Bureau of Mineral Resources, Geology & Geophysics

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Research Cruise Proposal : BMR Cruise 106

SEABED MORPHOLOGY & OFFSHORE RESOURCES AROUND CHRISTMAS ISLAND, INDIAN OCEAN

Project 121.32

BMR Offshore Sedimentary Basins Program

by

N.F. Exon

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CONTENTS

FIGURES

TABLES

SUMMARY

Christmas Island is an Australian territory lying south of Java in the Indian Ocean, at about 10°30'S and 105°40'E. It lies on oceanic crust of Late Cretaceous age, is moving north at 7cm/year, and is being raised as it climbs the bulge on the southern flank of the Java Trench. The island itself consists of Cainozoic volcanics and limestone, and has been extensively mined for Pliocene phosphate. It covers an area of 140 km^2 , and rises 360 m above sea level.

Australia has declared a 200 mile Fisheries Zone around the island, and the aim of this BMR investigation is to assess the seabed morphology, sediment thickness, and offshore mineral resources in a future Exclusive Economic Zone. This information will be of particular value to the Department of Foreign Affairs and Trade, when Australia negotiates a Christmas Island seabed boundary with Indonesia to the north.

Present knowledge indicates that oceanic crust is generally at 5000-6000 m around Christmas Island, and that it is overlain by 100-300 m of pelagic sediment which thickens northward toward the Java Trench. A number of volcanic ridges trend generally northeast or north-northeast, and are as shallow as 1200 m below sea level. Christmas Island itself sits on such a ridge. Shallow-water limestones and manganese oxide crusts have been dredged from the ridges. Deepsea coring programs show that pelagic foraminiferal ooze and marl give way to siliceous (diatom-radiolarian) ooze and red clay below 5000 m water depth. Volcanic ash from Indonesia is an additional component of the sediment.

Reconnaissance sampling has shown that manganese nodules are quite common in the deep sea, and that they carry moderate grades of the valuable metals, copper (Cu), nickel (Ni) and cobalt (Co). In a fairly similar geological setting to the west, in the central Indian Ocean, India has pioneer investor status for a nodule mine site of 150,000 square kilometres. At this site the grade of Cu+Ni+Co is about 2.55%, and nodule abundance is 5-7.5% of wet nodules per square metre, figures which suggest that the site has long-term economic potential.

The present project will commence with a 28-day geoscience cruise of R.V. "Rig Seismic" from 7 January to 4 February, 1992. The plan is to acquire about 2500 km of high-resolution reflection seismic and bathymetric data, to define seabed morphology and to allow regional mapping of sediment thickness and facies. The seismic data will be used as the basis of a sampling campaign to investigate sediment type, manganese nodule abundance and metal grade on the deepsea floor, and manganese crust thickness and metal grade on the volcanic ridges. The end result will be a comprehensive review of the geology and mineral resources of the Christmas Island offshore zone.

INTRODUCTION

The Australian Territory of Christmas Island, a raised atoll with a population of about 2000 people, lies on oceanic crust about 1600 km north-northwest of Australia's Northwest Cape, and 350 km south of westernmost Java (Fig. 1). The Australian Cocos-Keeling Islands group is 1000 km further west. Christmas Island resembles a 'T', with its stem running east-west (Fig. 2), has an area of 140 km^2, and is up to 20 km across. Australia has declared a 200 mile fisheries zone around Christmas Island.

The island is on the Indo-Australian Plate, which is moving north at about 7 cm/year, and is being uplifted on the bulge in front of the Java Trench 150 km to the north. It has the form of a plateau at 200-300 m above sea level, bounded by a series of sea cliffs and terraces. The plateau slopes to the south; the highest point is Murray's Hill (361 m) on the western end of the island. The natural vegetation is tropical rain forest.

The island is at the eastern end of the submarine Christmas Island Rise, which extends south-southwest for 700 km (Fig. 3). The Java Trench to the north is more than 6500 m deep, and the abyssal plains around the Christmas Island Rise are 5000-6000 m deep. The rise sits on oceanic crust of presumed Late Cretaceous age, and both it and the pedestal of the island consist largely of volcanics. On the island the volcanics are overlain by Eocene limestone, and an extensive Miocene limestone which is associated with extensive phosphate deposits. These deposits produced nearly 1,000,000 tonnes a year of phosphate rock

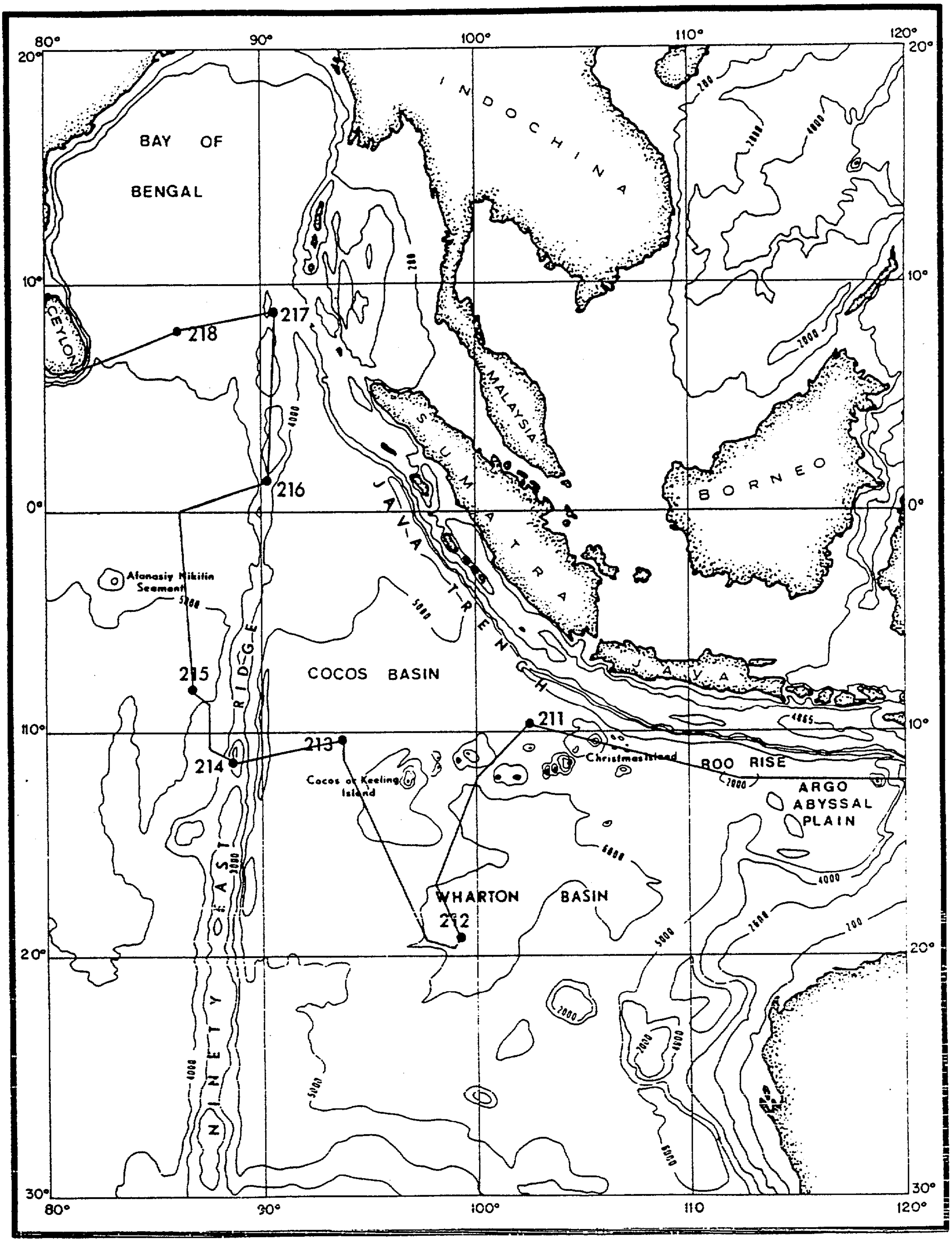

Figure 1. Locality map, showing bathymetry (m), physiographic provinces, and DSDP sites and ship's tracks. After Veevers (1974).

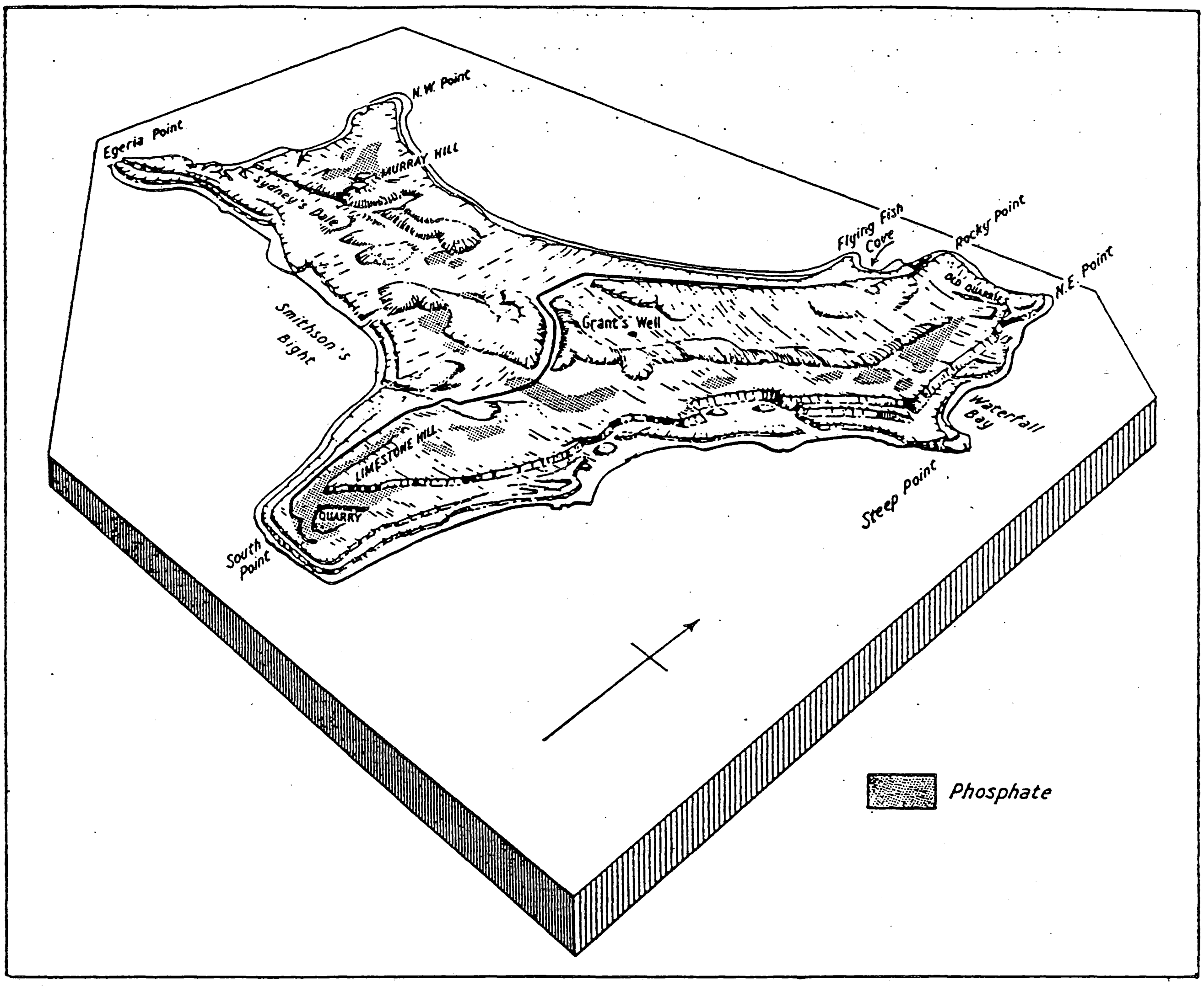

Figure 2. Physiographic sketch of Christmas Island. After White & Warin (1964).

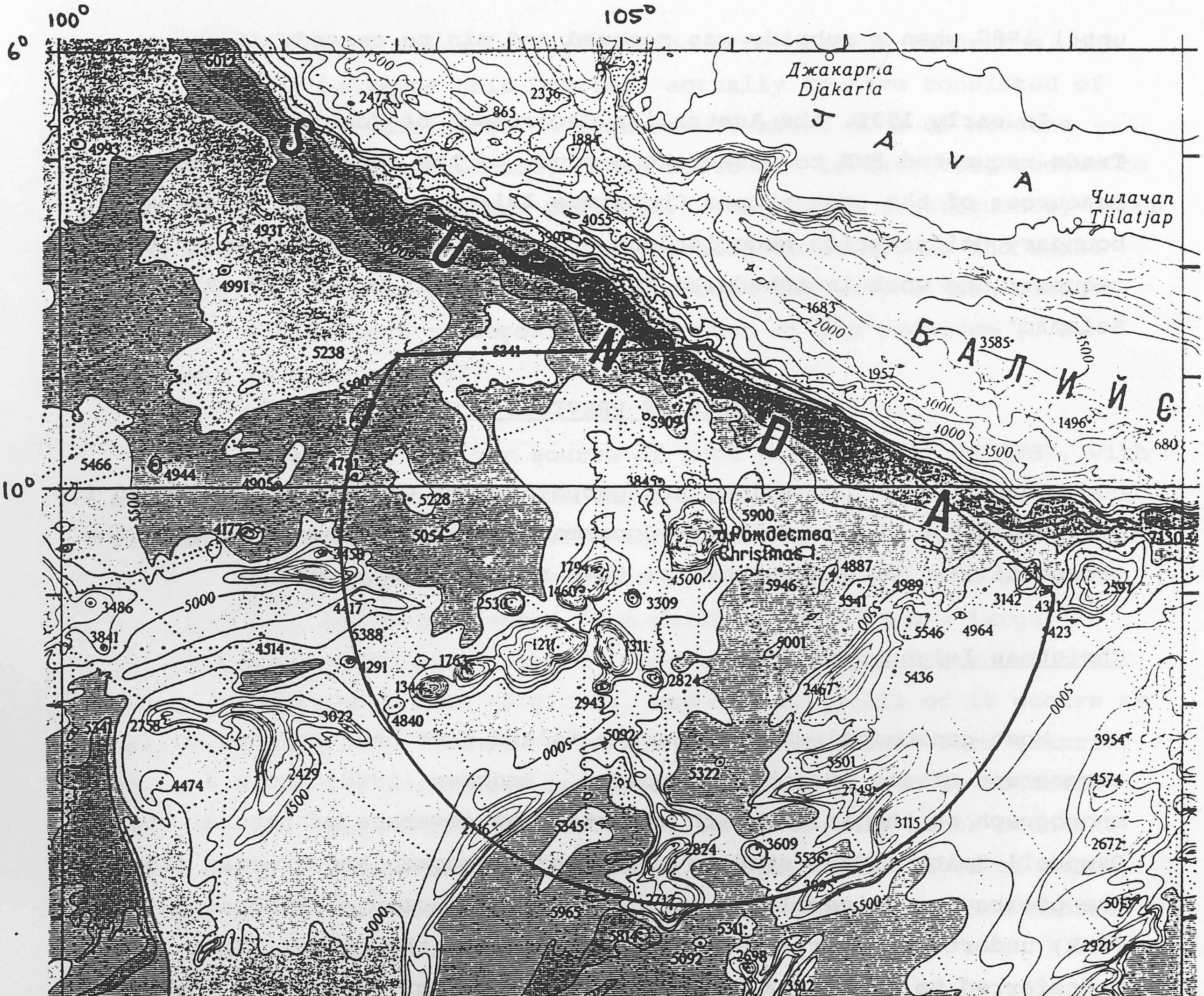

Figure 3. Bathymetric map of the area around Christmas Island, showing Australian Fisheries Zone. After IOC (1982) and Udintsev (1974)

until 1987 when a subsidy was removed and mining ceased.

In early 1991, the Australian Department of Foreign Affairs and Trade requested BMR to undertake a study of the non-living seabed resources of the area around Christmas Island, as an aid to seabed boundary delimitation negotiations. This proposal arises from the request; the work is scheduled for January 1992, using R/V 'Rig Seismic'.

RESULTS OF PREVIOUS STUDIES

A review of the geology and geophysics of Christmas Island and its offshore areas was produced by Jongsma (1976), who concluded that the prospectivity for minerals other than phosphate was poor.

Christmas Island geology

Most geological studies on the island have been related to assessment of its phosphate deposits. Andrews (1900) wrote a mnonograph on the island with an extensive coverage of natural history. Campbell-Smith (1926) studied the volcanic rocks, and Trueman (1965) the geology and mineralogy. The Australian Bureau of Mineral Resources (BMR) undertook several geological studies of the island after it was transferred to Australia from Straits Settlement Government control in 1957 : Warin (1958), White and Warin (1964), Rivereau (1965) and Barrie (1967). Polak (1975) carried out a geophysical investigation using magnetic, electrical, gravity and refraction techniques. Adams and Belford (1974) reported on the foraminifera of the limestones on the island. Subbarao et al. (1980) discussed the volcanics of Christmas Island, and Falloon et al. (in prep.) have carried out a recent survey of alkaline volcanics from Christmas Island and nearby seamounts.

The oldest rocks on the island are dominantly basaltic, and include alkali trachyte, trachybasalt, olivine basalt and limburgite (Campbell-Smith, 1926). These rocks are described by Subbarao et al. (1980) as members of an alkali olivine basalt suite, similar to the oceanic volcanics in DSDP Site 211 to the west, who stated that they were probably derived from intra-plate hot spot activity. These are overlain by thin Eocene limestones and conglomerates, which Andrews (1900) recorded as containing interbedded volcanics. Andrews (1900) recorded an "upper volcanic series" above the Eocene limestone, but Barrie (1967) believes this "series" actually to have consisted of windows of older volcanics. A sequence of about 50 m of Miocene limestone caps the succession. This limestone is detrital, medium to coarse grained and sometimes pelletal. The coarse constituents, often in a micrite cement, include algae, corals, foraminifers and small molluscs. The fauna and cross-bedding both indicate a back-reef or lagoonal environment of deposition for most of the sequence (J.A. Kaulback in Barrie, 1967).

The island was a major source of rock phosphate until 1987, with an average annual production of about 1,000,000 tonnes per year (BMR 1988,89), half going to Australia and supplying about a quarter of its needs. This phosphate was described by White and Warin (1964) and Barrie (1967) as having formed from guano residue from a large concentration of Pliocene birds. Phosphate is concentrated on the south side of the island (Fig. 2), and virtually all of it occurs as phosphate rock, with either "coherent" or "incoherent" form (Barrie, 1967). "Coherent phosphate" is massive, rubbly or pebbly material displaying a wide variety of textures; it is of only minor economic importance. "Incoherent" phosphate is a superficial layer of brown, mottled and white, soft, earthy and granular phosphate which mantles the plateau and terrace surfaces.

Barrie (1967) envisages the development of Christmas Island as follows : In Eocene and older times, a volcanic seamount of Hawaiian type formed. In the Eocene, limestone started to be deposited interbedded with volcanics. Oligocene sediments are absent, probably because of erosion and lack of volcanism. In the early Miocene, the seamount was in the euphotic zone and there was widespread development of organic coralline limestone. In the late Miocene, there is no record of deposition. In the Pliocene the seamount emerged and there were probably three principal islands connected with a fringing reef to form a sheltered area - progressively open, closed lagoon, and swamp (salt, brackish, and fresh water). Because of bird colonisation of the islands and the later emergent wave-cut platforms, phosphate developed as guano residue and subaerial phosphatised limestone (relict textures). This enriched the lagoonal waters, with precipitation forming oolites, and causing phosphatisation of debris on the lagoon floor, which included detritus of guano residue, phosphatised limestone, and limestone and volcanics which either then or later became phosphatised.

In the Pleistocene, emergence continued as the seafloor rose as it moved northward (at about 7 cm/year) toward the Java Trench. A series of terraces were cut, and the fringing reef limestone that developed contained phosphate detritus. In recent times the emergence has continued and later terraces were cut in pelletal limestone. Bird numbers diminished, weathering processes broke down older phosphates, a karrenfeld of phosphatic pinnacles developed beneath phosphate cover, and a soil profile developed.

Bathymetry

Bathymetric maps of the area around Christmas Island include those produced by Udintsev (1975, p.43, 1:5,000,000), Mammerickx et al. (1976, 1:5,000,000) and IOC (1982, 1:10,000,000). Udintsev's (1975) map is used as Figure 3.

Figure 3 shows that the abyssal plain in this part of the Wharton Basin lies at 5000-6000 m, and is cut by volcanic seamounts (including Christmas Island) and ridges. The ridges mostly trend north-northeast (e.g. Horizon Ridge), or northeast (e.g. Christmas Island Rise). The crests of the ridges within the 200 mile Christmas Island Fisheries Zone lie at varied depths: those along the Christmas Island Rise generally from 1200 to 1900 m; those at the northern end of Horizon Ridge from 2400 to 3200 m; and those seamounts 300 km south to southwest of Christmas Island from 2700 to 2800 m.

The highly exaggerated seismic profile shown in Figure 4 (from Veevers, 1974) gives a general impression of the bathymetry in the region. This bathymetry is completely controlled by the original volcanic topography of the oceanic crust and volcanic edifices, but the overall roughness of the surface has been reduced by the deposition of pelagic sediments in the lows to a thickness of up to 500 m. Volcanic ridges rise through the sediment, and above the general level of the abyssal plain, in many places.

Offshore geophysical surveys

A number of geophysical lines cross the area, but there has been no systematic study. Udintsev (1975) shows two seismic profiles that extend southward from the Java Trench almost to Christmas Island. These profiles (p.121) indicate that unconsolidated surface sediments are 100-200 m thick near the island and thicken steadily northward to 1 km thick in the axis of the trench. Beneath them are consolidated sediments, overlying volcanic basement, that are 500 m thick over most of the area between island and trench. A general thickness map (p.119) indicates that sediment cover is 100-300 m in the Australian Fisheries Zone around and south of Christmas Island, and that it thickens northward to more than 1 km in the Java Trench.

Deep Sea drilling Project Site 211, in the Cocos Basin some 250 km west of Christmas Island (Fig. 1), has provided some control for the seismic sequences. Veevers (1974) shows reflectors 1, 2, 3 and 4 in DSDP seismic profiles in the area (Fig. 4). In Site 211, Veevers identified Reflector 1 "as the boundary between a transparent Quaternary to upper Pliocene siliceous ooze-volcanic ash sequence (100 m thick) and a Pliocene turbidite sequence, reflector 2 is a surface within the turbidite sequence, and reflector 3 (seismic basement) is an andesine diabase sill, 10 metres thick, separated from basalt by 17 meters of Campanian nannofossil ooze". The sill was dated by McDougall (1974) using the potassium-argon technique, as 71 +- 2 m.y. old, that is near the Maastrichtian-Campanian boundary. The oldest sediment in Site 211 was early Campanian in age, suggesting that volcanic basement is roughly of that age. Veevers (1974) indicates that his reflector 3 is acoustic basement for some distance east of Christmas Island (Fig. 4), but eventually is underlain by reflector 4 which is presumably the top of oceanic basalt. This suggests that near the Roo Rise in the east oceanic basement is older than near Christmas Island, and this view is supported by the magnetic interpretations of Powell et al. (1988) and Fullerton et al. (1989). Veevers (1974) interpretation from DSDP Site 211 suggests that Udintsev's (1975) "unconsolidated" sediments are late Pliocene to Quaternary in age, and his "consolidated" sediments are Campanian to early Pliocene in age. This would suggest that the rapid thickening of the "unconsolidated" sediments northward is due to the input of volcanic ash from the Indonesian volcanic arc.

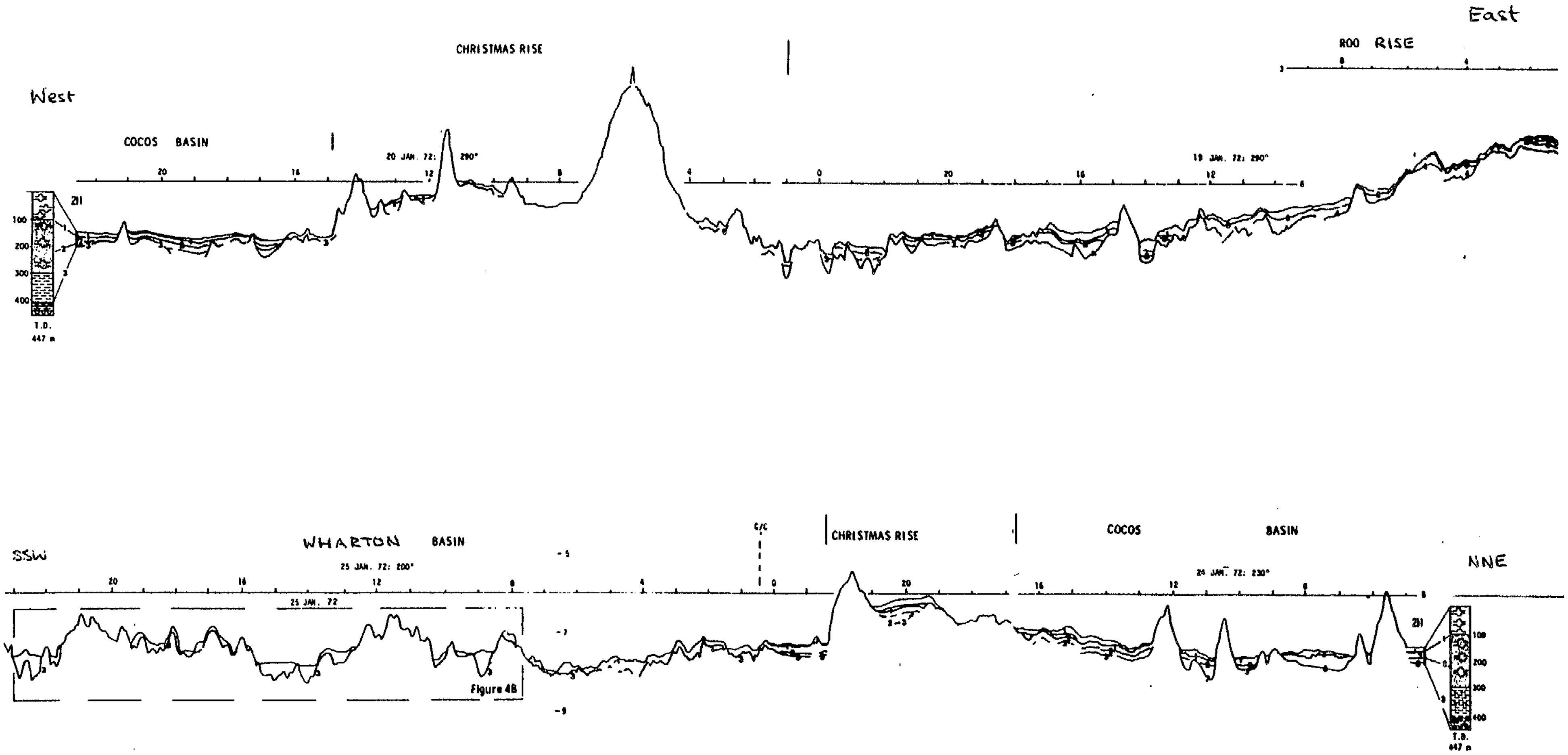

Figure 4. Line drawings of DSDP seismic profiles near Christmas Island. Locations in Figure 1. After Veevers (1974).

The marine gravity data from the area have been summarized by Udintsev (1975). An averaged Bouguer gravity anomaly map (p.89) shows clear east-west trends with a decrease northward from 400 milligals at 17°S to 200 milligals at Christmas Island; further north values fall slowly to 40 milligals at Jakarta. A map of free-air gravity anomalies of the Indian Ocean (p.98) shows major anomalies over Christmas Island and the ridge to the southwest. The abyssal plain in the region has an anomaly of 0-25 milligals, but the anomaly over Christmas island is about 175 milligals. The anomalies decrease northward to about -75 milligals in the trench axis, and reach a minimum of about -150 milligals above the forearc 100 km north of the trench. A map of magnetic anomalies of the trench area (p.80) shows little coherent pattern near Christmas Island; the anomaly is about -2 to -4 millioersteds just north of the island. According to Scheibner et al. (1991), Christmas Island lies within the area of northwest-southeast spreading that includes the Argo Abyssal Plain, and is younger than anomaly MO (103 m.y. = Aptian). They indicate that it is separated from the area of north-south spreading to the west by a north-south fracture zone cutting the Vening-Meinesz Seamounts at about 103°; this area lies near anomaly 33B (80 m.y. = early Campanian). This interpretation fits the age of basement in DSDP Site 211 of early Campanian (9°46.53'S, 102°41.95'E).

Offshore sampling

Offshore samples have been recovered in the Christmas Island region by dredging, coring and drilling. Dredging of seamounts and ridges has been carried out by R.V. "Vityaz" (Bezrukov & Andrushchenko, 1974; Skornyakova et al., 1980) and R.V. "Franklin" (Falloon et al., in prep.). The Vityaz locations are given in Table 1 and the Franklin locations in Table 2. The volcanic rocks dredged generally belong to the alkali basalt assemblage, and contain 45-55% SiO_2 and 1.7-4.5% TiO_2 (Falloon et al., in prep.). In addition reefal limestone has been recovered in a number of dredges. Manganese crust is present in many dredge hauls.

Sediment cores have been taken by R.V. "Vityaz", R.V. "Vema" and R.V. "Robert Conrad" (Tables 1 and 3). Shipboard descriptions by Lamont-Doherty Geological Observatory (Table 3) indicate that above the 5000 m isobath the surface sediments are foraminiferal ooze and marl,

TABLE 1. STATIONS WHERE MANGANESE NODULES AND CRUSTS WERE RECOVERED

Number	Latitude (degrees S)	Longitude (degrees E)	Depth (m)	Equipment (recovery in cm)	Surface lithology	Coverage
Vityaz 6729-1	9.133	104.667	5530	Bottom scoop		
R.Conrad 14-19	10.633	100.867	5273	Corer (757)	SC	SB
Vityaz 6731-5	10.833	104.633	3850	Dredge		
Vityaz 6731-6	10.833	104.633	4940	Dredge	SO	
Vityaz 6732-1	11.133	104.533	1585	Dredge	CO	
Vema 24-194	11.150	104.350	5256	Corer (435)	CS	B
Vityaz 6734	11.817	102.900	5078	Dredge	SO	
Vityaz 5172	11.985	105.150	4993	Corer (262)	CC	
Vema 24-193	14.117	106.533	4513	Corer (825)	CO	

CO = calcareous ooze, CC = calcareous clay, SO = siliceous ooze, CS = calcareous-siliceous ooze
SC = siliceous clay, B = buried, S = surface

TABLE 2 : DREDGE LOCATIONS YIELDING ROCKS DURING 1987 CRUISE OF THE R.V. "FRANKLIN" (FR9/87)

Dredge No.	Location		Latitude (degrees S)	Longitude (degrees E)	Water depth (m)	Sample Recovery
3	SW slopes of Christmas Island offshore from Eugeria Point	S F	10 28.57′ 10 29.00′	105 29.99′ 105 31.30′	1900-1700	Small pieces of basalt and limestone
4	as for dredge 3 above					Full bag of limestone and basalt
7	Scherbakov Seamount	S F	10 49.10′ 10 50.29′	104 44.46′ 104 46.21′	2200-2000	Full bag of reefal limestone some with basalt fragments
8	Vening Meinesz Seamount "1341m"	S F	11 20.75′ 11 18.96′	104 47.96′ 104 47.91′	2100-2000	Small fragments of mudstone/manganese crust
9	Vening Meinesz Seamount "1341m"	S F	11 17.92′ 11 17.54′	104 45.29′ 104 48.03′	2500-2400	Small fragment of altered manganese crusted basalt
11	Vening Meinesz Seamount "1344m"	S F	11 44.09′ 11 44.44′	103 16.51′ 103 17.04′	2000-1500	Two small rock fragments
14	Vening Meinesz Seamount "1763m"	S F	11 37.60′ 11 38.12′	103 38.40′ 103 41.63′	2000-1500	Two small rock fragments
15	Vening Meinesz Seamount "1763m"	S F	11 37.78′ 11 37.20′	103 40.84′ 103 41.02′	1900-1700	Full bag of altered basalt

S = start of dredge operations
F = end of dredge operations
After T. Falloon (pers. comm.)

TABLE 3. CORES TAKEN BY LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

Number	Latitude (S)	Longitude (E)	Depth (m)	Recovery (cm)	Description
Conrad 14-49	10°38′	100°52′	5273	757	Radiolarian glassy volcanic sandy clay (dark yellowish brown, moderate brown) to 220 cm; manganese sandy clay with Mn micronodules (very light brown) to 235 cm; and homogeneous clay (moderate to grayish brown) to 757 cm. Small Mn nodule at surface (analysed), and Mn micronodules at depth.
Conrad 14-52	10°00′	100°38′	5612	1360	Primarily radiolarian clay interbedded with diatomaceous clay, diatomaceous clay ooze, glassy volcanic sand, diatomaceous-radiolarian clay, clayey volcanic sand and radiolarian-diatomaceous clay. Coarse fractions consist of diatoms, Radiolaria, sponge spicules, biotite, disseminated manganese oxide, planktonic foraminifera and volcanic glass. All sediments free of carbonate.
Conrad 14-53	12°53′	103°40′	4544	579	Foraminiferal ooze (pale yellowish brown,pinkish grey), foraminiferal chalk ooze (very light grey); foraminiferal marl ooze (moderate orange pink, moderate yellowish brown, greyish orange); foraminiferal clay ooze (moderate yellowish brown) to 260 cm. Volcanic sand (very pale orange, dark yellowish brown) 260-273 cm, 421-422 cm. Sandy clay (dark yellowish brown, pale yellowish orange) and clay with Mn micronodules (greyish brown) 273-421 cm, 422-579 cm. Carbonate content high in ooze, nil in clay. Coarse fractions contain planktonic and benthonic foraminifera, Radiolaria, volcanic glass shards, diatoms, fish teeth, dark minerals, sponge spicules, echinoid spines, fragments of indurated clay, palagonite, basic and acidic rock fragments, manganese micronodules, quartz, ostracods, magnetitite, biotite and shell fragments.
Vema 24-193	14°07′	106°32′	4513	825	Foraminiferal-radiolarian marl, pale orange to moderate yellowish brown, 0-148 cm. Fragments of Mn coated volcanic rock are abundant at 78-102 and 132-148 cm, less abundant but common at 278-400 cm. Manganiferous clay with Mn micronodules, moderate yellowish brown to moderate brown 148-825 cm, carbonate free. Contains one nodule (analysed).

Vema 24-194	11°09′	104°21′	5256	497	Thirty cm of diatomaceous marl ooze underlain by radiolarian clay (30-195 cm) and glass tuff (195-210 cm) which grades at 210 cm into manganiferous clay. Tuff laminae and zones are frequent. Carbonate content is nil, except for top 30 cm. Coarse fraction (15-60 cm) consists of Radiolaria, diatoms, manganese-cemented clay aggregates, manganese micronodules and glass shards. Mn nodules are abundant at 258-275 cm and 388 cm (analysed).

but that in deeper water these give way to radiolarian (siliceous) clay. Volcanic glass shards form a number of sandy layers and were presumably derived from Indonesian eruptions. Red clay, frequently manganiferous, occurs at the base of several cores. Manganese nodules occur at the top of and within cores. Core recovery for the Lamont piston cores is excellent, varying from 5 m to 13 m.

Udintsev (1975, p.131) has mapped the sediment types around Christmas Island. North of the island, on the southern flank of the Java Trench, are terrigenous muds containing less than 10% $CaCO_3$. Around and south of the island, sediment types depend on water depth, and especially on the relationship to the calcite compensation depth (about 5000 m according to Berger, 1981), below which little or no carbonate is preserved. Above 4000 m, calcareous sediments with more than 30% $CaCO_3$ predominate - foraminiferal ooze and coccolith-foraminiferal ooze. Between 4000 m and 5000 m, red clay and diatom-radiolarian ooze with 10-30% $CaCO_3$ occur. Below 5000 m there is siliceous diatom-radiolarian ooze containing 10-30% amorphous SiO_2. South of 16°S in deep water the siliceous ooze gives way to red clay containing considerable zeolite in the form of Phillipsite, less than 10% $CaCO_3$ and less than 10% amorphous SiO_2. In both deepsea sediment types - siliceous ooze and red clay - the fraction finer than 0.01 mm is more than 70% clay. In both sediment types manganese nodules are present on the surface in places.

The Deep Sea Drilling Project took spot cores at Site 211 (Shipboard Scientific Party, 1974). The location of the hole west of Christmas Island (Fig. 1) was 9°46.53'S, 102° 41.95'E and the water depth 5528 m. The lithologic log (Fig. 5) indicates that 428.6 m of pelagic sediment overlies early Campanian basalt. The acoustically transparent near-surface seismic facies was cored at three levels and consists of clay-rich siliceous ooze with volcanic ash beds, of Quaternary to late Pliocene age and 95 m thick. It was described (Shipboard Scientific Party, 1974 : Site 211) as follows : "This unit is mostly siliceous ooze with a small admixture and a few thin (>15 mm) interbeds of volcanic ash. The major components of the siliceous ooze are diatoms, but Radiolaria, sponge spicules and, to a lesser extent, silicoflagellates are also common. Clay minerals of terrigenous and volcanic origin are abundant in the ooze, and in places the sediment becomes a radiolarian-rich clay. Glass shards, feldspar, and pumice

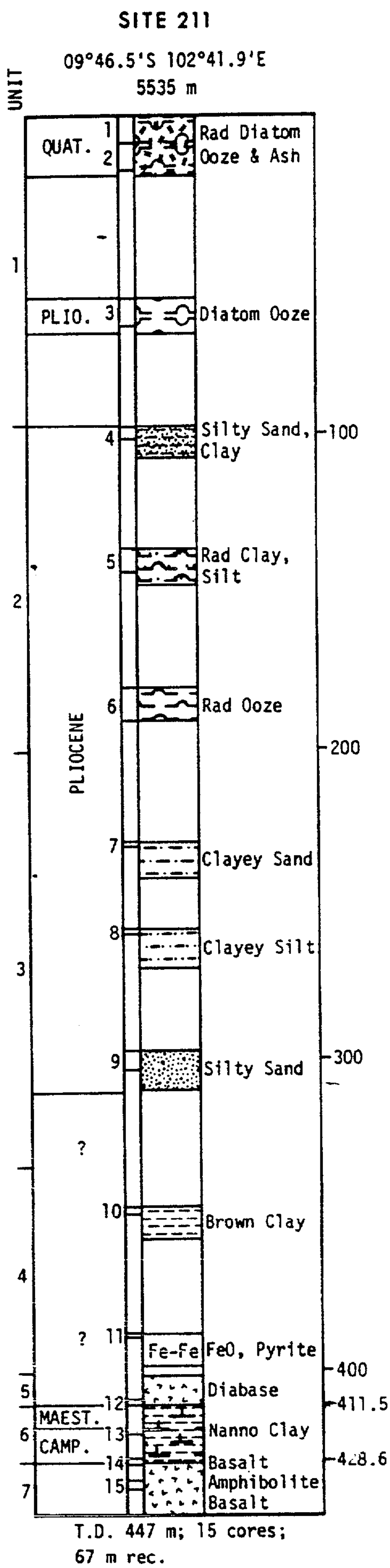

Figure 5. Lithologic units at DSDP Site 211, 250 km west of Christmas Island. Location in Figure 1. After Shipboard Scientific Party (1974).

fragments make up less than 10% of the siliceous oozes. The volcanic ash is mostly (50%-90%) made up of fresh clear rhyolitic glass shards of silt and fine sand size, the remainder of the components being clay minerals, quartz, feldspar, and heavy minerals". The shipboard scientific party considered that the rhyolitic ash most probably came from the volcanically active Indonesian arc system. Ash was first apparent in the late Pliocene (but there were large gaps in the core record), and the party suggested that this could represent either the onset of arc volcanism or the movement of the oceanic crust near to the Indonesian arc at that time.

Cook (1977), in a DSDP-based study of sediments in the eastern Indian Ocean, showed that radiolarian-diatom ooze was dominant in the upper 50-100 m of sediment in DSDP Sites 215, 213, 211 and 261, which form an east-west transect from just west of the Ninety East Ridge at 8^{o}S (Site 215) to the eastern Argo Abyssal Plain at 13^{o}S (Site 261). In general, siliceous ooze is restricted to Miocene and younger sequences. It varies in colour from brown to green and grey, and is composed largely of radiolarians and diatoms, with minor sponge spicules and silicoflagellates. Iron and manganese oxides occur sporadically as micronodules or as partings. Volcanic glass from Indonesia locally makes up to 25% of the sediment, and the clay content varies from minor to abundant. Texturally the ooze is about 60% clay, 30% silt, and up to 10% sand (largely larger siliceous organisms or glass). Chemical analysis shows that the sediment is high in silica, manganese and barium, and low in $CaCO_3$. Cook (op. cit.) suggests that "the appearance of these pelagic siliceous oozes in the late Tertiary is probably the result of the northward movement of the region into the zone of high equatorial productivity". The sedimentation rate in Site 211 is about 30 m/million years, considerably more than the rates calculated by Udintsev (1975) for Holocene sediments, of about 5 m/million years.

MANGANESE NODULES AND CRUSTS

The main long-term economic potential of the Christmas Island offshore area would appear to depend on the existence of high grade manganese nodule fields on the abyssal plains, or high grade cobalt-rich manganese crusts on the slopes of seamounts or rises.

The first deep-sea manganese nodules were dredged from southwest of the Canary Islands during HMS "Challenger's" pioneering research cruise of 1872-1876. The famous "Challenger Reports" contain careful descriptions of the dredged nodules, which vary in size and shape from something much like a potato, to something like a clump of sheep manure. Most nodules are onion-like in structure, and have formed by the precipitation of metal oxides concentrically about a nucleus. In places the nodules are distributed so densely as to form immense carpets on the abyssal plain, and in other places they are joined together to make a continuous crust of manganese and iron oxides up to 10 cm thick. Such carpets and crusts form an immense mineral resource.

The discovery of deep-sea manganese nodules led to a continuing debate on their origin. Nodules are most abundant where sedimentation rates are lowest, which generally means far from major land masses. They are believed to form at rates of about 1 mm/million years at the sediment/water interface - higher grade nodules from pore water in the surrounding sediments, and lower grade nodules directly from sea water. Grades of valuable metals in the nodules tend to be highest near the equatorial zones of high biological productivity (the plankton contain considerable nickel and copper). About 5 kg/m^2 of manganese nodules, with about 2% nickel (Ni) + copper (Cu) + cobalt (Co) content, is generally taken as a cut-off grade for potential nodule fields.

In the last 20 years, much work has been done on defining the potential mineral resources involved, and on finding the most economical method of recovering nodules containing valuable amounts of Cu, Ni, Co and other metals. Because these metals are abundant and readily mined on land (Cu and Ni in Australia), the conventional wisdom is that commercial deep-sea mining for manganese nodules is unlikely to be undertaken in the foreseeable future. However, the Soviet Union, Japan, France and India remain active in evaluation of new areas. It is quite possible that mining could be arranged on a bilateral basis, in Exclusive Economic Zones (EEZs), to avoid the complexities of mining under the provisions of the UN Law of the Sea, or the political ramifications of ignoring the UN system.

The assessment of nodule fields is done by surface vessels and submersibles. The surface vessels have a variety of remote sensing systems based on sonar and other acoustic signals, and also free-falling and tethered samplers and cameras. The United States, France, Japan and the Soviet Union have submersibles capable of working in the 5000-6000 m water depths of nodule fields.

No fully developed nodule mining system exists, but several prototypes have been tested (Padan, 1990). Perhaps the most likely type is a giant self-propelled "vacuum-cleaner" which would suck up the nodules in the surface sediments, and send them up an incredibly long pipe to the surface vessel, for separation from sediments, possibly some initial processing, and transport to land by bulk carriers. Nodule mining could have a major impact on the price of metals from conventional mines, and is opposed by some major suppliers.

The most prospective area in the world is considered to lie between the Clarion and Clipperton Fracture Zones, southeast of Hawaii. This area, which lies outside national EEZs, contains the richest known nodule fields, where a typical mining operation might recover about 3 million tonnes of nodules per year, containing about 30,000 tonnes Cu, 30,000 tonnes Ni, and 10,000 tonnes Co. Potential reserves are probably about 100 million tonnes of both Cu and Ni, and 20 million tonnes of Co - enormous figures. Another highly prospective area, for which an Indian claim has been accepted, is in the central Indian Ocean about 3000 km due west of Christmas Island. Here there are large areas where nodule grades (Cu+Ni+Co) exceed 2.3% and nodule abundance exceeds 5 kg/m^2. In 1987, a meeting under the auspices of the UN Preparatory Commission for the International Sea-Bed Authority, brought together four groups regarded by the UN as "pioneer manganese nodule investors", and groups operating outside the UN system, all of whom had overlapping and competing claims in the Clarion-Clipperton zones. A fascinating display of co-operation led to agreed boundaries separating the claims of all the groups!

In considering all the above information, and especially the potential vauue of Cu, Ni and Co resources, it is important to note that (in 1987) worldwide consumption of Cu was about 9 million tonnes, Ni about 800,000 tonnes, and Co about 27,000 tonnes (ratios of 300:30:1 approximately). Thus marine mining could more easily flood the market for Co than for Ni or Cu, and would depress Co prices most. The price ratios for Cu:Ni:Co are about 1:4:10 at present (Co around $15,000 per tonne).

Manganese crusts coat rocky outcrops, largely on volcanic islands and seamounts. They were first clearly recognized as potentially economic sources of cobalt by Halbach et al. (1982). Since then the USA, in particular, has made a major effort to define the extent of cobalt-rich crusts in its economic zone, especially in the Pacific Ocean. Similar surveys have been carried out in the Southwest Pacific under the auspices of the South Pacific Applied Geoscience Commission (SOPAC) and other research organizations. Relatively little effort has thus far been put into the assessment of cobalt-rich manganese crusts in the Indian Ocean.

The richest crusts (1% Co) generally lie in water 1000-2500 m deep, commonly in crusts 2 cm or so thick, but sometimes up to 20 cm thick. It is clear that potentially economic crusts form very slowly, from metals dissolved in the water column, and only in areas where there is little other deposition of material. It is widely accepted that cobalt-rich crusts are related to the level of the oxygen minimum zone in the oceanic water column. Because North Pacific waters are more depleted in oxygen than South Pacific waters, the North Pacific is likely to be more prospective for cobalt-rich crusts. High grade crusts already have been found in the Pacific as far from the Equator as 40^{o}N and 40^{o}S.

A detailed study of the crusts in the Marshall Islands EEZ in the Pacific from 6^{o}N to 14^{o}N, is provided by Hein et al. (1990). Using information from three cruises, they considered the Marshall Islands EEZ as having a high potential for Co-rich ferromanganese crusts. The interrelationships of Mn, Fe, Co, Ni, and Cu, show that these crusts fall within the normal range of central Pacific hydrogenetic crusts. The commonly cited cut-off grade for potential economic development is 0.8% Co. Crusts on the Cretaceous seamounts in the Marshall Islands are very high in platinum, manganese, phosphorous and nickel, and moderate in the most economically important element, cobalt, and also copper. Cobalt content increases to the east along with the oxygen content of the water column.

Hein et al. (1990) note that several seamounts in the Marshall Islands EEZ have crusts of over 100 mm thick and average thickness from individual dredges of over 50 mm. The commonly cited cut-off thickness for potential economic development is 40 mm. Because the mining of crusts from the rugged flanks and summit of seamounts and ridges will be difficult, crust thickness (tonnage) may be a more important factor in site selection considerations than grade. A weak negative correlation exists between crust thickness and Co content, so tonnage also has an inverse relationship with Co content. Crust thickness does not correlate with either Ni or Pt grades. Growth rates vary from 1.5 to 16 mm/m.y. and average 4.7 mm/m.y.

Hein et al. (1990) suggest that the Marshall Islands area probably has the highest potential for Co-rich crust resources in the central Pacific, especially if Pt can be recovered as a by-product. On an adsorbed water-free basis, bulk crusts in more prospective areas average 16.6% Fe, 25.6% Mn, 2.06% P, 0.70% Co, 0.11% Cu, 0.57% Ni, and 0.67 ppm Pt.. Analysis of a large number of thick crusts lowers the regional mean content of many of the metals, especially Co. These regional values are 12.2% Fe, 18.8% Mn, 0.41% Ni, 0.08% Cu, 0.51% Co, and 20 ppm Pt (Hein et al., Table 14).

The feasibility studies for nodule mining are far more advanced than those for cobalt-rich crusts, and there is every chance of limited nodule mining going ahead in the not too distant future. Much will depend on whether manganese nodule mining in the Clarion-Clipperton zone proves to be profitable. For some countries, cobalt-rich crusts may be a long-term prospect. In both cases continuing assessment is necessary, but in neither case can hopes be set too high. One of the main aims of the present cruise is to assess prospects for both nodules and crusts in the Christmas Island offshore area.

Points to be borne in mind in comparing the feasibility of nodule and crust mining include the physical difficulty of that mining. Cobalt-rich crusts occur in much shallower water (1000-2500 m) than high-grade (Ni+Cu) nodules (5000-6000 m), so in that sense are more mineable. However, crusts are generally bonded to a rough rocky surface, whereas nodules are cradled in soft sediments. Hence the collection of nodules at the sea bed should be much simpler than that of crusts.

Indian Ocean nodule mining site

In late 1987, the Preparatory Commission for the International Seabed Authority, in accordance with the 1982 UN Law of the Sea Convention, approved the application of India for pioneer investor status to a mine site with an area of about 150,000 sq km in the central Indian Ocean. Lease boundaries for this site are shown in Sudhakar (1989). The site lies between 10°S and 16°S and 72°E and 79°E, and has an average grade of Ni+Cu+Co of 2.55%, similar to grades in the mine sites in the Clarion-Clipperton zone east-southeast of Hawaii. Abundance appears to be somewhat lower at 5-7.5 kg/m^2. This area was pointed to by Frazer and Wilson (1980) and Cronan and Moorby (1981) as the most prospective in the Indian Ocean, with high metal grades but apparently rather low abundances, suggesting that it was a "paramarginal" deposit. India set up a new Department of Ocean Development in 1981, and a number of Indian research institutions devoted nearly US$100 million to manganese nodule exploration in the central Indian Ocean before the mining claim was accepted in 1987. Major appraisal work is currently underway, by agencies such as the Indian National Institute for Oceanography.

There has been an abundance of Indian papers (see "Selected Bibliography") on the nodule mining site and adjacent areas since 1980. The deposits lie in water depths of 5000-5500 m. The paper by Sudhakar (1989) summarizes the present state of knowledge, which indicates that the deposits on siliceous ooze are far more prospective than those on red clay as follows :

"Comparative studies on manganese nodules from two different areas (S and R) in the Central Indian Basin (CIB) show distinct variations in their composition, grade (percent Ni+Cu), and abundance (kg/m^2), which are explained in terms of various genetic processes. Area S is a zone of siliceous sediment in which nodules are characterized by high Mn/Fe ratios (mean 3.77), high percent Ni+Cu content (mean 2.41 percent) and high abundance (mean 7.48 kg/m^2). Area R is a zone of red clay where the nodules are characterized by low Mn/Fe ratios (mean 2.24), low percent Ni+Cu contents (mean 1.61 per cent), and low abundance (mean 4.68 kg/m^2). The mean Cu and Ni values are 1.19 percent and 1.22 percent, respectively, in Area S nodules, whereas Area R nodules show relatively lower concentrations of Cu (mean 0.68

percent) and Ni (0.92 percent), respectively.

The results indicate that the nodules from siliceous sediments approximate the diagenetic end members of the series, as described in the Pacific, and are similar in composition to the north equatorial Pacific ore grade nodules. Siliceous sediments in CIB offer the possible sites for first generation mining, where nodules having a mean concentration of percent Ni+Cu > 2.27 percent, at 1.8 percent Ni+Cu cutoff, and > 5 kg/m^2 abundance are recovered. Early diagenetic processes are predominant in the zone of siliceous sediment between 10^oS to 15^oS, whereas red clay nodules are more hydrogenous than diagenetic in nature. The sedimentary boundary between siliceous and red clays exists around 15^oS, which may be the boundary delimiting ore grade nodules to the north of 15^oS. It is evident from the Pioneer Area allocated to India by the United Nations that more than 95 percent of it (150,000 km^2) encompasses the region between the latitudes 10^o to 15^oS."

Jauhari (1990) studied the relationship between morphology and composition of nodules in the area. He showed that the high grade nodules from the areas of siliceous radiolarian ooze are relatively large, have a rough surface texture, and have formed by diagenesis of the underlying sediments. The lower grade nodules from areas of red clay are relatively small and smooth, and have formed largely by precipitation from bottom waters. A geochemical study by Valsangkar & Khadge (1989) indicates that rougher diagenetic nodules are of higher grade and that they consist largely of todorokite. This helps explain the high grade, because the divalent metal ions of Ni and Cu are readily incorporated into the todorokite phase (Usui, 1979).

If one assumes that, in the Indian Ocean mine site of 150,000 km^2, nodule wet density is 5 kg/m^2 (and the nodules are 1/3 by weight water), Ni and Cu grades (on a dry basis) are 1.2% each and Co grade is 0.12%, then the amount of Ni and also of Cu on the seabed is 6,000,000 tonnes, and of Co is 600,000 tonnes. Even if only half to a third of the site proves to be minable, these figures would still be very large.

Christmas Island Area

Direct information on manganese nodules and crusts for the area around Christmas Island is very limited. Key papers include Bezrukov & Andruschenko (1974), Udintsev (1975), Noakes & Jones (1976), Skornyakova et al. (1980), Skornyakova (1984), Frazer & Wilson (1980) and Cronan & Moorby (1981). Table 4 shows all analyses which we have access to at present. It covers only nine stations and a total of 17 analyses : 8 of surface nodules, three of buried nodules (which are very low grade), and four of crusts. The four surface nodules from the preferred depth of more than 5000 m (below the local CCD) have a Ni+Cu+Co grade averaging 1.35%, and a maximum grade of 1.87%, values well below those in the central Indian Ocean mine site. There is no information on local abundance available, although nodules have been encountered at a fairly high percentage of suitable sampling stations. For comparison, Noakes & Jones (1976) and Jones (1980) listed analyses for 5 deepwater stations to the south (15-17^{o}S, 104-106^{o}30'E). Average values were Mn 17.1% (range 14.6-18.5%), Fe 11.6% (10.7-13.1), Ni 0.51% (0.31-0.71), Cu 0.61% (0.21-1.06), Co 0.22% (0.15-0.33), and Ni+Cu+Co 1.34% (0.68-1.90).

Frazer and Wilson (1980) reviewed the nodule prospects of the Wharton Basin, including the Christmas Island area. Twenty one assays from 15 locations gave grades of Mn = 19.8%, Fe = 11.2%, Co = 0.21%, Ni = 0.65%, Cu = 0.54%, Ni+Cu+Co = 1.39%. These grades are very like those recorded by Cronan and Moorby (1981) for the Wharton Basin, and also very like those for surface nodules in the Christmas Island area (Table 4). Frazer and Wilson (1980) pointed out that the generalized map of surface sediments in the Indian Ocean prepared by Udintsev (1975) suggested that the Christmas Island area, with deepwater siliceous ooze and red clay, and similar latitudes, looks very similar to the central Indian ocean area (where the Indian mine site has since been taken out). However, they also noted that sediment types are more mixed in the Wharton Basin, water depths are generally greater (5500-6000 m rather than 5000-5500m), sedimentation rates are slightly higher, and terrigenous influx is greater. They reported that nodules were observed in 18% of cores, 82% of other bottom samples, and 56% of seafloor photographs. They concluded that "although nodule deposits in some parts of the Wharton Basin may be abundant enough for mining, grade is probably too low to make these deposits a resource even in the

TABLE 4 : ANALYSES OF MANGANESE NODULES AND CRUSTS

Number	Sample	Depth(m)	Mn	Fe	Metal percentage by weight Co	Ni	Cu	Cu+Ni+Co	Pb
Vema 24-193	Nodule	4513	11.40	13.50	0.28	0.23	0.19	0.70	
Vema 24-193	Micronodule	4513	5.00	7.00	0.10	0.18	0.01	0.29*	
Vityaz 5172	Nodule	4993	15.73	15.70	0.12	0.30	0.19	0.61	
Vityaz 6729-1	Crust (1)	5330	18.50	10.15	0.08	0.55	0.23	0.86*	
	Crust (2)	5330	15.24	11.76	0.09	0.58	0.26	0.93*	
Vityaz 6731-5	Crust	3850	10.62	14.28	0.27	0.18	0.12	0.57*	
Vityaz 6731-6	Nodule	4940	20.90	7.09	0.09	0.59	0.35	1.03	
Vityaz 6732-1	Nodule (no nucleus)	1585	19.09	13.09	0.37	0.33	0.06	0.76	
Vityaz 6732-1	Nodule nucleus	1585	10.94	7.49	0.26	0.18	0.04	0.48*	
Vema 24-194	Buried Nodule (1)	5256	6.70	7.90	0.04	0.06	0.07	0.17*	
Vema 24-194	Buried Nodule (2)	5256	2.20	3.40	0.02	0.06	0.08	0.16*	
Vema 24-194	Buried Nodule (3)	5256	1.50	7.10	0.02	0.06	0.03	0.11*	
Vityaz 6734	Crust	5078	15.75	12.77	0.11	0.51	0.27	0.89*	
Vityaz 6734	Nodule	5078	21.79	0.09	0.10	0.92	0.85	1.87	
RC 14-49	Nodule (1)	5273	20.40	14.20	0.12	0.69	0.48	1.29	
RC 14-49	Nodule (2)	5273	19.80	11.80	0.12	0.71	0.51	1.44	0.11
RC 14-49	Nodule (3)	5273	17.30	13.10	0.16	0.41	0.32	0.89	0.12
Average for all surface nodules (excludes * samples)			18.30	14.72	0.17	0.52	0.37	1.07	0.11
Average for surface nodules (depth 5078-5273 m)			19.82	9.80	0.13	0.68	0.54	1.35	0.11
Wharton Basin average (39 stations)+			17.5	11.9	0.18	0.55	0.41	1.14	0.07
Wharton Basin siliceous ooze (10 statns)+			20.3	11.4	0.17	0.70	0.56	1.43	0.10
Indian Ocean average (324 stations)+			15.4	14.8	0.23	0.46	0.27	0.96	0.09

+ After Cronan & Moorby (1981)

distant future".

However, Frazer and Wilson (1980) do acknowledge that the few Wharton Basin data may not be representative. Furthermore, there is no reason to consider that data from most of the Wharton Basin, which is floored with red clay (Udintsev, 1975), is likely to be representative of the areas of siliceous ooze (generally regarded as more prospective for high grade nodules) around Christmas Island. The only way to assess the prospectivity of the Christmas Island offshore zone for manganese nodules is to occupy many more bottom stations to better map sediment and nodule distribution.

Cronan & Moorby (1981) listed 39 analyses from the Wharton Basin (Table 4) which indicated that, compared to Indian Ocean average values, Wharton Basin nodules are enriched in Mn, Ni and Cu, and depleted in Fe, Co and Pb. They also noted that samples that came from nodules in siliceous ooze are highest in Mn, Ni, Cu and Zn (Table 4). Compared to Central Indian Ocean nodules, Mn was similar, but Ni and particularly Cu were lower.

The prospectivity for cobalt-rich manganese crusts on seamounts and rises is virtually unknown, and awaits a serious dredging program for an initial assessment. The four crust analyses in Table 4 have low Co grades, but are taken in water far deeper than the zone shown to be most prospective in the Pacific Ocean : 1000-2500 m, corresponding to the oxygen minimum zone in bottom waters.

Guides to manganese nodule prospectivity

In the Pacific and Indian Oceans, the same conditions seem to favour the formation of nodule fields of high grade and abundance (e.g. Cronan, 1980; Mizuno et al., 1980, Pautot & Melguen, 1979; Exon, 1982; von Stackelberg & Beiersdorf, 1991). These include :

1) Low sedimentation rates, which are favoured by distance from major land masses and volcanoes, and dissolution of carbonate and silica below the CCD, favour the formation of manganese nodules, which grow at very slow rates and normally dissolve if buried.

2) High productivity of calcareous and especially siliceous plankton is needed, because these are the sources of the Ni and Cu found in high grade nodules. High productivity in low latitudes depends largely on upwelling; productivity is high (100-200 $gm/m^2/year$) both north and south of Christmas Island (Dietrich & Ulrich, 1970). Upwelling is reflected by high organic carbon values in the surface sediments (Udintsev, 1975, p. 128), and organic carbon is important in the solution of Mn, Ni and Cu to form high grade nodules.

3) Diagenesis is the only mechanism which can form high-grade nodules. This means that sediments should be fairly rich in Mn, Ni and Cu, and porous so that pore water can move through them. Furthermore the sediment pore water should be reducing to allow solution of these metals, and bottom water should be oxidising to force precipitation near the sediment-water interface.

4) Sediments with low sedimentation rates, high Ni and Cu content, and high porosity, where bottom waters are oxidizing and pore water can be reducing, are exclusively deep-sea siliceous oozes. Only in such sediments can a combination of high grade nodules and high abundances be expected, and only in them have nodule mining sites been taken up.

5) Clearly then, on the present cruise, high grade manganese nodules must be sought in areas of siliceous ooze, mapped as being east, south and west of Christmas Island by Udintsev (1975). However, because sampling density is so low, and sediment patterns thus so uncertain, sediment and nodule distribution must be checked on long profiles across the entire Christmas Island offshore area. Siliceous ooze is normally transparent on seismic profiles, so they should be an aid in planning and interpreting the sampling program.

CRUISE OBJECTIVES

This is a multipurpose reconnaissance cruise, with the following major objectives :

1) To define seabed morphology and sediment thickness north of Christmas Island, as technical input to discussions between Australia and Indonesia on the delineation of the seabed boundary between the two countries.

2) To assess the non-living resources of the seabed in the Christmas Island offshore region, and especially manganese nodules and cobalt-rich manganese crusts.

3) To determine the nature and age of the Christmas Island volcanic pedestal, and those of other seamounts and rises in the region, and their relationship to the oceanic crust on which they stand.

4) To investigate the geological history of the region, including especially the tectonic, volcanic and sedimentary history.

CRUISE PLAN

The cruise is scheduled for 28 days in January to February 1992, commencing and finishing at Christmas Island. The following work is planned :

1a) Acquire about 1000 km of high-resolution reflection seismic and bathymetric data north of Christmas Island (Fig. 6) to define seabed morphology and sediment thickness.

1b) Acquire about 1500 km of regional high-resolution seismic and bathymetric data in two north-south lines and one east-west line, for the above purposes and also to provide targets for manganese nodule sampling. The combined program is listed in Table 5. At eight knots and including long transits the two programs (a + b) should take about 10 days.

2) Occupy about 104 free-fall grab stations, 13 core stations, and two multiple camera stations, to assess manganese nodule prospects

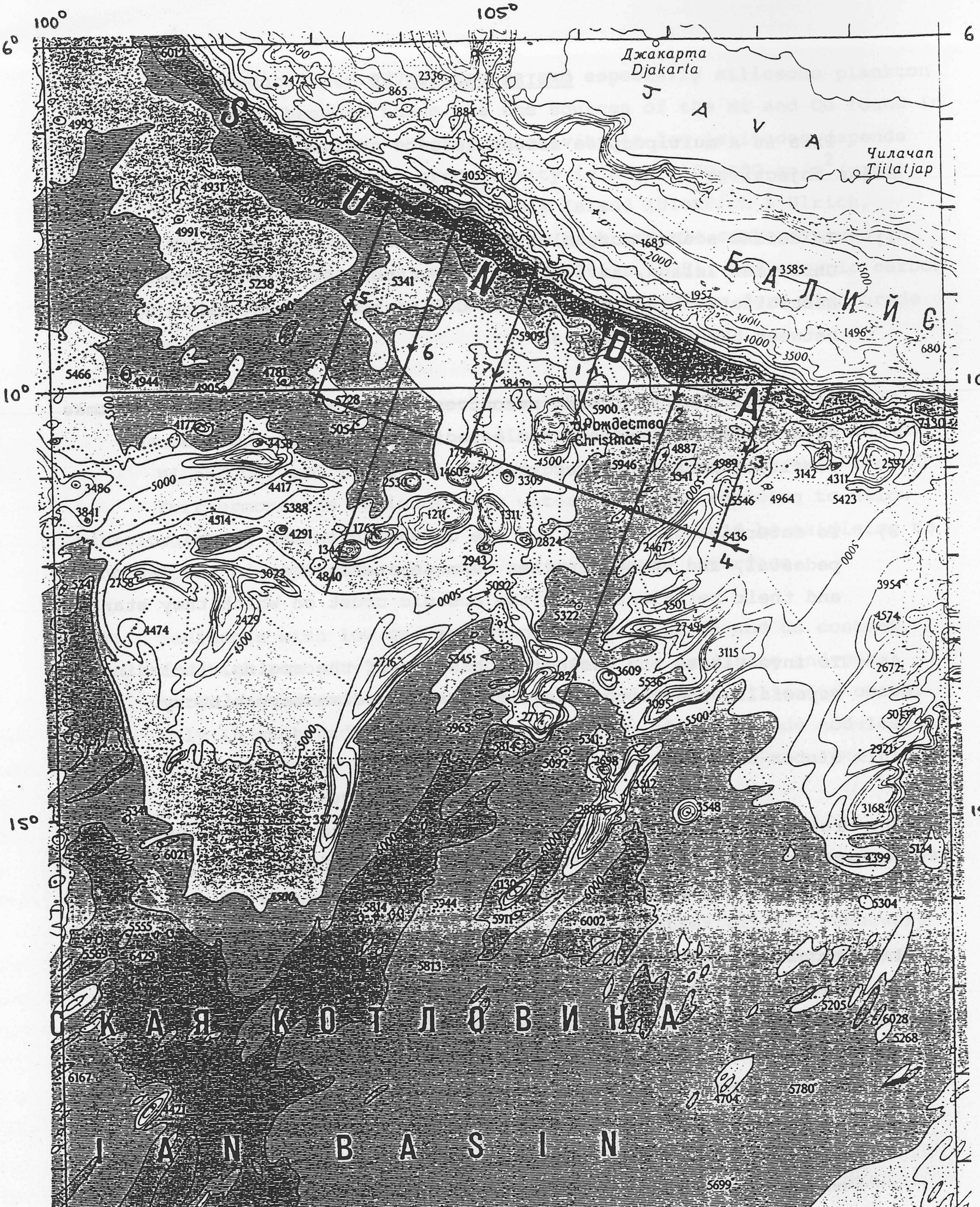

Figure 6. Map of proposed seismic tracks in the Christmas Island offshore area.

TABLE 5 : PROPOSED SEISMIC SURVEY TRACKS

No	Length nm	Length km	Purpose	Priority
1	80	150	Structure - Christmas to Java Trench	1
2	290	540	Structure - Trench to SSW - Mn sampling	1
3	130	240	Structure - NNE to Java Trench	2
4	290	540	Structure - WNW near Christmas Is - Mn sampling	1
5	160	300	Structure - NNE to Java Trench	2
6	280	520	Structure - SSW from Trench - Mn sampling	1
7	140	260	Structure - NNE to Java Trench	2
Totals	1370	2550		

along regional seismic lines, in groups of four stations each 1 km apart. At 9 stations, dredge volcanic slopes on regional seismic lines, at an average depth of 2500 m, to investigate cobalt-rich manganese crust prospects. Total sampling time would be about 14 days.

Field Program

A. Seismic lines 1 and 2 : 350 nautical miles (nm), including transits and set-up time = 1.5 days.

B. Nodule and crust sampling north along line 2 : 40 nodule stations in 10 groups, 5 cores, 2 dredges, 1 camera run, 290 nm transit = 4.5 days.

C. Seismic lines 3, 4, 5 and 6 : 800 nm, including transits and set-up time = 4.5 days.

D. Nodule and crust sampling north along line 6 : 32 nodule stations in 8 groups, 4 cores, 3 dredges, 1 camera run, 350 nm transit = 4 days.

E. Seismic line 7 : 140 nm, including set-up time, and transit of 130 nm to W end of line 4 = 2.5 days.

F. Nodule and crust sampling east along line 4 : 32 nodule stations in 8 groups, 4 cores, 4 dredges, 290 nm transit to E end of line 4 = 4.5 days

G. Transit from E end of line 4 to Christmas Island : 150 nm = 0.5 day.

Total = 22 days, so leaves 6 days in hand. However figures are not conservative, and it is uncertain whether seismic system will function efficiently at 8 knots. Program can easily be expanded by additional sampling if we have time in hand.

Assumptions : Group of nodule stations = 4 hours, core = 2 hours, camera run = 4 hours, dredge = 6 hours; seismic at 8 knots, transit at 10 knots, seismic deploy and retrieve time each 2 hours.

EQUIPMENT REQUIREMENTS

High-resolution reflection seismic equipment

One aim of the seismic program is to image the 300-1000 m of sediments overlying basement. In the area north of Christmas Island, related to our boundary claim with Indonesia, the main requirement is to have adequate penetration to map total sediment thickness in water depths of 5000-7000 m. Near the trench axis sediment thickness may exceed 1000 m, presenting problems for a small source.

Another aim of the seismic program is to image the 300-500 m of sediments overlying basement, in a manner which will allow resolution of sediment facies as an aid to manganese nodule search. A secondary aim is to identify dredge targets on the slopes of seamounts and volcanic rises. For these two purposes we need :

- Source - 80 cubic inch watergun; one in action at a time but 2 deployed, one from each side.
- Cable
  - 600 m active section configured as for 1991 BMR-JNOC survey
  - 96 channels, 6.25 m groups
  - large offset to keep cable down at 8 knots
  - 2 ms recording
  - 4 second records
- Recording requires aboard-ship identification of features, and records which can be made available to the Department of Foreign Affairs and Trade with the Cruise Record.

Other geophysical equipment

- Magnetometer
- Gravity meter
- Echosounder
- Pinger for coring and photographic work

Geological sampling equipment

- 11 Benthos free-fall grabs for nodule sampling
- 4 large chain bag dredges for crust and rock dredging
  - capable of conversion to nodule dredging by replacement of chain bag by metal box grid
  - small pipe dredges to be attached to large dredges.
- Coring equipment for 15 gravity or piston cores
- Van Veen grab to be deployed from main winch wire with pinger.
- Deepsea camera for deployment from main winch wire with pinter
- Time-depth recorders for dredging
- Appropriate shackles, steel rope, slings, sampling drums, weights for the van Veen grab, ballast for the free-fall grabs etc.
- Good-quality camera with black and white film for photographing nodules, crusts etc on deck.

Navigation

- Differential GPS. We will need accurate plots of cruise tracks aboard ship, so that we can return precisely to selected points for sampling. We also need such tracks for a Cruise Record for the Department of Foreign Affairs and Trade soon after the cruise.

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Follows from p. 31

ANNEX I : PROVISIONAL CREW LIST

Scientists :	N.F. Exon
	T. Graham
	L. Kalinisan
	One other
Science technicians :	T. McNamara
	C. Buchanan
	L. Hatch
	D. Wilson
	J. Reid
Geology technicians :	J. Stratton
	P. Davis
Electronics technicians :	L. Miller
	V. Wierzbicki
Mechanical technicians :	C. Green
	M. James
	B. Dickinson
	A. Radley
	C. Dyke
Outside participants :	S. Williams (ANU geology student)