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MINERAL RESOURCES OFFSHORE

by

L.C. Noakes and H.A. Jones

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INTRODUCTION

Important amongst man's recent achievements in science and exploration is his growing knowledge of environments offshore and of associated mineral resources. Although tin deposits were first mined offshore in the early years of this century, systematic investigation of mineral resources had to await new methods and equipment which have been developed in the last 20 years.

Production from the first offshore oil wells in the late 1940's indicated the new potential for shelf resources, which petroleum production in more recent years has now firmly established. Minerals other than petroleum have shown much less spectacular potential than has petroleum, which is certainly likely to continue as the most important resource of the continental margins; however, in the future metals are likely to be the dominant resource in the deep ocean basins beyond the continental margins.

New provinces offshore are of obvious importance to Australia with its long coast line, some 4 million km^2 of continental margin and, in addition, adjacent deep ocean basins; indeed offshore deposits already provide the bulk of our indigenous petroleum supplies.

The seabed can be divided into two broad environments on both morphological and geological grounds - the continental margin, including the continental shelf, slope and rise, and the deep ocean basins; each has its own set of geological characteristics which in turn give rise to potential for different mineral deposits. General morphology offshore is shown diagrammatically in Figure 1 and types of mineral deposits in Figures 2 and 3.

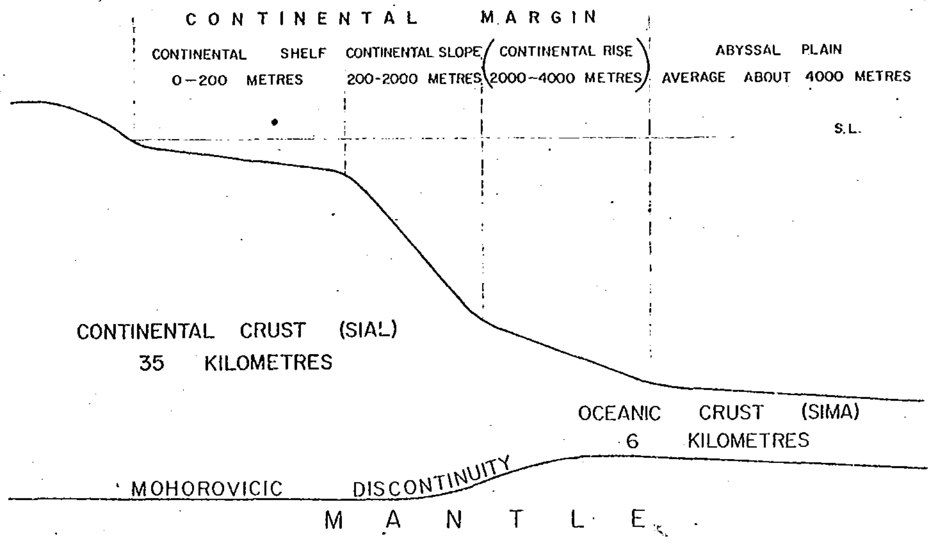

FIG 1 GENERALIZED MORPHOLOGY AND STRUCTURE

To accompany Record 1973/55

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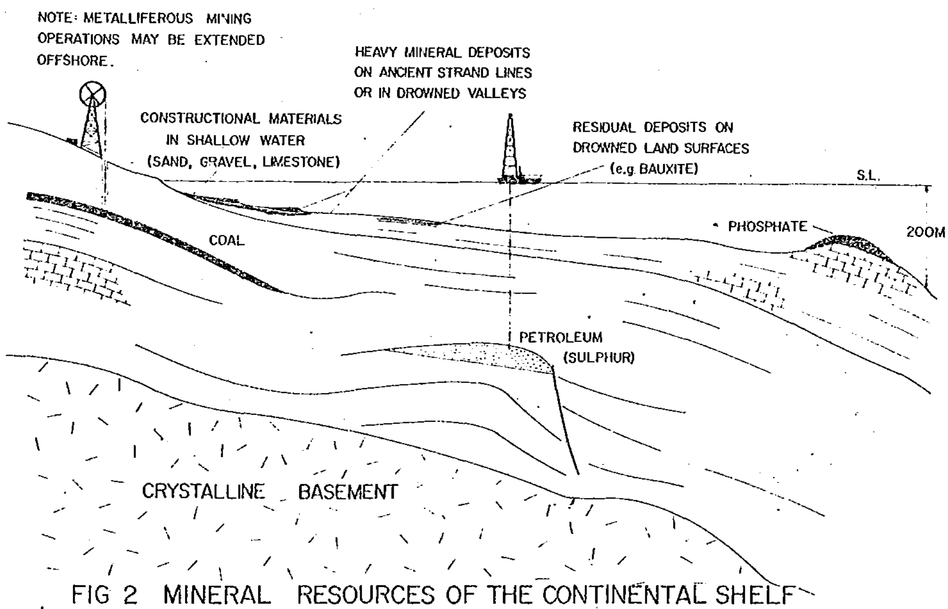

FIG 2 MINERAL RESOURCES OF THE CONTINENTAL SHELF

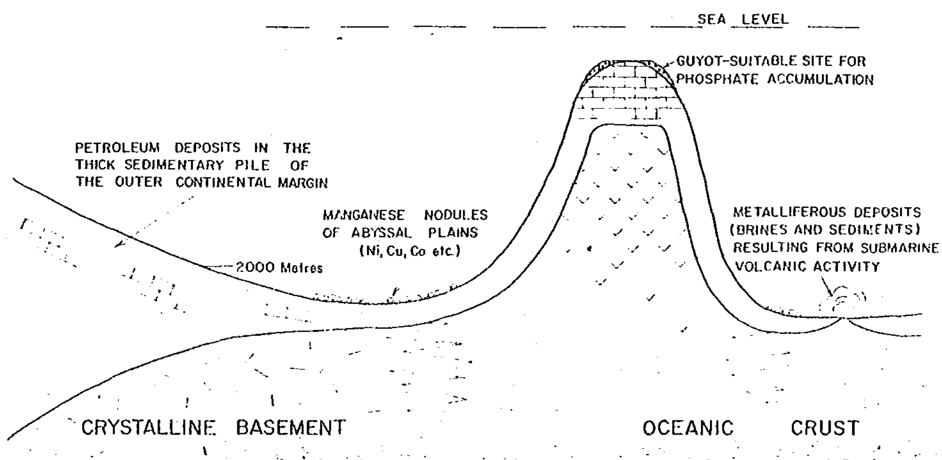

FIG 3 MINERAL RESOURCES OF THE OCEANS

The contrast between these two fundamentally different environments is inevitably reflected in the character of associated mineral deposits; as a prolongation of the continent, the continental margin may be expected to exhibit the range of mineral deposits well known on land, whereas the few types of mineral deposits already recognized in the deep sea basins represent a different group of which study has only recently begun.

This paper concentrates on minerals other than petroleum offshore as petroleum has been discussed elsewhere in this volume; it is no more than a progress report because knowledge of offshore environment is very incomplete and is continually broadening.

MINERAL RESOURCES IN AUSTRALIAN WATERS

Mineral search and development offshore in Australia has followed the world pattern, with early achievement in petroleum contrasting with much slower and less encouraging progress in the search for other minerals.

Initial enthusiasm for prospecting for detrital minerals and phosphorite in the late 1960's induced considerable reconnaissance of Australian shelves by both Australian and overseas teams for mineral sands, tin, and phosphorite, to which some prospecting for offshore bauxite was added later. Although most of this offshore reconnaissance found little encouragement and was discontinued, it provided useful data and delineated deposits of minerals sands off N.S.W. and tin off N.E. Tasmania as resources warranting further study.

In general, the need for the development of deposits of construction materials offshore was not sufficient to encourage exploration in the 1960's, but investigation has more recently begun, particularly off N.S.W., and with time will develop as the availability and cost of supplies on land encourage exploration offshore.

In the deep ocean basins around Australia limited reconnaissance has so far not suggested any occurrence of metalliferous muds, but the distribution and character of manganese nodules of the seabed in the Australian region is of growing interest.

Prospecting in Australian waters for these minerals - mineral sands, tin, gold, phosphorite, bauxite, and manganese nodules - deserves further coverage in the following sections of this paper, but with the exception of manganese nodules there is little new information about the Australian region since a summary of prospecting offshore was published by the Bureau of Mineral Resources (Noakes, 1970); for this reason manganese nodules have been given special emphasis below.

However, it is desirable at this stage to summarize the position as regards legislation offshore in Australia, as uncertainty in this field remains a hindrance to exploration for minerals other than petroleum. The introduction of joint Commonwealth-State legislation to control the exploration and development of petroleum offshore in Australian waters in 1967 - the Petroleum (Submerged Lands) Act - was very necessary to support expanding petroleum exploration in 1967, and ended the period earlier in the 60's when petroleum titles were granted offshore by State Governments by applying offshore their State Mining Acts, which covered petroleum exploration and development on land.

There was not the same urgent need to clarify legislation in the case of minerals other than petroleum at that time, and the practice of States' granting exploration titles offshore, based on mining acts referring to land tenure, continued.

However, proposals by the Commonwealth in the late 60's to assert Commonwealth jurisdiction offshore for minerals other than petroleum and to pass a Commonwealth act to provide a mining code for these minerals led to controversy. In the event and by gentleman's agreement some States have continued to grant titles offshore for minerals other than petroleum, with the concurrence of the Commonwealth in each case, so that exploration could proceed on the basis that if or when new legislation was passed, such titles would be transitioned along lines established for the transitioning of State titles granted for petroleum exploration before the enactment of joint Commonwealth-State legislation for petroleum offshore in 1967.

The legislative situation for minerals other than petroleum offshore continues to be unsatisfactory and a growing hindrance to exploration in early 1973, although the new Federal Government elected in late 1972 is expected to assert Commonwealth jurisdiction offshore and to provide legislation to cover minerals other than petroleum.

Mineral tenure in deep ocean basins, and in fact beyond the 200-metre isobath, is currently confused, and seems likely to remain so until international agreements through the United Nations resolve the limits of national jurisdiction offshore and, beyond these, the administration of the proposed international regime to cover the remainder of the oceans.

DETRITAL HEAVY MINERALS

Emery & Noakes (1968) have suggested a practical division of valuable detrital minerals into heavy heavy minerals (gold, tin, platinum, chromite), light heavy minerals (rutile, zircon, ilmenite, magnetite, monazite etc.), and gems (diamonds, sapphires etc.); this division recognizes that economic deposits of the heavy heavy minerals, with specific gravities above 6.8, occur principally in stream beds and less than 15 km from source, whereas minerals of the light heavy group, with specific gravities between 4.2 and 5.3, normally travel long distances, and economic deposits principally depend on the high-energy concentration of waves building beach deposits.

From these considerations, Emery & Noakes suggested a number of guidelines for the occurrences of economic deposits of detrital minerals on the continental shelf. In the first place, the most reliable guide to potential for heavy mineral deposits on the shelf is the occurrence of economic deposits either in stream channels or in beaches on land to establish provenance for minerals offshore.

In the second place, since economic deposits of heavy heavy minerals occur close to source, known sources of minerals on land, even extending to the shoreline, are not likely to give rise to economic deposits along the seaward continuation of stream beds for more than 8 km in the case of tin or for more than 15 km in the case of gold. Economic deposits of these minerals farther removed from known sources would require areas of bedrock on the shelf which were sufficiently exposed during recent low stands of sea level to provide mineral concentrations.

In the third place fossil strand-lines, formed seaward from land areas shedding light heavy minerals and providing economic concentrations along the present shoreline, are likely to include concentrations of beach-sand minerals; but these fossil beaches have been submerged beneath an encroaching sea which probably made some changes to original mineral concentrations. Likely processes and changes under these conditions are still obscure, but at least some reworking and changes in distribution of mineral concentration would be expected, with perhaps remnants of original beach concentrations existing beneath cover of reworked or younger sands.

If, as seems likely, the entire sand body would need to be worked offshore, where selective mining as practised on land would at least be difficult, the grades offshore are likely to be significantly lower than those found along the present beaches, requiring very careful investigation and perhaps new techniques to exploit.

Mineral Sands

Australia provides an outstanding environment in which to study mineral sand deposits offshore; such a study should start seawards of the rich rutile and zircon deposits of the central east coast.

Investigation of possible offshore deposits was begun by the Australian-owned Planet Metals Limited in 1965 off the central coast in areas between Newcastle and Brisbane. A number of companies followed Planet's lead and obtained prospecting permits offshore along the coast of N.S.W. and southern Queensland, but most if not all were subsequently surrendered.

In investigating occurrences of mineral sands offshore over the years, Planet and associated companies have developed new equipment and techniques for use in some aspects of offshore prospecting, particularly in the use of laser beams for positioning; research and development have been followed by some detailed investigations of mineral deposits.

Brown & MacCulloch (1970) have provided some interesting information on mineral occurrences found to date. Heavy mineral concentrates can occur in a blanket or layer of sand 1.5-5 m below the sea bed, overlying barren material, or more commonly in seams in fossil beaches beneath 3-5 m of generally barren sediments. Planet has identified and concentrated on a near-shore fossil strand-line in about 30-36 m of water; there is evidence of a second strand-line in 70-80 m of water, and beyond this two more strand-lines are postulated in depths of less than 140 m. Although much detailed assessment is still to be done, some indication of overall grade of a fossil strand-line along some 30 km of coast from 70-100 km north of Newcastle has been given by Brown & MacCulloch and in the Annual Report of Planet Metals for 1970. Total heavy mineral content of the sediments (presumably to a thickness of 10-13 m) averages 0.8%, with the rutile plus zircon content amounting to about a quarter of the heavies. Planet's Annual Report for 1970 refers to 375 million tons of mineral sand along this strand-line with an estimated grade of 0.20-0.22% rutile plus zircon, and to an indication of a further 500 million tons. As rutile and zircon are reported to occur in approximately equal quantities, the overall grade of these sediments, in terms of rutile, would be about 0.1%. The average grade mined on land is considerably higher than 0.1% and in fact on the east coast was running between 0.3-0.4% in early 1973; cut-off grades have fallen in places to at least 0.15%, but significant economies of scale will be needed before sand averaging 0.1% with an equivalent amount of zircon and currently grading about 17-18 cents per yard could be profitably mined offshore. Grades of deposits, necessarily mined in bulk offshore, are expected to be lower than those available onshore, particularly if compared to those on virgin beaches in the past. The principal challenge offshore may well be to mine and treat more cheaply than on land.

However, future needs for rutile and ilmenite (including the high-chrome ilmenite of the N.S.W. coast, discarded in the past) emphasize the importance of present studies offshore. Little is known of fossil strand-lines in deeper water, but they too are worthy of investigation to collect data bearing on shelf processes and on the distribution of heavy minerals as well as to seek additional mineral deposits which future technology may be able to exploit.

Results off the central coast are likely to influence prospecting other areas offshore from known coastal deposits. Offshore investigations extending northward towards Gladstone, on the central Queensland coast, would enter a dominantly ilmenite province in which much of the mineral is relatively low in chrome, but prospects seem to have proved discouraging. In Bass Strait, rutile and zircon were identified by Ocean Mining A.G. off Naracoopa, King Island, where these minerals are currently mined on land.

The main ilmenite province along the Bunbury coast in Western Australia, where ilmenite is accompanied by by-product zircon, monazite, and rutile, is known to include some offshore concentrations, although little work has yet been done. Ilmenite has a much lower unit value than rutile or zircon, but this is compensated for by much higher concentrations of heavies in the Western Australian deposits than on the east coast; some concentration of ilmenite and associated heavy minerals would be expected in submerged strand-lines off a rich ilmenite coast, but occurrence, grade, and conditions have yet to be established.

Occurrences of relatively low-grade concentrates onshore like those reported north of Perth and at Point Blaze (Ward, 1957) and on Melville Island in the Northern Territory (McKay, 1956) provide no present encouragment for offshore prospecting, on the premise that only under very unusual conditions would fossil strand-lines provide higher grades in bulk than would be available by selective mining onshore.

The same can probably be said for beach sand deposits containing ilmenite, rutile, and some chrome near Strahan, Tasmania, and for deposits of ilmenite along the southern coast of Western Australia.

On the other hand, although guidelines suggested for offshore prospecting seem logical on present knowledge, our understanding of the processes involved in heavy mineral concentration offshore is imperfect, and leaves room for research and new ideas which could pay dividends in terms of unsuspected deposits.

Tin and Gold

Following the guidelines of tin prospecting offshore suggested earlier in this article, the shelf off northeastern Tasmania, including that adjacent to the Furneaux Islands, and that off the north Queensland coast obviously show some possibilities. In both areas erosion of tin-bearing granites has given rise to economic deposits of alluvial tin along the valleys of coastal streams. Northeastern Tasmania would seem the more prospective area, with tin granites and alluvial deposits close to the coast and current tin dredging along the valley of the Ringarooma River close to the sea.

Tasmanian prospects were early recognized by Ocean Mining A.G., experienced offshore prospectors, who became the operative company of a consortium which included E.Z. Industries, Anglo-American Corporation, and Bethlehem Steel.

Preliminary reconnaissance offshore started early in 1966 and included shallow seismic profiling and reconnaissance drilling; this indicated prospects for offshore tin off the central east coast of Tasmania (Oyster Bay) in Ringarooma Bay near the northeastern corner of the island facing Bass Strait, and east of King Island, where some tin, rutile, and zircon were found. More detailed investigation indicated that the best prospects were in Ringarooma Bay, where a program including 138 drill holes in water depths ranging from 10-40 m was completed by early 1967 (Lampletti, Davies, & Young, 1968).

Company reports lodged with the Mines Department, Hobart, were released on open file when the company surrendered its prospecting licence in 1969. A summary of results in Ringarooma Bay (Young, 1969) indicates that tin concentrations were patchy but generally followed the continuation of the Ringarooma River offshore; holes 1 to 1.5 km apart gave some preliminary indication of reserves and suggested some 30 million cubic yards grading about 4 oz. of tin metal per cubic yard plus some zircon and high-chrome ilmenite, to a maximum water depth of 40 m; the sediments containing the tin were rarely more than 13 m thick. The report mentions, however, that closer drilling might upgrade reserves by delineating additional rich patches and that tin-bearing sediments are clearly likely to continue northwards, although into deeper water.

Neither quantity nor grade as presently indicated offers much encouragement offshore in the active seas of Bass Strait. Indeed, a grade of 4 oz. tin metal per cubic yard onshore, worth about 28 cents per yard, sold as concentrates in early 1973 prices, would presently be regarded as low grade for an economic deposit.

The shelf around the Furneaux Islands also attracted some attention in 1967, as both Flinders and Cape Barren Islands include tin-bearing granites and have provided small alluvial deposits in the past. Broken Hill Proprietary Limited and Utah Development Limited combined in this area to carry out seismic profiling and reconnaissance drilling, but found no prospects to warrant continued investigations.

Prospectors in these areas were aware of the possible occurrence offshore of the productive 'deep leads' known onshore - tin-bearing stream gravels covered by valley fill of younger sediments. However, "leads" onshore lie as much as 33 m below present sea level and under as much overburden, and such conditions offshore would not favour economic mining. The marine geology of this area, with notes on tin prospects, has recently been covered by Slater (1969).

Prospects off north Queensland do not appear as attractive as those off Tasmania, although no intensive investigation seems to have been done. The main tin province of the Herberton area, inland from Cairns, is situated on a plateau and has contributed little tin to the sea. However, between Cairns and Cape York a number of coastal streams, like the Annan River, contain some tin and could perhaps generate tin deposits offshore. Some offshore prospecting permits were held in this area in 1966-67 and subsequently surrendered, but no prospecting results were released.

Elsewhere in Australia, known tin fields seem too distant from the coast to provide offshore prospects. The small tin field of the Finniss River, shedding in part in Bynoe Harbour south of Darwin, is an exception, but offshore prospects seem unattractive; tin and tantalite shed from pegmatite and greisen dykes appear to have moved very little from source in this subdued terrain, and deposits presently known provide no suggestion of offshore continuation.

The only alluvial gold prospect known to have been investigated offshore in Australia was off Bermagui on the south coast of New South Wales, where records of mining last century reported rich gold values in beach sands. Planet Gold Ltd carried out a reconnaissance offshore in this area in 1967, but no results were released.

CONSTRUCTION MATERIALS

The only construction material now mined offshore in Australia is dead coral from Moreton Bay, Queensland, which has been used for cement manufacture at Darra for many years. Virtually unlimited and untapped resources of very pure limestone are present off the tropical coasts and in the Great Australian Bight. As yet there has been little incentive to explore these resources, although one company is investigating the prospects of a marine source of limestone close to Darwin. Dead coral in the Great Barrier Reef area promises future supplies of limestone along the central Queensland coast, although supplies on land are adequate for many years to come. Any future mining activity, particularly in the Great Barrier Reef area, will certainly be carried out under strict controls imposed in the interests of conservation.

No significant mining of sand or gravel for concrete aggregate has taken place offshore, although, in line with trends overseas, increasing interest is being shown in possible marine sources of this material, particularly of coarse aggregate.

In the U.K., marine dredging has increased rapidly since it emerged as a significant force in the industry in 1961. By 1971 over 50 specialized vessels, most in the 1000 to 2000 ton class, were engaged in dredging, and together supplied over 10 percent of the construction industry's total requirements (Dunham, 1970; Hill, 1971a, b). Coarse aggregate forms the bulk of the material mined and superficial deposits of as little as 1 m thickness are considered economic. Most deposits are close to shore and close to markets, although, with the increase in demand, mining is moving into deeper water. New ships being built for the industry are larger, in the 3000 to 8000 ton class, and are designed to work in water depths down to about 60 m.

There seems little doubt that marine aggregate will be extracted on a large scale near the major markets in Australia in the future. In 1972, applications for exploration licences for marine aggregate covered nearly all the New South Wales inner continental shelf from Port Stephens, north of Newcastle, to Tathra on the far south coast. At the time of writing (March, 1973) granting of licences is still delayed pending decisions on the conditions which will be imposed on the licencees, and no exploration work by mining companies has been undertaken.

Available information on the inner shelf sediments off New South Wales (e.g., Shirley, 1964; Davies & Marshall, 1972) is not particularly encouraging from the point of view of the occurrence of large deposits of gravel suitable for coarse aggregate. The prolific onshore sources of high-quality gravels found in northwest Europe (glacial drift in the North Sea and Irish Sea, and chalk with flints in the English Channel) cannot be matched in New South Wales. The recent reconnaissance work by BMR has proved the existence of adequate thicknesses of unconsolidated sediment over bedrock in many areas, but gravels are uncommon and usually of unsuitable composition. However, no detailed work has yet been undertaken and it is likely that suitable deposits along submerged stream channels or fossil beaches could be outlined by closely spaced sampling and drilling.

PHOSPHORITE

During the upsurge of interest in offshore mineral prospecting between 1965 and 1967, a number of companies searched for phosphorite under permits granted by State Governments. These permits covered extensive areas of continental shelf off the east coast of Australia and off Tasmania, in the Great Australian Bight, and off the west and northwestern coasts of Australia. Except on the west Tasmanian shelf, no significant discoveries of phosphate were made, although it must be admitted that in some cases little or no useful field work was carried out. This lack of success offshore, combined with the discovery on land of large deposits of phosphate rock in northwestern Queensland in August 1966, served to discourage the search for phosphorite on the shelf.

Theoretical considerations on the formation of phosphorite by upwelling of nutrient-rich deep ocean water point to the continental margin of northwestern Australia as an area of phosphate potential. A reconnaissance of this region was therefore carried out by BMR in 1967-68 (Jones, 1968, 1970); sediments with relatively high phosphate content were noted near the edge of the shelf, but maximum P_2O_5 values were less than 4 percent and nothing remotely approaching economic grade material was recorded.

The marine reconnaissance carried out by Ocean Mining A.G. in Tasmanian waters in 1966 located phosphate nodules on the southern and western Tasmanian shelf; deposition presumably is a result of upwelling, principally along the western coast. Reports from the company, available at the Tasmanian Mines Department in Hobart, indicate that the most encouraging concentrations and grades are likely to be found west of Tasmania and south and southwest of King Island. Nodules were found in depths ranging from 65 to 165 m, which is unusually shallow for phosphorite occurrences, and although the grade of most samples was less than 13 percent P_2O_5, there were at least four localities on the western shelf where samples graded 13 to 26 percent P_2O_5. However, these indications of possibly higher grade patches of phosphorite were not further investigated by the group.

In eastern Australian waters, phosphatic nodules were dredged from the continental slope off northern New South Wales by Global Marine Inc. in 1966 and there have been several reports of phosphatic material on the Tasman Sea guyots. Selected nodules from off Coffs Harbour assayed as high as 21 percent P_2O_5 (von der Borch, 1970), but most of the material was of very low grade and the survey was not continued beyond the reconnaissance stage.

These reports induced some company activity, but there was no way in which Australian Governments could support interest by providing some type of legal tenure over portions of the deep ocean beyond the shelf. The Bureau of Mineral Resources reconnoitred the area in 1969, but dredging of both the tops and sides of sea mounts in the Tasman Sea produced no evidence of phosphorite, suggesting that occurrence was patchy. Further work by the Bureau of Mineral Resources in 1970 has discovered phosphatic rock cropping out on the upper continental slope on the central east coast between 25° and 31°S at depths ranging from 197 to 293 m. Most samples contain only about 5 percent P_2O_5, but individual nodules assay as high as 26 percent (Marshall, 1971).

MANGANESE NODULES

Distribution

Increasing interest in the manganese nodules of the deep ocean floors, chiefly because of the copper, nickel, and cobalt they contain, has resulted in recent years in the collection of much additional data on their distribution and composition, as well as in research by international consortia into methods of recovery and metal extraction. A recent bibliography of manganese nodules covering the fields of geochemistry, mineralogy, mining, and legal aspects included almost 900 references (Glasby, 1972a, b).

Despite this interest, information on their chemistry and distribution is still very sparse, particularly in the Australian region. Figure 4 summarizes the available data on occurrences around Australia between 10° and 55°S and between 100° and 170°E[1]. Open circles indicate that manganese nodules are present (33 occurrences) and full circles show that analyses are available (19 additional occurrences, see Table 3). Crosses indicate that photographs show that no nodules are present on the sea bed (92 localities). Out of the total of 143 deep-water stations, nodules were reported at 52, or one third. The possibility also exists that nodules may be present under a very thin veneer of sediment where a photograph shows a barren surface; thus Mero (1965, p.145) reproduces a photograph from a Monsoon station showing only fine sediment, even though a dredge attached to the same wire as the camera recovered abundant nodules.

It is difficult to draw general conclusions on distribution patterns owing to the relatively small number of stations. In particular there are no stations on the Lord Howe Rise in the northern Tasman Sea

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[1] Data taken from compilations by Mero (1965), McKelvey & Wang (1969), Ewing et al. (1971), and Conolly & Payne (1972), with additional information from Eltanin cruises (L.A. Frakes, pers. comm.) and from the French organisation CNEXO.

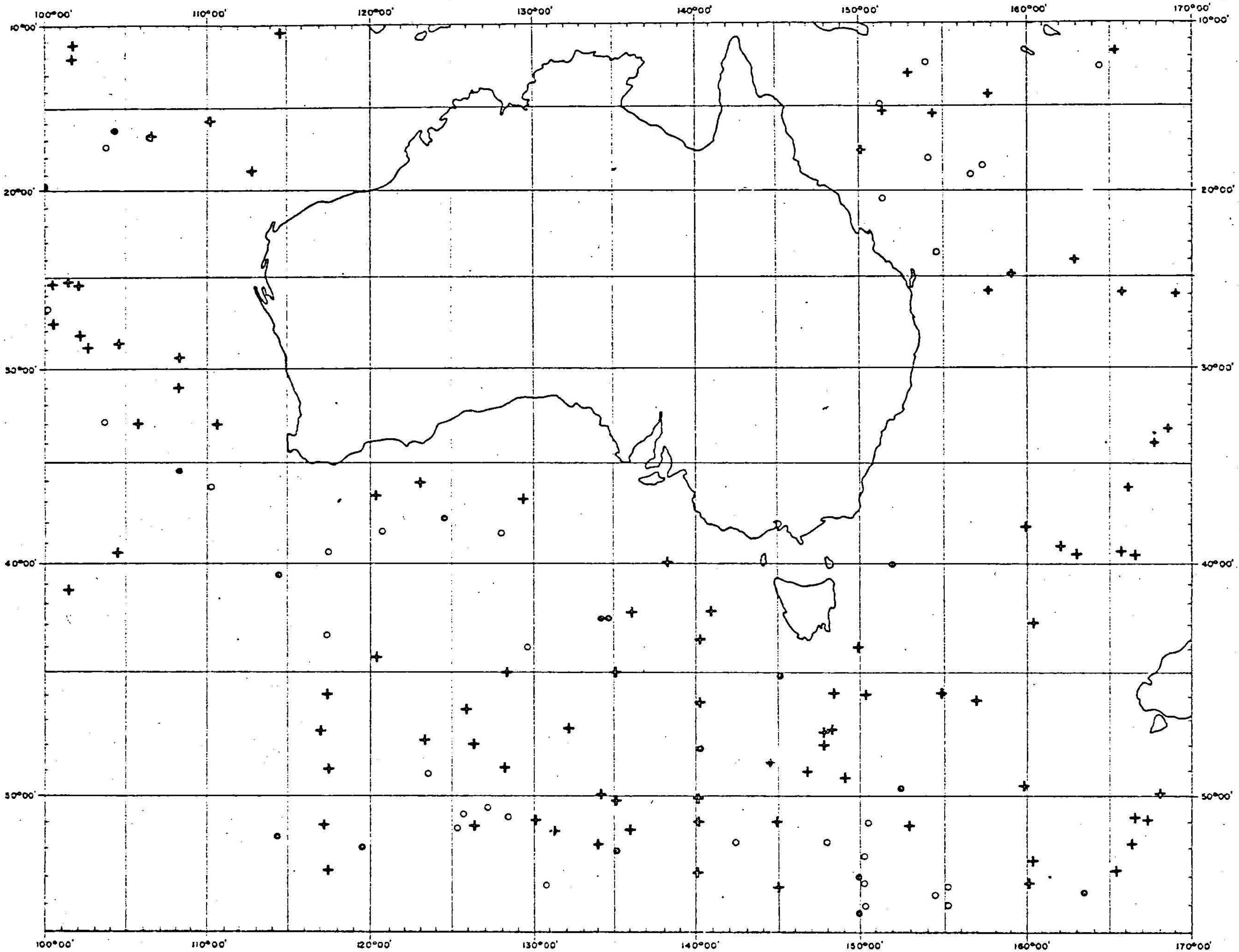

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FIG 4-MANGANESE NODULES IN THE AUSTRALIAN REGION. FOR DESCRIPTION SEE TEXT between 22° and 37°S, close to the 162°E meridian, which although above the carbonate compensation depth could still be a potential site of nodule accumulations. Data are also extremely sparse in the south Tasman sea, and in the Indian Ocean southwest of Cape Leeuwin and west of North West Cape. In each of these areas there are several 5° squares without a single station and others with only one or two.

The greatest concentration of nodule occurrences occurs south of 50°S in the region of 150°E. This is part of the extensive area of manganese pavement far to the south of Tasmania which has been outlined by Eltanin deep-sea cores (Conolly & Payne, 1972). Nodule occurrences predominate over barren areas also in the region of 50°S, 120°E; in the western Bight southeast of the Naturaliste Plateau around 40°S; and in the western Coral Sea. However, in none of these latter areas, with the possible exception of the western Bight, are there enough stations for conclusions to be drawn with any confidence on the presence of continuous or semicontinuance manganese pavements.

Composition

Manganese nodules vary considerably in composition, and although regional patterns in compositional changes have been outlined, a fully satisfactory explanation of the causes of these variations has not yet been put forward. In very general terms, Atlantic and Indian Ocean nodules are rather low in nickel and copper, and cobalt tends to increase at their expense in shallower water (around 3000 m). The Indian Ocean nodules show a regional increase in nickel and copper and decrease in cobalt eastwards, but no regional trends are discernible in the Atlantic.

Manganese nodules are more widespread in the Pacific and have provided most of the available data. The compilations of Mero (1965) and McKelvey & Wang (1969) show that the central and eastern Pacific nodules have the highest nickel and copper values, and again the ratio of cobalt to nickel plus copper increases with decreasing water depth. The average composition of surface nodules in various areas of the Pacific quoted by Cronan (1972) is given in Table 1 and the relation between water depth and nickel, copper, cobalt, and lead content from the same author is given in Table 2.

Horn, Horn & Delach (1972) have noted changes in the average metal content between nodules from areas of the seabed underlain by red clay and by siliceous oozes in the north Pacific; nodules associated with siliceous oozes contain more nickel and copper than those from areas of red clay, as shown by the following averages:

Nodules from Red Clay

Nickel %	Copper %	Cobalt %	Manganese %	Percentage Cobalt in combined Nickel, Copper, and Cobalt
0.76	0.50	0.28	17.43	18%

Nodules from Siliceous Oozes

Nickel	Copper	Cobalt	Manganese	Percentage
1.16	1.02	0.25	22.36	10%

Fifteen analyses from the Australian region in the area covered by Figure 4 are given in Table 3; all are in middle to high latitudes south of 35°S. The average values of nickel, copper, and cobalt are significantly less than those of the central and eastern Pacific, and are about equivalent to those of the northern Pacific (Table 1). They do, however, show considerable variation, and it is interesting to note that the Challenger sample from west of Tasmania analysed by Goldberg (1954) has the highest copper value (1.81 percent) we have seen recorded from any manganese nodule. A sample from nodules at Latitude 56°42'S, Longitude 140°01'E has been investigated in detail by Ostwald & Frazer (1973).

There are far too few analyses to allow conclusions regarding regional variations in composition to be drawn with any confidence. Nevertheless, there is perhaps a tendency for the western samples to be richer in nickel and copper, but not in cobalt, than the eastern ones. Thus the ten samples west of 135°E average about four times the nickel content and six times the copper content of the nine samples to the east of that meridian (see Table 3).

Although world sampling is very uneven some variations in metal content appear noteworthy. For example, the percentage of cobalt in the combined nickel, copper, and cobalt content is shown in the tables for nodules in each geographical division; the percentage of cobalt is of current economic importance, as will be noted later. On this basis nodules east of longitude 135°E in the Australian region show some affinity to those of the south and west Pacific in higher relative cobalt content, whereas nodules west of longitude 135°E in the Australian region show the considerably lower relative cobalt content of nodules in the N.E., S.E., central, and N. Pacific. Variations will of course be found within all regions and it will be noted that much the same division on relative cobalt content already noted between geographic regions applies to nodules associated with red clays and those associated with siliceous oozes within the N. Pacific region.

Very significant platinum content has been informally reported from some nodules in the central Pacific region, but confirmation is lacking. One sample from the Australian region, from latitude 56°42'S, longitude 140°01'E, was specifically tested for platinum in the laboratories of the Zinc Corporation Ltd, Broken Hill, by kind cooperation of the Company, with indications of platinum content of less than

0.08 p.p.m. - less than 30 cents per ton at current prices. Additional checks on platinum content are warranted to clarify the situation, but in view of the difficulty in obtaining accurate platinum analyses reported high platinum concentrations need rigorous confirmation.

Economic Prospects

Exploitation of deep sea manganese nodules presents very considerable problems both in the recovery of the material from abyssal depths and in the extraction of metals from the ore. In 1970, a pilot operation by a subsidiary of the American company Tenneco Inc. successfully achieved continuous dredging of nodules from the relatively shallow waters (700-900 m) of the Blake Plateau off the coast of Florida. The system used employed compressed air to lift the nodules to the ship through a string of 9-5/8 inch drill riser casing attached to the dredgehead by a flexible hose. Although this sytem was designed to operate at the much greater depths (4000-6000 m) of the high-grade open ocean deposits, it is not known whether it has in fact proved successful in deep water. A company owned by Howard Hughes of U.S.A. is also reportedly designing and constructing a new system for mining and treating nodules, but under considerable secrecy.

Another consortium headed by Japanese interests is known to have experimented in the central Pacific with a continuous line bucket system, but again although some press reports have claimed success, no technical evaluation of the operation has been released.

Commercial extraction of metals from the nodules also poses difficult problems; concentration cannot be effected by physical methods, smelting is uneconomic, and the large number of metals present interferes with chemical separation techniques. A breakthrough in metallurgical treatment has been claimed by Tenneco Inc., who have constructed a pilot plant at Gloucester Point, Virginia (Taylor, 1971). The process involves the reduction of manganese dioxides in the crushed ore by hydrogen chloride and water leaching of soluble chlorides of the metals released. The leach liquor enters a liquid ion-exchange process and final metal extraction takes place in electrolytic cells.

No doubt, in time, problems in the mining and treatment of nodules will be resolved; current uncertainty relates to the difficulties in establishing processes and costs and to the marketing of some of the products, notably cobalt and manganese. Manganese, and indeed iron, recovered as fine-grained oxides would not together be worth more than $4-6 per ton ex mine and may or may not be saleable, depending mainly on the location of mining and treatment operations. The value of other metals occurring in nodules, such as lead, molybdenum, and vanadium, is low and of the order of a few dollars, although the recovery of titanium warrants further consideration. However, the cobalt content of nodules can be much more significant and hence is currently of economic importance.

By way of example the approximate recoverable value of nodules from selected areas is shown in Table 4. In the case of the comparatively rich nodules associated with siliceous ooze in the North Pacific, cobalt provides 20% of the value of combined nickel, copper, and cobalt; but in nodules associated with red clay it provides 31% of the value. In the Australian region, cobalt would provide 20% of the value of nodules west of longitude 135°E but 40% of the value of nodules east of that longitude, although in this case total values are obviously sub-marginal under present conditions.

The problem of selling cobalt is made clear by considering the likely production of the three metals from one enterprise mining nodules from the siliceous ooze ore of the North Pacific. Assuming that viability would require the mining and treatment of some four million tons of nodules per year (in view of the capital cost involved it would need to be of this order), production on the basis of an overall 85% recovery would amount to some 40,000 tons of nickel, 35,000 tons of copper, and 8,500 tons of cobalt. Production of this order would amount to about 6-7% of the western world's current demand for nickel, 0.5% of the demand for copper, but 40% of the demand for cobalt. Marketing of the copper should present no problem and the production of nickel from one such enterprise should be accommodated, but the chance of selling any significant proportion of the cobalt would appear slight, particularly in view of the fact that current supplies of cobalt are already produced as by-products of non-ferrous mining operations. As cobalt can substitute for nickel in some uses, it is possible that some cobalt could be marketed at the price of nickel, thus somewhat reducing the apparent recoverable value of nodules, for example as shown in Table 4, but the likely additional demand for cobalt at the lower price is uncertain.

For these reasons interest has apparently been concentrated on areas in the central and northern Pacific where nodules unusually rich in nickel and copper provide some promise of viability on these metals alone. From the viewpoint of mineral conservation and wise use of world resources, such projects appear wasteful; indeed considering that there is no evidence of any impending world shortage of any of these metals and none to suggest that recovery from manganese nodules is likely to be significantly cheaper than from land resources, the large-scale exploitation of manganese nodules might appropriately be delayed until recoverable products can be more efficiently utilized. In the meantime there is obvious scope for further research into distribution, mineralogy, origin, mining and treatment.

Information to date in the Australian region provides no promise of early viability and no indication of the higher grades of nodules known in parts of the Pacific; but reconnaissance of ocean basins around Australia is still at an early stage. The southern ocean west of longitude 135°E obviously warrants further investigation, and areas farther north, off the west coast of Australia and along the Lord Howe Rise off the east coast, where sea conditions are more amenable to mining, need systematic reconnaissance. Manganese nodules certainly promise some future resources in the Australian region; the task of establishing the extent and grade of these resources has only just begun.

TABLE 1. AVERAGE COMPOSITION OF SURFACE NODULES FROM DIFFERENT AREAS IN THE PACIFIC OCEAN[1]

	1	2	3	4	5	6	7	8	9
Mn	15.85	33.98	22.33	19.81	15.71	16.61	16.87	13.96	12.29
Fe	12.22	1.62	9.44	10.20	9.06	13.92	13.30	13.10	12.00
Ni	0.348	0.097	1.080	0.961	0.956	0.433	0.564	0.393	0.422
Co	0.514	0.0075	0.192	0.164	0.213	0.595	0.395	1.127	0.144
Cu	0.077	0.065	0.627	0.311	0.711	0.185	0.393	0.061	0.294
Pb	0.085	0.006	0.028	0.030	0.049	0.073	0.034	0.174	0.015
Ba	0.306	0.171	0.381	0.145	0.155	0.230	0.152	0.274	0.196
Mo	0.040	0.072	0.047	0.037	0.041	0.035	0.037	0.042	0.018
V	0.065	0.031	0.041	0.031	0.036	0.050	0.044	0.054	0.037
Cr	0.0051	0.0019	0.0007	0.0005	0.0012	0.0007	0.0007	0.0011	0.0044
Ti	0.489	0.060	0.425	0.467	0.561	1.007	0.810	0.773	0.634
L.O.I.	24.78	21.96	24.75	27.21	22.12	28.73	25.50	30.87	22.52
Depth (m)	1146	3003	4537	4324	5049	3539	5001	1757	4990
(2)	(55)	(4)	(10)	(11)	(11)	(49)	(29)	(71)	(17)

1) Californian Borderland Seamount Province
2) Continental borderland off Baja California
3) Northeast Pacific
4) Southeast Pacific
5) Central Pacific
6) South Pacific
7) West Pacific
8) Mid-Pacific Mountains
9) North Pacific

1 After Cronan (1972)

2 Percentage of cobalt in combined nickel, copper, and cobalt

Table 2 Variation with water depth of Ni, Cu, Co, and Pb in surface nodules, Pacific and Indian Oceans[1]

	0 - 1000 m	1000 - 2000 m	2000 - 3000 m	3000 - 4000 m	4000 - 5000 m	5000 - 6000 m
Ni	0.318	0.413	0.323	0.363	0.651	0.624
Cu	0.096	0.058	0.053	0.199	0.361	0.457
Co	1.823	0.805	0.641	0.306	0.220	0.255
Pb	0.382	0.122	0.101	0.033	0.035	0.032

1 After Cronan (1972). Data from analyses of 99 nodules

Table 3. Analyses of manganese nodules from the Australian region

Vessel	Lat. °S	Long. °E	Depth (m)	Fe	Mn	Ni	Cu	Co
Eltanin	16.30	104.27	–	–	–	0.70	0.54	0.23
– " –	16.82	106.50	–	–	–	0.71	1.00	0.19
– " –	19.93	100.00	–	–	–	0.46	0.63	0.21
– " –	35.35	108.22	4576	14.0	14.8	0.26	0.12	0.18
Vema	37.83	124.50	5518	10.3	18.4	0.90	0.45	0.15
Eltanin	39.98	152.03	4244	16.0	12.0	0.20	0.06	0.08
– " –	40.55	114.53	4390	5.2	9.1	0.41	0.35	0.04
Challenger	42.70	134.17	4760	9.9	21.0	1.15	1.81	0.09
Eltanin	42.70	134.67	–	–	–	1.32	0.75	0.20
– " –	45.19	145.06	3969	19.0	7.0	0.12	0.14	0.07
– " –	48.15	140.13	4536	4.9	1.6	0.03	0.01	0.03
– " –	49.67	152.57	4262	13.0	5.9	0.07	0.11	0.07
– " –	49.70	152.55	4271	12.0	6.4	0.12	0.14	0.08
– " –	51.50	114.30	3524	8.0	21.3	1.40	0.53	0.15
– " –	51.98	119.63	3905	20.0	10.7	0.08	0.07	0.11
– " –	52.08	135.10	3367	20.0	8.5	0.19	0.18	0.05
– " –	53.02	150.00	3878	17.0	9.5	0.13	0.07	0.16
– " –	53.50	163.52	2689	17.0	10.5	0.09	0.06	0.16
– " –	54.23	149.97	4060	13.0	13.5	0.63	0.17	0.13
AVERAGE	(all samples)	(13)*		13.3	11.3	0.47	0.37	0.13
– " –	(west of 135°E)	(10)*		11.2	15.9	0.74	0.63	0.16
– " –	(east of 135°E)	(24)*		14.7	8.3	0.18	0.10	0.09

* Percentage of cobalt in combined nickel, copper, and cobalt.

TABLE 4 - APPROXIMATE RECOVERABLE VALUE OF NODULES FROM SELECTED AREAS

(in $A per tonne)

	North Pacific Associated with siliceous ooze	North Pacific Associated with red clay	Australian Region West of Long. 135°E	Australian Region East of Long. 135°E
Nickel	24.7	16.2	15.7	3.8
Copper	9.5	4.7	5.9	0.9
Cobalt	8.5	9.5	5.4	3.1
TOTAL	42.7	30.4	27.0	7.8
	%	%	%	%
Value of cobalt in combined Ni, Cu and Co.	20	31	20	40

Assuming an overall 85% recovery and the following prices per ton: nickel A$2500, copper A$1100, cobalt A$4000.

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