in extracting manganese, iron, and other metals from the sea water. When the colloidal particles reach the sea floor, they are attracted to any protruding objects, such as rock fragments, which would act as superior conductors in attracting the electrically charged colloidal particles. Through bottom currents carrying a new supply of colloids to the nucleus, the nodules are enlarged layer by layer, by a process of particle agglomeration. Photographs of the sea floor where manganese nodules are abundant show scour and ripple marks, indicating active bottom currents in such areas. Nodules can grow to appreciable sizes at locations where the rate of deposition of associated sediments is less than the rate of formation of the nodules. Once a nodule is buried in sea-floor sediments, it ceases to grow.

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The dominant agencies adding manganese to the ocean are probably river runoff, submarine volcanic eruptions and submarine springs; decomposition of sea-floor igneous outcrops and debris may also contribute. It is likely that the two sources of supply of manganese and associated elements - the continents and submarine volcanism - may be equally important. Depending on location, one type of process may predominate in furnishing manganese or iron for nodule formation.

A slow rate of growth of the nodules on the abyssal ocean floor is suggested by much observational data and by radiometric determinations. Accretion rate is probably of the order of 0.01 to 1.0 mm per 1,000 years. In contrast, the nodules occurring in continental slope areas with comparatively shallow water and close to continents, appear to form more rapidly, probably at the rate of 0.01 to 1.0 mm per year (Manheim, 1965). Evidence for such a high rate of accretion includes the formation of manganese crusts on unstable or recent materials. For example, a naval shell of the Second World War type, found in about 200 metres of water off San Diego, had a coating of iron-manganese oxides about 1.5 centimetres thick.

Regional distribution

Today our knowledge of the regional distribution of manganese nodules and crusts is essentially preliminary, based on a total of only several hundred samples taken from the world's oceans. Evidently, a great deal of exploration work is needed to outline the patterns of distribution and concentrations of manganese nodules on the ocean floor. Continued research on the origin and factors governing the deposition of nodules would help to indicate the favourable prospecting areas.

In the Pacific, manganese nodules and crusts are of common occurrence in the seamount region of the mid-Pacific, and on the deep-sea floor in the south-eastern and eastern Pacific. They are found at depths ranging from 57 fathoms on an insular shelf south of Honshu to about 3,800 fathoms in the Mariana Trench. At distances of more than 300 km from the continental landmass, there probably is no extensive area where manganese concretions, in one form or another, cannot be found. It is estimated that the Pacific Ocean may contain about 1,500 million tons of manganese nodules, which are being formed at an annual rate of about 10 million tons (Mero, 1967). In fact, many elements in the manganese nodules now forming on the Pacific Ocean floor are accumulating faster than they are being consumed; three times as fast in the case of manganese, twice so for cobalt, and equally fast in the case of nickel.

Nodules high in cobalt are most common in the mid-Pacific rise area, from which samples have assayed 31 per cent Mn, 2 per cent Co, and 0.8 per cent Ni (Mero, 1960C). This region of about 10 million sq. km lies west of Hawaii and includes the Society Islands of the South Pacific. Assuming a concentration of 4.8 kg/sq. metre (1 lb/sq. ft.), this region could contain about 57,000 million tons of nodules. These high-cobalt varieties are apparently associated with topographic highs in mid-ocean where water depth is less than 850 fathoms, the average depth of the remainder of the Pacific being 2,300 fathoms.

In the central portion of the south-eastern Pacific, the nodules tend to be high in nickel and copper content and may contain as much as 37 per cent Mn, 1.6 per cent Cu, 1.6 per cent Ni, and 0.3 per cent Co; average values are 27.4 per cent Mn, 0.2 per cent Co, 1.3 per cent Ni, and 1.1 per cent Cu. On the basis of photographs of the sea floor, this region is estimated to have a nodule concentration of 14 to 33 kg/sq. metre (3 to 7 lb/sq. ft.). Even taking distribution as only 4.8 kg/sq. metre (1 lb/sq. ft.), about 200,000 million tons of nodules (Mero, 1960b) may be calculated for the 36 million sq. km involved.

A belt in which the nodules are especially rich in manganese, but typically poorer in other metals is located about 500 to 800 km off the Pacific coasts of North and South America. Several samples collected in this region show an average grade of 48.8 per cent Mn, 0.04 per cent Co, 0.18 per cent Ni, and 0.2 per cent Cu. The area covers 5 million sq. km, with an assumed nodule concentration of 24 to 33 kg/sq. metre (5 to 7 lb/sq. ft.). Again calculated at only 4.8 kg/sq. metre (1 lb/sq. ft.), the potential amounts to about 26,000 million tons of nodules.

Low-grade manganese nodules occur in the north-eastern Pacific; the best sample showed only 20.7 per cent Mn, 0.3 per cent Co, 0.8 per cent Ni, and 0.6 per cent Cu, with the average 17.4 per cent Mn, 0.4 per cent Co, 0.7 per cent Ni, and 0.5 per cent Cu (Mero, 1960b). Nodules taken from the ocean floor in the south-eastern corner of the Pacific also appear to be of poor grade.

Manganese nodules are known on submarine banks in relatively shallow water off the south-east coast of Japan (Niino, 1959). They are probably associated with the manganese-rich springs entering the sea floor along the Fuji volcanic zone. This type of manganese deposit associated with submarine hot spring or volcanic exhalation, though not distributed as widely as the more typical nodules of the ocean floor, may occur in other areas and under favourable conditions could form large high-grade ore bodies of manganese and other metals[24/] (McKelvey, 1965). Such high-grade submarine deposits of this type could offer better exploitation possibilities and they should therefore be regarded as a practical target for current exploration.

From an economic viewpoint, the typical composition of nodules from the Pacific Ocean appears more interesting than that from the Atlantic. Direct comparison shows that Pacific nodules contain more manganese, cobalt, copper, molybdenum, and titanium. Nodules from the Atlantic are less variable in composition, averaging about 18 per cent Mn, 0.4 per cent Cu, 0.6 per cent Ni and 0.4 per cent Co. Occurrences with such a composition have been found on the Blake Plateau, off the Atlantic Coast of the south-eastern United States of America, between depths of 750 and 1,050 metres. An area within the north central part of the Blake Plateau recently investigated in detail (Pratt and McFarlin, 1966), shows a middle portion with a pavement-like concentration of manganese crusts, surrounded by an annular area in which manganese nodules are concentrated. The reason manganese nodules and crusts are forming on the Blake Plateau, in relatively shallow water and close to a continent, appears to be that the Gulf Stream flows through this area and the high currents apparently sweep the bottom free of terrigenous sediments.[25/] The occurrence of phosphate nodules to the landward side of this area of manganese oxide probably results from the

24/ This in fact has been the original mode of origin of several "massive sulphide" deposits contained in volcanic formations of different ages and exploited on land for metallic minerals, principally copper.

25/ Because of its comparatively shallow water depth and proximity to shore, this region has repeatedly been investigated by several United States mining companies, one of which is reportedly preparing to apply for an exploration concession for manganese deposits.

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presence here of Tertiary-age phosphatic strata outcropping in the continental shelf and slope. One notable exception to the low-grade nature of Atlantic nodules is from an area 600 km south-east of Bermuda, where the manganese content of one nodule was 44 per cent.

Nodules from the Indian Ocean show some similarity in composition to those from the Pacific, but the average contents of manganese, nickel, cobalt, and copper are slightly lower (Cronan, 1967). Nodules from the eastern Indian Ocean contain 17 to 29 per cent Mn, 0.3 to 2.0 per cent Ni, 0.1 to 1.3 per cent Cu, and 0.08 to 0.4 per cent Co. In contrast, the nodules taken from the western Indian Ocean are of lower grade, containing 12 to 22 per cent Mn, 0.2 to 1.0 per cent Ni, 0.03 to 0.4 per cent Cu, and 0.07 to 1.0 per cent Co.

Future economic potential

There is no doubt that the potential gross amounts of manganese and associated metals contained in ocean floor nodules are enormous. The possibility of commercial harvesting and processing has however caused controversy, with some experts of the opinion that the copper, nickel, and cobalt contents of the nodules, together with manganese, may warrant their commercial exploitation (Mero, 1967), while most people in the business believe that their economic potential is highly uncertain and is likely to remain so for years, if not for one or two decades.

Numerous practical problems must be solved, not only in engineering design but also in actual operation, before the economic potential can even be assessed. How to recover the nodules from depths of thousands of meters in the generally hostile open ocean conditions, is one technical and economic problem.

Even more important may be the way in which to extract economically the desired metals from such a complex and metallurgically-unfamiliar matrix. The peculiar way in which the metals are combined within the minerals and associated alumino-silicates and impurities, does not lend itself to existing extractive metallurgical processes developed for ores from land sources. The high silicon content of the nodules, averaging more than 8 per cent, is particularly unfavourable (Emery, 1965). The usual method of extraction by chemical reduction allows silicon to withhold about twice its weight of manganese, thus most or all of the manganese in the nodules would be lost in the waste product. Research on new extraction methods, mostly solvent extraction and ion exchange techniques, has been undertaken in the United States of America. A recent development is a newly-invented process by which the sulfur-dioxide gas in smoke streams from coal burning plants and installations would be utilized to dissolve and recover the manganese in the nodules. The efficiency and economic viability of this process is not known and it appears that much more investment is required for developing an inexpensive process that would allow the extraction of a number of the metals contained in the nodules. Such a major breakthrough in extractive metallurgy would of course also bring the vast quantities of low-grade ores on land into competition with the ocean floor resources.

II. MINERAL EXPLORATION AND EVALUATION TECHNIQUES

Mineral exploration and evaluation[1/] in the ocean environment involves more or less a sequence of activities similar to that applied on land - careful geological review indicates regions favourable for broad exploration programmes by topographic, geological and other surveys and the results of these lead to more detailed prospecting for the location of economic mineral deposits. However, many additional problems are to be faced when conducting such surveys on and under the sea and it is from this point of view that the various techniques utilized will be reviewed in the present chapter.

Weather and sea conditions pose difficulties in the efficient and safe execution of surveys from surface vessels, which require a fair degree of stability to obtain accurate data.[2/] The distance separating the shipboard scientist and the sea floor also creates a great barrier in most deep water investigations, and the great hydrostatic pressure at depths beyond the continental shelf prohibits any extensive sea-floor mapping by divers.[3/] Similarly, operations from deep submersibles are still limited to a few simple tasks, although development possibilities here are considerable. Another adverse factor is the light attenuation characteristics of sea water which restrict visibility and optical illumination to very short distances.

1/ By exploration is meant the broadly-based surveys using all available methods - generally of large areas in the first instance - leading by progressively narrowing the search to the location of mineral occurrences of possible economic importance.

By evaluation is meant the detailed investigation of mineral occurrences or deposits using all appropriate techniques, in order to discover their nature and origin, establish the quantity and tenor of the contained economic mineral(s), determined how best they may be exploited and generally consider all other factors affecting their economic development.

2/ In any given oceanic region for example, it is generally possible to count on only 100 to 200 working days per year.

3/ Man-in-the-sea experiments are now progressing to 183 metres or greater, but the diver's role at that depth will always be restricted to the few most critical engineering tasks which cannot be automated or remotely controlled.

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Underwater mineral exploration has been pioneered by the petroleum industry, which has successfully adapted land geophysical and drilling techniques for offshore work, now taking place in many continental shelf areas of the world. The current techniques are generally applicable to great depth of water.

It may also be noted that marine mineral exploration and evaluation shares much common ground with other scientific investigations of the ocean floor. Most of the oceanographer's sampling tools and techniques have been adopted directly in prospecting and naval research and development programmes have also contributed greatly - many new oceanographic devices are in fact commercial versions of systems and equipment so evolved.

It appears clear that the petroleum industry, the newly emerging ocean engineering industries and governmental research programmes undertaken by the developed countries, will continue to play a major role in advancing marine mineral exploration and evaluation. Feedback from these activities can be expected to benefit every country pursuing resources in the ocean environment.

Current marine mineral technology is capable, under many circumstances, of locating and evaluating a deposit in the sea, not unexpectedly at a cost rather higher than on land. Current limiting factors are essentially the engineering capabilities and high cost of deep-water exploitation which can generally only be justified for high-valued products recovered at a price competitive in the world markets or perhaps for strategic minerals.

A. Survey platforms and related technology

The first major requirement in extending mineral investigations beyond the continental shelf is the survey platform, usually a self-propelled surface vessel, from which various types of geological and geophysical surveys may safely and efficiently be conducted. The success of a mineral investigation programme hinges upon several factors involved in the design of such craft[4/] as well as in techniques for maintaining precisely the vessel's position over a specified sea bottom site, and for reoccupying the exact same position at a later time.

4/ Some factors evaluated by the Office of Naval Research Conference on Oceanographic Instrumentation and a study by H. Rowe et al. (1967), are seaworthiness and stability; size; speed range and endurance; living accommodation; initial and operating costs. Harbour facilities and other coastal logistics are not reviewed in this report.

Platforms

Whether a used ship is obtained or one is built to specifications, controlling factors are generally the same. Rowe (1967) has shown that a forty-eight to fifty-five metre vessel, patterned on the popular hurricane-test offshore oil supply boat, would be suitable for general purpose geological/geophysical surveys. A specially designed larger vessel would however be required for prolonged work at distance from base, and for core drilling to more than sixty metres (200 ft.) below the deep sea floor.

A new approach is the use of neutrally-buoyant platforms such as deep submersibles, which can cruise or be stationed at any desired depth, or directly on the ocean floor. The armada of manned undersea research vehicles has been growing rapidly in the last few years. Most of the available craft are basically "observation platforms" which enable human occupants to make visual studies of the ocean bottom. However, second generation vehicles not only possess greater depth and range capabilities but can also perform certain surveying and sampling tasks.[5/] Because of their manoeuvrability and ease of transportation to any area in the world by land, water or air (cargo plane), small underwater crafts are excellently adapted to reconnaissance surveys.[6/]

Position fixing

An accurate navigation fix is a critical factor in prospecting for undersea minerals and as the search narrows so do the errors in positioning that can be

5/ As an example, the "Aluminant", successfully used in mapping the ocean floor and sampling manganese nodules from the Blake Plateau off the eastern United States seaboard, can carry more than two tons of scientific payload during submerged cruises to 4,500 metres (15,000 ft.), depth and has a cruising range of almost 100 miles (160 km). Assisted by its two ballast systems and vertical propeller, the craft can remain in contact with the ocean floor and ride on its wheels. This vehicle could be the forerunner of a series of specialized exploration submarines able to perform certain types of geophysical surveys, geochemical prospecting, coring and sampling.

6/ An example of this type is the "Alvin" used by scientists of Woods Hole Oceanographic Institute in the West Indies for sea-floor sampling and geological studies, measures 22 ft. (6.6 metres) and has a displacement of fifteen tons, a depth capacity of 6,000 ft. (1,800 metres) and a cruising range of ten to twelve miles.

tolerated. While in general reconnaissance surveys, an accuracy of 1,000 ft. or more may be acceptable, 100 ft. or less is desirable in more detailed work and even further reduction to a few feet may be necessary in the delineation of a deposit.

During recent years many types of electronic navigation systems have been developed, which provide degrees of accuracy ranging from ± 1,000 metres to ± 1 metre, with maximum operating ranges varying from a few nautical miles offshore to several thousand nautical miles. There are two basic types: the hyperbolic pattern system and the ranging system. The hyperbolic pattern systems, with a master station and two slave stations at precisely positioned sites onshore, require a receiver aboard the survey vessel. There is no limit to the number of units or ships that can use this system simultaneously and it is permanently installed at various locations throughout the world. The ranging system uses a master station aboard ship with two slave stations at surveyed sites on shore.7/ Small portable systems are also available for local use to provide high accuracy within thirty to fifty nautical mile ranges.

Two well-developed procedures - the multi-point mooring system and the dynamic positioning system - are commonly used to maintain a ship's position relative to the survey-sampling sites on the sea bottom. Deep-sea mooring systems have been used at 1,000 fathoms (6,000 ft.) in the open sea, and occasionally at 2,000 fathoms (12,000 ft.). Good position control over the vessel can be effected with four-point anchoring system and a series of cores may be obtained along the

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7/ As well as division into hyperbolic and ranging types, electronic positioning systems may be distinguished, on the basis of type of signal, as "pulse systems" or "phase comparison (continuous wave) systems", the latter being more accurate but costing more. All combinations of these systems are available commercially. In the long-range group (> 500 nautical miles) may be mentioned the Loran A, Loran C, Decca Navigator, Delrac, Omega, Consol and Satellite Navigation systems; examples of intermediate-range systems (100 to 500 nautical miles) are Decca Hi-Fix, Decca Lambda and Lorac; short-range systems (< 100 nautical miles) include Radar, Alpine Precision Navigation Equipment (PRS), Shoran and Rana; high accuracy short-range systems include Autotape, Decca Hi-Fix (Minifix), Hydrodist (Tellurometer and Raydist). Costs of electronic positioning and navigation systems range from a few thousand dollars to millions of dollars per transmitter. The short-range systems are of greatest interest to the ocean engineer working on the continental shelf and slope. The intermediate range systems were also developed almost exclusively for survey work.

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line of operations by winching in the forward anchor cables and releasing those at the stern.8/

The ideal situation in maintaining position is to reduce to a minimum the number of physical connexions and attachments between the floating vessel and the sea floor. In deeper water where anchoring may not be practical or allows too much movement, dynamic positioning can be used, with auxiliary outboard propeller drive units placed both fore and aft providing excellent manoeuvrability and controlling the ship's position in relation to sonar position sensors held submerged around the vessel.9/

B. Bathymetric and topographic surveys of the sea floor

Bathymetric and topographic surveys of the sea floor require the utilization of sonic depth recorders.

The echo sounder works by transmitting brief-pulsed acoustic signals at high frequency (10 to 200 kc) from a source mounted beneath the ship's hull. On reaching the sea floor, the pulse of sound is partially absorbed and partially reflected back to surface. On returning to source the reflected pulse is amplified and presented by the recorder as a graphic profile of the sea floor topography. Where desirable, the readings can be corrected to true depth, if temperature distribution and salinity of the water are known. The new models of precision recorders are capable of determining details of bottom relief, usually to less than one fathom difference, at any depth, and are therefore most useful in survey work. Choice of system used depends on accuracy required, range of water depth, economic and other considerations.

Interpretation of the echogram characteristics10/ obtained from the simple sonic depth recorders helps to identify and differentiate the nature of the

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8/ For ease of handling of the anchors, the vessel should have at least type power unit (100 to 1,000 hp) and increased holding power can be obtained by multiple anchoring at each point. Sherwood (1967) describes the use of digital computers to arrive at the optimized design of deep-sea mooring system that has been demonstrated to be lightweight, of minimum cost, easy to deploy, and capable of holding a particular vessel in position for many days in deep sea.

9/ Such a system was used successfully when drilling in 11,800 ft (3,598) of water off Guadalupe Island, Mexico during phase I of the Mohole project.

10/ Strength, structure and audio quality of the echo, and echo extension.

sea bottom. As a general rule, a rocky bottom shows a rough trace on the echogram, whereas sand and mud bottoms are smooth. Strengths of echoes reflected from rock, sand and mud are diagnostic, and rocky areas are characterized by echo extension. As a reflector of sound sand is best, rock is intermediate, and mud is the poorest. Penetration of the bottom by sound at the high frequencies used in most depth recorders is usually taken to indicate a soft non-compacted mud, as compact mud, sand and rock would permit little penetration.

Undersea sonar mapping by side scan sonar[11/] (side looking sonar) has now developed to the point where techniques clearly enable man to "see" in the opaque oceanic waters for moderate distance up to a few hundred metres, with field of observation covering more than half a kilometre. One of the system's shortcomings as a mapping instrument is the current inability to produce accurate depths. An additional potential application of the system lies in the fact that the signal characteristics and degree of backscatter change when passing from one type of sea floor material to another, such as moving from a sandy bottom to a mud bottom. Visual identification of sea floor characteristics could certainly be provided by refined techniques.

Some underwater cameras permit stereo photography to be taken, which can yield precise vertical measurements by photogrammetric techniques. However, conventional photogrammetion is not applicable to the mapping of the vast areas covered by the oceans, as optical photographs cannot be made of areas larger than a few hundred square metres because of light attenuation and absorption within a very short distance from its source.

11/ Developed from a compromise between the ultra-high resolution short-range acoustic lens imaging systems and the long range, low resolution sub-marine sonars. The basic principles involve repeatedly projecting short pulses of acoustic energy in a fan-shaped beam (narrow on the horizontal plane and wide in the vertical plane) from a rotable source in a surface vessel or submarine carrying the system). Graphic recording of return signals show the lateral displacement of any objects in the path of the pulses. As the vessel proceeds, a plan view of the bottom area covered is built up on the chart. The records frequently resemble a large-scale aerial photograph with depressions (as acoustic shadows) showing up lighter and elevations depicted darker than the average bottom return.

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C. Geological prospecting

As discussed previously, there is a fundamental difference between those deposits which are associated with bedrock now buried under the sea, and surficial deposits within the ocean environment. It will be appreciated that in the first case, a thorough review and study of the regional geology and mineral occurrences of coastal and shallow water areas will sometimes indicate potentially favourable prospecting grounds further from shore. Petroleum exploration activities, which gradually have been extended from land and coastal areas to continental slope areas are here the outstanding example. Most sea-based petroleum production is from the seaward extensions of geological structures originally discovered on land (e.g. Persian Gulf, southern California), or from structures with a distribution pattern established for a similar environment on land (e.g. salt domes off Louisiana and Texas).

Chemical precipitates make up most of the deposits now forming in the ocean environment. Studies on the origin of undersea mineral deposits, such as outlined previously for phosphorite nodules, help to identify favourable ocean environments for specific numerals, thus reducing unnecessary effort in random sampling.12/

Sea floor surficial sampling beyond the shelf

Sampling of the deep-sea floor for the purpose of locating mineral deposits has only recently been seriously contemplated, consequently new devices and techniques are still largely in the experimental stage and most work today makes use of the conventional methods and tools developed for oceanographic study of the sea floor. While there are available not less than a hundred variations of bottom sampling devices, all suffer from one basic limitation - they cannot be used to

12/ In order to achieve more efficient exploration at minimum effort and cost, mathematically designed search models have been used in laying out grids for geophysical surveys, geochemical prospecting, sampling, drilling and other exploration work. During recent years efforts have also been made in the application of computer techniques and mathematical models to indicate statistically the probability of finding mineral deposits in certain areas. Such approaches are applicable for underwater prospecting, as for land-based work.

probe deeper than about six to seven metres, although cores up to thirty-four metres have been taken in very soft sediments. These samplers generally cannot penetrate rock, gravel, or hard sand bottom. Deep-sea-floor sampling is still so inefficient that usually only a discouragingly small number of samples and amount of material result from a day's work.

Commonly used sampling devices are the grab sampler (snapper or clamshell sampler), which uses two or four jaws to cut into the sea floor sediments and then snap around them to take a sample.13/ These simple devices are generally the first ones to be used in prospecting surficial deposits on the sea floor beyond the continental shelf, particularly for calcareous oozes, siliceous oozes, manganese nodules, phosphorite nodules and glauconite.

Wireline dredge samplers are dragged over the ocean floor to obtain large-size pebbles, boulders and pieces of rock strata outcropping on the sea floor. This somewhat primitive method, used successfully in deep sea since the Challenger expedition in the 1870's, is proven capable of recovering manganese and phosphorite nodules.14/ The principal disadvantage of dredging is the lack of exact location of the sample and how representative it is of the bottom material.

Free fall corers (gravity and piston type) have long been used by oceanographers to take short core-lengths of soft sediment. The device is essentially a weighted section of pipe, which is dropped from the sea surface into the bottom and retrieved by cable. By applying the piston principle15/ cores of

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13/ Used for extreme depths and proved effective on most types of bottom; penetration ranges from a few centimetres to over half a metre, depending on bottom characteristics, weight of sampler and radius of its biting jaws; using a high-powered winch a very large clam-sampler can secure samples of several kilogrammes from 2 to 3,000 metres depth.

14/ Simplest least expensive type is the "pipe dredge", a length of larger diameter pipe with rear end sealed off with a screen or chain bag. "Box dredges" or "frame dredges" are simply sheet metal boxes open at one end, with grating or chain bag sealing off the other.

15/ In this type the core tube falls over a wireline-attached piston, which remains stationary at the water-sediment interface while the tube falls below the piston. The core is "sucked" up into the tube under the pressure within.

up to twenty metres length may be obtained, as compared with a maximum length of around five metres for the purely gravity type device. Neither type can penetrate rock, gravel or hard sand bottom, thus limiting use for mineral prospecting. Increasing deformation of the core as penetration increases and sediment is forced into the tube is another handicap.

Several lightweight remote-controlled corers have been used to take short cores of unconsolidated materials, including compact sand and gravel. Most of these devices are now used in shallow waters up to about 180 metres deep, but the designs could be improved for use at greater depths. These devices consist of a coring tube three to ten metres in length, with a top-mounted mechanical vibrator, mounted on a frame or tripod which can be set on the ocean floor.[16/]

Several types of remote-controlled rotary corers have also been developed, which are essentially self-contained rotary core drills lowered to the sea floor, powered and controlled from the surface ship, and usually able to take short core lengths in all types of material, including consolidated rock strata. Other lightweight coring equipment using percussion, vibratory or rotary drilling techniques are generally limited to depths of less than 100 metres, with sea-floor operation by divers, or surface vessel-operated by means of drill pipe suspended to the sea floor.

Deep-water core drilling systems

Core drilling is one of the most important, time-consuming and expensive phases of mineral investigation, particularly so in deep water beyond the continental shelf. It is indispensable in the search for economic minerals associated with bedrock formations underlying the sea floor, as it permits the entire rock sequence penetrated to be systematically logged, sampled and analysed. The desired depth of penetration may vary from less than fifty metres for certain surface or near-surface deposits, principally surficial chemical precipitates, to 7,000 metres for deep petroleum exploration. A two-fold classification divides

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16/ The only connexions to the surface vessel are the lifting cable and the electric cables and/or air hoses to power the mechanical vibrator and drive the corer into the sea bottom by a continuous vibrational impulse.

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exploratory drilling systems into rigs mounted on surface vessels and those operated on the sea floor by remote control.17/ The techniques are however in a state of flux at present, and there remains a great need to develop more efficient less expensive drilling techniques for shallow core holes of 500 to 1,000 metres in the abyssal sea floor.

Sample analysis

The desirability and even necessity for a certain amount of shipboard sample processing and analysis is obvious, particularly on extended cruises far from land. Preliminary results so obtained permit reorientation of programme for maximum effectiveness of the operation. The choice of shipboard laboratory facilities depends upon the objectives of the prospecting programme and the available shipboard space and scientific manpower.18/

Bottom photography and television

As a result of steady improvement in capability and quality over the last two decades, a considerable number of underwater cameras can take excellent bottom

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17/ Between 1953 and 1961, core drilling by a group of oil companies off California using a portable rotary rig mounted on a converted fifty-two-metre Navy patrol vessel successfully drilled a total of over 9,000 metres in 450 metres of water, with casing and coring to depths of 810 metres below the sea floor. Since 1953, other improved ship-mounted rigs have been constructed, most notable being that used for the first phase of the Mohole project in 1961, drilling in 3,598 metres of water, with nearly 3,900 metres of 11.4 cm drill string suspended from a thirty-metre derrick mounted on a seventy-nine-metre vessel. The larger and more expensive drilling barges are now capable of operation in 6,000 metres of water, with core-drilling capacity to 900 metres below the deep-sea floor. The only known sea-floor-operated drill rig that can work in 183 metres of water and drill up to thirty metres uses an electric down-hole motor, weight, drill bit and a flexible drill stem which is stored on a reel on the submerged platform. Core runs are limited to one-metre length. Other submerged deep-drilling equipment is reportedly being designed.

18/ Most types of laboratory may be installed aboard ship either in space below deck or portable vans fastened on deck. Sedimentological, mineralogical, palaeontalogical and chemical analyses may all be catered for, as well as mineral processing tests.

photographs in the deepest regions of the ocean. These have proved very useful, particularly in assessment of nodule concentrations in the ocean floor. Electronic flash units and automatic film advance allow large numbers of photographs to be taken before bringing the camera to surface.19/

Television scanning20/ together with bottom sampling, has also been used in evaluation surficial deposits of manganese and phosphorite nodules, giving an estimation of area coverage and size/shape variations of the nodules. In addition to its use as a survey tool, television has been applied successfully in monitoring undersea petroleum activities and other construction work. It will certainly play an important role in monitoring all future mineral exploitation activities.

D. Geophysical prospecting

Of all the supporting services available to the exploration geologist, geophysical methods have generally been the most readily adaptable to undersea investigations and technology in this field has therefore developed considerably, as will be outlined below.

Sub-bottom profiling (Continuous seismic profiling, sonic profiling)

Since the beginning of the use of echo sounders in oceanography, it has often been observed that in some cases sonic pulses can penetrate for short distances into soft mud on the sea floor and reveal its stratification characteristics on the depth recorder. This led in the early 1950's to prototype sonic devices for continuous seismic profiling being developed to survey the sub-bottom configuration below the sea floor. Many types of acoustic energy source, other than high explosives, have since been incorporated in the development of new systems of

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19/ Commercially available cameras generally can take pictures at distances of about 3 to 10 metres above bottom, covering a field of 5 to 50 sq. metres.

20/ Television was used underwater in 1947 at Bikini Atoll and in 1951 it was invaluable in identifying the sunken submarine "Affray" in the English Channel. Modern deep sea systems consist of a television camera housed in a water-tight case, designed to withstand the hydrostatic pressure at the abyssal depth of 6,000 metres. An artificial lighting system is usually required. Monitoring and power units are installed aboard ship. Continuous scan may be recorded on television tape recorders. Mero (1966) has continuously scanned along the tracks of a prospecting vessel for distances as great as 80 km, in depths of water up to 2,400 metres.

sub-bottom profiling, which has become the most useful of all exploration tools in the search for mineral deposits in the sea floor.[21/]

Sub-bottom profiling equipment consists essentially of three major functional elements: an acoustic energy source which is generally a ship-towed transducer, an acoustic receiver unit consisting of arrays of sensitive crystal detectors or hydrophones also towed in the water, and an amplifier and recorder system for processing the incoming signals and present them as continuous profiles of sub-bottom stratification. Many sophisticated profiler devices are now available. The only basic difference in the many varieties offered lies in the nature of the sound source used, which governs the frequency and total energy output, and in turn the sub-bottom penetration and resolution capabilities. Systems may conveniently be classified as acoustic,[22/] electric discharge,[23/]

21/ In principle, sub-bottom profiler systems use a powerful acoustic source to transmit sound pulses of lower frequency than those of the echo sounders; these can penetrate the ocean floor to various depths. The sound pulse is repeatedly generated every few seconds and portions of it are reflected from the interface between different sediment and rock layers underlying the ocean floor. The reflected signals are received, suitably amplified, and recorded graphically as a continuous profile showing the thickness, configuration and internal structures of unconsolidated sediment layers and bedrock structures such as faults, folds, salt domes, etc.

22/ Piezoelectric and magnetostrictive type acoustic transducers were the first ones used in the development of sub-bottom profiling systems. The marine sonoprobe devices generally operate in a frequency range of about 3,000 to 5,000 cps and can provide very high resolution records for the top 10 or 20 metres of soft sediment layers. The "pinger probe" is another high-frequency profiler device, using sound pulses at the frequency range of 5,000 to 12,000 cps with extremely short pulse interval. The pinger probe can define the detailed configuration of soft clay and silt layers of less than 30 cm in thickness but is severely limited by its extremely shallow sub-bottom penetration and its inability to penetrate sands and gravels.

23/ Several profiler systems use electric spark discharge devices to generate a sudden electric arc explosion (high voltage spark) underwater. The plasma existing between the electodes, at temperatures of a few thousand degrees Centigrade, generates a steam bubble in water and initiates a broadband sound pulse energy which usually has its peak frequency in the range of 50 to 500 cps. The electric power used varies from several hundred Joules in some equipment for shallow sub-bottom penetration, to 120,000 Joules in other systems designed for deep penetration to a limit of about 3 km.

electromechanical,[24/] mixture explosion,[25/] pneumatic sound,[26/] and hydraulic vibrator.[27/] The last, a development of the vibratory seismic technique previously used on land for petroleum exploration and now available for work at sea, marks a significant breakthrough in the field of exploration geophysics.

Penetration and resolution vary widely in the sub-bottom profiling systems. Those using high frequency energy sources generally provide high resolution with low penetration, those using low frequency energy give low resolution and deep penetration, with a few newly developed versatile systems falling between the two limits.

There is a continuous advancement towards the development of more powerful and versatile energy sources, improved penetration and resolution, and better interpretation of weak signals by computer techniques.

24/ Essentially an aluminum plate, spring-loaded against an insulated, flat copper coil. When electric energy surge of more than a few hundred Joules is put to the coil, the sudden massive induction current explosively repels the aluminum plate and generates a broad-band sound pulse with frequencies generally between 500 and 2,500 cps. It can provide high-resolution records for shallow to moderate sub-bottom penetration up to a few hundred metres.

25/ Acetylene-oxygen mixture contained in long rubber tubes is used to generate explosions within the rubber tubes and initiate powerful broad-band low frequency acoustic energy with peak frequencies generally between 15 and 60 cps. The system can provide medium-resolution records for deep sub-bottom penetration up to about 6,000 metres.

26/ The pneumatic sound source device is used to generate acoustic energy from the rapid release of the potential energy stored in an enclosed volume of compressed air. It has generally been used in shallow penetration profiling work.

27/ The seismic energy source of the marine "Vibroseis" system is essentially four synchronized hydraulic-driven transducers which are suspended on cables and towed by ship at a depth of 12 metres below the water surface. The vibrators emit coded seismic energy and can control the input frequencies (within a preselected range generally from 1 to 100 cps) introduced into the water and thence into the sea floor. The reflected signals are recorded on magnetic tape in analogue and/or digital formats and then processed by computer techniques to produce the final profiles. Using this system sub-bottom penetration up to 6,500 metres has been obtained, and the results are even better in quality than those from land vibroseis surveys.

Magnetometer surveys

After the Second World War, the anti-submarine airborne magnetometer was widely applied to large area reconnaissance in petroleum exploration, since it can indicate the approximate thickness of the sedimentary sequence above basement rocks and delineate sedimentary basins. A modified ship-towed design was later adopted by oceanographers in geomagnetic research to locate the large-magnitude crustal structures and probe several kilometres below the ocean floor. With the advent of the fluxgate, proton free-precession and lately the vapour magnetometers, all measuring the earth's total magnetic field with a high degree of accuracy, these instruments have become much more useful in marine mineral exploration. Although all three types are adaptable to magnetic survey from surface vessels or submersibles, the precession magnetometer is more sensitive and more easily handled than the fluxgate magnetometer, and the vapour types have an extremely high degree of sensitivity which enhances their usefulness when working from the sea surface.

Magnetic anomalies outlined by marine surveys can be interpreted according to the conventional mathematical and computer methods developed for work on land. Magnetic surveys can sometimes reveal the major rock types, faults and other structural features of the ocean floor. They may also indicate the possible occurrence of magnetic ores, such as concentrations of heavy ferromagnetic minerals on the sea floor, or intrusive dykes in the bedrock.

Gravity surveys

Measurement of the acceleration of gravity at sea was first conducted aboard Netherlands submarines by Vening Meinesz, who devised a multiple-pendulum system that could compensate for small amounts of motion of a submerged submarine. Later, in the United States of America the conventional, portable, rugged and accurate gravimeter (spring type) used on land was converted to a sea-floor gravimeter, housed in a water-tight diving chamber with telemetering and remote control from a surface vessel. This was successfully used in offshore oil prospecting in shallow waters and as a result many salt dome were found in the Gulf of Mexico.

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In recent years marine gravimeters have been further developed. Several designs are mounted on a stabilized platform aboard a surface vessel and can continuously record gravity profiles while the ship is under way. A newly developed system can digitize the gravity data and record it on magnetic tape. Although shipborne survey provides more gravity data in less time and at lower cost, its accuracy is still one order of magnitude below that of the sea-floor gravimeter. Nevertheless the results are very useful in reconnaissance exploration and regional geological studies, particularly in interpreting the large structures and bodies of specific rock types in the ocean floor.

Here again, gravity data can be corrected and interpreted according to the conventional mathematical and computer techniques that have been developed for work on land.[28/] Sub-bottom structure cannot be defined from gravity survey alone as for any set of gravity data, an infinite number of interpretations are theoretically possible. Therefore, gravity data are best utilized together with the results of magnetic, sub-bottom profiling, seismic, and geological surveys.

Marine seismic surveys

Standard seismic refraction and reflection surveys, using high explosives to generate shock waves, have been used at sea for years. Both require the initiation of a shock wave and a series of pressure-sensitive or velocity-sensitive detectors (hydrophones or geophones) placed some way from the shock wave source.

The refraction method depends on the refraction of the shock wave at the interface between two rock media having different wave propagation velocities. From the recorded travel times and distances of the shock waves, it is possible under favourable circumstances to determine the depth to any discontinuity, velocity in the rock, and attitude (dip) of the interface. Refraction survey generally indicates broad geological features without great detail. Deep-sea

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28/ Similar to the trend of magnetic interpretation work, gravity interpretation is also making increasing use of computer techniques for regional and residual computations, field value interpolations, trend surface analysis, and mathematical simulation of the gravimetric effects of theoretical models.

refraction surveys have been made in many parts of the world by oceanographers to secure information about the earth's crust under the ocean. The method has not been employed very much in offshore petroleum exploration, except to a limited extent in prospecting for salt domes at not too great depth below the sea floor.

Reflection surveys, which depend on the reflection of a shock wave at an interface between two rock media having different acoustic impedance, require less distance between the shock-wave source and the detectors. The method is capable of deep penetration to a depth of 7,000 metres or more below the ground surface. In marine work, an array of detectors encased in a waterproof cable is strung out behind the survey vessel. The explosives are fired at intervals of a few minutes while the boat is under way, and continuous reflection records are thus obtained. Marine reflection survey has become a highly efficient single-ship operation, and output is usually ten to twenty times that achieved by land survey. It has been used in oil exploration in many parts of continental shelves throughout the world. Recently, surveys have been initiated in several continental slope areas.

The marine reflection method has been continuously improved, and it is now customary to employ ingenious systems of stacking shot points and detectors, magnetic tape recording in digital and analogue formats, and computer techniques to remove the undesirable "noise" for a better resolution of thinner strata, deeper penetration, and better interpretation of weak signals.

It appears that future research in marine reflection methods will continuously emphasize the development of more powerful non-explosive seismic energy sources, such as the "Vibro-Seis", which may eventually replace the use of high explosives. Governmental agencies of various countries where offshore petroleum work is being conducted are becoming more aware of the non-explosive seismic methods from a standpoint of protecting fish and other marine life.[29/]

29/ The Ministry of Industry and Handicrafts of the Government of Norway has completed a thorough study concerning the effects of underwater explosions on marine fauna.

Other geophysical methods

Of the other methods, electrical systems, which depend on the resistivity, electrical potential, induced polarization, natural telluric currents and other characteristics of different rock types and ore bodies, have not been applied in the marine environment. It appears certain, however, that some electrical methods will eventually be developed for mineral prospecting in the sea.

As submarine phosphorite nodules are known to contain significant amounts of U_3O_8, the possibility of radiometric beneficiation processes has been experimented with in the laboratory. Application of the principle as a sea-floor radiometric prospecting technique is feasible. A scintillation detector system could be towed from surface vessels or submerisbles, to scan and measure continuously the gamma radiation intensity of the sea-floor, in direct prospecting for certain surficial minerals.

Although not yet experimented with as a prospecting method, it appears almost certain that the measurement of heat flow on the ocean floor will eventually be developed for this purpose. It has been suggested (Taylor-Smith, 1961) that local positive anomalies of high intensity heat transfer may be located over metallic ore bodies of higher heat conductivity, with negative anomalies characterizing non-conductive ore bodies and rock masses. Such heat-flow anomalies in the ocean floor should be easily and consistently recognizable, particularly as the bottom water temperature in the abyssal ocean shows so little variation as to be almost a uniform environment.

Shipboard integrated geophysical systems

With the advent of sophisticated automatic sensing and recording devices and computer techniques, it has become possible to simultaneously measure many parameters during routine oceanographic surveys and marine geophysical surveys. Integrated systems designed for specific surveying purposes have been installed on several vessels. In most of the integrated geophysical systems, data-acquisition operations include synoptic measurements and recording of shipborne magnetometer, gravimeter, echo sounders and sub-bottom profiling data along with synchronous reference to time, navigation fixes, and ship's course and speed. The data are presented on analogue recorders and type-written printouts, and at the same time they are also recorded on magnetic tape for digital computer processing.

In actual operations two modes of integrated data system are generally employed: under way and on-station. In the first the collected raw data are processed on-line by the computer to provide continuously a comprehensive result of the survey in progress. The echo-sounding data is corrected for acoustic velocity variations to give the true bottom depth. Gravity data is processed by the shipboard computer in real-time to correct for Eotovos and to compute raw gravity, free-air anomaly, and Bouguer anomaly. The ship's geographic position is computed from the readings of electronic navigational fixes, and is then combined with coded time reference, ship's log and gyro data to interpolate a continuous track of ship's position. Magnetic data is recorded and corrected for geographic position and other variations. The sub-bottom profiling result is displayed on the facsimile recorder, and it is also permanently recorded on magnetic tape for off-line computer processing at a later time.

During the on-station mode of operations, the ship may remain on site for hours to conduct core-drilling, bottom sampling, or other oceanographic measurements. The physical and chemical oceanographic data collected on station are usually processed on-line to give the corrected result. The magnetic and gravity data collected previously may be further processed to make other desirable corrections, such as instrument drift, daily variations, and magnetic storms. The sub-bottom profiling data on magnetic tapes may be processed by the computer to remove multiples, reverberations and other noise, and to produce more refined sub-bottom profiles.

III. DEEP WATER PETROLEUM EXPLOITATION TECHNOLOGY

In petroleum exploration various techniques are applied to discover whether or not a commercially exploitable accumulation of hydrocarbons exists in a given area. In other words, it is necessary to demonstrate not only the existence of such an accumulation but also that it may be extracted economically. As in other mineral search, petroleum exploration comprises broadly based reconnaissance surveys including general geology, photogeological mapping and when necessary gravimetric or aeromagnetic surveys, which provide a preliminary assessment of potential, followed by the more detailed evaluation - intensive geological and geophysical (seismic) investigations - leading where appropriate to exploratory drilling, the only method of ascertaining that a deposit exists. Since oil or gas accumulations have been found at less than 300 metres and greater than 6,000 metres, depths of wildcat or exploratory wells[1/] vary considerably. When exploration results are favourable, development follows, with the drill again providing the only means of delineating the deposit and estimating its reserves, which are then tapped by development (production) wells.

With due allowance for the underwater environment and its surficial bottom deposits, petroleum exploration and evaluation in offshore areas follow a pattern roughly similar to that on land. As direct study of the bedrock is rarely possible, however, even greater dependence must be placed on indirect methods such as sonic depth recording for bathymetric and topographic survey of the sea floor; sea-floor sampling of geological formations with various devices and eventually by core drilling; bottom photography and undersea sonar mapping.

In offshore geophysical reconnaissance, aeromagnetic surveys are mostly used in the first stage with more accurate seismic prospecting providing a means by which the structures of buried formations and deposits may in many cases be established with the greatest reliability. New methods of seismic reconnaissance using non-explosive energy sources - the "electric sparker", "boomer", "gas exploder", "pneumatic sound", "vibrosis transducer" - have recently been developed. Mineral exploration techniques in general having been outlined in chapter II the following

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1/ In the oil industry, "wildcatting" is a widely used term for exploratory drilling.

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pages will deal particularly with offshore technology applicable only to the petroleum industry and described conveniently under drilling platforms, offshore drilling operations and oil well completion and production.

A. Drilling platforms

As transition from onshore to offshore drilling has been very gradual, it is difficult to establish when the first offshore well was drilled. Testing of offshore extensions of known oil fields was first accomplished by directional (angle) drilling from shore-mounted rigs or drills located on near-shore piers. Although the first offshore oil production was obtained in 1923 from wells in Lake Maracaibo, Venezuela, the real beginning of offshore exploration was not until after the Second World War when ocean drilling started in 1947.

From an early beginning using largely aquatic versions of land-based equipment and techniques, marine oil-well drilling, reaching out into deeper waters, has developed an ingenuous technology, utilizing the most up-to-date equipment and knowledge of ship design, underwater construction, wave motion, corrosion, stress, strain and fatigue in materials, advanced diving systems, submersibles, communications, computers, instrumentation, guidance system, power systems, and so on.

During the last ten years, maximum water depth for wildcat wells has increased from 30 metres (100 ft) to more than 182 metres (600 ft).[2/] Today, mobile platforms and rigs can handle routine test drilling in about 300 metres of water and may even be capable of operating in 1,000 metres. However, although offshore oil production technology has not yet reached the limits of its present capability for routine operations in very deep water, large-scale operations in these conditions would not appear to be economically justified in the immediate future, as the cost of the platform and rig increases rapidly with increasing water depth. Maximum water depth of producing wells has increased over the past ten years from 21 metres (70 ft) to 87 metres (285 ft) but completion of such wells at depths beyond the continental shelf still requires a great deal of technological development.

2/ The current world record is 192 metres (632 ft) drilled in the Pacific off southern California in July 1965.

The first water drilling installations were simply normal land-type rigs placed on a fixed platform, the latter often containing only the drill itself with ancillary equipment carried on a floating barge. At about the same time mobile installations appeared, with the whole rig supported on a floating pontoon, which was hauled out and immersed in shallow water (up to 4 metres maximum). Further development of this equipment produced the first sea drilling apparatus, by separation into an immersed portion which lay on the bottom, and an above-surface section supporting the drilling installation, the two joined by solid metallic structures; this was the beginning of sea-mounted drilling platforms. Increasing water depth necessitated sitll further development of a new class of equipment - the self-elevating platform - which retained the same two features of mobility and bottom support. Finally, a new type of drilling installation has been created to tackle deep water exploration - the drilling boat, used initially to drill offshore stratigraphic core holes, has been developed into a more elaborate and powerful prospecting vessel. Offshore platforms may be divided into three major categories, on the basis of type of support - fixed platforms, semi-fixed platforms and mobile platforms.

Fixed platforms

In the United States of America, 80 per cent of offshore wells for petroleum have been drilled from fixed platforms; this gives an idea of their importance. The end point in this type of development is the artificial island, as for example the four islands completed in Long Beach harbour early in 1967, to develop the eastern part of the Wilington field.[3/] Many fixed platforms are supported on piles driven into the sea bottom. The first ones constructed in Louisiana were wooden and immersed concrete structures have also been used, but most platforms today are made of steel, with tubes or piles driven deeply into the bottom, supporting an immersed metal frame on which the above-surface bridge is constructed. Such platforms may have variable dimensions, load capacity and water depth.

3/ These are the largest of the type so far used in offshore development work; they have been constructed using quarried rock, dredge material and sand, with a coarse "armour" rock enclosing the island for protection against erosion.

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The early development stage in offshore drilling produced the large self-contained fixed platform,[4/] supported by steel or reinforced concrete piles driven into the sea bed. These large units were designed to carry all necessary equipment and supplies, withstand severe storm conditions, and house a large number of workers, self-supported for extended periods of operation.[5/] For exploratory drilling, the obvious disadvantage of the fixed structure is lack of mobility. Its best application is therefore in exploiting known oil fields, as a number of deviation wells may be drilled and completed as producers from the same platform. To date, fixed platforms have not been erected in water depths greater than 91 metres (300 ft), but a new design concept featuring a single column platform supported by caissons and guidelines has been proposed as a deep-water possibility up to 183 metres (600 ft) depth. With the present technology, technical and economic limits for fixed platforms would appear to be the outer continental shelf. Beyond 100 metres depth there will be a number of limiting factors - lack of equipment for handling heavy structures, inadequate ocean floor foundation capability, lack of oceanographic information for design, and rapidly escalating costs.[6/]

4/ The first true open sea-drilling unit was a fixed platform constructed in 1947 in 14 metres of water about 19 km off Louisiana. This platform was built on 100 steel piles driven about 60 metres into the sea floor. In the last few years, new types of four-leg supported platforms and single-column supported platforms have been constructed to combat the severe winter ice and tidal currents in Alaska's Cook Inlet and to combat the hurricanes in the Gulf of Mexico. A platform of this type weighs about 4,000 tons and can support an additional 2,000 to 4,600 tons of equipments and supplies. With one or at most four legs penetrating the sea surface, it presents less resistance to the rafting sea ice, currents, wind, and waves. The construction cost of such a winterized fixed platform in not very deep water may range from $6 million to more than $8 to 10 million.

5/ Initial expenditure on fixed platforms is high, especially in remote areas. As a rule of thumb, cost of construction in not very deep water in a convenient area such as the Gulf of Mexico can be taken as about $700 per ton of material used. In moderately deep water up to about 91 metres (300 ft), cost of a fixed platform is estimated as at least $1 million per 30 metres (100 ft) of water depth. Cost of dismantling, moving and rebuilding on another site is also considerable.

6/ For the 100 to 183 metres depth range in the Gulf of Mexico, unit cost of a bottom-supported platform is $6 to 12 million.

The high cost of the large fixed platform for wildcat drilling brought about the introduction of a smaller version, serviced by a support vessel. In this tender-serviced fixed platform, deck-size is reduced to the minimum,[7/] it is therefore less expensive and dismantling is much easier should no commercial production be established. The fixed structure deck carries only the derrick, draw-works, rotary table, engine, rig and minor ancillary equipment, with the supporting tender accommodating most of the heavy equipment; living quarters; fuel, fresh-water and drilling mud tanks; cementing unit and other supplies. Earlier tenders were mostly converted Second World War vessels; support craft are now specially designed and some use the vessels' engines to supply power requirements for drilling operations. For the difficult task of maintaining a drilling tender[8/] stationary in the open sea, on a fixed heading near a fixed platform for extended periods of time, a "spread mooring" arrangement of eight anchors is used. In severe storms the tender can be pulled away to a safe distance from the platform by adjusting the anchor lines.

Semi-fixed platforms

These installations are designed to rest on the sea bottom only during drilling operations, thereafter they are floated and position shifted rapidly and independently with the platform's own facilities. There are two categories in its group - self-elevating platform rigs and submersible drilling barges.

Self-elevating platform rigs, like fixed platforms, may be "autonomous", that is carrying all the drilling installation and equipment; or "assisted" if a supporting tender is also used. The principle involved is that of a metallic barge or caisson carrying the drilling installations, which is jacked up above the water on a number of vertical metal piles bearing on the sea bottom. In transporting the platform, the piles are lifted to the maximum extent in order to diminish hauling stress. When the sea bottom is not solid, the lower ends of the piles may require caisson-type terminations for stability, which limits penetration. On the basis of difference in self-raising mechanism, two systems may be distinguished,

7/ One of the first models had a deck area 9.5 metres by 23 metres, stood 6 metres above high water level, and supported on sixteen steel piles driven 30 metres into the sea-bed.

8/ About 99 metres in length, 15 metre beam and 7.5 metre draft.

the Delong System using a varying number of tubular or square section piles, and the Le Tourneau System, using three piles of metallic frame triangular section.[9/] Jack-up rigs are now considered to be the most versatile for shallow to moderate depths of water up to 91 metres (300 ft). By the end of 1967, some 90 units were operating around the world. Their major advantage is being bottom-founded, thus providing a very stable deck even in stormy seas. Their good mobility is especially suitable for exploratory drilling in unproven areas, and some have been towed for vast distances, traversing the Suez and Panama Canals.[10/] As currently developed, they are capable to more than 91 metres (300 ft) of water. Although design for 183 metres (600 ft) has once been proposed, it appears that 120 metres or slightly more could be the technological and economic limits for jack-up rigs.

Submersible drilling barges are a direct development of the inland-type barges first used in 1933 for drilling in a few metres of water in the coastal marshes and protected areas of Louisiana; by the use of ballast tanks, these barges could be either floated or settled on the bottom. Vertically movable pontoons are used in the submersible drilling barges to effect stability during the sinking operation. When the main hull is safely on bottom, the pontoons are also lowered to increase the bearing load and reduce resistance to waves. In the 1950's many types of submersible

9/ In the Delong System, the number of piles varies from three in light platforms to fourteen for some autonomous structures. Vertical movement is achieved through a step-by-step progression using jacks usually placed in pairs around the piles. In the Le Tourneau System, the edge of each triangular section carries an electrically driven rack and pinion mechanism for raising and lowering in a continuous motion. To increase potential in deeper water without a prohibitive increase in dimension, some Le Tourneau models feature piles which may be inclined to give a wider-spread base and greater stability. The Dixilyn No. 250 uses a variable tilting mechanism to control the angle of the legs as the elevation changes. Unit cost is $6 to 9 million, weight up to 6,500 tons, legs 130 metres long.

10/ The Soviet Union's new jack-up unit, the Chazon, has been towed across the North Sea and Baltic, then 5,000 km through rivers and canals to the Caspian Sea.

unit were built, with many ingenuous designs 11/ to improve stability, minimize wave force, reduce bottom scouring and extend depth capability. The trend in submersible design has been away from pontoons and moving parts which can be damaged or cause operating problems during rig moves. Of thirty sumbersible rigs in operation today, most are limited to shallow water less than 25 metres. The number will not increase substantially because of increasing competition from the self-elevating platforms and semi-submersible barges as wildcatting and test-drilling moves steadily into deeper waters.

Floating platforms

As fixed or semi-fixed platforms often prove too costly for exploratory drilling and are also handicapped by inability to work in very deep water, platforms were introduced which have no connexion with the ocean floor and are even mobile, to a certain degree, during drilling operations. There are two categories - ship-type floating rigs (drilling ships and barges) and semi-submersible rigs. In this type of drilling the two main requisites are the vessel's stability 12/ and its ability to remain in position. Horizontal movement must be kept within a radius of 5 per cent of the water depth, otherwise excessive movement away from the well head on the ocean floor will result and may cause a blow-out or loss of the well.

All earlier drill vessels used conventional mooring systems until 1961, when the introduction of the dynamic positioning system permitted experimental drilling in 3,568 metres (11,700 ft) of water, the deepest any rig has operated in to date. 13/ However, well-head equipment was not used and the system lacked the capability of re-entering the well once the drill string was pulled. In 1964 a unique turret mooring system was introduced 14/ in which the entire anchoring system is connected through a central well and tower, permitting change of heading and

11/ For example hinged pontoons; recessed pads; fixed hull extensions; floating drydocks; spuds and mud skirts; streamlined hulls; bottle-shaped stabilizing columns, etc. These designs have reduced the dangers of being moved off location by severe storms but it is still necessary in some cases to use sand bags, etc. to protect locations where the bottom is soft and strong currents cause scouring.

12/ Special ballast tanks help keep the vessel in trim when staking drill pipes or carrying out other operations affecting balance.

13/ First phase of Mohole project.

14/ On the $4 million vessel "Discoverer".

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complete circular turn-around in the anchored vessel, which can thereby compensate for wave motion without losing position.

Since 1960 the size of ship-type rigs has been increasing reapidly, mostly self-propelled ships with a few barges requiring to be towed by tugs. Most vessels drill through a "centre well" or "moon pool" above which the derrick is mounted, an arrangement giving better stability than "over-the-side" derricks but making it more difficult to get away from a well should a storm come up or the hole get out of control. High mobility[15/] is a big advantage of ship-type rigs and their large loading capacity makes them independent of supply facilities for long periods. They are particularly suited to exploratory drilling in deep water. One major disadvantage is lack of stability under strong winds, waves and currents, when drilling may be interrupted for as much as 30 per cent of the time in rough sea conditions. They are more efficient in protected waters and calm open seas, or areas with one prevailing wind and current direction, than in waters with rapid shifts in sea direction such as the Pacific and the Gulf of Mexico.

Development of underwater wellhead equipment has increased the water depth record for exploratory wells from 76 metres (250 ft) to 192 metres (632 ft). At present, about 300 metres water depth appears the maximum using conventional mooring systems, with dynamic positioning allowing operation in perhaps 1,000 metres and also providing the best long-range answer to the problem of keeping station in ultra deep waters. However, using a propulsion drive system for some months is appreciably fuel-consuming, and riser pipe design will continue to be a critical problem.

Semi-submersible rigs have been developed in the form of a "transparent" hull which is less sensitive to sea conditions and permits drilling in a partially submerged position, with improved stability. This is in some ways a reversion to the earlier submersible barges in that the drilling platform is a rigid superstructure raised up from the hull, but instead of the hull resting on the sea-bed, buoyancy chambers permit its submergence to a sufficient depth to minimize wind and wave disturbance. In recent years there has been a rapid increase in the number

15/ One ship sailed from the Gulf of Mexico to Australia in seventy days fully equipped for drilling. Unit cost is about $4 to 5 million, cheaper than other types of deep water drilling unit.

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of such rigs, to approximately twenty units by the end of 1967.[16/] One advantage of the semi-submersible lies in its main buoyancy chambers being located below the level of most wave action, thus offering greater operating efficiency in rough conditions with lost time generally less than 5 per cent.[17/] They are very suitable for moderate to deep waters and rough sea conditions. As disadvantages may be listed trimming and towing characteristics and mooring problems; efforts are being made to improve these in new designs. In most models stability has been gained at the expense of mobility and the ready world-wide operational capacity of the ship-type rig is therefore lacking. Using heavy mooring systems, drilling is possible in water depth up to 305 metres (1,000 ft) and probably even deeper if it should be economically justifiable.

Drilling platform hazards

In addition to those hazards applicable to land-based work, which themselves are accentuated in offshore drilling, the latter operation carries the risk of accidents particular to the ocean environment. Fixed drilling or production platforms permanently installed in shallow waters are always subject to damage in hurricane and severe storms.[18/] Over the past sixteen years there have been twenty-five major accidents with mobile drilling platforms where the loss was greater than $1 million; eighteen of the twenty-five units involved were completely destroyed. During the period 1958-1964 major accident rate averaged 1 to 2 per cent, but hurricanes and other catastrophes raised the rate to 7 per cent in 1965. During the past sixteen years there have also been about twenty-four less costly accidents where the damage was appreciable but less than $1 million.[19/] Several general conclusions may be drawn from a review of the accident records:

(a) Approximately 60 per cent of the major accidents occurred while the rigs were moving or preparing to move, 20 per cent were caused by well blowouts and fires, and the remaining 20 per cent by hurricane and severe storms;

16/ The newest models cost about $6 to 8 million each, construction time ten to fifteen months.

17/ The units can also sit on the bottom in shallow enough waters.

18/ In the Gulf of Mexico, hurricanes Hilda in 1964 and Betsy in 1960 caused multi-million dollar loss and damage.

19/ The petroleum industry has established a weather prediction service covering the major offshore development areas such as the Gulf of Mexico, Persian Gulf, North Sea. The service is staffed by petroleum engineers further trained in meteorology; advance warnings of about two hours can be given.

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(b) The maiden voyage is a dangerous period. Eleven of the total twenty-five major accidents occurred either at, or on the way to, the rig's first location;

(c) The various prototype rigs have had a relatively high accident rate;

(d) The jack-up rigs are most vulnerable while moving or preparing to move and several have experienced foundation failures on the sea bed or structural failures with the legs and jacks. Three have been lost because the hulls were flooded for one reason or another;

(e) The semi-submersible units have also had a high accident rate;

(f) The submersible barges operating in shallow waters have had a lower accident rate, and there has not been a major accident since 1957. An important reason is that most submersibles have no moving structural members, and many are so designed that they would be difficult to capsize in the shallow water depth for which they are designed.

All the foregoing has increased the insurance cost levied on offshore platforms by the London underwriting market. The rate for a semi-submersible rig is about $1,500 per day. As operations extend into deeper more hostile waters, accidents will continue to be a worrisome problem despite all safety precautions such as highest standard of periodic inspection and maintenance of equipment, most rigorous training and discipline for the crew, and so on. Only the highest trained and most experienced personnel are qualified for large mobile platform operation and special crews with special skills are used in the most difficult task of moving the rig from one location to another.[20/]

B. Drilling operations

With regard to the drill itself, while the classic land-based type of rig has long been used on offshore platforms, and mobile rigs continue to be used for drilling on fixed platforms, semi-fixed or floating platforms require the drill to

20/ The joint committee of Offshore Operators and the American Association of Oilwell Contractors has published a manual of guidelines on stability and safe operating practices as applied to raising, lowering and moving barges of various hull designs.

be a fixed and integral part of the construction. Rather than any radical change, however, adaptation of the drill rig for marine work has occurred as a progressive evolution. In particular, power has been increased considerably to allow for better and quicker drilling with adequate capacity for all ancillary operations and contingencies. A number of factors have here led constructors to prefer diesel electric transmission, which would be considered unduly sophisticated and costly for onshore operations, but permits the design of a compact and relatively light winch/derrick assembly with special advantages in drilling multiple directional wells.[21/]

From the point where the platform has been properly located and positioned, drilling operations are very similar to those performed onshore, allowing for some differences made necessary by the ocean environment.

Spudding-in

This first step in starting the hole presents special problems, particularly in deep-water. It involves the installation of two important components of a marine rig - the marine conductor[22/] (riser system) and the blowout preventer[23/] (BOP stack).

On fixed and semi-fixed platforms the BOP stack and well head equipment are usually installed on the platform above sea level. This is the so-called mudline suspension system in which the casing is also extended from the sea bed to the platform. All mobile platforms rigs use the subsea system in which the BOP stack and wellhead equipment are placed on the sea floor, with the BOP stack operated from the overlying platform by means of hydraulic hose connexions or electric cables.

21/ As well as reducing weight and other advantages, diesel electric transmission reduces congestion in the winch assembly which may be removed from the mud pumps and rotary table alignment without increase of power being necessary. Engines generating 500 to 700 hp generally power the major driving components.

22/ A string of large diameter pipe extending from the wellhead on the seafloor to the drilling platform, providing the necessary water-proof contained and guide for running the drill pipe, casing and tools into the well. It also serves to keep sea water out of the well so that drilling mud and cuttings may be circulated and brought to the platform.

23/ A safety device used to prevent fire and other catastrophies. It normally weighs about 30 tons, is more the 4 metres high, and can close off the well in case excessively high sub-surface pressures associated with natural gas threaten to blow the drilling fluid out of the hole.

With the assistance of a guidance and alignment structure, the marine conductor, BOP stack and associated assemblies are lowered to the sea floor.24/ Most marine drilling locations have a considerable thickness of soft marine ooze on the sea floor, into which the marine conductor is driven to find a good seat in the underlying rock. A string of large diameter casing pipe is then lowered from the surface inside the conductor and cemented in the hole, thus making ready for normal drilling to begin. The drilling string with the drill bit is run through the conductor and BOP assembly and rotated at speeds of 50 to 200 revolutions per minute.25/ Special drilling fluids (drilling mud), often of density twice that of water, are circulated at high speed to cool the drill bit, carry the cuttings out of the hole, stabilize its walls, and contain the high subsurface pressures encountered.26/

When the drilling bit becomes worn, which is frequently, from several hours up to a full day (depending mainly on depth) are required to withdraw all the drill pipes, replace the bit, and return the drilling string to the hole. During the course of drilling, strings of casing are run periodically within the marine conductor and BOP stack and cemented inside the hole. This prevents weaker formations from crumbling and caving protects against high-pressure formations, and makes it possible to re-enter the well for subsequent operations.27/ Co-ordination

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24/ The upper end of the conductor is suspended just below the drilling floor and kept under constant tension by using buoyancy chambers, with top mounted flexible joints allowing some vertical movement (up to 6 metres) of the floating platform, and horizontal displacement up to 5 per cent of water depth. In very rough weather, the control valves on the well may be closed and the marine conductor released from the top of the BOP stack, thus preventing damage to the equipment or rig. Probably 200 metres is about the limit of present marine conductors; there is a need for improved design for deeper conditions with less failures and weather downtime.

25/ A splined joint is usually installed high up in the drilling string to ensure that a constant load, varying from 10 to 35 tons weight, is placed on the bit even when the floating platform moves considerably.

26/ The platform carries a complete standard drilling fluid system, including several hundred tons of chemical for mud control. Circulation is by a number of pumps of up to 1500 hp each.

27/ A typical 3,660 metres (12,000 ft) well requires over 300 tons of casing and over 150 tons of cement.

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and supervision of drilling operations at remote locations have been improved in the last few years by adopting[28/] a micro wave system to transmit to onshore headquarters continuously recorded data such as mud weight, pump pressure and speed, rotary torque and speed, penetration rate, pit level and hook load.

Well testing

Various types of geophysical well-logging are carried out in the intervals when the drilling string is out of the hole, or after its completion. Electric wire-line equipment can be lowered inside the hole to indicate the lithological characteristics of the wall rock and its contained fluids, or to take rock samples. As with drilling data, microwave systems have recently been adopted to transmit logging data to onshore headquarters.[29/] Drill-stem tests are conducted when potential oil or gas producing horizons are encountered. The drill-stem tester is lowered into the well to obtain samples of the representative fluids contained in the strata; the zone of interest may be isolated by setting one or more packing seals at appropriate levels. Completion tests are the final production tests of a well after it has been completed to produce from selected zones.[30/]

Well abandonment

If a well is dry, it is necessary to set cement plugs in the hole and remove all the casing strings and marine conductors to a few metres below the sea bottom, in compliance with safety regulations. High explosives or sand-jetting were used to

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28/ In the Gulf of Mexico.

29/ A small computer on the rig digitizes the log as it is run, and the coded data is transmitted directly to an onshore computer, where it is converted back to the original recognizable form for analysis by the onshore staff.

30/ Large-sized gas-oil separators and flow tanks on the platform, or on a separate tank barge are used to measure and store the considerable quantity of oil, gas and brines produced from the well. Disposal of this material into the sea or atmosphere requires precautions for the prevention of fire and pollution. In well-developed offshore producing areas with many rigs operating in proximity, oil well service companies maintain a number of support vessels to cater for the necessary logging, testing, cementing, aciding, perforating and other services.

sever the casing strings and conductors in earlier years, but large mechanical cutters which can exert a force as great as 300 tons now do the job in less time at lower cost. The BOP stack, wellhead, landing base and guideline alignment structure are recovered leaving the location free of man-made obstacles to navigation.

Drilling costs

The average drilling platform or barge requires an investment of $3 to 9 million. The operating cost of one string-drilling operation, including the use of the platform, ranges from $5 to $7 million per year, that is $15,000 to $20,000 per day, including the cost of supporting vessels and aircraft ($2,000 to $3,000 a day). Rig mobilization, moving, positioning and demobilization may entail another $1 to $2 million per year. Even in the shallow water areas of the continental shelf, daily average operational costs are four times those of comparable land drilling operations. The cost of an exploratory well may range from $350,000 to more than $2 million depending on water depth and location. If oil is found, installation of production facilities make a completed well two or three times more costly than a dry hole. As petroleum exploration is carried further from the shore, the construction of heavier platforms becomes more and more expensive and a major challenge therefore faces the designers of these structures. The present trend towards more expensive units must be reviewed if petroleum activity beyond the continental shelf is to prosper.

Drilling crew

There are normally two complete crews of twenty or thirty men each on the drilling platform at any one time. These include drillers, engineers, stewards and cooks, who work alternate twelve-hour shifts, and are frequently relieved in rotation by a third crew from the onshore base. Extra care must be taken to minimize the accidents caused by working in the confined space and wet conditions of the deck and during the transfer of crews in bad weather. When the seas are too rough to unload bulk materials from ships - sometimes for days on end or for weeks - transportation is limited to helicopter. As well as choosing the type of man who can adapt to work and life on the platforms, the most rigorous training and discipline are essential. To promote safety, regular boat, fire, and blowout prevention drills are conducted, including practice for dispersing the personnel in case of a major hazard.

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C. Oil well completion and production

Oil or gas well completion and production techniques are more complex than drilling operations in the ocean environment. All the producing facilities, either installed above water on on the sea floor, must be designed to withstand the rigours and tremendous extremes of weather during the life of the producing field, which often extends from twenty to fifty years. In addition, flexibility must be built in for convenient operation, maintenance and repair of the producing well. Offshore production facilities were first installed above surface but with the extension of oil exploitation into deeper waters the production systems installed on the ocean floor were developed.

Above-water completion and production systems

In the conventional above-water completion and production systems, casing is extended from the sea floor to the deck of a fixed platform where the conventional BOP stack, wellhead, production "tree" and other facilities are installed. This offers the convenience of quick installation of the simpler equipment with easy access for operation and services. However, the cost of above-water completion increases rapidly with water depth.[31/] In very shallow water areas, above-water completion and production techniques are rather simple and inexpensive. The "single well platform approach" is widely used off Louisiana and Texas in less than ten metres of water, where each well is protected by a small four-pile structure, know as the "well jacket". Production passes through flowlines to a nearby platform where oil and gas are separated and transferred to shore in pipelines.

Large self-contained multi-well, multi-deck production platforms are advantageous for shallow to intermediate water depths up to about seventy metres. They can support from ten to thirty producing wells, including the wellhead equipment, oil-gas separators, dehydration equipment, living quarters, and all the

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31/ In 30 or 40 metres of water an above-water completed well costs about $200,000. In 80 to 100 metres of water, it rises to about $425,000, quite apart from the cost of using a bottom-founded platform.

necessary production facilities. Today, specially designed production structures are used, with the necessary equipment located in the most desirable position on the platform. In some instances, fixed structures with high pressure compressor installations serve as "injection platforms" for returning the natural gas produced, often more than a few million cubic metres per day, through injection wells to the reservoir in order to conserve the reservoir pressure and prolong the producing life of the field.32/

Directional drilling techniques are used when a number of wells are drilled and completed from one platform. Wells are drilled at angles up to 65° from the vertical to tap reservoir locations more than a mile distant from the wellhead. Large oil reservoirs may thus be drained effectively from one or two large platforms. Directional wells are 20 to 40 per cent more expensive than vertical holes but elimination of individual flowlines is a great saving and various production facilities may conveniently be installed on the platform.

To reduce the cost of offshore drilling and production operations, multiple completion is used wherever possible to tap the different producing horizons at the same time. If these are too numerous, a certain number can be exploited during a first phase and others during a second phase of production. Tender-assisted production platforms are generally resorted to in over 70 metres of water, at which depth large self-contained platforms become very expensive.

Oil well servicing and workover (remedial work) are essential for maintaining and regulating oil and gas production at the optimum rate so that maximum return on investment can be achieved. From time to time, the producing wells require down-hole measurements, removal of paraffin and cleaning out, corrosion prevention, prevention of hydrate formation in the gas flowlines, and some means of well stimulation and other remedial action such as perforating and acidizing. Above-water completed wells can conveniently be serviced by various conventional well

32/ The largest offshore installation complex in the world is the Soviet Union's "Neftyanye Kamni" (literally "oil rocks" or "oil city") which was constructed in 1949 in a shallow water petroliferous area of the Caspian sea, 105 km from land. The city consists of numerous bottom-supported platforms, with about 200 km of interwinding wooden trestles providing access. Besides all the drilling and production facilities on the platforms, there are several two-storey hostels, cafes, gymnasiums, and other living facilities to accommodate more than 3,000 people living and working in the city.

maintenance tools and techniques, using workover rigs and wireline techniques in which equipment attached to wireline is run mechanically into the well. The workover rig can be broken down and moved by barge or helicopter to the production platform where it is re-assembled for well servicing.

The water depth record for above-water completed producers increased from 21 metres (70 ft.) to 87 metres (285 ft) between 1948 and 1966. This will be increased further to at least over 120 metres in 1968. Various prototype designs and feasibility studies are being made for greater water depths, and the ultimate technological and economic limitations for deep water bottom-founded production platforms are in fact not yet known.

Ocean floor completion and production systems

The extension of oil exploitation into deeper waters, with the attendant cost of above-water wellheads becoming prohibitively high, has initiated the development of subsea systems for economic and safe completion of producing wells on the ocean floor.[33/] These systems are often required when directional drilling from a single fixed platform cannot reach all parts of a large reservoir, in which case "satellite" underwater completions of peripheral wells yield production which can be gathered at the centralized facilities on the main production platform. Another application is when potential oil reserves are not large enough to justify an expensive production platform, in which case sea-floor completion, with piping to sea or onshore storage facilities, may be used. As presently developed, sub-sea completion in very deep water appears to be rather less expensive than that above water.[34/]

33/ The first ocean floor producer was completed in 1960 off the Peruvian coast; another was completed in 1961 about 2 km off the coast of California, in 40 metres of water, 50 others have since been completed using various underwater techniques.

34/ Initial expenditure of about $60,000; the figure does not depend greatly on water depth.

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Sub-sea systems have attractions in high traffic and hurricane prone areas.[35/] However, servicing and workover operations of underwater producing wells are still very costly, and may involve technical difficulties. While more protection against winds, waves, and fire hazards is afforded by this system and there is less hindrance to ship traffic, it is extremely difficult to get underwater wells under control in the event of blowouts. Choice of system, "sub-sea", or "above-water" depends on many factors - well depth, water depth, sea floor, weather and sea conditions, distance from coast and nearest port, shipping traffic and so on.

The most important component of the sub-sea system is the underwater production tree (Christmas tree). On the termination of drilling operations, the BOP stack is retrieved together with the marine conductor, and the Christmas tree is lowered to the sub-sea wellhead by means of a running string or guide lines. Flow lines and control lines are then connected to the tree, and the guide lines attached to a buoy to mark the location of the well. Most production trees are designed for remote installation by hydraulic control but divers, underwater manipulators and submarine work boats are often required to assist. Closed circuit television is used extensively to check on the position of underwater production components. The valves on the sub-sea production tree are either operated manually by divers or remotely controlled from a centralized production facility by electrohydraulic or hydraulic systems.[36/] Continuous research is being undertaken by the petroleum industry to improve remotely-actuated sub-sea wellhead installation and equipment control and mechanism.

35/ Of over 5,000 large and small installations in the Gulf of Mexico, more than 1,600 are beyond the territorial waters of the United States and the number is increasing. These obstructions to navigation will increase ship collision rate, particularly in darkness and bad weather. A pattern of "fairways" or "approach avenues" has been established as a partial solution.

36/ A recent development is a nuclear powered electric underwater wellhead control system which is designed to operate uninterruptedly for up to three years. Production tree controls are actuated by coded acoustic signals sent out from a central production station located on a platform or on land, and many wells are controlled from the same station.

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Deep diving systems contribute greatly to the over-all success of subsea completion, production, and servicing operations. The "technical diver" is still the oil industry's most reliable and economical tool for underwater work. In shallow waters, divers working with conventional helmets and diving suits can help to connect flowlines and risers, locate and repair pipelines, recover lost equipment, inspect equipment damage, and perform many routine operations. Various power-operated tools and special devices have been designed for use by divers.[37/] As divers go into deeper waters, their ability to do muscular work decreases and future productivity will depend more and more on various tools and manipulator systems, with the diver serving primarily as a set-up man and observer. However, with increasing water depth, more complex manipulator systems will be economically justified.

In 1965, working dives to 166 metres (540 ft) were successfully carried out during drilling operations in the Gulf of Sirte off the coast of Libya and the current spectacular progress with mixed-gas breathing and refined techniques of saturation diving has extended the practical limit for economically useful work to 183 metres (600 ft) or more. This figure will certainly increase. For deep water tasks requiring more than a few hours to complete, the divers are provided with a supporting base to which they may return for rest periods while remaining under pressure.[38/] Although other new systems such as capable robots and subsea work boats are being developed to perform underwater tasks, the particularly tricky maneouver or unforseen situation will continue to require human intervention. The

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37/ For example, a portable ultrasonic probe can check and detect minute cracks and flaws in underwater joints and structural components so that necessary repairs can be made to prevent catastrophic underwater structure failures, and a design of hand-held sonar which extends the diver's range of vision to a radius of 219 metres (720 feet) is a great help in locating underwater installations.

38/ Several variations of the diving bell principle are in use to meet this need. For example, the "Purisima" chamber a pressurized double sphere vessel can carry a diver and an observer down to more than 150 metres. One sphere can be kept near atmospheric pressure and occupied by an observer, and the other kept at water pressure for use by a diver. Other new designs are being developed including the "Cachalot" system which now permits divers to remain for a week or longer at a time in the depth range from 259 metres (850 ft) to 457 metres (1,500 ft).

diver still has one advantage - the sense of touch. Recent studies indicate that the use of certain breathing gases could ultimately extend the safe diving range to 400 metres (1,310 ft) depth, which would eventually make all of the continental shelves and some shallow-water portions of continental slopes accessible to divers. However, more research and development work is needed before divers will be capable of extensive work below 183 metres (600 ft).

Although currently available deep submersibles are not designed for heavy work underwater, several have been used for inspecting submerged oilfield equipment. New designs are now being specially developed for such tasks. Although many of the present subsea work boats are unable to develop enough torque in their mechanical arms to tackle heavy work, it is clear that they will become increasingly useful in underwater oilfield operations.

As subsea oil well operations are extended into deeper water, there is an increasing need to develop underwater-robots - remotely controlled manipulator systems for performing deep water tasks with greater safety and at lower cost. The underwater "Mobot"[39/] (manipulator-operated robot) was the first achievement in this direction. The Mobot is driven electro-hydraulically and controlled through an electrical cable suspended from a surface support vessel. By means of the television and sonar systems installed, the personnel aboard continuously maintain

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39/ Approximately 4 metres high, weighs more than 3 tons, and can be used to depths of 304 metres (1,000 ft). The Mobot is equipped with two underwater television cameras and a sonar, two electrically-operated propellers, a gyro-compass, and a hydrophone. A hydraulically powered socket wrench fixed to a movable arm is the principal work tool; this can loosen and tighten bolts, turn valves, connect underwater cables, replace hoses, handle pipes, and clean fouled mechanisms. The Mobot, and the wellhead equipment it works on, have compatible designs, such as screws of the right size for it to turn and guide rails on the sea floor to ride around the well. In 1962, the Mobot accomplished its first job, without intervention by divers, in the development of a gas field under 73 metres (240 ft), of water off California. An improved more versatile Mobot can be leased for $2,500 per 8-hour day, and $315 per hour overtime. A further development (in 1964) is the Universal Underwater Mobot which has four working arms for multi-purpose underwater operations. Recently, the Institute of Oceanology in the Union of Soviet Socialist Republics has developed a robot with a working depth of 4,000 metres. This device, nick-named "Crab", is equipped with two mechanical arms which can be used to recover geological specimens, train lights and television cameras. It may be capable of assisting in underwater oil field jobs.

visual and acoustic contact so that underwater operations can be precisely directed. It is now used routinely in more than 122 metres (400 ft) of water.40/

The use of undersea robots has made it possible for the shipboard operator to accomplish the necessary work without exposure to the stresses of the deep water environment. The safety and comfort of the operator, and the accessibility of the control desk to technical and supervisory personnel are major advantages in this system. Improved methods and reduced costs will in turn reduce the depth at which robots become more economical than divers using power tools and support equipment.

Subsea well servicing and workover in maintaining subsea wells in continuous production over a number of years poses a problem. Although some routine servicing work can be performed by divers, robots, and small submersibles, complete workovers to remedy any major difficulties encountered inproduction often require expensive and complicated technology. One conventional technique uses stringers or risers, which are placed within the lubricator head of the production tree and extended above the water surface to a mobile platform. The well is thus temporarily transformed into an above-water completed well and the necessary workover can be carried out from a platform or barge by a floating workover rig with wireline units. Another conventional approach uses the "caisson" or "Snorkel Tube" technique which renders the underwater well accessible to inspection and workover in a dry environment. A caisson of appropriate size, usually larger than 1 metre in diameter, is placed over the wellhead and driven deeply into the sea bed or flanged with the wellhead unit. After pumping out the water, the wellhead becomes accessible for repair and workover. Although this technique is more useful in shallow waters less than 30 metres, it has been proposed for depths down to 200 metres.41/

It is obvious that the economic advantage of an underwater completion is soon lost if the subsequent servicing or workover of the well must be carried out above water from a barge or platform with a workover rig. Extensive research has been undertaken by the petroleum industry to develop new less expensive techniques for

40/ As there will be many wellheads and few Mobots, design concepts in this field are on the lines of the wellhead equipment being as simple as possible and the Mobot as complex as necessary.

41/ An unusual application of this method in 1963 has not only accomplished workover jobs but also permanently transformed subsea wells in shallow water into above-water completed wells.

subsea well servicing. It appears that the recently tested "through the flowline technique" using "pump-down" tools will eventually take over from the expensive floating workover units currently used.42/

Completion techniques for high-pressure petroleum reservoirs below the ocean floor in deep water have not yet been developed as a practical proposition. The vast majority of subsea completions have been diver-assisted, and the technology has not yet developed to the stage where subsea completion, production, and servicing operations can be carried out with any degree of regularity. As work moves into deeper water, the demand will grow for improvement of subsea systems with more reliable underwater mechanisms, such as production tree valves and flowline connectors. Continued engineering effort will be needed to substantiate future breakthroughs. In concluding this section it may be said that deep water production problems rather than drilling problems, are the major factors limiting oil exploitation in the ocean environment. It is generally agreed that subsea completion of wells will be the only economical and practical solution below 75 metres (250 ft.) water depth. With refined techniques, this system will also become increasingly attractive for shallow waters.

42/ The pump-down tools are made somewhat flexible so that they can pass through flowline bends of 1.5 metre radius and reach a satellite subsea well 1.6 km distant from the gathering station or the fixed platform. They can be pumped into a tubing string of the well and after completion of the designated work, pumped back through a second flowline. Recent subsea tests have shown that the tools can perform various servicing jobs, such as set and retrieve tubing plugs, remove stuck tools, perforate, acidize, squeeze cement, consolidate sand with plastic, and wash sand from casing below tubing. A new procedure of the "through the flowline technique" is now being developed which would make it possible to plug back a subsea well and "recomplete" the well to produce from a new petroliferous zone.

IV. OCEAN MINING METHODS

Ocean mining operations today are limited to nearshore areas and mostly in protected calm waters and world total production from these operations has shown little change in recent years. At present the activities of mining corporation relating to deep-sea minerals are generally limited to small-scale exploration and some engineering development, while awaiting technological advances, which are to a large extent dependent on increasing knowledge and understanding of the controlling elements in ocean environment. Most investigations to the present have been limited to design concepts and engineering feasibility studies.

However, the picture could quickly change by interlock of ocean mining technology, offshore petroleum technology and other branches of ocean engineering. The development of deep-sea vehicles and undersea stations and some aspects of ocean engineering are being pursued with annual expenditures of several hundred million dollars by the Governments of a few industrialized countries. Future breakthroughs in ocean engineering must be expected to benefit marine mining technology and bring down exploitation costs. Gradual depletion of high-grade land deposits and changes in world demand for minerals will also be stimulants.

It is logical to expect exploitation capability to be developed by progressing outward from shallow waters to the outer shelf and then to the slope and beyond. Despite the high risk, commercial mining in the deep ocean, probably initially for high-valued deposits, will become a reality in the same way as mineral economics have allowed the exploitation of lower-grade land deposits buried at great depth.

Consideration of marine mineral exploitation methods, with particular reference to the bottom resources beyond the continental shelf, involves at the outset some review of the techniques already established and being improved for operations in shallow waters. Modification and adaptation of appropriate components of shallow water technology must play a large part in establishing a base from which deeper-water mineral development will advance. Certain environmental conditions in the latter will however demand many new approaches to resolve problems not encountered previously.

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A. Water dredging methods

It is appropriate to review briefly some techniques of offshore exploitation of placers and other unconsolidated deposits in shallow water, before considering their possible application in the deeper sea environment of the continental slope and the abyssal floor beyond. For all practical purposes, this limits discussion to the various dredging methods used in working these offshore deposits, which can be expected to have some application in developing methods for mining surficial deposits such as phosphorite and manganese nodules.

Placers and other unconsolidated deposits have been commercially exploited for many years in a number of calm shallow-water areas in various parts of the world. Today there are over seventy offshore dredging operations actively exploiting such diverse materials as sand and gravel, lime shells, diamonds, gold, tin, iron and other heavy mineral sands for zircon and titanium minerals. In recent years the mining of placer deposits nearshore has become the most widely publicized facet of ocean resources utilization, largely because of the sudden awareness of the immediate potential of these shallow-water unconsolidated deposits and the future potential of phosphorite and manganese nodules in deep-water.

Offshore dredges currently used in shallow-water are largely modifications of a few types of conventional land mining equipment; they are unsophisticated but still more costly than similar equipment for operations onshore. The economics of offshore dredging operations are dictated by many conditions such as low offshore production rates and an extremely wide range of dredging costs. As a general rule, however, the greater the throughput, the lower is the unit cost.1/

The current types of offshore dredges are the clamshell dredge, the bucket-ladder dredge, and those employing the hydraulic system, namely the air-lift dredge and the suction dredge.

1/ Offshore dredging operations range in throughput from 2,500 to 350,000 cubic yards (1,912 to 267,760 cubic metres) per month, at a cost of $0.15 to $74.50/cubic yard ($0.20 to $97.40 per cubic metre). In contrast, typical onshore operations range in throughput from 100,000 to 500,000 cubic yards (76,500 to 382,500 cubic metres) per month, at a cost of $0.08 to $0.25 per cubic yard ($0.10 to $0.33 per cubic metre) (Romanovitz, Cruickshand and Overall, 1967).

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The clamshell dredges use large grab buckets, clamshells, and other digging and lifting tools, suspended on steel cables and lowered to the sea floor where they can bite into the unconsolidated bottom material and contain the load within the closed shell. The bucket and load are then hoisted above water where the shell is opened to dump the load. Clamshell dredges are well suited for working in moderately deep waters and in waters with high current velocities and high wave motion. The advantages of this type of dredge are ability to operate in different depths of water with no major adjustment to the equipment, ease of changing of bucket types as digging conditions require, and low maintenance cost.

Bucket-ladder dredges use an endless chain of steel buckets which dig into the bottom material below the level of the floating dredge. The dredged material is continuously drawn up the ladder, dumped into a hopper, and then fed to various screening and concentrating devices aboard the dredge vessel to separate the valuable minerals. The tailings are discharged to the rear as the vessel proceeds forward through the deposits, by hauling in on anchored headlines. Bucket-ladder dredges have good digging ability and allow excavation of moderately hard strata, which is highly advantageous in placer mining, because the high values are often concentrated on or immediately above the bedrock surface. They are however severely limited by water depth and sea conditions.

Air-lift dredging works on the principle that air injected into the bottom of a pipe, submerged at least 60 per cent of its length in water, will produce a density differential in the pipe, which forces the column of air-water mixture to flow upward in the pipe. This flow creates a powerful suction at the bottom end of the pipe, capable of bringing up silt, sand, gravel and boulders together with tons of water. Air-lifts are about as simple as any dredge device can be. Their essential mechanism consists of two pipes, and they may be constructed on the site with limited shop facilities and require only compressed air to operate. However, when operated without the assistance of water jets and other devices, air-lifts are extremely inefficient. The depth at which air-lifts can be used is severely limited as the cost of supplying compressed air increases with the depth of dredging (Mero, 1965).

In the suction dredge, a movable suction pipe with a support ladder, pumps with meters and controls, and a discharge line are mounted on a floating hull. Commonly, when digging in semi-consolidated sediments or soft to medium hard rocks, a cutter head, normally of the rotating hollow bit type, is mounted on the lower end of the suction pipe, to break up the ground and direct the flow of solids into the suction pipe. During dredging operations, the vessel is generally anchored at the stern by hawsers, or by spuds driven into the bottom, and the vessel is swung in an arc from the point of anchorage to give a maximum sweep to the cutting and suction mechanisms.

Of the four types of dredge outlined above, the clamshell could conceivably be developed for deeper sea work but apart from other factors the time spent in raising and lowering the bucket would increase costs considerably and probably prohibitively. The bucket-ladder principle is even more unlikely to be adapted, as it is essentially a shallow water concept. Recent improvements in size and capacity of hydraulic suction dredges for engineering construction work has caused renewed interest in their application for offshore mining work, and preliminary designs have been made for recovery of sea floor nodule deposits at depths greater than 4,000 feet using this method. At such depths it will probably be necessary to establish additional pumping capacity submerged near to the intake. Hydraulic dredging will almost certainly be applied in deep sea mineral recovery, to a much greater extent than any of the other methods just described.

Sea and weather conditions cause considerable loss of time in offshore mining operations. The problem is more acute in offshore mining than in petroleum production, because the former requires flexibility and mobility of equipment whereas petroleum is largely produced using fixed installations that can withstand extremes of weather and sea conditions. As long as operations are conducted from the air-sea interface, ocean miners may be compelled to adhere to a "hit-and-run" philosophy using equipment designed for quick mobilization and demobilization. On the other hand, the mobility and flexibility of the present-day dredges offer major advantages in offshore mining, as many vessels developed for one type of shallow-water placer operation may easily be moved for long distances to mine a different material at another location.

B. Deep-water mining systems and their components

The lack of precise information on the characteristics of marine mineral deposits, on the marine environmental conditions and on the performance of mining equipment in this environment, greatly hinders accurate planning of the complex mining operations in deep water. In examining the technological and economic requirements as well as the deficiencies of available equipment, several industrial corporations and governmental organizations now emphasize a parametric or system approach, in which the various components and links are examined critically in logical sequence to determine alternative solutions and bring to light technological gaps. Components may then be synthesized into "candidate systems", for which technical feasibility and costs are evaluated (Welling, 1966). This leads to an optimized design for a set of precise and definitive parameters. It may only be accomplished, however, by close study of the fundamental relationship between factors which are natural and fixed and components which can be adapted and controlled (Romanovitz, Cruickshank and Overall, 1967).

Factors which are natural and fixed

These are mainly the characteristics of marine mineral deposits and the marine environmental elements.

Characteristics of unconsolidated deposits embrace many elements such as the range of material sizes, abundance and distribution of ore, specific gravity of ore, overburden thickness, and properties of the ore and gangue minerals. All of these influence the choice of excavating and lifting tools and beneficiation processes, as indeed they also do on land. There is however a lack of knowledge of the physical properties of placer deposits even on land and an almost complete absence of knowledge of the subject offshore.

Ocean environmental elements will largely determine the choice and design of the various components constituting undersea mining systems (Romanovitz, Cruickshank and Overall, 1967). These include the dynamic aspects of water motion, particularly where the ocean's upper boundary meets the atmosphere, water depth, sea water corrosion and fouling characteristics, sea-floor topography and foundation characteristics, and distance from the mining site to shore facilities.

Although water motion and water depth are the only two of these elements not involved in onshore placer dredging, the effects of the other factors, such as water corrosion, bottom topography, foundation characteristics and trafficability of the bottom, become more acute in ocean mining.

Components which can be adapted and controlled

There are essentially six components involved in "mining systems" for surficial unconsolidated deposits, namely excavating, lifting, supporting platform, mining control, beneficiation and disposal of products and wastes (Romanovitz, Cruickshank and Overall, 1967).

Of the existing methods of dredge excavation outlined previously, the clamshell and bucket-ladder devices are not affected by being immersed in water, the hydro-jet devices are not as efficient in water as on dry land, while the suction devices are of course unique to a submerged system.

Regarding the lifting components, all the designs with a rigid connexion to a surface platform, such as the dipper, the bucket-ladder and the suction ladder, are severely restricted with respect to depth capabilities and water motion. By contrast, the wire-line equipment and flexible hydraulic lines are not much limited in these respects.

The possible choices of platform include many available types of floating vessels, semi-submersibles, submarines, above-water platforms with bottom support- (fixed platforms and mobile pack-up platforms), and undersea bottom vehicle. Selection depends on the stability required, mobility, work space, and prevailing sea conditions. However, many of these platform designs have not yet been utilized in offshore mining. It would be highly desirable to utilize in mining systems the platform design knowledge that has gradually been acquired by the petroleum industry at an offshore investment of several thousand million dollars.

As regard mining control components, all rigid types such as headlines, spuds driven into the sea-bed, and platform legs, have severe depth limitations. Dynamic positioning and other flexible controls also present problems. Thus, new designs are needed to cope with the combined effects of water motion and water depth.

In most offshore placer dredging operations, beneficiation is carried out aboard the dredging vessel or on a floating barge nearby. Choice of methods depends largely on the characteristics of the mineral deposit, but because of the violent motions to be expected in the open sea, it is generally restricted to those processes not requiring complete stability such as washing, sizing, comminution, flotation, amalgamation and gravity and magnetic separations of a limited nature (Welling and Cruickshank, 1956).

Waste disposal will present a problem when mining in deep water far from shore, as it may be necessary to transport tailings to remote areas to prevent contamination in the mining zone. Indiscriminate waste disposal could also affect fish life. By contrast, dredging near shore permits the tailings to be pipelined either for replenishing beach sands or for land reclamation use.

To the preceding components should be added transportation. This is however a lesser problem because of the advantageous low cost of sea transport. Direct pipeline discharge to shore facilities can also be considered. The cost of handling and transportation must of course be weighed against the cost of reducing the bulk on site by beneficiation. Many factors such as the availability of power, docking facilities, distance to smelter, and production rates will influence decisions in these matters (Welling and Cruickshank, 1956). In future deep-sea mining it would also be possible to stockpile the recovered material in underwater sumps in suitably adjacent areas. In future mining of deep-sea nodules, the topographic depressions on seamounts are indicated locations for such underwater ore sumps.2/

C. Some recent devices for deep-sea mining

Certain recent devices of possible application in future ocean mining have been incorporated in design studies of possible systems. The least complex is the Towed mining device system developed in the United States of America in which a dredge head (air lift or suction dredge) mounted on a wheeled vehicle or sled would be towed along the ocean floor by a flexible pipeline secured to a surface vessel or dredge platform. The direction and speed of the mining device would thus be controlled by the heading and speed of the surface ship. An underwater acoustic

2/ There have also been proposals to use seamounts as sites for automatic oceanographic stations, undersea navigation network, and manned undersea installations.

system, with several transponders anchored on the sea floor is proposed to monitor the position of the mining device relative to the bottom area being mined. The ore, together with waste material could be dredged from depths down to a few thousand metres and pipelined to the surface for loading into ore barges and transfer to onshore facilities. Some beneficiation at sea prior to ore transfer to the transport barges may also be accomplished. A similar deep-sea dredging system designed in Canada particularly for recovery of manganese nodules (Ball, 1967), uses a light-weight media such as kerosene, instead of air-lift or suction, to actuate an upward flow through a conduit running from the ocean bottom to the sea surface. A very high flow velocity lifts the heavy nodules faster than they can sink through the stream.3/

Another deep-sea hydraulic dredge design operated from a surface vessel would be self-supported and consist essentially of a flexible pipeline, a submerged float, a submerged pump and motor, and a pick-up head (Mero, 1965 and 1967). The capital cost of such a system, including research and development of a mining control vessel, has been estimated at about $10 million. The capital investment indicated for the necessary processing and transport systems is about $100 million to $150 million (Mero, 1967). The go-ahead for such a system would probably depend among other factors on a breakthrough in metallurgical extraction technology to permit commercial utilization of manganese nodules.

One of the more sophisticated ocean mining approaches is the self-propelled bottom mobile mining system developed in the United States of America in which a suction dredge is mounted on a bottom mobile crawler or wheeled vehicle. The device can be precisely navigated and moved along the desired mining path without

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3/ On reaching the surface, the mixture of nodules, kerosene and sea water is discharged onto a screen to separate the nodules, and the kerosene and sea water is separated in a settling tank. The kerosene is filtered and recycled through the pumping unit. A self-propelled surface vessel is used to control the major submerged components, including a dredge for scraping nodules from the sea floor, a size segregator or screen to prevent oversized nodules from entering the duct, a vertical duct for raising nodules to the surface and a parallel pipe to carry light-weight media from the surface to the mixing-chamber in the lower portion of the main duct. Another vessel, an ocean-going tug, is employed to tow the dredge along the ocean floor.

traversing a previously mined-out area and without leaving any unmined strips. It may be controlled to mine deposits of varying thickness. The power necessary for mobility, navigation, and dredging operations is supplied by cable from the mining control vessel at surface. The dredge material can be hydraulic - or air - lifted in a pipeline to the surface where it is loaded into barges, or piped directly to shore facilities.

Another advanced more versatile concept is the Buoyant submersible mobile mining system consisting essentially of a submersible hydraulic dredge vehicle and a number of submersible ore hoppers. Both the vehicle and the hoppers can be maintained almost neutrally buoyant under water, either by incorporating propellors along the side of the structure, or by maintaining air in free-flooding buoyancy chambers. Power is supplied to the vehicle and hoppers by cables from the surface ship. Ore is recovered by the hydraulic dredge vehicle and loaded into the hoppers which are raised to the surface for unloading by means of buoyancy tanks. The empty hopper can then be winched downward along a wireline attached to the dredge vehicle and reseated in the vehicle for reloading. In another concept, all the hoppers are filled and the entire vehicle/hopper unit is then brought to surface for unloading at sea directly to shore facilities.

V. PROBLEMS RELATING TO MARINE MINERAL DEVELOPMENT BEYOND THE CONTINENTAL SHELF WHICH REQUIRE SPECIAL ATTENTION

The advance of marine mineral development in the interests of mankind requires that special attention be given over the next few years to two main series of problems - those related to research activities and those of a jurisdictional nature.

A. Need for further scientific and technological research

As has been stated in previous chapters of this report there is great ingenuity in the design and construction of new techniques and devices for the exploration, evaluation and exploitation of mineral resources in the ocean environment. Research continues and will be intensified over the coming years. There is no reason to doubt that further advances would be made, which would be reported to the Council at the appropriate time.

It must however be stressed that the engineering development necessary for further progress will depend greatly on more specific knowledge being gained on the sea floor and its characteristics, on the nature and origin of marine mineral deposits and on marine environmental conditions.

The sea floor

Much more data on the ocean bottom relief than are available at present are required for the planning of certain stages of mineral evaluation and all aspects of exploitation using the sea floor as a load-bearing media. These include all relief features such as slopes, outcropping rock ledges, cliffs, overhangs, gullies and flat areas, which are most conveniently portrayed by bathymetric charts. Present-day assessment indicates that at a chart scale of 1:1,000,000 only 15 to 20 per cent of the sea area is adequately covered by bathymetric data;[1/] such is the paucity of our knowledge of submarine topography.

1/ According to a study carried out by the International Hydrographic Bureau in Monaco, sufficient bathymetric data for a chart scale of 1:1,000,000 exist for only 15 per cent to 20 per cent of the sea area. The data are definitely insufficient for 35 per cent to 40 per cent of the area, and for the remaining 40 per cent to 50 per cent are either entirely lacking or very scarce. If charts at larger scales are considered, and these will certainly be required in areas selected for detailed studies, the results are even more disappointing.

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The bearing strength, shearing properties, stability and other characteristics of the bottom sediments must also be determined, in order to assess their mechanical properties and capacity for supporting the expected loads, to predict the amount of settlement to be expected, and estimate the possibilities of scouring, turbidity currents, slumps, submarine landslides and slope failures.

Geological setting

Particularly in the case of petroleum, natural gas, sulphur and other minerals associated with bedrock now buried at considerable depths below the sea floor, the search for new deposits will depend for orientation on an adequate appreciation of the geological history of the survey area, depicted in the form of geological maps in sufficient detail. It must be said that at present even the geology of the continental shelves of the world has been little investigated and is poorly understood; far less is known about the continental slopes and the continental rises which constitute a zone of transition between the continents and the ocean basins.

Again, continued research is needed on factors governing the origin and distribution of manganese nodules and other surficial deposits, as for example the circulation and associated physical, chemical and biological processes controlling the formation of marine phosphate.

Marine environmental conditions

It has been mentioned in a previous chapter that the installations and facilities required for marine mineral development must be structures designed to withstand the dynamic forces that affect the ocean contents as a whole.

As is the case in harvesting the seas living resources, progress is retarded by inadequate knowledge of controlling factors, for example the dynamic and thermal interactions taking place between the ocean and the atmosphere and certain water variables such as temperature and salinity. The interdependence of the oceanic and atmospheric environments, with their great interchange of energy and material, renders impossible the study of either one in isolation. As an example heat energy contained within the ocean influences air currents, which as prevailing winds activate water currents.

It would not be appropriate in this report to review in detail the many elements which will affect equipment and control activities in the marine environment; these include temperature, pressure, buoyancy, corrosion, accoustic and electromagnetic properties, icing characteristics and many other chemical, geological and technical factors. Increased knowledge and understanding is required in all of them and it is therefore essential that systematic effort in these various domains be encouraged by Governments and institutions, national as well as international, and the world community kept informed of the progress made.

B. Promotion of mineral development and jurisdictional issues

Although the knowledge of marine mineral deposits and appropriate methods for their development in various environmental conditions is indeed very incomplete, it is, nevertheless, true that current technology is already capable of locating, evaluating and exploiting undersea minerals in a number of cases, which can be expected to increase noticeably over the next decade.

In the existing circumstances, a major deterrent to initiative in advancing marine mineral development is the absence of a proper jurisdictional framework which will guarantee to mining ventures the economic security they are entitled to expect, as well as safeguard the interests of other legitimate activities.2/

Investment scale and risks

The cost of operations carried out to locate and evaluate mineral deposits under the sea is higher than on land and it cannot be anticipated without reasonable expectation of economic exploitation. Again, the costs of exploitation of minerals under the sea are expected to be much higher than similar ventures on land. Not only will the various operations require a high degree of technological competence in many areas, but tens of millions of dollars and even more will in fact be necessary for initial investment in ships and equipment, design and construction of processing plants and other facilities. Only the very largest organizations in a few industrialized countries are capable of responding to such a challenge. The economics of ocean mineral exploitation depend a great deal on the distance to onshore bases and to market. For large-scale mineral recovery

2/ This chapter is based on views and ideas expressed in articles written by Dr. Francis T. Christy of Resources for the Future, Inc.

operations at sea, it is essential to provide optimum-designed systems for transmitting the required energy or generating it on site, for shipping great quantities of raw materials to shore facilities via pipelines or surface vessels, for transporting equipment and personnel, and for maintaining communications. The costs of such supporting services increase appreciably as development is carried further from shore into the deeper ocean. This being the case, it is clear that marine mineral development will only be justified if high-valued products are to be recovered, at a cost which will permit competitive marketing.3/

For any entrepreneur proposing to embark on such a venture, a major concern will surely be to obtain maximum security for the investment, in the first instance by obtaining exclusive rights to a sufficiently large area for a sufficient length of time to offer the prospect of a fair return. Several methods and procedures by which rights might be allocated have been suggested; however, all of them presuppose administrative machinery to which the entrepreneur can address himself to obtain exploration permits, evaluation licences and exploitation rights, as may be necessary for the operations proposed.4/

Safeguarding against harmful effects

As already mentioned, the size of enterprise and the scale of production expected will have to be extremely large for economic viability. The situation

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3/ This may not apply to the special case of strategic minerals.

4/ Most national legislation require exploration ventures to be carried out under the provisions of a permit issued by appropriate administrative authorities; a major objective is to identify and assess the suitability of the applicant and ensure a certain order in his activities. An exploration permit is generally granted for a specified period of time and may cover a relatively large area. Its nature may be general or restricted to the search for particular minerals and no exclusive rights are entailed.

Evaluation licences, sometimes granted as "exclusive prospecting licences", generally cover much more restricted areas, precisely defined, for the period of time deemed sufficient to complete the necessary work. Supervision over the terms of the licence is exercised by the competent government authority. In most existing legislations, these licences carry the right to future exploitation of the ore discovered.

Exploitation rights vary in form according to types of minerals involved and national legal traditions; the rights of the entrepreneur are defined and granted for a fixed period of time. The exploitation licence normally carries the obligation for its holder to demonstrate the effectiveness of mining operations in order to justify periodic renewal of the lease. Non-observance, or equally non-payment of taxes or royalties stipulated, can result in the licence being revoked.

could therefore arise where the world market for the minerals involved would be strongly affected.[5/] This could be particularly harmful to those developing countries relying on the production of related commodities.

Finally, the operations required in evaluating specific deposits, and much more so those necessary for their exploitation may seriously affect environmental conditions - for example, pollution may be caused - and, consequently, affect other activities in the neighbourhood, such as communications through cables in the sea, shipping, fishing etc.

In such circumstances, any administrative machinery set up for the over-all control of mineral development and the guarantee of economic security to those entrepreneurs engaged in its operations, would require to be very broadly based, with extensive powers and responsibilities. Furthermore, it would have to be established in such a way that the international community would recognize its authority, the system of allocation adopted, the rate of royalties or fees to be levied, as well as the use of the latter.

A jurisdictional régime

Intimately connected with the administrative issues which have been mentioned above is the question of the way in which jurisdiction is to be exercised over mineral resources lying on and under the sea floor beyond the continental shelf.

With regard to the continental shelf itself, the question of rights for exploration and exploitation of its natural resources was made clear when the Convention on the Continental Shelf was adopted during the United Nations Conference on the Law of the Sea, held in Geneva from 24 February to 27 April 1958.[6/]

5/ According to David B. Brooks in "Low-Grade and Non-Conventional Sources of Manganese", the amount of manganese, for example, thrown on the market by a single producer might be so great that the price would drop from 90 cts. per unit (1963 price) to 50 cts. The cobalt price might drop from $1.50 per pound to $1.00 and nickel from 70 cts. to 65 cts. a pound. Such actions by two or three producers would, of course, have even greater effect.

6/ The Convention became effective as of 10 June 1964. At the end of 1967, sixty-two States were part of it. Article 2 of the Convention stipulates: "The coastal State exercises over the continental shelf sovereign rights for the purpose of exploring it and exploiting its natural resources".

However, as defined by the Convention, the question of where the outer limit of the continental shelf occurs, and, consequently, where the exclusive rights of the riparian countries cease to apply, remains practically open.7/

It would therefore be necessary to arrive in the near future at a more precise definition for the outer limit of the continental shelves of the world, which should be laid down by the international community to the satisfaction of all countries concerned.

Whatever results may be obtained, the crux of the matter is essentially that of the jurisdiction under which the resources lying on and under the sea floor beyond the continental shelf are to be placed. This requires early consideration and decision at the international level.

Specific proposals

Several alternatives have been proposed and discussed in legal and technical publications, as well as in numerous meetings held during the past two years. They were reflected in the debates of the twenty-second session of the General Assembly. As such it seems appropriate to summarize them briefly for the information of the Economic and Social Council.

It has been suggested for instance that the establishment of a jurisdictional regime should be delayed until more experience has been gained in the actual development of mining operations.8/ It was stressed however that this would leave the solution in the hands of chance and allow particular *de facto* situations to complicate unduly the possibility of obtaining agreement at the world level.

Another proposal was to apply the *national lake concept*, according to which a coastal State would extend its jurisdiction across the deep-sea floor as far as the midway line between it and the coastal States opposite to it "Where the depth

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7/ According to article 1 of the Convention, "The term 'continental shelf' is used as referring (a) to the sea-bed and subsoil of the submarine areas adjacent to the coast but outside the area of territorial sea, to a depth of 200 metres or, beyond that limit, to where the depth of the superjacent waters admits of the exploitation of the natural resources of the said areas; (b) to the sea-bed and subsoil of similar submarine areas adjacent to the coasts of islands".

8/ It should be noted in this respect that leases have already been granted by riparian countries well beyond the continental shelf and the greater the delay, the more complicated the issues will become.

of superjacent water admits of the exploitation of natural resources". It was argued however that this would evidently favour countries with coastlines bordering several seas and oceans, in contradistinction with those not enjoying such geographical positions; that considerable advantage would accrue to those countries under whose domain are a number of islands scattered in various parts of the world; and that sharing of the ocean floor on such a basis would, in addition, exclude land-locked countries from any of the benefits to be derived in exploiting its resources.

Others suggested that a national flag solution be adopted to identify the jurdsiction which ought to have plenary control over the development of the resources so discovered. In this concept it was contended that it would be sufficient to recognize the flag of the craft or other surface mechanism from which the evaluation and/or the exploitation is controlled. This, evidentally, would require that the entrepreneur receive the full protection of the country whose flag he flies. Opponents to this solution retorted that it would more or less recreate situations of a colonial character which may lead to serious political difficulties among nations.

From the articles and reports on the debates relating to the question, it appeared that the adoption of either of the solutions outlined above would make it very difficult to deal satisfactorily with the problems mentioned earlier, such as the rate of output, which must be controlled in order not to affect adversely the world market; due respect for other recognized international operations such as cable communications, shipping, fishing, etc.; not to mention the danger of environmental pollution and the general interests of developing countries, whether they possess a seaboard or are land-locked.

In this context, another alternative has often been suggested, namely, the international régime, according to which one public international body having jurisdiction over the resources on and under the sea floor beyond the continental shelf would be established. The advocates of this solution contend that it would come closest to meeting the various requirements and legitimate aspirations already mentioned. They add too that it would, more likely be acceptable over the long term, better able to protect the interests of those providing the investment and encourage economically efficient operations.

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In other words, the proponents of the international regime approach consider it to be the one which incorporates the necessary ingredients which should be acceptable to all concerned - developed and developing countries, coastal States and land-locked countries. They say that if properly established, the international regime would provide an orderly system by which the developed countries could exploit the deep-sea floor on reasonable terms, with a better and certainly cheaper guarantee of exclusive rights than would be possible under any other approach discussed above, at the same time permitting the non-exploiting nations to participate in the benefits through sharing in the royalties obtained.

An attempt has been made in this chapter to identify and review briefly the main sectors in which our present state of knowledge and experience falls short of that necessary to stimulate development of mineral resources beyond the continental shelf.

Some of the present gaps are essentially of a technological nature, or the way in which to cope with the complexity of marine environmental conditions. The paucity of our knowledge of submarine topography and the related need for intensified mapping of the sea floor have been noted as well as our lack of information on the nature and distribution of deposits. Finally, problems of an institutional and administrative nature have been raised.

We are not however in a static situation but rather in a period of continuous activity and endeavour which needs to be followed closely. The Council may therefore wish to urge Governments and organizations concerned to continue and increase their efforts, and request that it be kept informed regularly on the progress obtained in the various domains relating to marine mineral resources development.
