

Resources of the Sea

MINERALS FROM THE OCEANS

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(with nine tables, eight text-figures and three plates)

ABSTRACT

Mineral resources are present offshore either as bedrock or superficial deposits. Bedrock deposits include petroleum, coal, sulphur, evaporites, and metals. Many of these deposits can be exploited in shallow water using currently-available technology including drilling platforms, solution extraction, and underground mining from onshore installations which extend offshore. Genetically, there are two kinds of superficial deposits; those which formed on the continent but which were subsequently submerged by the post-glacial rise in sea level (lateritic deposits and some types of placer deposits), and those which have formed under submarine conditions at the present time or in the recent past. Deposits of this second group include construction materials, some placer deposits, phosphorites, and glauconite, all of which are found primarily on the shelf and upper slope; and deposits of the deeper oceans, including deep-sea oozes, manganese nodules, and metalliferous muds and brines. Dredging techniques are used for exploiting superficial deposits in shallow waters; various types of dredges are being tested, or are planned for the deeper-water deposits. Although it is probable that many offshore mineral deposits will not be exploited in the near future, they nevertheless constitute long-term resources of considerable importance.

INTRODUCTION

In response to a growing awareness of the finite nature of onshore mineral deposits and the great technological advances of the past 20 to 30 years, man's attention is turning increasingly to the mineral resources of the oceans. The oceans cover 70.8 percent of the earth's surface (table 1). Much of this area is still relatively unknown, but already we know of many mineral deposits on the underlying seafloor. The ocean is not however a vast cornucopia of minerals just waiting to be exploited. The costs of developing an offshore mineral deposit are generally very considerable. Most of the known deposits are unlikely to be developed during this century. Nevertheless they may constitute an important resource for the future and each will be examined here briefly, whether development is imminent or not.

Before discussing the mineral deposits, it is necessary to consider first the various geological and physiographic divisions of the earth, and particularly the oceans, because of the bearing these have on mineral potential. The crust is divided into oceanic crust and continental crust. The continental crust is composed of light sialic rocks, and underlies the continent and the continental margin including the continental shelf, the slope, and possibly the rise, (fig.14 ). Oceanic crust underlies the deeper abyssal regions of the oceans; it is iron-rich, and generally basaltic. Thus physiographically and geologically there are two different provinces, each with its own particular features and mineral potential (fig. 15). The continental margins which extend from the high water mark to the base of the slope at a depth of 4000-5000 m have many geological (and mineral) affinities with the onshore continental mass. The continental shelf in particular is commonly underlain by much the same geological succession as is present in the adjacent onshore area. The abyssal zone on the other hand has many unique features, particularly the very slow rate of sedimentation in most deep-water areas, and the attendant thin sedimentary sequence (seldom more than 1000 m, commonly very much less). This is reflected in the fact that the mineral deposits

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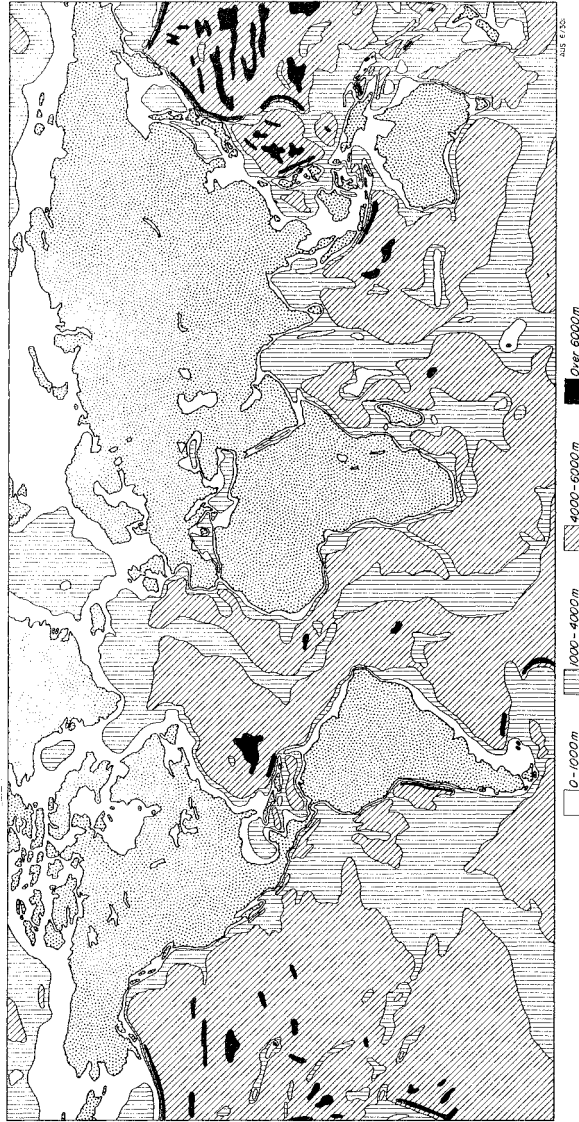


FIG. 14. - Bathymetry of the oceans.

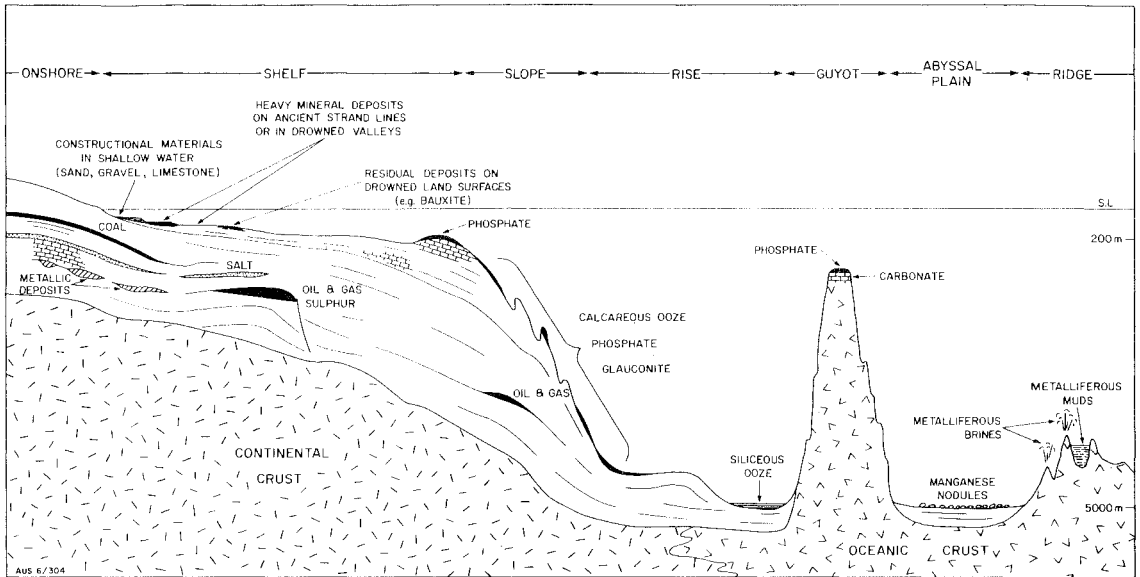


FIG. 15. - Schematic representation of the structure of the continental margin and adjacent ocean, and the location of mineral deposits.

TABLE 1

AREAS OF MAJOR PHYSIOGRAPHIC FEATURES OF THE WORLD'S OCEANS (after Menard and Smith 1966)

	area (millions of km <sup>2</sup> )	percentage of the seafloor
Land	143	-
Ocean	362	-
Continental shelf	27.1	7.5
Continental slope	28.3	7.8
Continental rise	19.2	5.3
Mid ocean ridges	118.6	32.7
Abyssal plain	151.5	41.8
Trench & associated features	6.1	1.7
Miscellaneous (volcanoes, etc.)	11.2	3.2

found in the deep oceans are rather different from those found on land or on the continental margin.

Reviews of offshore minerals published in recent years include those by Emery and Noakes (1969), McKelvey and Wang (1969), Mero (1965), Noakes (1970), Noakes and Jones (1975), Keiffer (1968) and the United Nations (1970, 1972). A number of these publications also deal with technological, economic and legal aspects of offshore mineral deposits. In this brief review I shall deal primarily with the occurrence and genesis of offshore mineral deposits, and where possible will consider Australian examples.

TABLE 2  
OFFSHORE MINERAL DEPOSITS

ENVIRONMENT	SUPERFICIAL		BEDROCK	
	TYPE OF DEPOSIT	EXAMPLE	TYPE OF DEPOSIT	EXAMPLE
CONTINENTAL  SHELF	bauxite (chemical) lateritic iron(weathering) gold, tin, diamonds (placer) gravel (construction)	Solomon Island SE Asia, SW Africa North Sea	oil and gas coal metalliferous deposits	Bass Strait, North Sea Europe SW England
	rutile, zircon (mineral sands) siliceous sand (construction) carbonate reef and sand manganese nodules phosphorite	E Australia E U.S.A. Queensland British Columbia NW Tasmania; SW Africa	sulphur evaporites	Gulf of Mexico North Sea
CONTINENTAL  SLOPE  AND  RISE	barite nodules manganese nodules and crusts glauconite phosphorite carbonate mud and ooze	Indonesia Pacific New Zealand Chile	oil and gas metalliferous sulphur evaporites	Gulf of Mexico, N Atlantic Tasmania Gulf of Mexico Red Sea
DEEP OCEAN (ABYSSAL PLAIN AND SEAMOUNT MID-OCEAN RIDGE, TRENCH)	phosphorite ) carbonate reef) glauconite siliceous ooze carbonate ooze metalliferous muds and brines manganese nodules	E Indian Ocean Central Pacific Pacific widespread widespread Red Sea; E Pacific Central Pacific	oil and gas evaporites	Sigsbee Knolls Red Sea

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## TYPES OF OFFSHORE DEPOSITS

The two basic types of offshore mineral deposits are termed here "superficial" and "bedrock" (table 2). Superficial deposits are located on the seafloor and generally extend no more than a few metres below the sediment-water interface. They have formed predominantly, though not exclusively, in response to marine conditions prevailing at the present time or in the fairly recent past. A small group of superficial deposits are, however, the submerged counterparts of onshore deposits; these include lateritic iron and bauxite, both the product of lateritic weathering; placer deposits such as gold, tin and diamonds, which are found in drowned river gravels or drowned glacial outwash deposits. Bedrock deposits occur at depths of up to thousands of metres below the sediment-water interface and represent the sub-aqueous equivalent of onshore mineral deposits, including petroleum, coal, metalliferous deposits, sulphur and evaporites. Deposits of this type appear to be abundant under the shelf, present to a lesser extent under the slope and possibly the rise, and rare to absent in the abyssal zone (fig. 16).

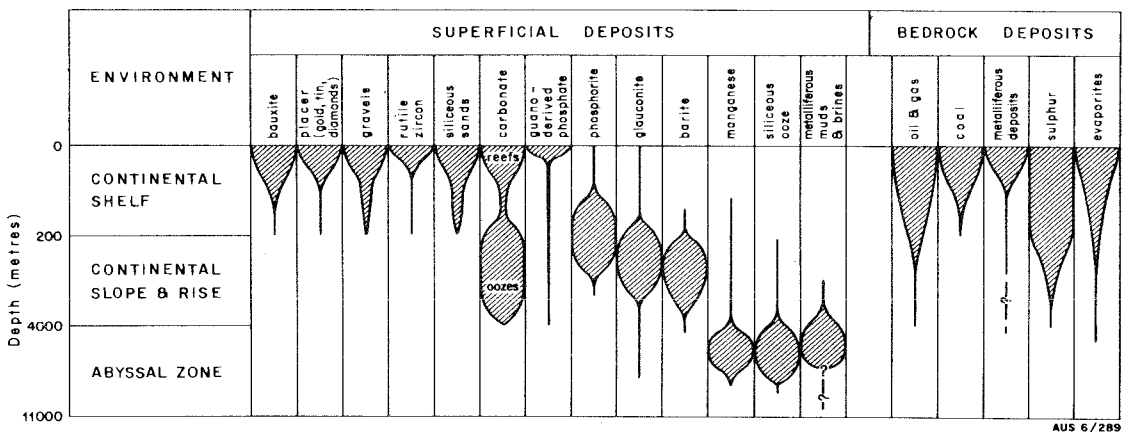


FIG. 16. - Vertical extent of offshore mineral deposits.

### Bedrock Deposits

Petroleum: Petroleum is dealt with by Hopkins (this volume) and is not considered in detail here. Weeks (1969) has estimated that proven offshore recoverable reserves are of the order of 90 billion barrels. Total reserves are likely to be considerably in excess of this but our present lack of knowledge of the deeper-water sediments inhibits our ability to give an accurate forecast. The sediments underlying the outer shelf and the slope are likely to contain major petroleum fields in many parts of the world. Foundered portions of the continental margin, such as the Exmouth Plateau off north-western Australia, may be important petroleum producers in the future. Little is known about the sediments of the continental rise, although Emery (1969) considers that there is likely to be a lack of suitable reservoir rocks in these sediments. The sediments of the abyssal zone are generally too thin and commonly too poor in organic material to constitute good potential petroleum producers. Nevertheless they cannot be completely discounted as oil and gas has been penetrated in deep water during the course of the Deep Sea Drilling Project. This includes the Sigsbee site in the Gulf of Mexico, which encountered oil and gas at a water depth of 3582 m (Ewing *et al.* 1969), and in the Tasmanian region at Deep Sea Drilling Sites 280 and 282 (water depths of 4181 m and 4207 m respectively) where oil staining was also encountered (Kennett *et al.* 1975). The present limitations to the exploitation of oil and gas beyond the shelf edge are imposed more by technology than geology. As the necessary technology is developed,

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there seems little doubt that an increasing proportion of the world's petroleum production will come from offshore.

Coal: Sub-sea coal seams have been exploited from onshore-based underground mine workings for many years off the coasts of Japan, the United Kingdom, and Canada. A number of the east Australian sedimentary basins which are coal-bearing onshore are known to extend offshore. The offshore Sydney Basin in particular is likely to contain coal seams of potential economic importance, which might feasibly be worked from shore-based workings. Coal seams undoubtedly extend to the edge of the shelf in places. Their extent in the slope sediments is less certain though it is reasonable to assume that they will be considerably less abundant there than under the shelf. There are reports of coal from deep water; brown coal was reported from site 214 on the Ninety East Ridge at a water depth of 1665 m and a depth of about 400 m below the sediment-water interface (von der Borch *et al.* 1974). It is highly unlikely that sub-sea coal will be mined any further than a few tens of kilometres from the present shoreline in the foreseeable future. The United Nations (1970) predicts that with existing technology, conventional mining operations could be extended sub-sea up to 24 km from the coastline, and that changes in technology could extend this to as much as 50 km from the shoreline within the next 20 years.

Metalliferous Deposits: Most types of onshore metalliferous deposits might reasonably be expected to be present in places under the continental shelf. The summary by the United Nations (1970, p. 41) reports that "more than 100 sub-sea underground mines with inclined or vertical shaft entry from land, islands or artificial islands have recovered minerals such as coal, iron ore, nickel-copper ores, tin and limestone off the coasts of Australia, Canada, Chile, Finland, France, Greece, Ireland, Japan, Poland, Spain, China (Taiwan), Turkey, the United Kingdom and the United States". Except where mining is carried out under a very shallow rock cover, sub-sea mining does not pose severe technological problems and conventional mining techniques can be employed for the most part. The major limitation is posed by having shafts extending considerable distances from the mining entrance resulting in major logistical and economic problems. Offshore shaft mining either with a surface or sea-bottom entrance may overcome this problem (fig. 17). It is reasonable to expect that sub-sea metalliferous mining in bedrock may eventually extend to the edge of the continental shelf in places. Whether there are likely to be metalliferous deposits of any significance in the bedrock underlying the slope is not known. However, if any high-value metalliferous deposits are present and the shelf is narrow, bedrock mining might conceivably continue under the upper part of the slope. One of the few positive indications of mineralization in bedrock in deep ocean areas comes from the results of Deep Sea Drilling (Site 282) off northwest Tasmania where native copper has been reported in basalt (Kennett *et al.* 1975).

Sulphur: Native sulphur is obtained from salt domes in the Gulf of Mexico area, using the Frasch extraction process (fig. 17). Offshore extraction has been undertaken at two sites and a number of other salt-domes underlying the shelf in the Gulf are also likely to contain sulphur. In addition, drilling of the Sigsbee Knolls proved the presence of sulphur in a water depth of 3582 metres. Salt domes are present offshore in many parts of the world, particularly underlying the shelf and the slope (e.g. off northwestern Australia). Diapiric structures are also present in the abyssal zone e.g. in the northeast Indian Ocean but commonly there is no indication of whether these diapirs are salt domes or clay diapirs. Outside of the Gulf of Mexico, no offshore sulphur-bearing salt domes are known, but the geological conditions prevailing in diapirs elsewhere, are commonly similar to those encountered in the Gulf of Mexico, and drilling of such structures should ultimately result in the discovery of further offshore sulphur deposits.

Evaporites: Salt deposits are abundant in onshore and offshore sedimentary basins in many parts of the world, including Australia. Australian occurrences include the

Bonaparte Gulf where halite is present in both bedded and diapiric forms, the offshore portion of the Carnarvon Basin where there are up to tens of metres of bedded salt deposit, and the Browse Basin in the Northwest Shelf and the offshore Capricorn Basin (at the southern end of the Great Barrier Reef) where there are thin beds of anhydrite. The offshore portions of the Canning Basin and the Adelaide Geosyncline may also contain salt but have not been tested by deep drilling. There are no known offshore occurrences of potash in the Australian region.

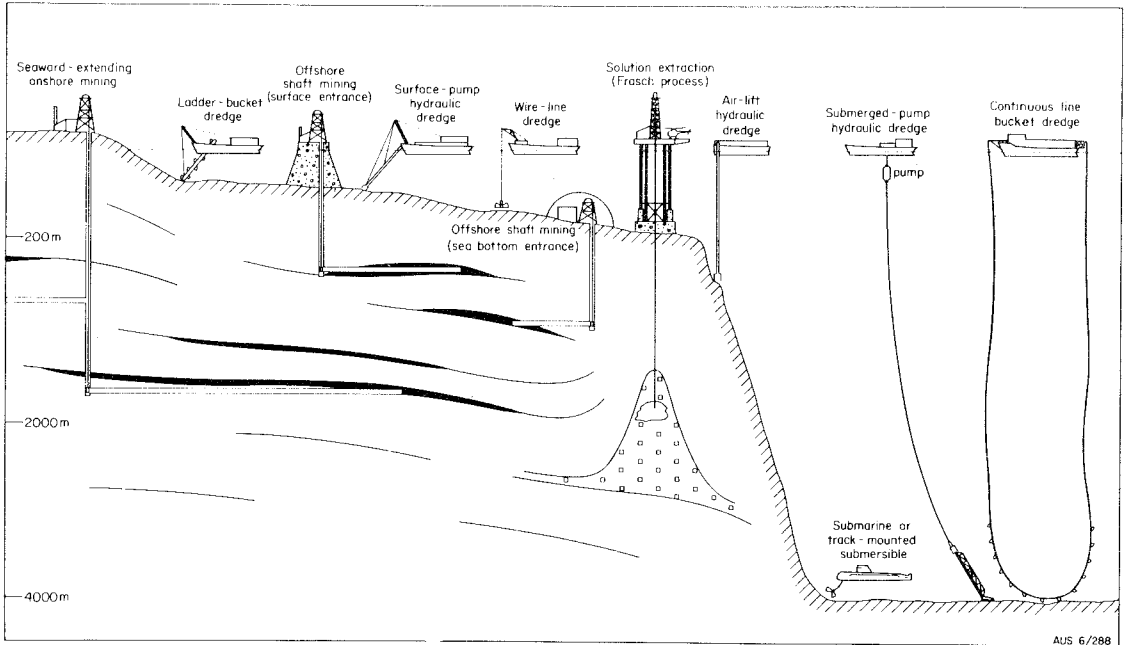


FIG. 17. - Some offshore mining methods in use at the present time or likely to be used in the future.

Salt deposits also extend under the slope and into the abyssal zone. Deep Sea Drilling has established the presence of evaporites in the Red Sea, the Mediterranean, and the Gulf of Mexico, and analyses of pore waters also indicate that salt deposits are present near the Timor Trough (Veevers *et al.* 1974) and elsewhere.

#### Superficial Deposits

Unlike bedrock sub-sea mineral deposits, superficial deposits must be mined off the sea bottom using extraction plants which are either floating, submersible, or semi-submersible (fig. 17). In very shallow water the same mining procedures (dredges) can be used as for shoreline deposits but more commonly new methods are necessary, involving long suction lines, or bucket ladders, submarines, and various other submersible mobile mining systems especially in deeper water. In general, costs must be expected to increase substantially with increasing water depth.

Bauxite and Lateritic Iron: Bauxite and ferruginous laterite are onshore superficial deposits formed in response to lateritic weathering, and in places such deposits are present offshore as a consequence of relative sea-level changes (fig. 18). An exploration program for bauxite was recently undertaken in the Gulf of Carpentaria, offshore from the Weipa deposits but results do not appear to have been encouraging. Offshore bauxite deposits occur in the Solomon Islands and are believed to be of commercial interest, but no detailed information is available. Elsewhere little or no

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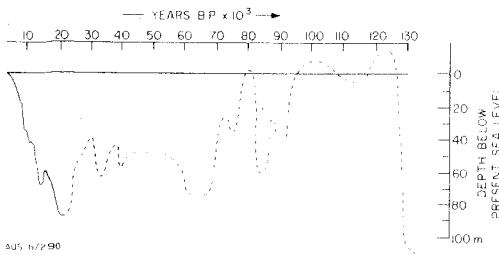


FIG. 18. - Pleistocene sea-level changes (after Morner 1971).

they are seldom, if ever, transported in the marine environment. They are however present in offshore Pleistocene stream beds, as extensions of present-day continental placer deposits which have been submerged by the post-glacial rise in sea level (fig. 18). Such deposits are unlikely to extend far across the shelf because potential source areas are likely to have been covered by a veneer of older interglacial sediments which would have protected them from erosion.

Beach deposits at Nome, Alaska, have yielded an estimated 190,000 kg of gold (Archer 1972), and as a consequence active exploration programs have been undertaken on the Alaskan Shelf. Significant quantities of gold have been found in many areas but no offshore mining has been undertaken. Gold and tin have also been reported in the Soviet sector of the Sea of Japan, but no attempt has been made to exploit these deposits. Exploration leases for offshore gold were taken out off the south coast of New South Wales some years ago, in an area adjacent to an old onshore gold working. The company (Planet Gold Ltd.) did not announce the results of the survey, but as it subsequently relinquished the leases it is reasonable to assume that the results were not encouraging.

Offshore tin operations have been more successful. As early as 1907 tin was dredged offshore. Until recently the dredges operated only in sheltered waters but now they have moved into more open waters and work in water depths of up to 40 m. Dredges have operated successfully off the coasts of Malaysia, Indonesia and Thailand (fig. 19). Exploration has been undertaken in other parts of the world, and cassiterite-bearing sands have been reported off Cornwall (Lee 1968). No commercial deposits appear to have been discovered in Australian waters; a limited exploration program has been undertaken offshore from the North Queensland Herberton tinfields, but as Noakes and Jones (1975) point out the tinfields are some distance inland and are unlikely to have contributed any significant amount of tin to the coast. Some exploration was carried out in the Oyster Bay area off Tasmania. A more comprehensive exploration program was undertaken off northeast Tasmania near Ringarooma Bay by Ocean Mining A.G. on behalf of a consortium of companies. The program included geophysical surveys to determine the course of the Pleistocene Ringarooma River, and an extensive drilling program. Intersections of tin were recorded in a number of the drillholes; however, Young (1969) reported that overall, tin concentrates were rather patchy, but detailed work might delineate richer patches. Increasing tin prices may revive interest in offshore Tasmanian tin deposits.

**Diamonds:** Diamond-bearing deposits are of very limited onshore extent, consequently it is not surprising that offshore diamonds have been reported only off the coasts of southwest and southeast Africa (Fleming 1972; Nesbitt 1967). Diamonds are found there in both modern beaches and Pleistocene beaches which have been submerged by the post-glacial sea-level rise (fig. 18). Some of the diamonds are found in gravel deposits which are believed to have formed when energy conditions were greater than those encountered at the present day (Murray *et al.* 1970). The distribution of some of the

offshore exploration appears to have been undertaken for deposits of this nature, although they are likely to be fairly widespread, particularly at low latitudes where there has been extensive lateritic weathering. In view of the abundance of onshore deposits, any such deposits are unlikely to be worked in the near future.

**Gold and Tin:** The heavy placer minerals, gold, tin, platinum and chromite, termed the heavy minerals by Emery and Noakes (1969), are normally found in fluvial gravels, 15 km or less from their source. Because of their high specific gravities,



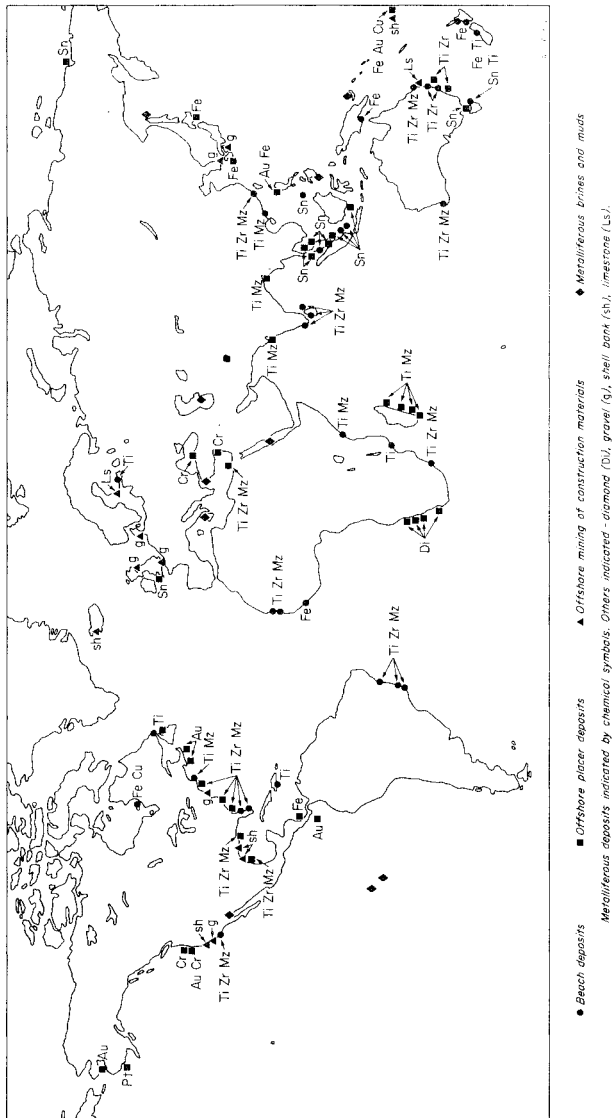


FIG. 19. - Location of some offshore mineral deposits (after McKelvey and Wang 1971).

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diamond-bearing sediments to the north of the Orange River (the principal source of the diamonds) is probably the result of present-day current patterns.

The De Beers group has undertaken an extensive program off Southwest Africa, and has successfully dredged (by airlift) diamond-bearing sediments from water depths of 40 m. The offshore deposits are of a higher grade than the onshore deposits. By 1969, some 0.75 million carats had been mined offshore but operating costs were considerably in excess of those of onshore mining, and offshore operations are believed to be suspended at the present time. Few (if any) other offshore areas in the world are regarded as having any potential for diamond-bearing sediments because of the lack of nearby diamondiferous source rocks.

Sand and Gravel: Extensive sand and gravel deposits are present on the continental shelf in a number of areas, particularly off the coast of western Europe and the north-eastern United States (fig. 19). The European and North American gravels are believed to be derived from the Pleistocene glacial and fluvioglacial deposits which were deposited on the shelf areas during the last low sea-level stand. Consequently, the gravels are mostly continental deposits which have been subsequently submerged. Much of the sand in these areas is probably also derived from glacial and fluvioglacial sediments which have also been subjected to redistribution by the prevailing currents. In addition, sands are also being carried onto shelves by present-day coastal drainage.

Siliceous sands and gravels are used extensively as construction materials, and increasingly in Europe and the United States these commodities are being obtained offshore (fig. 19). In 1968, the United Kingdom obtained 10 percent of its sand and gravel needs (equivalent to 11 million tons and worth 6.5 million) from offshore sources (Dunham 1970). By 1970 the amount dredged had increased to 13 million tons, equivalent to 12.4 percent of the total production of sand and gravel in the United Kingdom. Archer (1972) reports that dredging vessels operate competitively with onshore deposits, up to 120 km from the home port and in water depths of 60 m. In the United States, where offshore aggregates provide 2 to 3 percent of total production, most of the material is from estuaries rather than the open shelf. It is likely that there too the search for suitable aggregates will extend onto the shelf.

Information available on the east Australian shelf (Davies and Marshall 1972) indicates that the chances of finding suitable sand and gravel are not particularly good owing to an abundance of carbonate and a lack of coarse sediment (because of the absence of glacial sediments). Nevertheless, there is an increasing need to find suitable sources of offshore sand and gravel for the Newcastle-Sydney-Wollongong conurbation, a need which is likely to act as a catalyst for further offshore exploration.

Carbonate: Calcium carbonate is used extensively in the construction industry particularly in concrete manufacture. It occurs in the form of *in situ* reef material, as carbonate sands and gravels derived either from the break-up of reefal material or from shelly detritus, colitic deposits, and as carbonate muds and oozes. All of these forms are of biochemical origin.

Coral reefs are abundant along many tropical and sub-tropical coasts, including those of northern Australia. Currently, dead coral reef is dredged from Moreton Bay, Queensland for the local cement industry. The Barrier Reef contains enormous quantities of calcium carbonate (mainly aragonite) but environmental consideration would preclude mining of the reef. Carbonate-rich sediments are present in many other parts of the Australian shelf in environmentally less sensitive areas such as the Great Australian Bight; while onshore deposits of limestone are adequate in most areas, local demand might stimulate small-scale offshore operations in the future.

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Elsewhere, a number of carbonate dredging operations have been established including dredging shell banks off Iceland in 45 m of water. Oyster shell accumulation in shallow bays off Texas, Louisiana and Florida are also mined, total production from this source in 1968 being 18 million tons with a value of about \$US 30 millions (Archer 1972). Aragonitic muds are also extracted (by suction dredging) from a water depth of up to 30 m on the Bahama Banks.

Enormous quantities of carbonate ooze, resulting from the accumulation of the tests of calcareous micro-organisms, particularly foraminifera, are found on many continental slopes and marginal plateaux within 40 degrees of the equator and where there is little or no terrigenous sedimentation. The deposits extend to the carbonate compensation depth at approximately 4000 - 5000 metres. Below this depth calcium carbonate dissolves. Some areas of the abyssal plain are covered by calcareous ooze as a result of abnormally high carbonate productivity in the surface waters (e.g. near the equator) or as a consequence of turbidity flows bringing calcareous slope sediments into the abyssal zone. It is unlikely that any of these deep-sea carbonates will be mined in the foreseeable future, because of the presence of virtually unexhaustible supplies on the continents and the shelf.

Mineral Sands: Rutile, zircon, ilmenite, magnetite and monazite (termed the light heavy minerals by Emery and Noakes 1969) are present as beach deposits in various parts of the world including Australia, Brazil, Ceylon, Egypt, India, New Zealand, and Japan (fig. 19). From previous discussions on the use of onshore deposits as indicators of the presence of offshore deposits and also the effects of Pleistocene and Holocene sea-level changes, it would be reasonable to expect fossil strandline deposits to occur seaward of the beach deposits.

An extensive exploration program was undertaken off the east Australian coast between Newcastle and Brisbane by Planet Metals (Brown and MacCulloch 1970) using various drilling and sampling techniques and an accurate positioning system. A number of strandlines were identified at about 30-36 m, 79-80 m, and at 120 m. Only the -30 metre beach was examined in detail. Noakes and Jones (1975) refer to offshore mineral sand reserves of 375 million tons with rutile plus zircon averaging 0.20 to 0.22 percent. This is significantly less than onshore grades (averaging 0.3 to 0.4 percent), and consequently the offshore deposits are uneconomic at present; however, onshore environmental considerations, particularly the high cost of restoring dunes to their pre-mined condition, could radically alter the economics of onshore operations and may make the offshore deposits a much more attractive proposition. Minor deposits of rutile and zircon occur off King Island in Bass Strait, and might also be expected offshore from the ilmenite beach deposits of central Queensland and south-western Western Australia, but any accumulations are likely to be even more marginal than those already discovered between Newcastle and Brisbane. Despite this, all of these deposits constitute an important resource for the future. In addition further exploration programs and improvements in metallurgical technology could upgrade the prospects of many areas.

Iron sands, composed primarily of magnetite, form beaches in several parts of the world, particularly in volcanic regions. These have been worked offshore in Japan and New Zealand where they are mined primarily for domestic consumption. Japanese offshore production reached 1.4 million tons in 1964, constituting approximately 3 percent of the total Japanese production (Okana *et al.* 1968). Although reserves are large (approximately 650 million tons) the deposits are both low-grade (9% iron) and titaniferous. The New Zealand deposits also have the disadvantage of high titanium content. The abundance of high-grade onshore iron deposits makes it difficult for offshore iron sands to compete, but it is likely that these and other low-grade deposits will continue to be used locally because of either distance from alternative sources, strategic considerations or the need to conserve foreign exchange.

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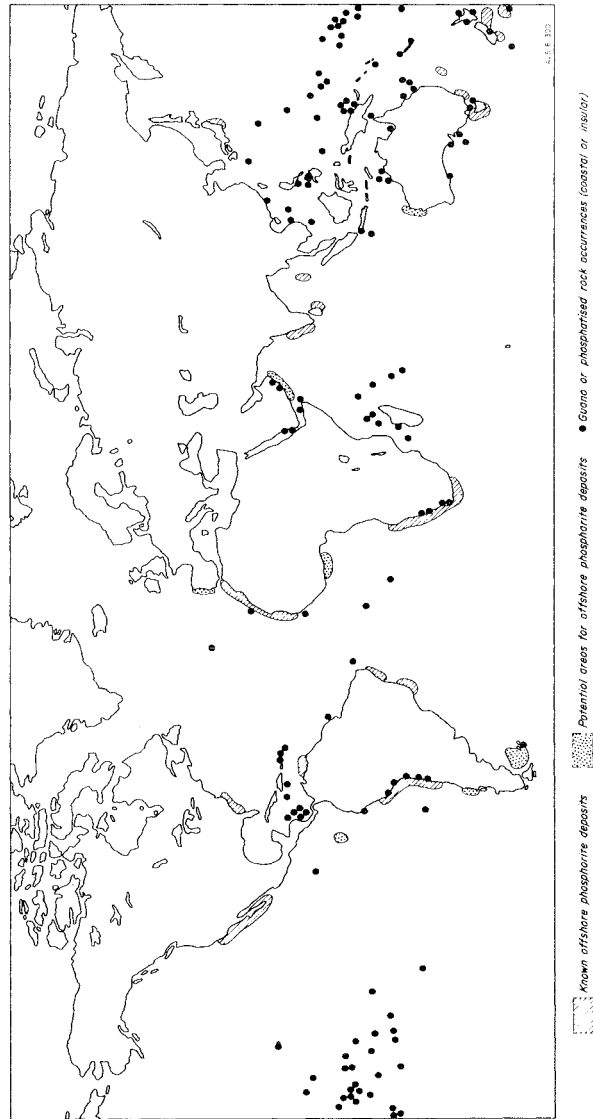


FIG. 20. - Offshore phosphate deposits (after McKelvey and Wang 1971, and other sources).

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Phosphate Deposits: There are three types of phosphate deposits - phosphorites, guano (or guano-derived) deposits and igneous apatites. "Bedrock"-type igneous apatite bodies such as those of the Kola peninsula in northeastern Russia might be present under the continental shelf, but such deposits are rare on land and would be difficult both to discover and to work commercially offshore.

Guano deposits occur widely (White and Warin 1964; Hutchinson 1950), particularly in areas with a high organic productivity in the surrounding ocean, and where the island is isolated (fig. 20). Those factors produce a large bird population, and an attendant abundance of avian guano. In some instances the guano forms a primary source of phosphate. More commonly, tropical weathering and leaching produces phosphate-rich ground-waters which phosphatize the underlying rocks, generally reef lime-stones, though in some cases there is also phosphatization of underlying volcanic rocks such as on Christmas Island in the northeast Indian Ocean (Trueman 1965). Some such guano-derived deposits have been submerged below sea-level as a result of a relative rise in sea-level. Offshore deposits of this type have been prospected for in the central Pacific by Barrie (pers. comm.), and Cook (1974) has used oceanographic data for the southwest Pacific to delineate areas where offshore deposits might also be found. In the Indian Ocean, Bezrukov (1973) has discovered a number of seamounts capped by phosphate, which are thought to be submerged guano deposits.

Offshore phosphorites are more extensive than guano deposits. They are now known to occur off southern Africa, southern California, Baja California, the eastern United States, northwest Africa, southeastern South America, northern Chile and Peru, the Andaman Island (Indian Ocean), eastern Australia, northwest Tasmania, and the eastern and southern coasts of the South Island of New Zealand (fig. 20). Kolodny (1969) and Kolodny and Kaplan (1970) have shown that most of these shelf phosphorites are residual phosphorites of Tertiary age. Phosphorites are forming at the present day off southwest Africa (Baturin 1969, 1970, 1971; Baturin *et al.* 1972) and off Peru and northern Chile (Veeh *et al.* 1973). Both areas are regions of extensive upwelling and abnormally high organic productivity. For many years it was thought that the collophane (carbonate-fluorapatite) precipitated inorganically in the water column, in response to an increase in pH as the cold water ascended (Kazakov 1937). However, it now appears that phosphorites form primarily by the phosphatization of sediments below the sediment-water interface. This produces localized patches of collophane. Increased current velocities and/or changes in sea-level lead to subsequent reworking of the sediments. The coarser patches of phosphatized sediment remain as a lag deposit and the finer matrix is winnowed out, resulting in the phosphatic sediment being upgraded to a high-grade phosphorite (Cook 1967; 1975). This upgrading is also demonstrated in table 3 by the increasing  $P_2O_5$  content of offshore deposits, with increasing lithification.

TABLE 3  
MAJOR ELEMENT COMPOSITION OF OFFSHORE PHOSPHORITES

	% $P_2O_5$	% CaO	% $CO_2$	% F	% $SiO_2$	% $Al_2O_3$	% $Fe_2O_3$	% MgO
1 soft nodules	23.85	35.92	5.30	2.45	14.80	0.45	0.80	1.70
2 hard nodules	32.74	46.42	6.33	3.02	0.15	0.04	0.20	1.70
3 soft nodules	15.73	24.90	2.31	1.60	22.23	6.11	2.79	1.80
4 hard nodules	25.62	38.64	3.04	2.55	12.30	3.31	1.79	1.60
5 hard nodules	10.0	17.7	4.1	1.05	10.6	2.3	40.2	2.55

Samples 1 and 2 from the southwest and African shelf;  
samples 3 and 4 from the Chile shelf (after Baturin 1971);  
sample 5 from the Tasmanian shelf (Cook unpubl.).

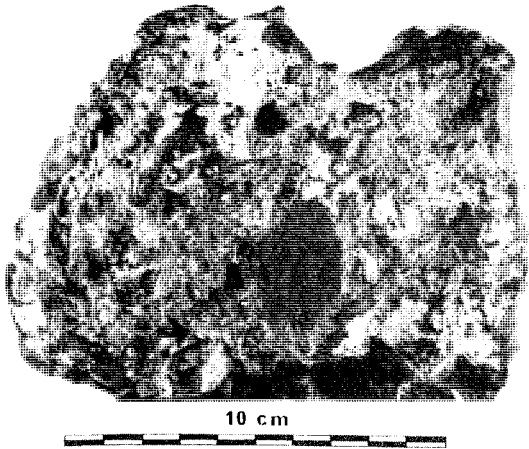


PLATE 1. - Portion of a phosphatic pavement from off the East Australian coast.

Similar phosphorites are also known from the Chatham Rise and the Campbell Plateau (Norris 1964, Summerhayes 1967a, Watters 1969) off New Zealand. All the known Australian occurrences are fairly low grade (table 3) and are of the nodular type, with few consolidated beds. All are believed to be Tertiary (Miocene?), though there may have been some more recent surface phosphatization.

The east Australian deposits range in water depth from 197 to 385 m and contain up to 21.2%  $P_2O_5$ . The Tasmanian phosphorites which were discovered by Ocean Mining A.G. range in water depth from 65-165 m and contain up to 26 percent  $P_2O_5$ . No estimate of reserves is available though the Tasmanian deposits are probably considerably larger than the east coast deposits. Thus, at present the Tasmanian phosphorites, being richer, more abundant and in shallower water than the East Australian deposits are of greater commercial interest. However, in common with all other offshore phosphorites they have the disadvantage of being a fairly low-priced commodity. Recent steep price rises to about \$US70 per ton (April 1975) are unlikely to continue as there are abundant onshore supplies. Under the present pricing conditions, some offshore phosphorites off southern California have attracted much interest from mining companies (Wilson and Mero 1966) in the hope that the high costs of dredging (probably in excess of \$US20 per ton) can be offset by the nearness of the southern Californian market.

Although numerous offshore phosphorites are already known (fig. 20), there are

The phosphorites presently exposed on the shelf are in the form of consolidated beds or pavement (off parts of southern California), nodules (Algulhas Bank; Blake Plateau), sands (off Baja California), and muds (off Chile and Peru). They occur in water depths ranging from 50 m or less off Baja California to 3800 m off the Algulhas Bank. The deep-water phosphorites are probably allochthonous. The Peruvian-Chilean phosphorites occur at water depths of 100 to 400 m (Veeh *et al.* 1973), whereas those off southwest Africa are forming on the inner shelf between 50 and 150 m (Senin 1970).

In the Australian region, offshore phosphorites are present on the outer edge of the east Australian shelf (Marshall 1971, von der Borch 1970) as a capping on some of the seamounts of the Tasman Sea (plate 1), and on the west Tasmanian shelf (plate 2).

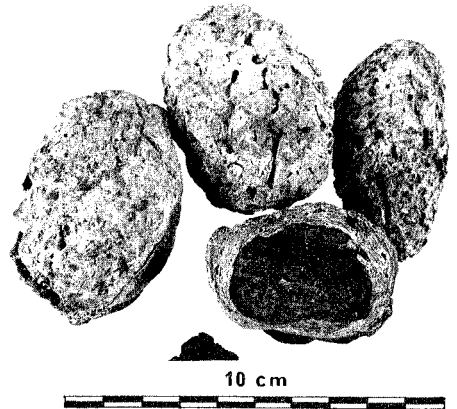


PLATE 2. - Phosphorite nodules coated with a calcareous veneer; sample off the northwest Tasmanian coast.

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prospects for finding further deposits, particularly in areas of known upwelling and slow rates of terrigenous and carbonate sedimentation including the west coast of Australia (though results obtained by Jones (1973) have been disappointing), off west Africa, Portugal, the northwest Indian Ocean, and the Andaman Islands. Many other potential areas could probably be identified, initially using available oceanographic data and then detailed marine chemical work, underwater scintillometers (Summerhayes *et al.*, 1970) and extensive bottom-sampling programs. Whether an expensive offshore exploration program can be justified on the Australian continental margin is perhaps questionable in view of the abundance of onshore deposits in northwest Queensland. However, as phosphorites are also important "hosts" for uranium and rare earths, their future significance cannot be gauged solely on the basis of their phosphate content.

Glauconite: Glauconite is abundant on many continental margins, particularly those with a slow rate of terrigenous or calcareous sedimentation, and where the waters are warm. Deposits are particularly common on the upper part of the slope between about 200 and 1000 m, but some are also found in the abyssal zone. It is uncertain whether these deep glauconite deposits are the result of *in situ* formation, or have been carried into the abyssal zone by turbidity currents.

Glauconite is used as a water softener, and as a source of potassium; it may also be used as a direct-application soil-additive. No details are available on the economics of offshore glauconite mining, though there are probably sufficient onshore glauconite deposits to make offshore extraction uneconomic in most areas for some considerable time. However Norris (1964) suggested that in view of the high rate of potash application to New Zealand soils, the glauconite deposits of the Chatham Rise merit consideration as a soil additive for the New Zealand market. Glauconite is present as an accessory mineral (up to 10%) in Australian shelf sediments (Jones, pers. comm.) but nowhere is it known to be sufficiently abundant to constitute a "greensand" which might merit mining in the future. However our present knowledge of the Australian shelf is poor, and large deposits may be present particularly on the outer shelf in areas where there is little or no sedimentation.

Barite: Barite nodules occur at scattered localities on the outer part of the shelf and on the slope off Ceylon, southern California and Indonesia (United Nations 1970). They have also been intercepted at a number of drilling sites in the Deep Sea Drilling Project. Offshore barite is currently being mined off Alaska in up to 25 m of water. The barite is a bedrock deposit which is mined by blasting and dredging (Stevens 1970). The economics of this operation cannot, however, be compared with a deep-sea barite nodule program because of the nearby, and pre-existing mining infrastructure in the case of the offshore Alaskan bedrock barite. Barite nodules appear to be too scattered for dredging operations to be competitive with onshore mining.

Manganese: Manganese nodules (also known as polymetallic or multimetallic nodules) cover large areas of the sea floor (fig. 21). They are most abundant on abyssal plains but are also present on marginal plateaux (e.g. Blake Plateau) and in places are found in shallow nearshore waters (e.g. the Baltic Sea and the Arctic Ocean). Manganese incrustations occur in places, particularly on mid-ocean ridges and adjacent to submarine fumaroles. However, only the abyssal zone nodules are of present commercial interest.

An extensive literature on manganese nodules has developed in the past few years dealing with their occurrence, geochemistry, genesis and exploitation. Consequently it is only intended to deal with the topic here in outline. Detailed accounts are given by Bezrukov and Andrushchenko (1974), Cronan and Tooms (1969), Glasby (1972a), Horn (1972), Horn *et al.* (1972), Hubred (1975), Mero (1965), Summerhayes (1967b), Swan (1974) and Tooms *et al.* (1969).

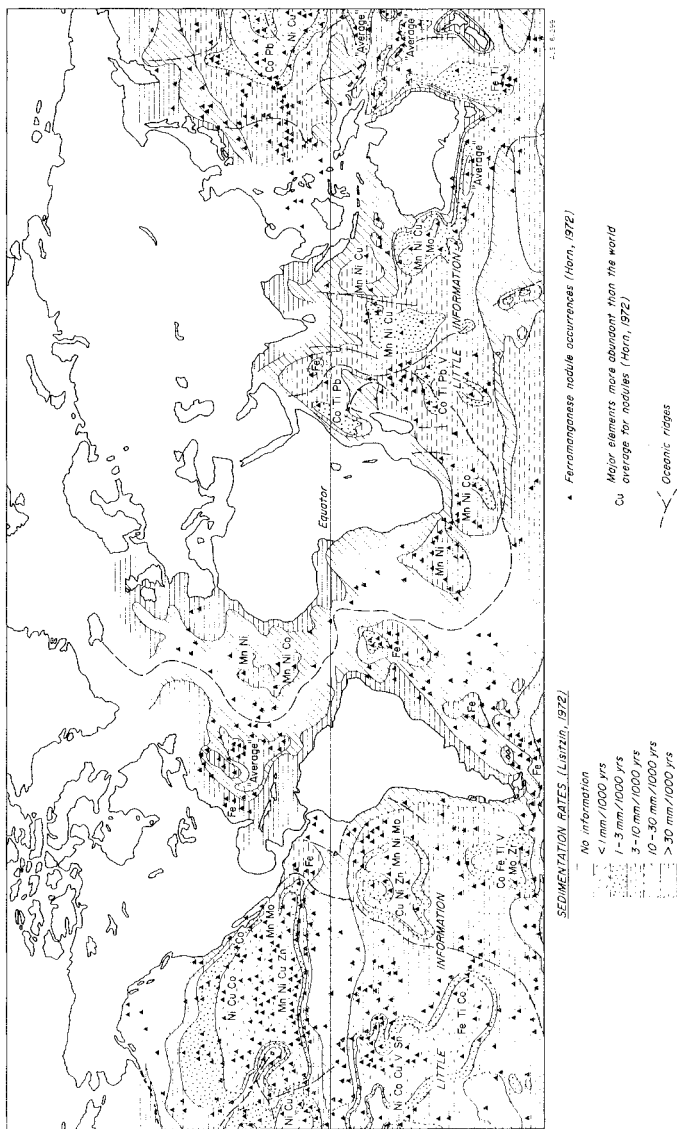


FIG. 21. - Distribution of manganese nodules (after Horn 1972) and the rate of sedimentation (after Lisitzin 1972). High concentration of manganese nodules are evident in areas of slow sedimentation.



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Manganese nodules range in shape from spheroidal to disc-like (plate 3), and in size from micronodules of one cm or less to one m or more in diameter and weighing up to several tonnes. Most are two to five cm in diameter. Their external surface is smooth, botryoidal or cracked. Internally they are horizontally, concentrically or radially layered. They commonly contain a nucleus such as a volcanic fragment, a bone fragment, a shark's tooth, or clay. The manganiferous coating around the inclusion is composed predominantly of  $10\text{\AA}$  manganite at shallow-water sites and  $\text{MnO}_2$  at deep-water sites (Glasby 1972b). Their

elemental composition is rather variable. Manganese and iron are dominant, with cobalt, nickel and copper present in minor amounts and trace amounts of molybdenum, chromium, platinum, titanium, gold and zinc (tables 4 and 5). Increasingly, it is the higher than average concentrations of the minor and trace elements which are being sought rather than the nodules with a high manganese content, with cobalt, nickel and copper being of particular importance. The maximum values so far recorded for these metals in manganese nodules are 1.8 percent copper (Goldberg 1954), 2.5 percent cobalt and 2.0 percent nickel (Fraser and Arrhenius 1972). The central and eastern Pacific nodules are richer in copper, cobalt and nickel than elsewhere in the world's oceans. The ratio  $\text{Co}/\text{Ni} + \text{Cu}$  is found to increase with decreasing water depth. Just how these high concentrations arise is not known; theories for the enrichment include entrapment of cations by negatively charged oxide ions, concentration by bacteria, and various types of diagenetic reactions. Similarly, there are various theories to account for the source of the manganese and the formation of the manganese nodules. These include terrigenous, volcanic, submarine fumarolic or extra-terrestrial sources, with concentration of the manganese by chemical precipitation, biochemical precipitation (by the action of bacteria), submarine weathering, or diagenetic remobilization of the manganese below the sediment-water interface. The rate of nodule growth appears to be very slow (only a few millimetres per million years); in many instances slower than the rate of sedimentation of the deep-sea clays in which they occur. This presents a problem, for the nodules are present only as a surface veneer. There are nevertheless instances of shells from World War II being found covered with a manganese coating several millimetres thick. Therefore in some circumstances the rate of manganiferous sedimentation can be quite rapid, though the overall rate is slow because of long breaks in the sedimentation.

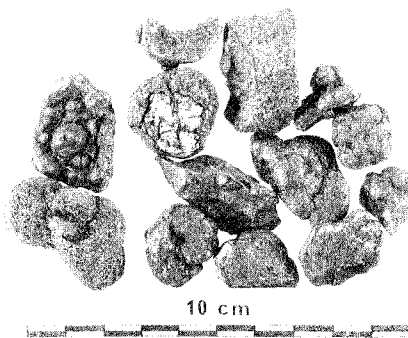


PLATE 3. - Manganese nodules, from the Southern Ocean.

TABLE 4

AVERAGE COMPOSITION OF MANGANESE NODULES IN THE ATLANTIC, PACIFIC AND INDIAN OCEANS (after Cronan 1972)

%	Atlantic	Pacific	Indian
Mn	16.18	19.75	18.03
Fe	21.82	14.29	16.25
Ni	0.297	0.722	0.510
Co	0.309	0.381	0.279
Cu	0.109	0.366	0.223

Manganese nodules are present in all the oceans of the world. They are most abundant and richest in those areas which are far removed from sources of terrigenous sedimentation and where the rate of sedimentation is lowest (fig. 21). The richest

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areas known to date both from the point of view of their cobalt, nickel and copper content and from the point of view of abundance of nodules are in the Pacific (table 4), particularly the central and east Pacific. Hubred (1975) considers that a typical potential mining site in the central Pacific would have a nodule density equivalent to 10 km<sup>3</sup> per m<sup>2</sup> of ocean floor and would cover an area of about 300,000 km<sup>2</sup>. He envisages an operation yielding 1.5 m tonnes per year, but even at this rate of mining, it would take 1000 years to mine the area out. Mero (1967) estimated the Pacific reserves of manganese nodules at 1.7 x 10<sup>12</sup> tons, representing 4 x 10<sup>9</sup> tons of manganese, 1.6 x 10<sup>10</sup> tons of nickel, 8.8 x 10<sup>9</sup> tons of copper and 5.8 x 10<sup>9</sup> tons of cobalt. Since the time of that estimate, further nodule fields have been discovered and the Mero estimate may be conservative.

TABLE 5

## AVERAGE METAL CONTENT OF MANGANESE NODULES IN THE AUSTRALASIAN REGION AND SURROUNDING AREAS

Pacific and Indian Ocean values after Cronan and Tooms 1969.  
Australian values after Noakes and Jones (1975).

%	central Pacific	southern Pacific	western	eastern	Australian region
			Indian Ocean	Indian Ocean	
Mn	15.71	16.61	13.56	15.83	13.3
Fe	9.06	13.92	15.75	11.31	11.3
Ni	0.956	0.433	0.322	0.512	0.47
Co	0.213	0.595	0.358	0.153	0.13
Cu	0.711	0.185	0.102	0.330	0.37

A number of methods have been proposed for the mining of nodules (fig. 17) including continuous-line bucket dredges, hydraulic suction dredges employing submerged pumps, and various types of submersibles. Some of these methods are being evaluated, but up to the time of writing (March 1975) no company had started mining on a commercial basis, an indication not only of the dredging and metallurgical problems which have still to be solved, but also of the legal problems associated with deep ocean mining. Nevertheless in November 1974 the company Deepsea Ventures Inc. (a subsidiary of Tenneco Inc.) filed a claim to mining rights with the United States Government for an area of 60,000 km<sup>2</sup>, 1300 km west of Baja California, in water depths ranging from 2300 to 5000 m (Anon 1974).

Noakes and Jones (1975) consider specifically the distribution of manganese nodules in the Australian region and found that out of 143 deep-water stations, nodules were present at 52. They record that the greatest concentration of nodules occurs south of 50°S; however, this may be more a reflection of the considerable amount of work undertaken by the *Eltanin* in the southern Ocean and the lack of work elsewhere than the true distribution pattern. The few analyses so far undertaken suggest to Noakes and Jones that the nodules of the region are less rich in cobalt, nickel and copper than those of the central Pacific (table 5). However, too few analyses are available, and an extensive program of abyssal zone sampling is required around Australia before the region can be fully evaluated. Because of the abundance of terrigenous sedimentation in the Tasman Sea the chances of finding high-metal nodules are poor. The region south of Australia has somewhat better prospects, but the writer believes that the southeast Indian Ocean has the best prospects because of the clear indication there of both a slow rate of sedimentation and the wide areas of pelagic clays below the carbonate compensation depth. In addition, the marginal plateaux, such as the Naturaliste Plateau and some of the mid-ocean ridges merit attention. For the present, however, there is insufficient information available on the abyssal sediments around Australia on which to base any evaluation of the future potential the region might have for high-grade manganese nodules.

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TABLE 6  
 AVERAGE COMPOSITION OF DEEP SEA SEDIMENTS  
 (recalculated from El Wakeel and Riley 1961)

%	Pelagic sediment		
	calcareous	argillaceous	siliceous
SiO <sub>2</sub>	27.0	55.4	64.0
Al <sub>2</sub> O <sub>3</sub>	8.0	17.6	13.4
Fe <sub>2</sub> O <sub>3</sub>	3.9	8.3	6.3
CaO	28.5	1.4	1.6
MgO	2.3	3.8	2.5
Na <sub>2</sub> O	0.8	1.5	0.9
K <sub>2</sub> O	1.5	3.3	1.9
MuO	0.32	0.47	0.41
P <sub>2</sub> O <sub>5</sub>	0.15	0.14	0.27
TiO <sub>2</sub>	0.44	0.84	0.65
CO <sub>2</sub>	23.3	0.77	0.93
total H <sub>2</sub> O	3.9	6.5	7.1

Siliceous Oozes: Siliceous oozes (table 6), composed of the tests of diatoms and radiolaria, cover large areas of the sea floor. They are particularly abundant in areas of high productivity in polar and sub-polar waters, below the carbonate compensation level (below about 4000 m), and in areas of upwelling such as the zone of upwelling associated with the equatorial counter-current. This low-latitude ooze is well-developed in, for instance, the northeast Indian Ocean. Pure siliceous ooze in the form of diatomaceous earth is used extensively for insulation, as a filter, and as a concrete additive. Where it is present in relatively shallow water and near to potential markets it is likely that siliceous oozes will be mined in the future. No potential sites with these attributes are known in the Australian region, though the region south of Tasmania probably has the greatest potential.

Pelagic clays may also be considered a resource of the future. They cover much of the ocean floor below about 4000 m (estimated by the United Nations (1970) at 100 million km<sup>2</sup>) and contain abundant iron and aluminium (table 6), as well as greater than average concentrations of manganese, copper, cobalt, nickel, lead, vanadium, and rare earths (table 7). However they constitute very low-grade "ores", and this, combined with the depth of water in which they occur, makes them a possible resource for the distant future only.

Metalliferous Muds and Brines: Metal-rich muds and brines have been discovered in the Red Sea, on the East Pacific Rise and more recently on the mid-Atlantic Ridge. All occurrences appear to be the result of submarine volcanic (fumarolic) activity comparable perhaps with that documented by Ferguson and Lambert (1972) from the shallower water of Rabaul Harbour, New Guinea. The best known of these occurrences is the Atlantis II Deep of the Red Sea in about 2000 m water depth, where the bottom muds contain approximately 0.9% copper, 2.6% zinc, 0.1% lead, as well as significantly higher than average concentrations of silver, gold and tin (table 8). Maximum concentrations known include 21% ZnO, 4% CuO, 0.8% PbO, 85% Fe<sub>2</sub>O<sub>3</sub> and 5.7% Mn<sub>3</sub>O<sub>4</sub>. The sediments are gel-like and contain a wide range of metallic minerals including various

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iron oxides and hydroxides, sphalerite, pyrite, marcasite, manganese oxides and hydroxides, and sulphides and carbonates of copper and lead. The Atlantis II muds have been penetrated to a depth of 10 m using piston cores (Degens and Ross 1969). Seismic information suggests that the sedimentary column may be as thick as 100 m, but drilling at DSDP Site 226 indicated only 5 m of sediment, resting on basalt (Whitmarsh *et al.* 1974); therefore the total thickness of metalliferous sediments is somewhat uncertain.

TABLE 7

AVERAGE TRACE ELEMENT CONTENT OF DEEP SEA SEDIMENTS  
after (a) Goldberg and Arrhenius (1958) and (b) Turekian and Wedepohl (1961).

	Pacific average (a) (ppm)	clay average (b) (ppm)
Sr	710	180
Ba	390	2300
Li	59	2.6
Cu	740	250
Pb	150	80
Zn	-	165
Co	160	74
Ni	320	225

TABLE 8

AVERAGE METAL CONTENTS OF BOTTOM SEDIMENTS IN THE ATLANTIS II DEEP  
(after Manheim and Siems 1974). DSDP Site 226. N - not detected.

	range of metal contents in sediments (ppm)	mean metal content (ppm)
Si	2 - 12	6.5
Al	1 - 5	2.4
Fe	1.5 - 10	11.8
Mg	0.15 - 2	0.9
Ca	3 - 20	9.5
Ti	.002 - 0.7	.08
Mn	.007 - 0.7	.12
Ag	3 - 100	50
As	N	N
B	10 - 20	10
Ba	N - 75000	9000
Cd	N - 100	600
Co	15 - 200	80
Cr	N - 200	30
Cu	1000 - 7000	5000
Mo	5 - 200	65
Ni	N - 100	20
Pb	70 - 5000	2300
Sn	N	N
Sr	150 - 1000	470
V	10 - 200	40
W	N - 50	50
Zn	500 - 10000	5000
Zr	N - 15	10

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The hot brines in the Atlantis II Deep and other Deeps also contain high metal contents. Because of their density the brines have settled in the Deeps. The composition of brines in the Atlantis II Deep and the Discovery Deep are given in Table 9. These figures show that salinities and metal contents are much greater in the brines than in normal seawater - in some cases thousands of times greater. The Atlantis II Deep covers an area of about 12 x 5 km, the Discovery Deep about 4 x 2.5 km; consequently a considerable volume of metalliferous brine is present in these pools. A process involving pumping such brines to the surface is technologically feasible, though it may not yet be commercially viable. In the Australasian region metalliferous muds and brines might be present in localized basins associated with some of the active ocean ridges, such as the Australian - Antarctic ridge; in volcanic regions where there are likely to be submarine fumaroles such as in the New Britain region and in the Bay of Plenty (New Zealand); alternatively some basins of the southwest Pacific such as the Laue Basin may be potential areas. In general, however, prospects for finding metalliferous muds and brines in the vicinity of Australia are poor.

TABLE 9

## COMPOSITIONAL RANGE OF SOME HOT BRINES

Red Sea values after Manheim (1974); Matupi values after Ferguson and Lambert (1972). Normal seawater values after Goldberg (1961).

	Average seawater (ppm)	Red Sea bottom water (ppm)	Atlantis II Deep Brine (ppm)	Discovery Deep brine (ppm)	Matupi area thermal waters (ppm)
Cl	19000	22500	156000	155000	14000 - 46000
Ag	.003	-	0.1	0.1	-
Ba	.03	-	0.9	0.3	-
Co	.005	-	0.16	0.13	-
Cu	.003	-	.03 - .52	.01 - .34	.05 - .06
Fe	.01	-	82 - 100	.05 - .15	3.5 - 108
Mn	.002	-	82 - 100	55 - 66	2.7 - 111
Ni	.002	-	-	.002 - 0.34	-
Pb	.00003	-	0.5 - 0.6	.08 - .21	.05 - .09
Sr	8.0	9.2	45 - 48	44 - 46	-
U	.003	3.3	.48	-	-
Zn	.01	-	4.6 - 10	0.8 - 2.8	.03 - 2.53

## CONCLUSIONS

In the foreseeable future, petroleum will continue to be by far the most important offshore resource. Sulphur will continue to be extracted by solution mining and this method may eventually extend to evaporites, particularly potash. Underground "bedrock" mining will extend progressively farther under the continental shelf as onshore resources are depleted, but high mining costs probably preclude mining extending more than 20 km from the shoreline in this century; or more than 50 km in the foreseeable future. The future progress of offshore mining of superficial minerals is difficult to gauge. Construction materials (sand, gravel, shallow-water carbonates) will increasingly be obtained offshore, manganese nodules will probably be mined commercially before the end of the century, and perhaps before the end of the decade if deposits sufficiently rich in copper, cobalt and nickel are found. Offshore phosphorites might be used locally, particularly if transportation costs continue to escalate. Metalliferous muds and brines may eventually be mined, but much more exploratory work will be necessary before this resource can be evaluated. Tin will continue to be dredged from progressively deeper water, extending several kilometres beyond the present limit of exploitation. Gold may eventually be won offshore, and offshore

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mining of diamonds may eventually recommence off south-west Africa. Rutile, zircon and other "light heavy minerals" will not be won from presently-known offshore fossil strand lines in the immediate future, but may prove feasible if richer deposits can be found or as onshore deposits are depleted. Glauconite deposits, deep-sea barite deposits and calcareous and siliceous oozes represent resources for the distant future.

In conclusion then, there are extensive offshore mineral resources, some of which are being exploited at the present, some of which will be mined in the fairly near future and many which will only be exploited in the more distant future. But even if all the geological, technological and financial problems can be overcome, there still remains the legal problems governing the mining of offshore minerals in what are presently regarded as international waters. This may well prove to be the most difficult obstacle to the future exploitation of offshore minerals.

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