Economic and Development Potential of Manganese Nodules within the Cook Islands Exclusive Economic Zone (EEZ)

Pacific Islands Development Program
and
Program on Resources: Energy and Minerals

East-West Center

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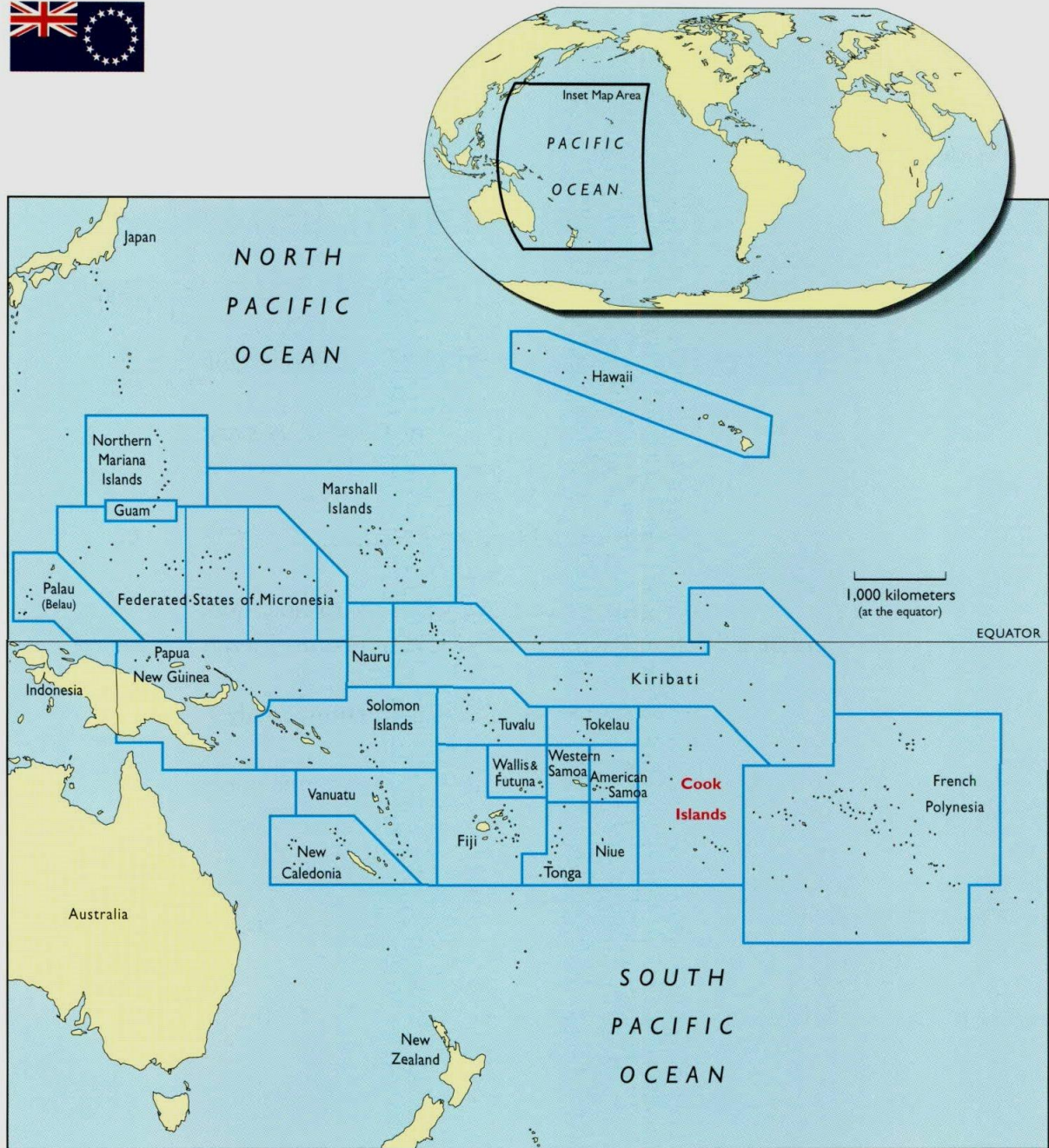
South Pacific Applied Geoscience Commission (SOPAC)

The location of the Cook Islands relative to other Pacific island nations. The blue lines do not constitute recognized territorial boundaries; they merely group islands under the same political jurisdiction.

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Top The Cook Islands is serviced by international airlines. (Island Image)

Bottom Telecom Cook Islands serves as an international communications systems network. (TCI Center)

Front Cover An aerial view of Rarotonga—the main island and commercial center of the Cook Islands. (Island Image)

Back Cover Manganese nodules are found in high densities in the south Penrhyn Basin in the Cook Islands EEZ.

Foreword

Located between 156° and 167° West longitude and between 8° and 25° South latitude, the Cook Islands is a modern micro-State in the middle of the South Pacific. The acceptance of the 200-mile Exclusive Economic Zone (EEZ) concept in international law has meant that the Cook Islands and other archipelagic countries have vastly more submarine territory than they do land area. This has opened up not only challenges but also unprecedented opportunities to us.

Having approved and monitored closely for several decades a deep-sea scientific research program in our waters, the Cook Islands has discovered that its EEZ possesses great amounts of mineral deposits, with nodules containing concentrations of cobalt, nickel, manganese, and other valuable non-living marine resources. With that in mind, my Government commissioned the East-West Center's Program on Resources: Energy and Minerals to (1) define the resource potential of the nodules; (2) evaluate the economic, technological, and market aspects of a mining operation; and (3) provide an overview of the development options.

This brochure presents in an abbreviated form the main findings of the Program's study so that they might be brought to the attention of all potentially interested parties. The study was sponsored by the Center's Pacific Islands Development Program (PIDP).

My Government is committed to the long-term, commercial exploitation of those resources, in conjunction, as appropriate, with those having requisite expertise and resources to offer in such an exciting and promising venture. I would welcome expressions of interest from those wishing to learn more about the study's findings and to pursue commercial possibilities further.

Honorable Sir Geoffrey Henry, KBE
Prime Minister
Cook Islands

An aerial view of Aitutaki Island, the Cook Islands. (Island Image)

Introduction

Manganese nodules were first discovered on the ocean floor in 1873 by the HMS *Challenger,* 160 miles southwest of the island of Ferro in the Canary Group (Murray and Renard, 1891). The possibility of mining manganese nodules was not seriously considered until the middle part of the 20th century, even though small subsea mining operations for other materials had taken place offshore in earlier times.

There was active interest by the private sector in the 1970s to develop deep-sea mining technologies to commercially recover manganese nodules from the sea floor. By the late and early 1980s commercial interest waned as a result of high risks, low profits, and long time horizons for development, and many private companies shelved major deep-sea mining projects (Johnson and Clark, 1990). Some governments (Japan, Germany, France, Sweden, Finland, West Germany, and the former Soviet Union), however, continued to fund scientific research but on a much smaller scale than Japan, which is presently funding a large R&D program to develop a pilot deep-sea nodule mining system. During the period from the 1960s to the present, there have been numerous new major discoveries of deep-sea resources and a revolution in technology relating to deep-sea mining and processing. Today, Japan, France, Germany, India, China, and Korea are still actively exploring for deep-sea mineral resources, including manganese nodules.

Five areas in the Pacific have been identified by Piper et al. (1985) to contain abundant nodules. These areas are as follows:

1. Clarion–Clipperton Fracture Zone
2. Northeast-Pacific Musicians Seamount area
3. Central Southwestern Pacific Basin
4. Southern Ocean around 60°S
5. Northern Peru Basin

The Clarion-Clipperton Fracture Zone (hereinafter CCZ) is considered by various authors to contain the most promising concentration of potentially economic nodules primarily because of high copper and nickel contents of at least 1% each. The cobalt concentration in this "prime" zone, although considerably lower than those of copper and nickel, averages approximately 0.24%, equaling the concentration of the richest cobalt mines found on land (Manheim, 1986).

During the 1970s, the Third United Nations Conference on the Law of the Sea (UNCLOS III) recognized the coastal States' sovereign rights over all living and non-living resources within an Exclusive Economic Zone (EEZ) of 200 miles. The recognition of this zone gave archipelagic countries such as the Cook Islands vastly more submarine territory than land area (see Figures 1 and 2).
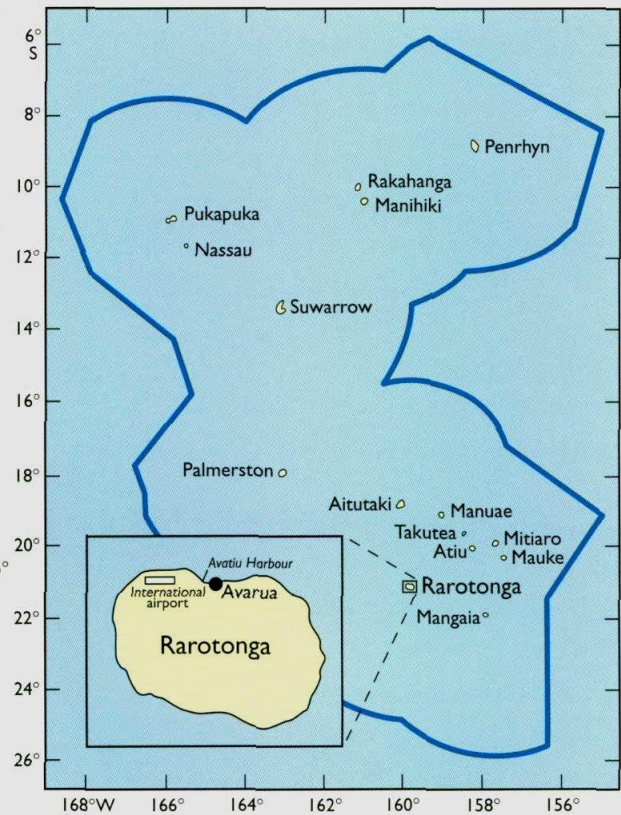
The Cook Islands 200 mile Exclusive Economic Zone (hereinafter CIZ) occupies approximately 2.5 million km² of which almost 70% is in deep ocean at a depth of approximately 5 km. The CIZ encircles the country's two main island groups: the southern group, including the islands of Rarotonga, Mangaia,
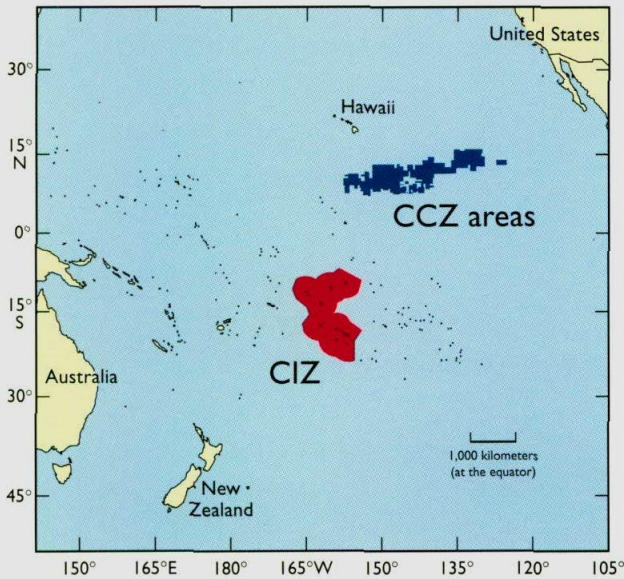
Figure 1. Locations of the Cook Islands EEZ (CIZ) and Clarion–Clipperton (CCZ) registered nodule mining areas. Note the size of the two areas.

Figure 2. The Exclusive Economic Zone (EEZ) of the Cook Islands.

Atiu, Mitiaro, Mauke, Aitutaki, Palmerston, Manuae, and Takutea; and the northern group, comprising the islands of Penrhyn, Manihiki, Pukapuka, Rakahanga, Suwarrow, and Nassau (Figure 2).

The Cook Islands climate is generally very pleasant. In Rarotonga the average temperature is 25°C with a maximum of 32°C and a rare minimum of 16°C. In the northern group atolls, temperature averages 29°C with a maximum of 37°C and minimum of 20°C. Rainfall is normally around 200 cm a year in any part of the islands but can vary considerably from year to year. Wind is predominately from an easterly quarter with average speeds varying from 16 km/hr in the northern group to 13 km/hr in the southern group. Solar radiation averages 19.3 MJ/m² in the northern group and 17.5 MJ/m² in the southern group. The country is situated in an area of the South Pacific subject to the occasional tropical cyclone, which strikes the southern group in particular with varying degrees of intensity.

The Cook Islands is a micro-State in the South Pacific. Rarotonga, at 21°12'S and 159°47'W, is the largest and most populated island with a land area of 6,920 ha and a height up to 652 m above sea level. The main coastal road surrounding the island is 32 km long. The population of Rarotonga is approximately 8,000, which is not quite half of the total Cook Islands population of some 18,500 people.

The Cook Islands economy is based on a thriving tourist industry, market gardening, its offshore finance center, and a rapidly growing black pearl industry. However, mining offers significant potential as much of the CIZ contains manganese nodules with abundances as high as 56 kg/m². The nodules are lower in copper and nickel content than those elsewhere but much higher in cobalt and many rare
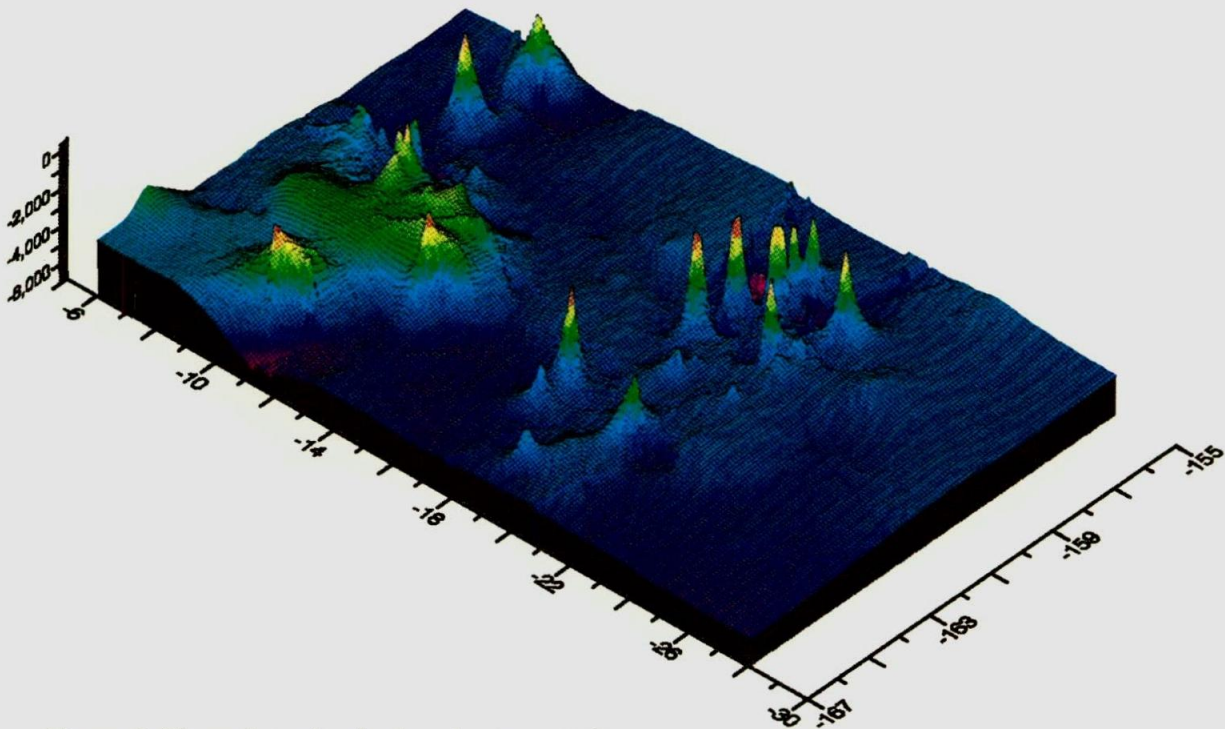
Figure 3. Three-dimensional submarine topography of the CIZ. Water depths are in meters.

elements. The economic value of these nodules either in a given area or for a given mass does appear at present metal prices to be greater than for nodules in other locations.

Sea Bottom Geology and Topography

Tectonically, the CIZ is situated on the southwest Pacific Plate, which is moving northwestward at a rate of about 10 cm/yr (Doutch, 1981). The southwest Pacific Plate was created by northwest spreading from the East Pacific Ridge (Wood and Hay, 1970).

The major submarine topographic elements of the CIZ include seamount chains, isolated seamounts, plateaus, sea hills, and deep-sea plains. A simplified three-dimensional diagram shows the overall submarine topography of the CIZ (Figure 3).

Based on submarine topographic characteristics, the CIZ can be divided into four distinctive submarine geomorphologic regions:

(1) the southern north Penrhyn Basin in the northeast, (2) the Manihiki Plateau in the northwest, (3) the Aitutaki Passage in the center, and (4) the Cook Islands seamount line in the south (Figure 4). Each region is characterized by its ocean floor topography, subsurface geologic structure, and ocean current activity. The difference in geologic and topographic environments may determine the regional ocean circulation and sedimentation, which in turn affect the concentration and metal content of the manganese nodules in the CIZ.

Generally, in the northern region, the broad ocean plain, knolls, and hills are the major topographic features. In contrast, in the middle region the Manihiki Plateau is a prominent feature that has played an important role in ocean circulation throughout the history of the region; the Aitutaki Passage is dominated by a relatively narrow flat bottom or semi-flat bottom from a macroscopic point
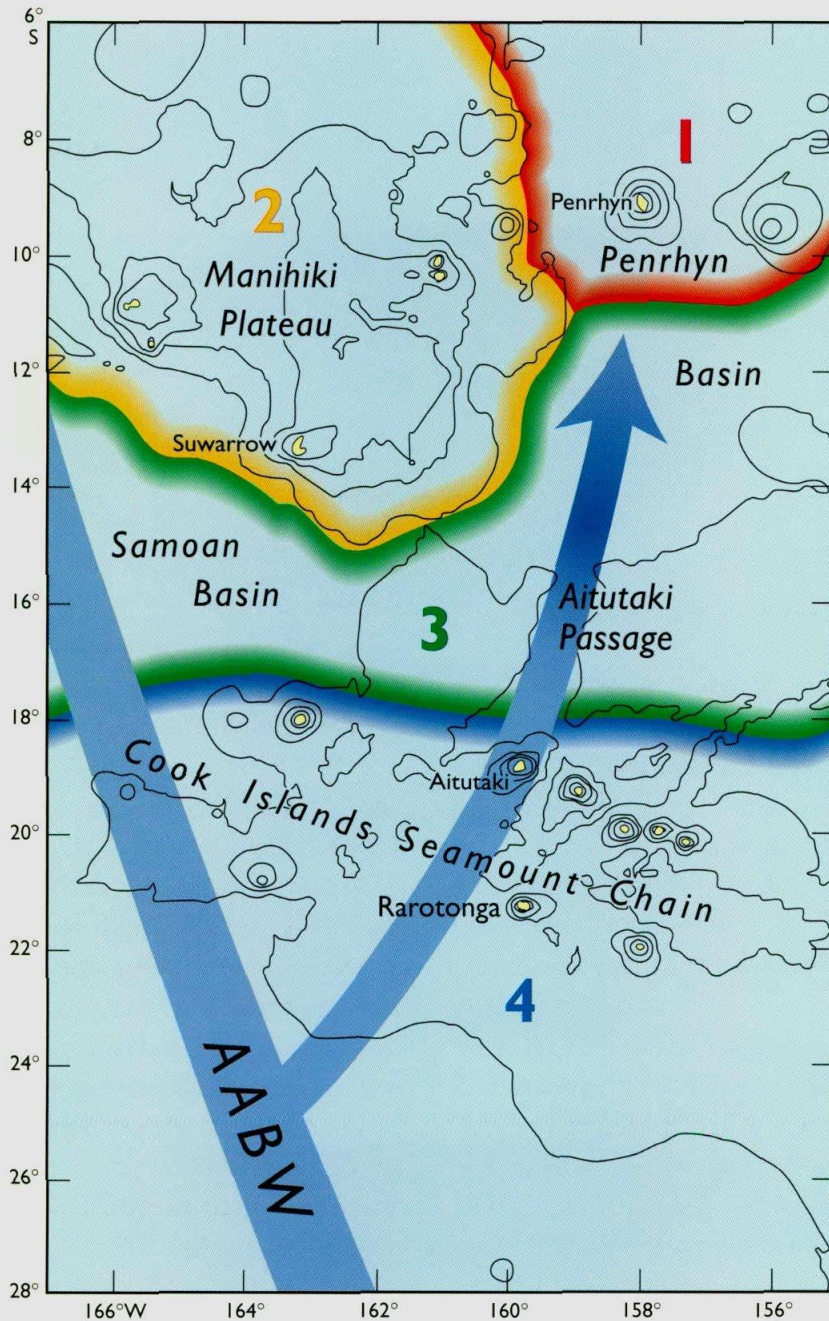
Figure 4. Submarine geomorphologic regions of the CIZ. The contour interval is in 1,000 meters.

of view, and the sea-floor features in the southern region are mainly seamount chains and hills. The zone of high abundance of manganese nodules in the middle region is characterized as topographically flat or semi-flat with knolls several hundreds of meters high.

The subsurface geologic structure of the CIZ consists essentially of basalt basement with overlying consolidated and unconsolidated sediments. The basalts are lavas and hyalo-clastites, whereas the sediments are Quaternary brown clay, calcareous clay, and
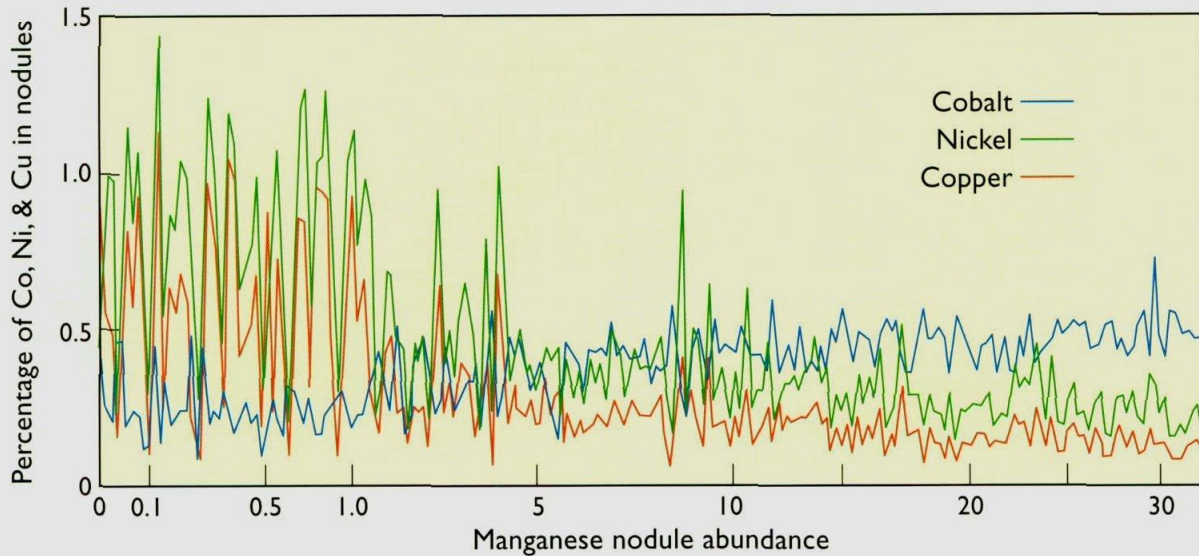
Figure 5. Nodule abundance vs. cobalt, nickel, and copper concentrations.

calc-siliceous clay. The surface sediments of the sea floor can be classified into two types: unconsolidated and consolidated. The unconsolidated sediments, identified by the sub-bottom (SB) profiles as transparent layers in the uppermost layer of the sediments, are mainly distributed on flats and sea knolls with thickness ranging from 0 to 40 m. In contrast, the consolidated sediments, recognized by SB profiles as opaque layers in the uppermost layer, are mainly distributed on seamounts and sea knolls; most opaque layers are considered to be exposed basement rocks.

The thickness of the unconsolidated sediments seems to be affected by the Antarctic bottom water (AABW) current that flows northeastward through the CIZ. Compared with the southern and northern regions, the central region has a relatively low sedimentation rate because of a stronger AABW current caused by the narrow Aitutaki Passage. A NNE elongated zone of high concentration of manganese nodules occurs in the central region implying that the high abundance of manganese nodules may be caused by the strong AABW current that erodes or dissolves

the sediments and creates an environment suitable for continuous nodule growth.

The AABW current not only influences the concentration of manganese nodules, but also affects the distribution of the major metal content of the nodules in the CIZ. Generally, the cobalt content is high in the southern and central regions where nodule abundance is also high. Conversely, copper and nickel contents are high in the northern region where nodule abundance is generally low (Figure 5) as a result of a relatively strongly oxidized ocean floor environment. In the central and southern region high nodule abundance regions are due to the effect of stronger AABW current. A relatively strongly oxidized environment also favors the deposition of iron and cobalt.

In contrast, a weakly oxidizing ocean floor environment would be formed in the northernmost region due to the weakening of the AABW current after it passed the Aitutaki Passage and reached a broad ocean plain region. The weakly oxidizing ocean floor environment would be favorable for the deposition of manganese, nickel, and copper.

Comparison of the Cook Islands and the Clarion–Clipperton Nodule Provinces

The Depositional Environments

The depositional environments for the manganese nodules of the CCZ and the CIZ are both tectonically and geochemically quite different, and it is these differences that primarily account for the textural, abundance, and chemical variations between the two areas.

The CCZ is located just north of the equator and contains the most studied nodule deposit in the world's oceans. The CCZ nodule area, known as the "Manganese Nodule Belt," is within the area bounded by 90°–160°W and 5°–15°N, an area delimited by the Clarion–Clipperton fracture zones on the north and south, respectively. The CCZ is characterized by gently rolling abyssal hills (Meyer, 1973; Horn et al., 1972), high nodule densities, and a sea floor composed predominantly of siliceous radiolarian oozes and clays (Horn, et al., 1972; Hans-H, 1973; Meyer, 1973).

The CIZ nodule fields located south of the equator are, as expected, quite different from the CCZ nodule fields. The oceanic crust on which the islands of the CIZ are resting was formed sometime during the Cretaceous as compared with the Late Cretaceous to Early Tertiary age of formation of oceanic crust on which the CCZ prime nodules are resting.

In a very general sense, the sea bottom topography of the CIZ is somewhat similar to the CCZ area. The predominant sediment types, on which abundant nodules were sampled, are quite different being reddish to grayish brown abyssal clay and siliceous or calcareous oozes and clays (Landmesser and Kroenke, 1976; Landmesser et al., 1976; Monzier and Missegue, 1977; Glasby, 1978; Exon, 1981; Glasby et al., 1983, 1986).

The CIZ nodules and those of the CCZ also started forming about the same time (Glasby et al., 1983); however, the proposed nodule growth method of hydrogenetic adsorption (Glasby, 1978) of metal oxides from the enriched bottom currents is different from that of the CCZ (Figure 6). Also different is that the source of the metal ions is postulated to be associated with the tectonic activities that formed the CIZ islands and from activities associated with the 100 MA triple junction in the south Penrhyn Basin (Winterer et al.,
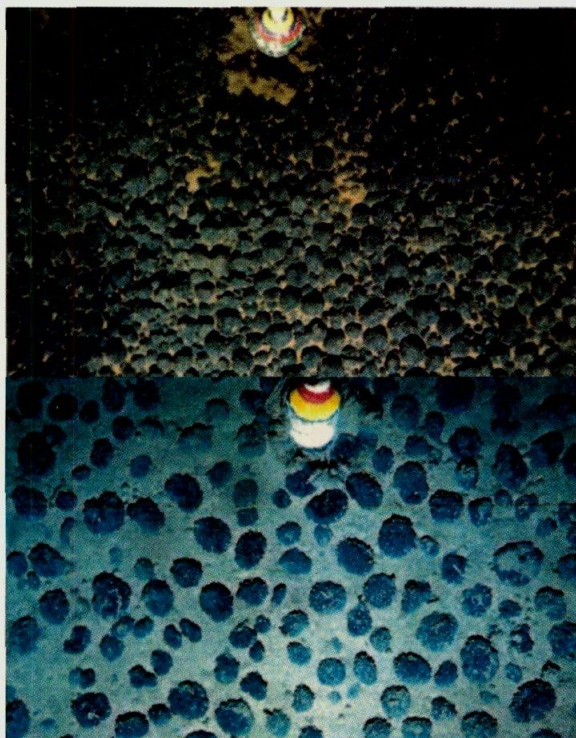
Figure 6. Mode of occurrence of manganese nodules on the sea floor in CIZ (above) and CCZ (below). The scale of both pictures is indicated by the size of weights that have a diameter of 10 cm.
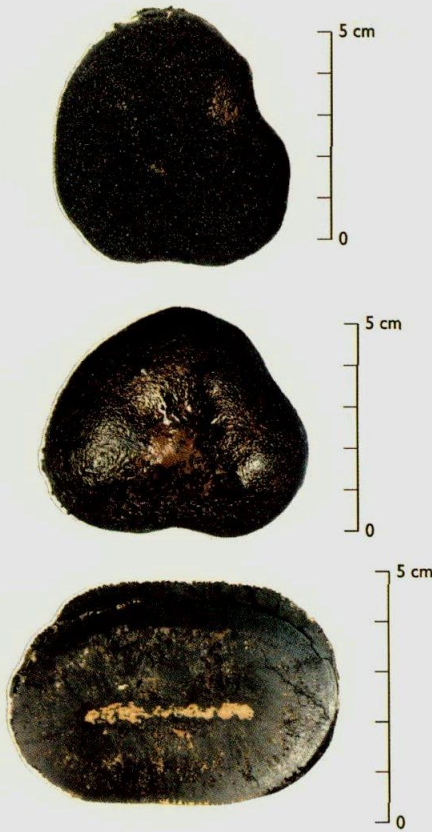
Figure 7. Smooth-microbotryoidal surface (*top*), rough bottom surface textures (*middle*), and internal structure (*bottom*) of nodules from the CIZ.

1974). It is mainly the presence of the intensified AABW flow (Landmesser et al., 1976) that keeps the nodules afloat on the sea floor and produces a typical surface texture and internal structure of the nodules (Figure 7).

Apparently, because of the different tectonic setting and ocean circulation environment, the geological and geochemical characteristics of the CIZ nodules are distinct from those of the CCZ nodules. A comparison of nodule geology and geochemistry of the CIZ with those of the CCZ is shown in Table 1.

Comparison of Nodule Distribution and Metal Grades in Nodules

Central to achieving the results required to undertake a comparative analysis of nodule distribution, it was necessary to gain access to nodule data from the CCZ that are comparable in detail with those from the CIZ. A geostatistic method, variogram (David, 1977), was used to compare the nodule distribution and abundance of the CIZ with seabed nodule deposits in the CCZ (between 7°–16°N and 124°–152°W).

Figure 8 shows an example of the variograms produced for a comparison of values of metals in a square meter in the CIZ central region and CCZ area A. As Figure 8 shows, the average value of metals in 1992 metal prices in the CIZ central region is US\$2.50/m^2, which is US\$0.22/m^2 greater than that of the metals in the CCZ area A. The variogram analyses of cobalt abundance in the CIZ central region also show particularly high values of 80–113 g/m^2 in an area between 14°–18°S and 157°–161°W. A comparison of an average of metal grades in nodules between the CIZ and CCZ is shown in Table 2.
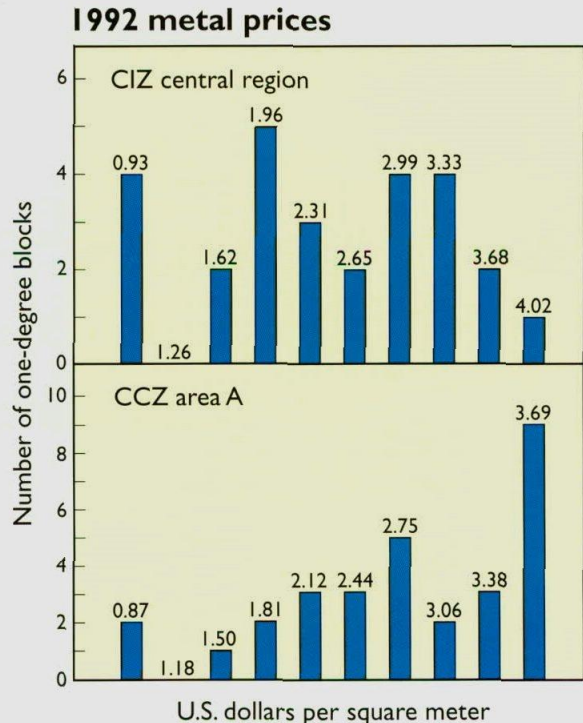
Figure 8. *Economic values of CIZ central region and CCZ area A in 1992 metal prices.*

Table 1. Comparison of nodule geology and geochemistry of the CIZ with those of the CCZ

NODULE AND SEDIMENT	COOK ISLANDS EEZ (CIZ)	CLARION-CLIPPERTON ZONE (CCZ)
Size and shape of nodules	1–6 cm, sometimes 8 cm; mostly 2–6 cm in diameter. Spheroidal to ellipsoidal, discoidal, some polynucleate, irregular deformed and often flattened; also present are plate, pebble thin, and massive types.	Common (small) ave. 1–2.5 cm, medium ave. 3–4 cm, large ave. 5–6 cm. Discoidal, ellipsoidal and widespread poly-nodules; pancake- to hamburger-shape on siliceous ooze (5–10 cm size nodules).
Surface texture and internal structure of nodules	Smooth-microbotryoidal, black or light brown surface color with microbotryoidal texture; in Aitutaki granular surface texture on one side and microbotryoidal on the other. Outer 1–4 mm of manganese oxide and an inner layer of hard, lustrous manganese oxide w/ variable amounts of clay minerals, outer 1 mm by direct deposition from seawater, inner layers by replacement of preexisting volcanic core by manganese oxides.	Rough, botryoidal, smooth, presence of large equatorial collars. Concentric banding that may be symmetric or asymmetric depending on shape of nodule.
Depths of nodule located	High nodule concentrations: 4,900–5,400 m; high Ni+Cu+Co: 5,000–5,400 m in south Penrhyn Basin (SPB); 5,000–5,500 m in north Penrhyn Basin (NPB); Ni and Cu enrichment 5,000–5,300 m regionally.	Nodule concentration 4,000–5,600 m; Ni maximum at 4,900 m.
Abundance and coverage of nodules	3–24 kg/m^2 between 9°–11°S and 155°–157°W; 30 kg/m^2 around 15°S; mostly 1 kg/m^2, a few >9 kg/m^2, ave. 2.5 kg/m^2 between 11°–20°S and 158°–161°W; 6–23 kg/m^2 in Aitutaki; mostly <5 kg/m^2 in NPB. General coverage 52%, as high as 90%; 25–50% in Aitutaki, 68% in SPB.	10 kg/m^2; ave. 11.9 kg/m^2; 10–15 kg/m^2. Maximum % of coverage >50%, 20–50% is common between 7°–13°N and 118°–155°W: 50–100% in easternmost and westernmost areas, central area 0–25%, some 25–50%.
Nucleus type and nucleus source	Often a small piece of altered volcanic material w/ evidence of manganese oxide replacement. Terrestrial or biological nucleus source.	Often one, sometimes two or more aggregates, weathered basalt piece and nodule fragments; fracture zones, seamounts source.
Sediment type	Brown silty clay in eastern part of Samoan basin; chocolate brown clays; pelagic clay; in areas <4,800 m calc-siliceous clay is common; in SPB; burnt sienna clayey mud; stiff grayish brown abyssal clay; homogeneous dark-brown to dark-reddish-brown pelagic silty clays in Aitutaki; varies from calcareous ooze to calcareous clay in NPB.	Radiolarian ooze: S of 10°N and between 90°–160°W; red deep sea clay; north of 10°N; brownish color radiolarian clay and ooze.
Deposition rate	2mm/thousand years in Aitutaki passage .	Radiolarian ooze: 3 mm/thousand years, red clay: 1mm/thousand years.
Thickness and age	Thickest 50–1,000 msec in deep parts and terraces, mostly less than 10 m; age ~70,000 years ago, in Aitutaki Passage.	Tertiary Age (between 65 and 1.7 million years).
Source of sediment	Low biological productivity at sea surface; metalliferous elements from once-active tectonic features-postulated triple junction in SPB, AABW.	High biological productivity at the sea surface; type r (rough) nodule elements are diagenetic, type s (smooth) mainly hydrogenetic.
Benthic life	Stick structures and large spiral loops in Aitutaki mounds.	Benthic life is responsible for keeping the nodules on the sediment surface.
Hiatus ages	70,000 years ago in Aitutaki Passage.	Major erosional event 70,000 years ago; early Miocene-late Pliocene also the period for initiation of nodule growth.

Table 1. (continued)

NODULE AND SEDIMENT	COOK ISLANDS EEZ (CIZ)	CLARION-CLIPPERTON ZONE (CCZ)
Cu average	General <0.5 wt%; >0.75 wt% in NPB just south of equator, and max of 1.25–1.41 wt% at 7°–8°S; <0.5 wt% and <0.25 wt% south of 10°S.	Average 1 wt%.
Ni average	General <0.5 wt%; 0.5 wt%–>0.85 wt% in NPB; max 1.25–1.7 wt% (3°–4°S and 7°–8°S), at equator and <0.5 wt% south of 10°S.	Average 1.0–1.2 wt%.
Co average	0.5–0.58 wt% 13°–17°S and 19°–23°S max (CIZ); <0.25 wt% increasing towards Rarotonga from S and SW in NPB north of 5°S; 0.5 wt% south of 10°S; max of 0.5–0.6 wt% between 13°–17°S and 19°–23°S.	Average 0.25 wt%.
Ni + Cu + Co	Max is 2.02 wt%; max. of 2.5 wt% at 3°S ; highest (1.0 wt.% or less) near Rarotonga; >2.5 wt% east of Manihiki, between 3°S and 7°–8°S; max 2.02–2.1 wt%.	Average is 2 wt%.
Major	δ-MnO$_2$; some 10 Å Manganite, δ-MnO$_2$; (Aitutaki) δ-MnO$_2$.	Todorokite.
Minor	Quartz, feldspar are always present; sometimes montmorillonite and goethite; montmorillonite-phillipsite or montmorillonite-feldspar; (Aitutaki) zeolite, magnetite, quartz, illite(?) and plagioclase.	Uniform amounts of quartz and feldspar.
Topography	In SPB characterized by gently rolling plains, abyssal hills, by steep, narrow scour channels, w/up to 40 m relief.	Gently rolling abyssal hills.
Current	Deep water masses: Pacific Deep Water overlying Antarctic Bottom Water separated by Benthic Front at about 3,500 m; (1.3°C) AABW.	AABW winnows sediment and uncovers nodules.
CCD depth	4,800 m in NPB 5,100 m, in SPB 4,900 m; 5,000 m at 17°S to 5,300 m at equator.	4,600 m.

Table 2. Comparison of major metal grades in nodules in the CIZ and the CCZ

|	METAL AND GRADE (%)							
	Mn	Fe	Co	Ni	Cu	Pb	Ti	Pt (ppm)
CIZ nodule	18.0	18.0	0.44	0.32	0.18	0.9	1.1	0.2
CCZ nodule	29.0	7.0	0.23	1.22	0.99	0.5	0.61	na

Evaluation of Manganese Nodules of the CIZ

Nodule Abundance

A major factor in any assessment of potentially economic occurrences of manganese nodules is that of abundance (concentration of nodules per unit area), which is determined primarily by the geologic and topographic environments and their impact on ocean circulation patterns and sedimentation. An effective way to assess overall nodule abundance, based on sample data, is to construct an isoline (lines of equal abundance) map of the CIZ based on the abundance of nodules (expressed in kgs) per unit area (expressed in m^2).

Overall, Figure 9 shows that the Cook Islands EEZ has a uniformly high abundance distribution, densities over 10 kg/m^2, over broad zones (ranging from 100 km to 300 km in width and extending NNE) throughout the central areas of the CIZ. The highest abundance of nodules (over 30 kg/m^2) occurs in the area of 15°–16°S and 159°–160°W where the narrow Aitutaki Passage joins the broad ocean floor of the south Penrhyn Basin (Figure 10). Surrounding this area is a broad zone of high abundance that correlates with the northward extension of the Aitutaki Passage. The spatial relationship of the highest abundance with the Aitutaki Passage area is related to both the presence of a strong AABW current and the surrounding topographic elements of the Aitutaki Passage and the south Penrhyn Basin. Specifically, it is believed that the AABW current carrying a concentration of chemical elements (Cu, Ni, Co, Mn) may reduce its speed and drop most of its chemical elements as it flows through the Aitutaki Passage and meets a relatively broad ocean-floor
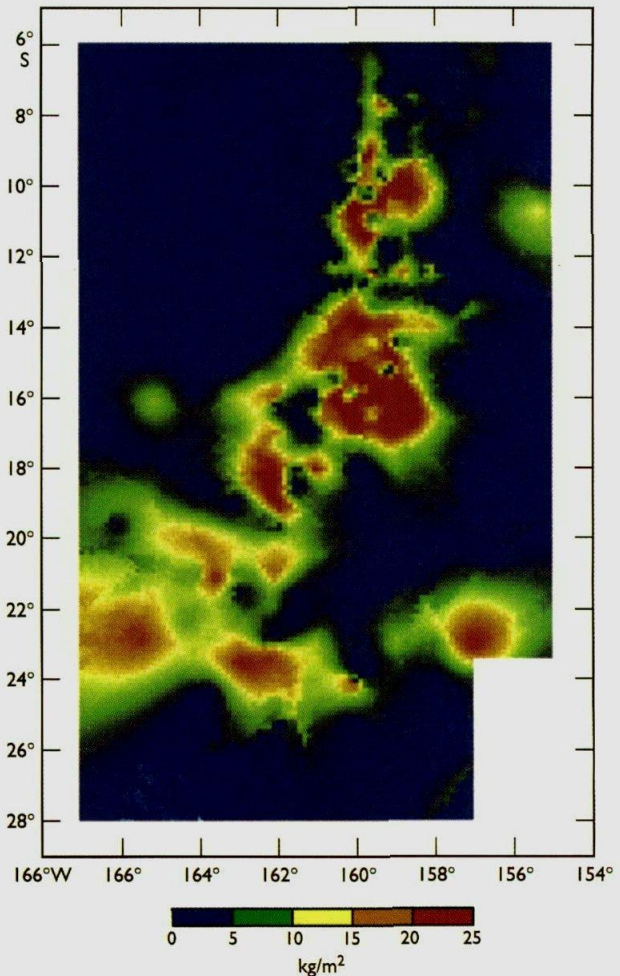
Figure 9. Manganese nodule abundance isoline map of CIZ. Units in kg/m^2. White rectangle in SE corner indicates no data.

environment. In contrast, the north Penrhyn Basin located east of the Manihiki Plateau shows a low abundance of manganese nodules, probably due to the relatively weak AABW current and higher sedimentation rate in the area. The east Samoan Basin also presents a low abundance of manganese nodules.

Distribution of Manganese Nodule Composition

Manganese concentrations in nodules are high in the northern area of the CIZ as a whole and increase from south to north. Maximum values of 20–25% occur in the areas between 6°S and 10°S in the center of Penrhyn Basin and eastward to the Manihiki Plateau. Minimum values of between 10–15% Mn occur primarily south of 12°S, the exception being nodules in the southern Cook Islands area near 22°S, 160°W where values rise to 20–25% Mn (Figure 11A). The manganese distribution is best explained by the existence of a relatively weakly oxidized ocean-floor environment caused by a weak AABW current in the central Penrhyn Basin. Such a relatively weakly oxidized environment would be favorable for the accumulation of manganese.

Cobalt is present in nodules in concentrations of less than 0.3% north of 8°S, and increases to between 0.3 and 0.5% from 8° to 21°S, then decreases again to 0.3% or less for most of the area south of 19°S (Figure 11B). The cobalt concentration tends to correlate with nodule abundance, i.e., the higher the nodule abundance the higher the Co content. A zone containing maximum values of between 0.5 and 0.8% Co extends NNE discontinuously along the zone of maximum nodule abundance between 21° and 10°S. As noted previously, the zonation of the cobalt distribution is influenced by a combination of ocean currents, particularly the AABW, and ocean floor topography. A relatively strong AABW current longitudinally passing through the center of the CIZ resulted in the formation of a relatively strongly oxidized ocean floor environment that was favorable for the development of cobalt-rich manganese nodules.

Regional nickel concentrations show a clear pattern of high nickel value distributed in the northeastern area of the CIZ. Maximum values of between 1.25 and 1.70% occur in the central Penrhyn Basin at around 6°–9°S, but there are also high values of 1–1.2% around 13°–11°S. Low nickel values of between 0.1 and 0.5% occur in most of the area south of 13°S, except in an area between 22° and 24°S where
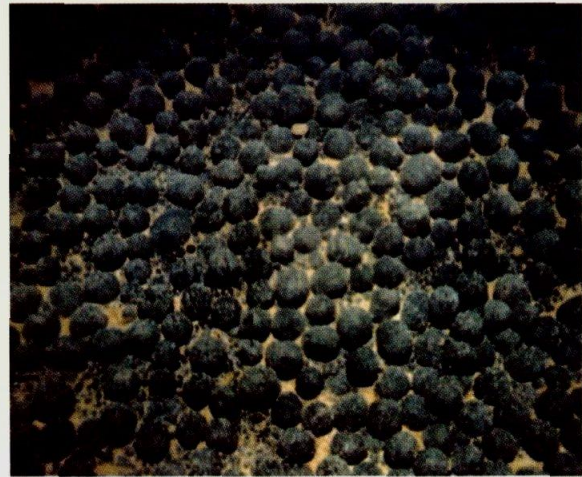
Figure 10. Nodule abundance as high as 56 kg/m^2 with a coverage of 96% occurs in an area around 15°S and 159°W.

nickel values are greater than 0.5% (Figure 11C). Unlike the cobalt concentration pattern, the nickel concentration relates inversely with the abundance of manganese nodules in the CIZ.

Regional copper concentration patterns follow nickel fairly closely although there are some minor differences in their distribution. Like the nickel distribution, copper maximum values of between 0.8 and 1.25% occur north of 9°S. Copper values decrease to 0.3–0.1% in most of the area south of 9° (Figure 11D). The concentration of the copper and nickel in the nodules of the CIZ are also related to the ocean circulation of the region. The relatively weakly oxidized ocean floor environment, created by the weak AABW current, favors deposition of nickel and copper in the manganese nodules.

A. Manganese
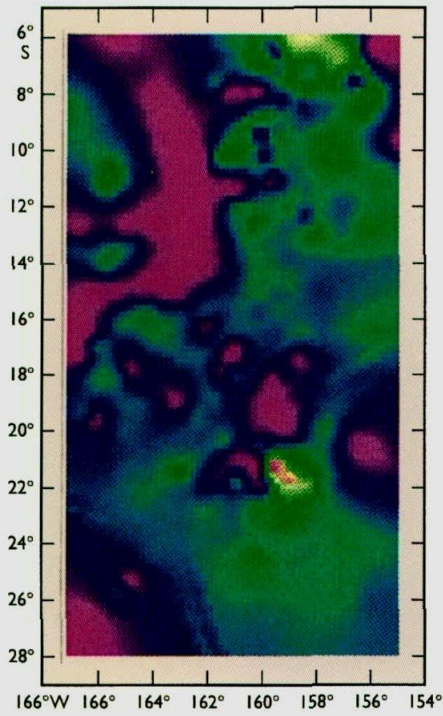
B. Cobalt

C. Nickel

D. Copper

Low   Weight percent   High
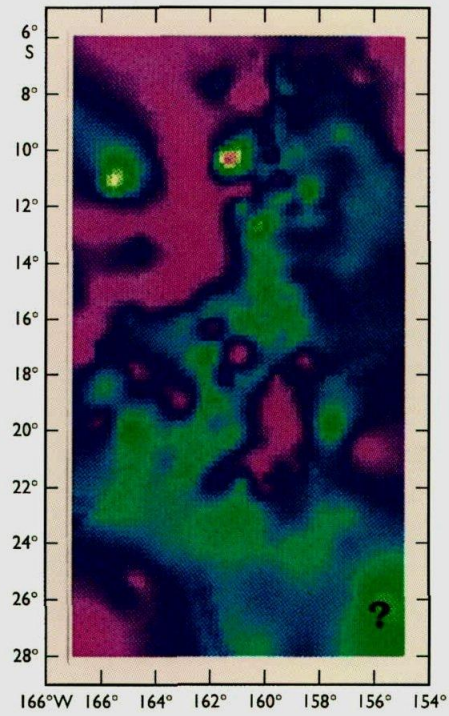
Manganese Nodule Resources Estimate

To estimate the total amount of potentially minable manganese nodules within the CIZ, the area of calculation of nodule abundance is divided into four categories (Figure 12): (A) areas where nodule abundance is 5–10 kg/m²; (B) areas where nodule abundance is 10–15 kg/m²; (C) areas where nodule abundance is 15–20 kg/m²; and (D) areas where nodule abundance is >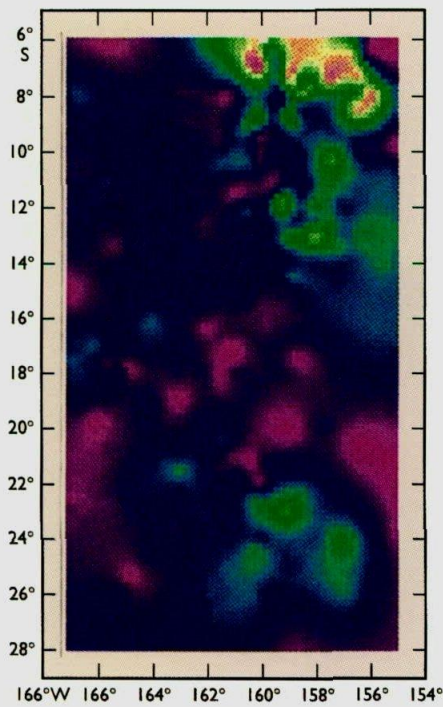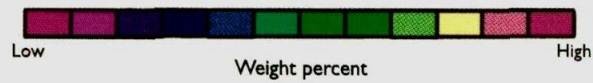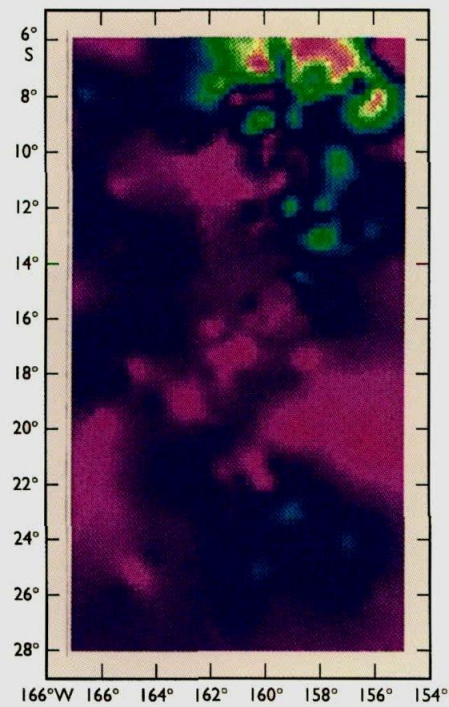20 kg/m². A level >5 kg/m² is a commonly proposed cutoff abundance for mining purposes, according to Bastien-Thiery et al. (1977). Estimates of the total nodule (in-place), metal, and economic value are based on the four categories of nodule abundances. The grades (weight percent) of the cobalt, nickel, and copper used to calculate metal quantities and values are averaged by each corresponding area of nodule abundance. The results of calculated total nodules (in-place), metal, and economic value of the nodules in the CIZ are shown in Table 3.

Obviously, the great amount of metals contained within the manganese nodules in the CIZ is mainly due to their great abundance and high cobalt grade. The high cobalt content in the manganese nodules coupled with high nodule abundances makes the total resource value of cobalt in the CIZ, where the nodule abundance is greater than 5 kg/m², reach US$967.34 billion. The cobalt resource value alone accounts for 85% of total metal resource values in the CIZ; however, it should be mentioned that the amount of in-place manganese nodules cannot be entirely recovered because of geological, mining, and processing recovery losses. An estimate of recoverable resource and its total economic value in the CIZ is shown in Table 4.

Figure 11. (*opposite page*) Distribution of Mn, Co, Ni, and Cu in nodules from the CIZ. The "**?**" in SE corner of 11B indicates no analysis available.

A. 5–10 kg/m²

B. 10–15 kg/m²
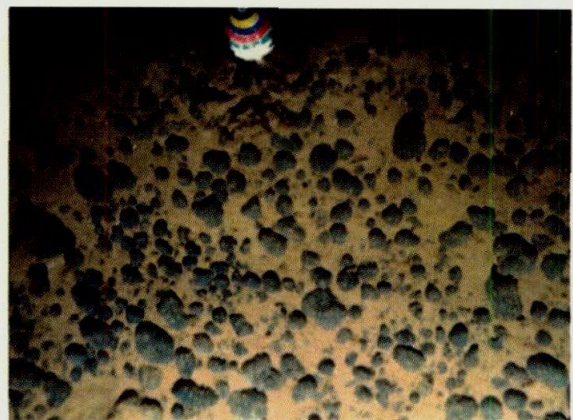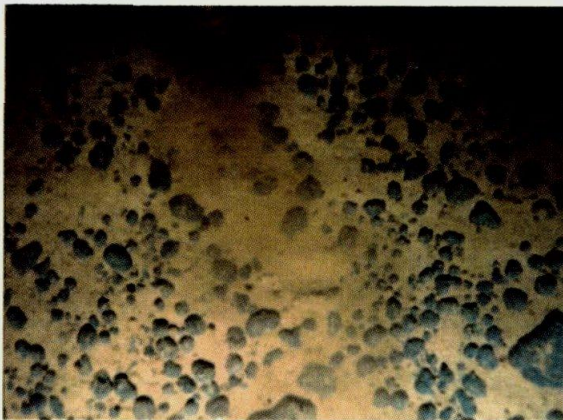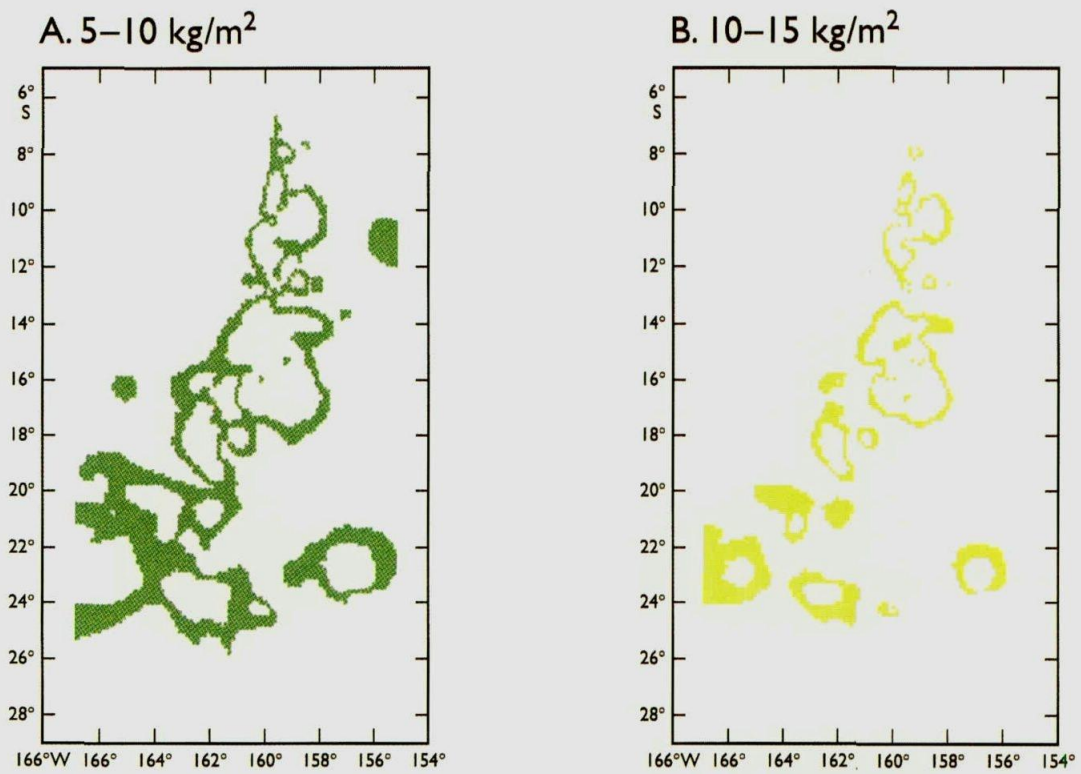
Figure 12A–D. Nodule abundance area maps, each with a corresponding seafloor photograph below, in the CIZ.

C. 15–20 kg/m²

D. >20 kg/m²

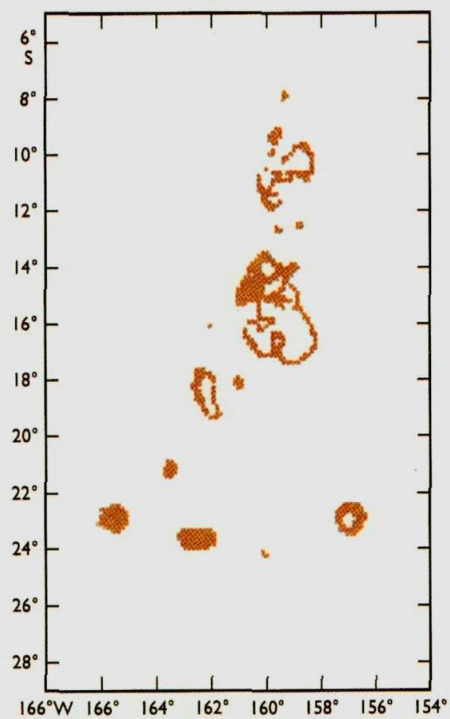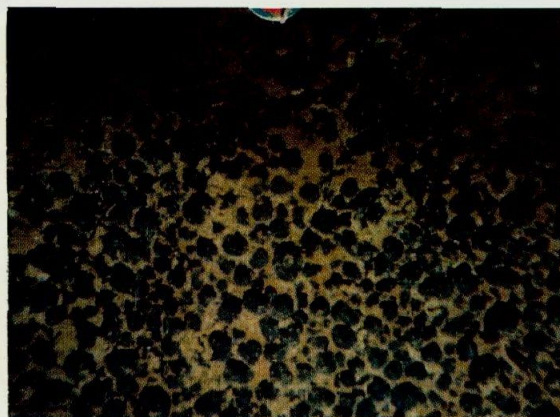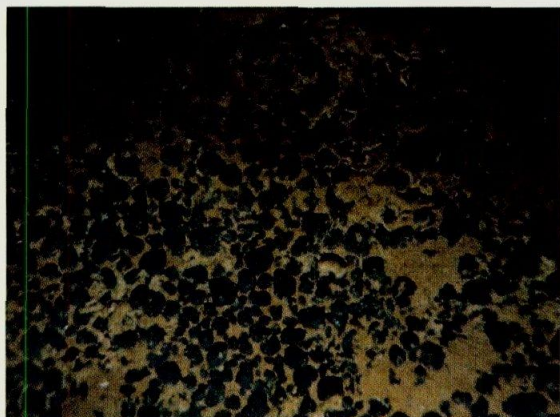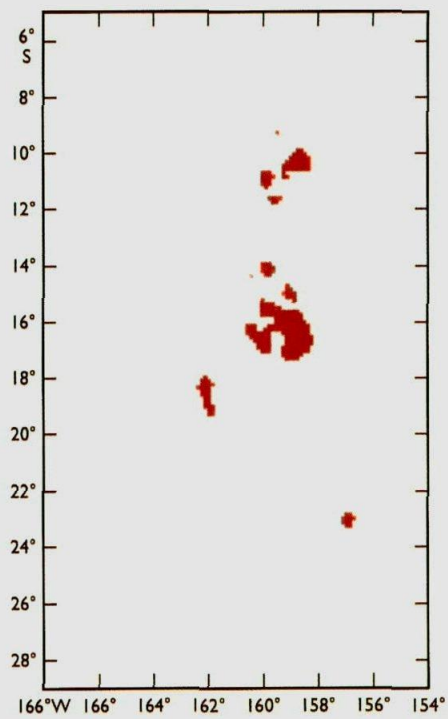Table 3. Total resources and economic value of cobalt, nickel, and copper in Cook Islands manganese nodules

Nodule Abundance in Area	Area (km²)	COBALT		NICKEL		COPPER	
		Quantity (1,000 metric tons)	Present Value (Billion US$)	Quantity (1,000 metric tons)	Present Value (Billion US$)	Quantity (1,000 metric tons)	Present Value (Billion US$)
> 5-10 kg/m²	359,073	10,643	316.38	10,270	57.21	5,907	13.14
10-15 kg/m²	144,001	7,390	219.68	5,922	32.99	3,488	7.76
15-20 kg/m²	91,248	7,381	219.42	4,287	23.88	2,387	5.31
>20 kg/m²	57,901	7,127	211.86	3,943	21.97	2,275	5.06
Total	652,223	32,541	967.34	24,422	136.05	14,057	31.27

Total Value   US$1,134.66 Billion

Table 4. Estimate of recoverable resource and its economic value in the CIZ

Recoverable Resource = Total Resource - [Geologically excluded resource (30%)
  + Mining excluded resource (30%)
  + Processing and recovery excluded resource (10%)]

Recoverable Resource = 100% - (30% + 30% + 10%) = 30%

Cobalt	Recoverable Resource	= 30% x (211.86 + 219.42)	=	US$129.38 billion
Nickel	Recoverable Resource	= 30% x (21.97 + 23.88)	=	US$13.75 billion
Copper	Recoverable Resource	= 30% x (5.06 + 5.31)	=	US$3.11 billion
	Total Co, Ni, Cu Recoverable Resource		**=**	**US$146.24 billion**

Assume 1.5 Mt/yr production

	Product Produced*	% of World Market (in year 2000)	Market Size* (in year 2000)	Assumed Prices (US$ per lb)	Assumed Average Grades (wt %)
Cobalt	6,600	18	37,500	15.00	0.44
Nickel	4,800	1	927,000	3.20	0.32
Copper	2,700	–	11,130,000	1.01	0.18

* metric tons

Manganese Nodule Exploration, Exploitation, and Beneficiation Techniques: Current and Future Trends

Conventional Exploration Techniques

In the area of the CIZ, several exploration cruises have been conducted over the past ten years. The three-yearly surveys of the R/V *Hakurei-Maru No. 2* (Figure 13) have provided the primary data sets used in this study such as topography, nodule abundance, bottom sediments, and geochemistry (JICA & MMAJ 1986, 1987, and 1991). The central activity of the above programs was the collection of free-fall grab samples (Figure 14), which provide the basic nodule data for this study. Each station consisted of three sampling attempts, which were set at the southern apex of a right-angle isosceles triangle with 1.4 nautical miles (2.6 km) as the length of the equal sides. In 1985 and 1986 free-fall grab samplings with 42.4 or 21.2 nautical mile (78.5 or 39.3 km)-grid spacing were carried out over 85,000 km² of the northern region and over 237,700 km² of the central region, respectively. In 1990 free-fall grab sampling, with a 60 nautical mile (111.1 km)-grid spacing, was conducted over 1,037,000 km² of the southern region (Figure 15).

During the sampling surveys, three types of echo sounders were used: a Narrow-beam Sounder (30 kHz) bathymetric profiler and a Precision Depth Recorder (12 kHz), which recorded bathymetric profiles, a Multi Frequency Exploration System (MFES), and a Sub-bottom Profiler, which estimated nodule abundance. Direct sea-bottom observations were conducted along limited survey lines using

Figure 13. Japanese R/V *Hakurei-Maru No. 2.*

Figure 14. Free-fall grab sampling.

either a deep-towed Continuous Deep-sea Camera (CDC) or a Finder Deep-sea Camera (FDC). Because of the width between track lines it was difficult to make isoline maps of detailed bathymetry, sediments, or nodule abundance. *Therefore, it must be emphasized that the survey conducted in the CIZ was only a*
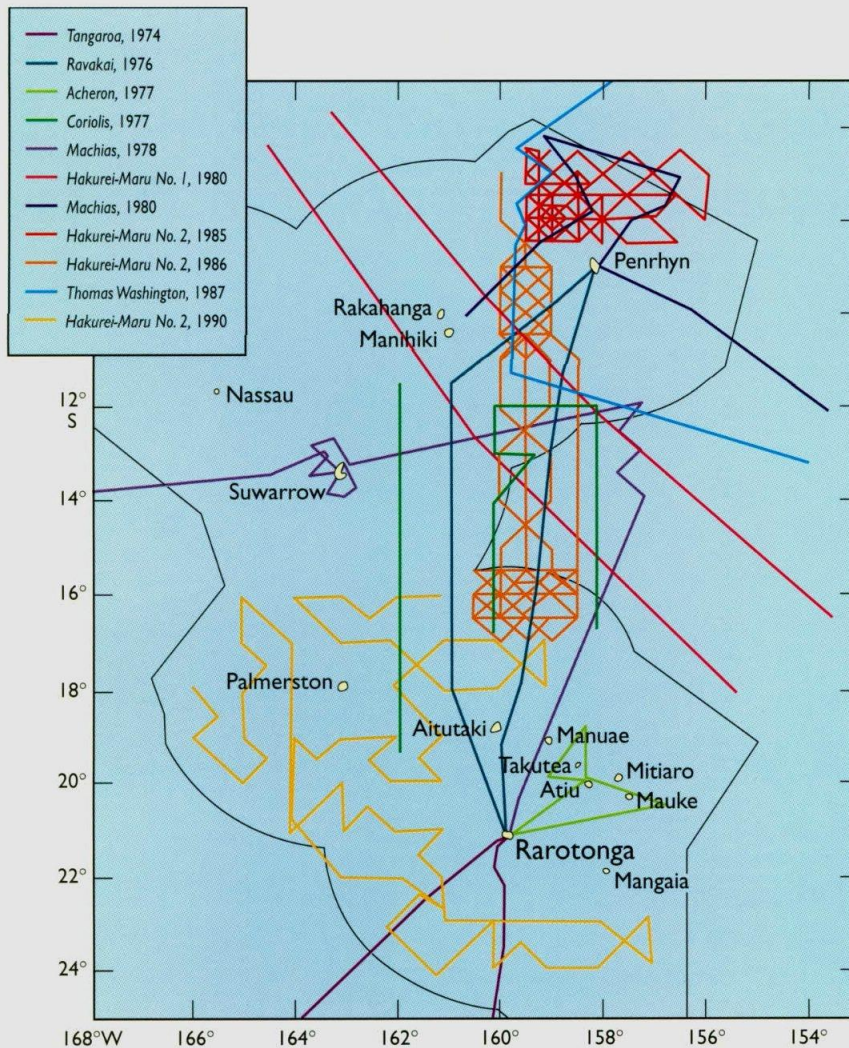
Figure 15. Survey tracks in the CIZ.

reconnaissance grid survey.

Although most data sets are kept confidential, reconnaissance grid surveys seemed to have been conducted in larger areas of the CCZ. An advanced exploration system for detailed survey, the High-Speed Exploration System (HSES), was developed by the international consortia of Ocean Management Inc. (OMI) and successfully tested in deep-sea trials in 1981 (Fellerer, 1986). HSES is a deep-towed fish having three functions: side-scan sonar, parametric sub-bottom profiling, and multibeam echo sounding. Nodule abundance can be measured by the backscatter of acoustic energy when correlated with reference to sea-bottom photos. Such a versatile system is indispensable to an efficient detailed survey of manganese nodules.

Future Manganese Nodule Exploration

Recent rapid advances of technology in marine exploration have resulted in the use of new technologies in acoustic measurements and remote control, and new products were

Table 5. Major equipment for exploitation of manganese nodules

EQUIPMENT TYPE	PURPOSE	APPLICATION AND FUTURE DEVELOPMENT
ACOUSTIC		
Conventional echo sounder	Bathymetry	Large scale morphology; replaced by MBES.
Sub-bottom Profiler	Substratum chart	Type of sediment and tectonic structure; parametric and FM pulse techniques can improve resolution under substratum with higher penetration rate.
Multi Freq. Exploration System	Nodule abundance	Rough nodule abundance; narrow beam can improve resolution.
Multi Beam Echo Sounder	Wide-swath bathymetry	Large-scale morphology; interferometric techniques can generate sea-floor image, which can infer rough nodule abundance and 3-D visualization by combining with bathymetry.
Side-Scan Sonar	Seafloor image	Small-scale obstacle; next-generation towed system can improve swath range and towing speed; quantitative analysis can calculate detailed abundance with reference to sea-bottom photos.
OBSERVATION		
Deep-sea Camera	Single photo	Attached to sampling tools.
Deep-towed Camera System	Continuous photos	Imaging processing can calculate nodule abundance automatically.
Deep-towed TV System	Video tape	High-sensitivity TV camera observes larger areas of the sea floor.
Remotely Operated Vehicle	Continuous photos	Image processing can calculate nodule abundance automatically.
SAMPLING		
Free-Fall Grab	Nodule	Geochemical analysis and physical property.
Dredge Bucket	Bulk of nodule	Indispensable as ground truth data.
Spade Corer	Nodule and sediment	
Piston Corer	Sediment	

introduced into the marketplace of ocean exploration and development. Although these state-of-the-art products were mainly suited for shallow-water applications, such as offshore oil and gas development, they are also applicable to deep-sea mineral resources. The only adjustments that need be made are to account for pressure resistivity under deep water, which sacrifices resolution and accuracy because of the distance data have to travel. Future applications for nodule exploration can be divided into three categories (summarized in Table 5), namely, acoustic, visual observation, and sampling.

Mining Systems

In the past two decades, at least five international consortia have performed extensive research and development on manganese nodule exploration. In at least three cases, these studies led to an actual testing of a pilot miner (Charles et al., 1990). On the basis of new technical developments and a more realistic view of the mining site many consortia, such as those including the United States, Germany, France, Japan, and India, were able to design their own mining systems. These designs included all the aspects of operation from exploration to processing. The manganese nodule mining and processing systems that were studied, designed, and optimized led to high recovery rates of metals and moderate op-

Table 6. Comparison of seabed mining systems

	MINING SYSTEMS		
	Jet Mining Device (JMD)	Continuous Line Bucket (CLB)	Self-Propelled Miner (SPM)
Producer	US	Japan	France
Function	Utilization of water jet to direct nodules into a trough for transport to the surface	Drops chained buckets to dredge nodules and raises them to the surface	Utilization of self-propelled miner and pumping system to transport nodules in high concentration
System built	Cable, power, and control ship location, tender, transport vessel support cable, retrieval conduit jet mining device	One-ship or two-ship system, deflectors, cable, buckets, hydrodynamic	A miner, hydraulic pumping device, and mining vessel
Mining capacity	N/A	N/A	1.5 million metric tons annual production
Advantages	Flexibility for control of the collector sub-system can achieve high areal efficiencies and avoid obstacles down to a small size	Relatively lower capital costs, transmission below the surface either electrically or hydraulically	Flexibility for control of the collector sub-system can avoid obstacles and achieve high areal efficiencies
Disadvantages	Higher reliability requirement, high capital investment and operation costs	Potential tangling of the descending and ascending segment of the line, lower production rate	High reliability requirement, high capital investment and operation cost
Impact on seabed environment	Disturbance limited in target area	Relatively large ocean-floor area	Disturbance limited in target area

erating costs. In the future it is anticipated that manganese mining and processing technologies will reach such a stage of technical reality and economic viability that the commercial mining of nodules will be possible. Three nodule mining systems, the Jet Mining Device (JMD), Continuous Line Bucket (CLB), and Self-Propelled Miner (SPM) as possible options for deep sea mining for the CIZ are compared in Table 6.

Processing Systems

Types of processes. Haynes et al. (1985) reviewed several methods for recovering Mn, Ni, Co, and Cu metals from manganese nodules by use of pyrometallurgical and hydrometallurgical processes or a combination of both. The extraction techniques can also be classified by type of lixiviant used to solubilize the metals of interest. These lixiviant types are ammonia-chloride- and sulfate-based systems. Each has its own characteristic with respect to extracting valuable metals from the manganese nodules. For purposes of the study, three main manganese nodule processing systems were chosen, based on the type of the lixiviant, as possible optional systems for future manganese nodule processing in the CIZ. A comparison of these three nodule processing systems is shown in Table 7.

Table 7. Comparison of nodule processing systems

	PROCESSING SYSTEMS		
	Cuprion Ammoniacal System (CAS)	Reduction and Hydrochloric Acid System (RHS)	Smelting-Sulfuric System (SSS)
Producer	US	US	US
Function	Utilization of ammonium carbonate and sulfate solution to leach metals from nodule	Reduction of nodule matrix with hydrogen chloride to leach metals by dissolution	Utilization of sulfuric acid to leach metals from nodule
Metal Release Rate (percent)	Mn 0.85 Ni 95.4 Cu 89.5 Co 73.2	Mn 91.1 Ni 92.8 Cu 87.5 Co 92.2	Mn 90.1 Ni 97.8 Cu 90.5 Co 92.9
Processing Capacity (annually)	3 million metric tons dry manganese nodules	1 million metric tons dry manganese nodules	3 million metric tons dry manganese nodules
Advantages and Disadvantages	3-metal (Ni, Cu, and Co) recovery; relatively low capital and operation costs	4-metal (Mn, Ni, Cu, and Co) recovery; relatively high capital and operation costs	4-metal (Mn, Ni, Cu, and Co) recovery; relatively high capital and operation costs

Table 8. Four major commodities of manganese nodules

	MANGANESE	NICKEL	COPPER	COBALT
World Resource	4,803 Mt (land-based) 6,330 Mt (deep-sea nodules and crusts)	130 Mt (land-based) 290 Mt (deep-sea nodules and crusts)	1,600 Mt (land-based) 230 Mt (deep-sea nodules and crusts)	11 Mt (land-based) 60 Mt (deep-sea nodules and crusts)
World Reserve	800 Mt (1992)	47 Mt (1992)	310 Mt (1992)	4 Mt (1992)
Mine Production	18.8 Mt (1992)	0.92 Mt (1992)	8.9 Mt (1992)	24,800 t (1992)
Refined Production	24.6 Mt (1990)	0.85 Mt (1991)	10.6 Mt (1991)	26,000 t (1990)
Price	US$0.97/lb (1993)	US$2.72/lb (1993)	US$1.02/lb (1993)	US$15.00/lb (1993)
World Consumption	N/A	0.81 Mt (1991)	10.75 Mt (1991)	22,094 t (1990)

Note: Prices are calculated as average price from January to April of 1993 in London Price.
Source: United Nations, 1985; U.S. Bureau of Mines, 1993.

World Resource, Supply, Demand, and Price of Mn, Ni, Cu, and Co

According to a United Nations report (1985), a conservative estimate of weight of manganese nodules in the sea, where recovery on a commercial scale is anticipated, is 23 billion tons. The resources of four major metals, Mn, Ni, Cu, and Co, estimated in the seabed manganese nodules take 56.4%, 83.8%, 31.0%, and 95.2% of total reserves of land and ocean, respectively. World resources, reserves, production, price, and consumption of Mn, Ni,
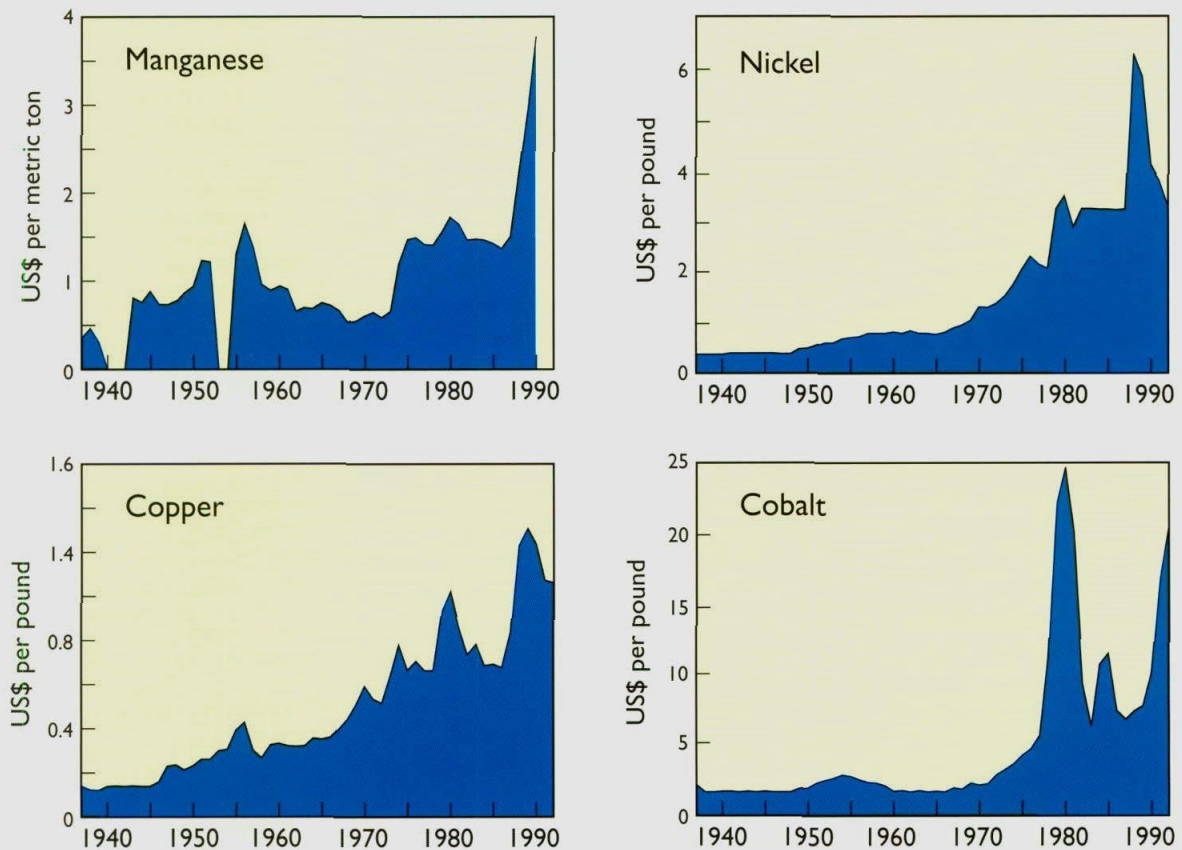
Figure 16. World prices of commodities in manganese nodules.

Cu, and Co are summarized in Table 8.

Manganese is essential for the iron and steel industry, which consumes over 90% of all manganese mined. Manganese is the cheapest of the metallic elements used to alloy with iron and is one of the more abundant elements in the earth's crust.

Because 90% of the manganese mined is used by the steel industry, the trend of manganese demand follows that of steel production. The International Iron and Steel Institute forecasts that the average annual growth rate for world manganese demand in 1991-95 will be about 1% (U.S. Bureau of Mines, 1991).

For the third consecutive year, the price of metallurgical manganese ore increased

significantly and set a new record high for price in commercial transactions (Figure 16). This price increase spurred the reactivation of several manganese mines around the world but was not enough to start new mine development. However, in the long term with the expectation of an overall downward turn in the steel industry, prices for manganese will fall.

Nickel is essential for the iron and steel industry, which uses more than 60% of the world nickel production in the manufacture of stainless steel. Nickel occurs both in land-based deposits and in manganese nodules and crust on the ocean floor. Over 50% is consumed in capital investment-related applications, such as construction, chemical apparatus,

shipbuilding, and aerospace. Supply and demand for nickel have been finely balanced since 1987, with producers struggling to satisfy demand. These developments led to a squeeze on inventories and the price of nickel averaged over US$6/lb in both 1988 and 1989 (Figure 16).

Copper has been one of the important materials in the development of civilization and has been used for at least 6,000 years. World copper consumption at the beginning of the 20th century amounted to some 0.5 Mt and it is over 11 Mt today. Copper ranks third in world metal consumption after steel and aluminum. The net increase in copper consumption was almost equally divided between industrialized countries and developing nations. The industrialized countries increased their consumption by 2.3% on average; a 3% increase in Western Europe, and an 8.9% rise in Japan more than compensated for the marginal fall in the U.S., Canada, and Australia. Consumption of developing countries amounted to 1.62 Mt, 18.1% of the total and 3.9% higher than that of 1989. South Korea had a 20% rise in consumption contrasting with a 10.1% fall in Taiwan. Recently, China has rapidly increased its copper consumption with an annual import of 200,000 tons (0.2 Mt) from the world market .

In the second half of the 1990s, the market balance is expected to improve and turn into a deficit of supplies. Over the long term, copper prices in real terms may be expected to fluctuate around the long-run marginal cost. The average forecast price for the 2000–2005 period is US$0.85/lb (in constant 1989 dollars).

Cobalt is one of several vital alloying elements used in the aerospace industry and in the electrical product industry. Cobalt provides a property that is heat resistant, high strength, and wear resistant and imparts superior magnetic properties. Applications include machine tools, carbides, jet engine parts, electronic devices, permanent magnets, and pigments and dryers for paints and allied products. Cobalt, now considered a strategic metal, developed through the centuries from a coloring additive into an essential element in many alloys.

Cobalt demand prior to the 1930s was some 4,000 t/y used mainly in ceramics as a coloring agent and in steel for tools. As demand grew with the introduction of cemented carbide and magnets, mines were opened in Zaire, Morocco, and Zambia in the late 1920s and early 1930s. In the 1950s, additional capacity was established in the U.S., the USSR, Japan, and Finland, taking world refinery capacity for cobalt into the range of 35,000 to 40,000 t/y, which has remained since. As the demand for cobalt for use in superalloys grew, production exceeded 20,000 t/y for the first time in 1970 and in 1986 reached an all-time high of 25,800 t.

In the immediate short term, the outlook for cobalt is subject to the supply/demand situation with some established producers actively seeking new sources of concentrates in order to maintain refinery output. There is little doubt that demand will overtake supply within the next two or three years.

World reserves, resources, productions, price, and consumption of Mn, Ni, Cu, and Co are shown in Table 8.

Deep Seabed Mining Economic Analysis

Economic and Technological Considerations

Although extensive deposits of manganese nodules have been defined and explored, primarily in the CCZ of the Pacific Ocean and most recently in the CIZ, and numerous new discoveries of manganese crusts and polymetallic sulfides have been made, deep-sea mining is considered to be deferred until well into the 21st century. The primary reasons for this delay in exploitation can be easily classified into at least three areas, i.e., technological, economic, and political. A fourth area, environment, may well become a critical issue in the future.

Deep-sea mining is faced with four fundamental questions:

1. Will sufficient economic changes occur in the world economy overall and the metals industry specifically to provide a stable economic environment for development?
2. Will modifications of existing technologies, largely derived from onland mining and offshore petroleum technologies, provide the basis for economic deep-sea mining or will new technologies, mining concepts, and mining systems be required?
3. Will deep-sea mining proceed under the U.N.-sponsored Convention on the Law of the Sea (UNCLOS) or under the Reciprocal States Understanding of 1985 or a combination of both?
4. Will present environmental costs and constraints escalate, with increasing global environmental awareness, to a point that deep-sea mining is both economically and politically impossible?

Although no definitive answer is available for any of these questions, deep-sea mining research has proceeded to a point where some of the fundamental questions can be resolved.

1. Existing economic analyses of manganese nodule mining indicate that such ventures are marginally economic with high internal rates of return (IRR) from 10 to 15%, whereas insufficient studies have been made to determine the economic viability of crust or polymetallic mining ventures. In the long-term deep-sea mining ventures will have to compete with existing and planned onland mine development that will require high grades, high efficiency, and comparable production.
2. Available data indicate that modification of existing technologies will result in deep-sea mining becoming more competitive with onland mines. However, breakthroughs in mining concepts and the adaptation of new technologies may result in significant further increases in the economic viability of deep-sea mining.
3. Deep-sea mining will most likely proceed under a combination of UNCLOS and the Reciprocal States Understanding, but irrespective of the type of agreement, deep-sea mining will require substantial government support if it is to maintain its present capability and research program.
4. Environmental costs and constraints

should be expected to increase in the future; however, present research indicates that problems associated with the mining/discharge plume, recolonization, and long-term environmental impact may not be as severe as originally thought.

Overall, deep-sea mining stands at the crossroads of the future. Recent advances and ongoing research have substantially improved the economic viability of deep-sea mining, and new deposit types open new frontiers for development. Simultaneously low metal prices, oversupply, and uncertain demand necessitate a cautious approach to investment. It would appear that the future in deep-sea mining belongs to those few nations and industries that have the foresight and the means to pursue development into the 21st century.

Financial Analysis

From the late 1970s to early 1980s various economic analyses indicated that the nodule mining and processing were unlikely to meet the IRR required for such risky investments (Little, 1984; Andrews et al., 1983). However, since the late 1980s, some progress has been made in mining and processing of seabed manganese nodules, and prices of metals, in particular, cobalt have steadily increased. If the future prices of the major three metals (nickel, copper, and cobalt) are as anticipated in the commodity market analyses chapter, a financial analysis of the Cook Islands nodule project, within an anticipated framework, should be made to evaluate the feasibility of future commercial manganese mining in the CIZ. The main purpose of the financial analysis is to calculate the most popular financial indicator, the IRR. The general form of the equation that was used to calculate the IRR for this financial analysis is:

$$NPV = 0 = \sum_{n=1}^{m} \frac{\text{Net cash flow for year } n}{(1+i)n}$$

NPV = Net present value (model uses 0 for computing IRR).

i = the IRR expressed as decimal that will result in an NPV of 0.

m = number of years in the cash flow stream.

n = time (in years) from the net cash flow being discounted to time zero.

Net cash flow = the values represent the revenues minus all costs and taxes.

For the purposes of this analysis a simplified financial model developed by Johnson and Otto (1985) was used to examine the impact of changes in the major variables including energy, nonfuel materials, transportation, labor, capital, prices of metals, and sales revenues. Table 9 contains a summary of model assumptions of the Cook Islands project, and the calculation result based on these assumption is IRR = 10%.

Impacting Capital Cost Issues

In calculating the IRR of the proposed Cook Islands manganese nodule project, the single largest capital cost item was that of US$1,265 million projected for the development of a new processing facility. Numerous authors (Clark, 1991; Johnson and Otto, 1985; Charles et al., 1990) have suggested that these costs might be considerably reduced if an existing processing facility, such as are designed for handling lateritic nickel ores, was converted to process manganese nodule concentrate. Although the details and costs of such a conversion have not been defined, it is technologically feasible to undertake such a conversion and therefore this option was considered, in

Table 9. Model assumptions of Cook Islands project

PROJECT DESCRIPTION

Two mining vessels operating in the CIZ
Transport fleet
Pyrometallurgical processing plant—4-metal recovery (Mn recovery as ferromanganese)

SCHEDULING

Year:	1 to 4	Construction
	5	75% production (2.25 million dry metric tons)
	6 to 24	Full production (3.00 million dry metric tons)

CAPITAL EXPENDITURES [a]

Distributed 20%, 30%, 25%, and 25% over Years 1, 2, 3, and 4

• Mining equipment, ship conversion, and transport	US$288 million
• Processing plant	US$1,265 million
Total	**US$1,553 million**

100% equity financing
Working capital of US$144 million is not recovered

OPERATING COSTS [a]

Year:	5	US$398 million
	6 to 24	US$530 million

METAL RECOVERY

	Grade (%)	Processing Efficiency (%)	US$/lb
Cobalt	0.45	85	15.00
Copper	0.19	90	1.20
Manganese	18.00	80	0.25
Nickel	0.32	90	3.20

TAXATION

20% straight-line depreciation
Loss carry-forward
No tax credit
No depletion allowance
Effective tax rate: 35%

[a] Constant 1992 US dollars.

general, in the present study. Utilizing essentially the same base case as defined in Table 9, *but* with reducing the cost of the processing plant from US$1,265 million to US$500 million (hence an overall reduction in total capital expenditure from US$1,553 million to US$788 million) the IRR was recalculated. The reduction in capital expenditure for the processing plant increased the IRR from 10% to 13%, demonstrating the possible importance of developing a mining scenario that utilizes existing processing facilities.

It must be emphasized that the above analysis shows only the potential benefits from conversion of an existing processing facility to handle ore/concentrate from a possible Cook Islands mining venture. Whether such a conversion could be efficiently and economically made would require extensive engineering and economic analysis and in the end may not represent a viable alternative. Nevertheless, it is presented as an area for future study, the results of which might well alter the economic viability of a nodule mining program.

Policy and Economic Issues

Development Options and Considerations

In defining and analyzing the development options for the manganese nodule resources of the CIZ, the following assumptions have been made, which have both constrained and directed the evaluation process:

1. Manganese nodule mining is a high risk endeavor from both a technological and a market perspective.
2. Available technology and expertise for manganese nodule mining are primarily concentrated in the hands of a limited number of countries, primarily France, Germany, India, Japan, and the United States.
3. Nodule mining is a highly capital intensive industry requiring a capital commitment in excess of US$1 billion to initiate a project.
4. Any development options should maximize the economic returns to the Cook Islands government, minimize the "risk exposure" of the Cook Islands, and provide for sustained long-term development and growth.

In considering future development the Cook Islands has at least four major options for development. A comparison of these options is shown in Table 10.

Although these options are not complete in terms of the number of possible options or in the assessment of costs and benefits, they do encompass the overall spectrum of possible options and highlight the major costs and benefits that would need to be considered. It is concluded that the best options for the Cook Islands, given the assumptions previously discussed, are Options 2 and 3. Both options provide for a reasonably full participation of the Cook Islands in the mining activity, provide increased revenues through profit sharing, and overall reduce the risk to the nation of participating in the largely "pioneering" endeavor of deep-sea mining.

Technology Considerations

Although manganese nodules have been successfully mined, on a pilot scale, from the deep ocean and because existing technology is therefore capable of such mining, the future of nodule mining in the CIZ may well be determined by technological advances that materially enhance the economics of deep seabed mining. The major areas of technological advances have been discussed previously, but among the most important advances are those associated with:

1. Increased economies of scale
2. Selective mining of high grade nodules
3. Improved process control and reliability
4. In-situ processing
5. New lifting concepts and materials
6. Robotics and artificial intelligence.

Although many new technologies have been discussed in this report, they are largely prototypic or theoretical at present and unproven in the marine environment. These technologies do not rule out the *possibility* of new technologies having a major impact on the development and mining potential of the CIZ manganese nodules, but the *probability* of such advances, based on the historical record of both the mining industry

Table 10. A comparison of CIZ nodule resource development options

	OPTION 1	OPTION 2	OPTION 3	OPTION 4
Option Descriptions	Joint venture with a foreign transnational corporation with government holding a minor "free equity" position (10%) in the venture.	Joint venture with a foreign transnational corporation with CI government holding a majority (>74%) equity position.	Undertake a consortium-type development with multiple companies participating, within which CI government is the lead participant.	CI development utilizing sub-contractor for mining, processing, and distribution.
Perceived Benefits	Relatively risk-free. R&D activities provided by foreign corporation. Allows for minimal risk and provides input into management decisions. Sale of product and market development are the responsibility of transnational corporation.	Increased profit sharing. Maximum transparency is assured for the project. Government control of product distribution and sale.	Available R&D and technology. High level of transparency for government with regard to project. Reduced costs overall. Modest profit sharing but with a dispersed risk to government. Sale of product stability enhanced. Possible "speed up" of mining development.	Total control over project and project activities. Complete profit retention. Provides flexibility to hire most contractors. Government control of product distribution and sale.
Perceived Negative Benefits	Limited management control and limited profit sharing vis-à-vis a participatory agreement. Assumed liability for success or failure of project. Social political costs to government by not having "control" over the nation's resource.	R&D costs plus technology costs are jointly borne by government and industry, increasing costs and risk to the government. Increased operating costs borne jointly by government for life of the mining activity. Overall responsibility for product distribution and sale.	Limited management control. Reduced profit sharing vis-à-vis some other option. Complex organization and operational structure for venture. Consortium member will be "wedded" to their technology.	Government assumes full costs and risks for development and operation. Overall responsibility for distribution and sale of product. Goverment assumes all risk for R&D.

and technological advances overall is quite low. Overall, each new technology, such as a new mining method, a new lifting method, a new energy source, or a new processing method dramatically increases the cost and risk of any proposed mining venture.

Metal Considerations

The uncertainty of manganese as a viable commodity has led many analysts to discount, or not consider, revenues from manganese in their financial analysis. This possibility needs to be considered by the Cook Islands in any decision as to whether or not to mine manganese nodules. Excluding manganese, however, would mean that over 80% of the contained value of metals is therefore in cobalt, the metal of primary concern in terms of any decision to proceed with a nodule mining enterprise.

Although the analysis in this study concludes that the cobalt market is both growing and diversifying and that cobalt prices are expected to increase over the intermediate term, there is concern with respect to the economics of a manganese nodule development project. This uncertainty arises from six factors:

1. The cobalt market is a small market overall with less than 25,000 t/yr consumed worldwide.
2. Four of the top five producer countries

(Zambia, Zaire, Russia, and Cuba) presently have unstable regimes/economies resulting in serious concerns regarding supply security.

3. Cobalt prices are presently "producer prices" with Zambia and Zaire determining the international prices.

4. Cobalt production is primarily a by-product of other metal mining activities, which results in a very low production cost—particularly in Zambia and Zaire, the world's two largest producers.

5. Economic downturns worldwide and specifically in Russia lead to oversupply and lower prices.

6. Large international stockpiles represent a significant "overhang" onto the market and concerns as to long-term price stability.

All of these factors represent significant risk factors with respect to the development of a manganese nodule mining operation in the Cook Islands. These risks would almost certainly need to be overcome, or minimized, before any commercial mining operation may be undertaken.

Summary

The manganese nodules of the CIZ represent both a geologically unique resource of cobalt, copper, nickel, and manganese and with minor amounts of platinum and rare earths and potentially a commercially exploitable deposit of substantial economic value. The present study has focused on defining the resource potential of the CIZ nodules, evaluating the economic, technological, and market aspects of a mining operation, and finally providing an overview of the development options that the CIZ should address when considering possible development. The major summary of the present study is as follows:

1. Based on the geology and topography, the CIZ can be latitudinally divided into four major regions. The eastern central region, occupying most of the Aitutaki Passage area shows the most abundant manganese nodule concentration in the CIZ. Metal concentration in the nodules, particularly in cobalt, copper, and nickel, is inferred to be related to the circulation of the AABW currents within the CIZ. This physio-chemical control results in the cobalt content in the nodules being highest (0.5–0.8%) in the southern and central regions. Conversely, copper and nickel contents are highest in the northern region.

2. The manganese nodules of the CIZ and the CCZ differ in form, structure, and chemical composition. The CIZ nodules are generally smaller, smoother in surface, and more symmetrical than the CCZ nodules. The nodule abundance and compositions of the CIZ are significantly more spatially correlated, i.e., more uniform in abundance and composition than in the CCZ. The cobalt abundance in the CIZ central region shows particularly high values of 80–113 g/m^2 in an area of 14°–18°S and 157°–161°W. The CCZ nodules contain an average metal content of Cu 1%, Ni 1.3%, and Co 0.23% as compared with those of CIZ nodules that contain Cu 0.19%, Ni 0.32%, and Co 0.45%.

3. The resources of the CIZ are estimated to consist of a total weight of nodules, with a cut-off grade of greater than 5 kg/m^2 in an area of 652,223 km^2 of the CIZ, to be 7,474 million tons containing 32,541,000 tons of cobalt, 24,422,000 tons of nickel, and 14,057,000 tons of copper. These figures are, however, *not* recoverable reserves, which would be at least 60–70% lower.

4. The fluid dynamic deep-sea mining system, continuous line bucket, and self-propelled miner system are possible options for future manganese mining in the CIZ. The self-propelled miner system, though costly, is able to mine 1.5 million tons of nodules annually, as tested in the course of development studies. The fluid dynamic system offers far more flexibility for control of the collector sub-system than the line bucket system but has a higher reliability requirement and higher operation cost. In contrast, the line bucket system potentially involves relatively fewer capital costs. The cuprion ammoniacal leach, the reduction-hydrochloric acid leach, and the smelting-sulfuric acid leach processes are possible options for the processing of CIZ nodules. In laboratory tests, the cuprion system can recover

95.4% Ni, 89.5% Cu, and 73.2% Co from the manganese nodules, whereas the reduction-hydrochloric acid system and the smelting-sulfuric acid system can recover 92.8% Ni, 87.5% Cu, 92.2% Co, and 97.8% Ni, 90.5% Cu, 92.9% Co, respectively, from the nodules.

5. For cobalt there was a modest price increase from US$11.00/lb to US$15.00/lb in 1991–92 and the price may continue to rise in the short term. Nickel prices have averaged over US$6/lb since 1988 compared with the average of US$2.11/lb during the 1982–87 period; though the price decreased slightly in the early 1990s, it is expected to continue to rise in the long term. Copper prices in 1990 and 1991 were US$1.23/lb and US$1.09/lb, respectively; however, over the long term, copper prices in real terms may be expected to fluctuate around the long-run marginal cost, and the average forecast price for the 2000–05 period is US$1.59/lb (in constant 1989 dollars).

6. Existing economic analyses of nodule mining activities indicate that such ventures are marginally economic with the IRR ranging from 10 to 15%. Environmental costs and constraints may increase in the future; however, problems associated with the mining/discharge plume, recolonization, and long-term environmental impact may not be as severe as originally thought. Financial analyses show approximately a 10% IRR

on a three million dry metric tons nodules production/yr project over a 24-year-term operation. Future metal prices are the most important factor and will significantly change the IRR of the CIZ project.

7. Development of CIZ nodules will require substantial investment in research and development either to upgrade existing technologies or to develop new technologies. Energy, economic, market, and environmental considerations strongly indicate that on-land processing should be done near markets and available smelters and refining capacity and not in the Cook Islands.

8. As the CIZ has undergone only reconnaissance exploration at present, it will be required that more detailed exploration and evaluation be carried out in the most favorable areas before a final decision regarding economic viability can be made.

9. Development options for possible mining consist of (a) private sector development solely, (b) joint private sector/Cook Islands development, (c) Cook Islands development via sub-contractors, and (d) consortium development with Cook Islands as the principal member. From the available development options it is suggested that the Cook Islands adopt either the option of consortium development with the Cook Islands as a principal member or a joint private sector/Cook Islands option.

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