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BMR CRUISE 107: SEABED MORPHOLOGY AND OFFSHORE RESOURCES AROUND CHRISTMAS ISLAND, INDIAN OCEAN

by

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SUMMARY

Christmas Island is an Australian territory lying south of Java in the Indian Ocean, at about 10°30' S and 105°40' E (Fig.1). 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 was 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.

Oceanic crust is generally at 5000-6000 m around Christmas Island, and it is overlain by 100-400 m of pelagic sediment which thickens northward toward the Java Trench. A number of volcanic ridges trend generally north east or north-north east, and are as shallow as 1200 m below sea level. Christmas Island itself sits on such a ridge. Volcanic rocks, largely basaltic, 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 only 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 average grade of Cu+Ni+Co is much higher at 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.

BMR Cruise 107 used R.V. *Rig Seismic* in a one-month research cruise in February 1992 in order to obtain additional seismic profiles and seabed samples from the region. There had been some 30 previous geoscience cruises passing through the region, but none were designed to solve problems related to the Christmas Island EEZ. However, they have provided several thousand kilometres of useful geophysical profiles and 17 bottom samples in the potential EEZ, and these will be incorporated into our final evaluation of the region. Water depths are generally 5000-6000 m, but volcanic edifices rise above the abyssal plain in many places (Fig. 1).

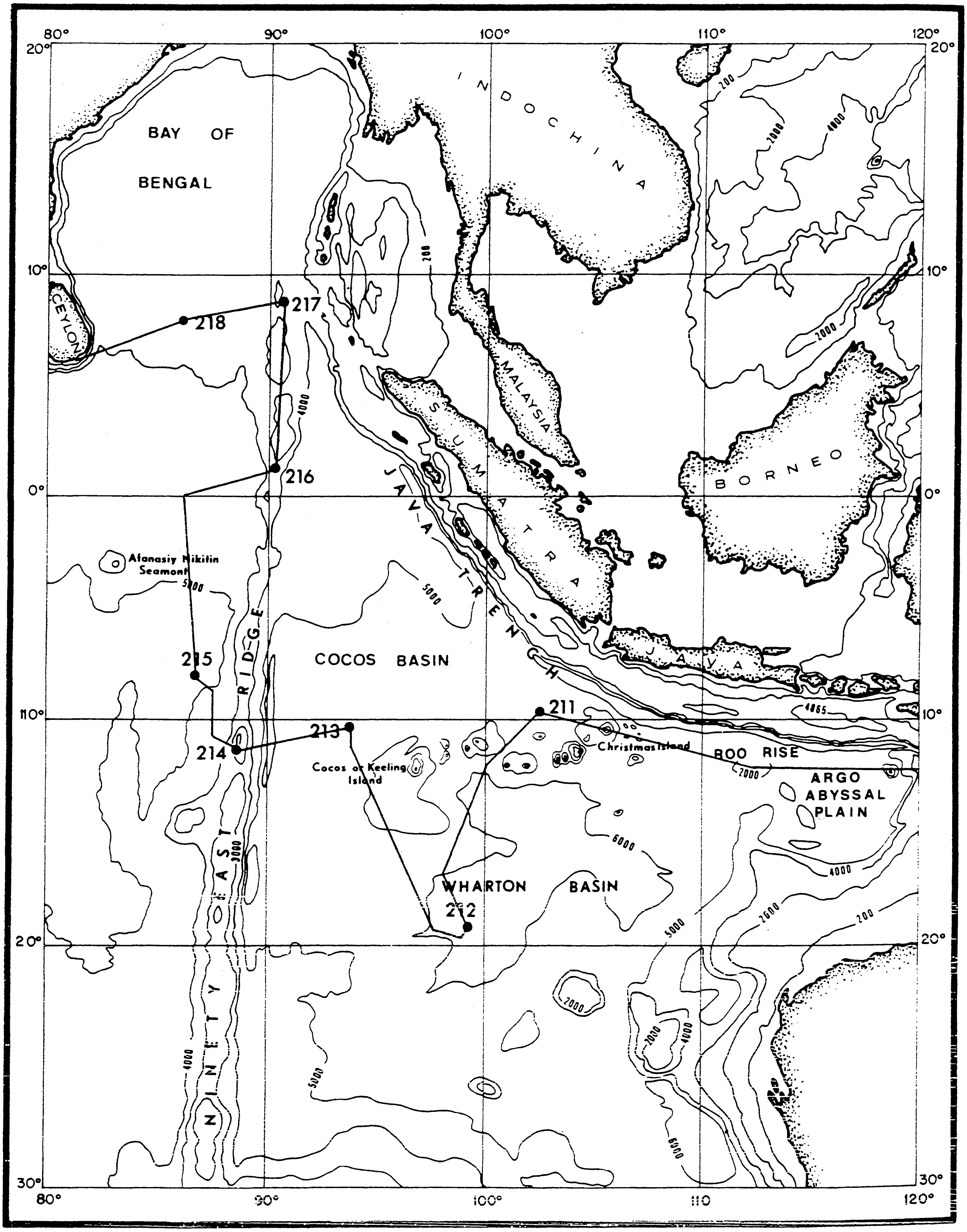

Figure 1: Locality map, showing bathymetry (m), physiographic provinces and DSDP sites and ships' tracks. After Veevers (1974).

About 2100 km of seismic profiles were recorded across the region, mostly north of Christmas Island (Fig. 2), at speeds of 6.5 to 9 knots, using two 150 cubic inch airguns venting at the sea surface as the energy source, and a 600 m long, 24 channel seismic streamer. Processing indicates that data quality is satisfactory for mapping the sequence above the volcanic basement that generally lies less than half a second (two-way time) below the seabed. Total sediment thickness is usually less than 200 m on the Christmas Island Rise in water depths of 3000-5000 m, and 150-400 m on the surrounding abyssal plain. The seismic profiles, along with results from Deep Sea Drilling Project Site 211 in the west, confirm that Veevers' (1974) regional seismic reflectors are present, and that the sequence can be divided as follows:

- R0-R1: transparent Quaternary to Miocene siliceous ooze and ash (from Indonesia) 50-200 m thick
- R1-R2: well-bedded Neogene turbidites and siliceous ooze 50-250 m thick
- R2-R3: variably bedded Tertiary turbidites and siliceous ooze; brown, ferruginous, unfossiliferous clay; and Campanian-Maastrichtian nannofossil clay. R3 is the top of Cretaceous oceanic crust (a diabase sill in DSDP Site 211 was dated as 71 Ma [Campanian] by Ar^{40}/Ar^{39} methods).

During the cruise a great deal of bottom sampling was carried out for geological and resource assessment purposes, using dredges, corers, and Benthos free-fall grabs (Fig. 2). Despite the early loss of 4500 m of wire from the deepsea winch during dredging operations (which constrained future dredging to water less than 3500 m deep, and coring operations to depths of less than 4600 m), the sampling program was quite successful (Table 1):

TABLE 1. SUMMARY OF BMR CRUISE 107 SAMPLING STATIONS

Equipment	Water (m)	Stations	Success	Recovery
Dredge	1600-3700	12	9	Basalt, trachyte, volcaniclastics, hyaloclastics, shallow and deepwater carbonates, Mn crusts
Piston core	453-5923	9	7	10.7 m: ooze, marl, clay
Gravity	1993-3665	6	2	10.15 m: ooze, marl
Freefall grab	4574-5929	28 (84*)	28 (82*)	Clay, volcanic pebbles, Mn nodules (9 stations)

* deployments

Six rock types were dredged from the seamounts (Table 1), many of which lie on ridges trending northeast. The seamounts often have the flat tops characteristic of guyots, suggesting that they were once subject to wave erosion; their peaks now lie in water 1200-3200 m deep. The volcanic

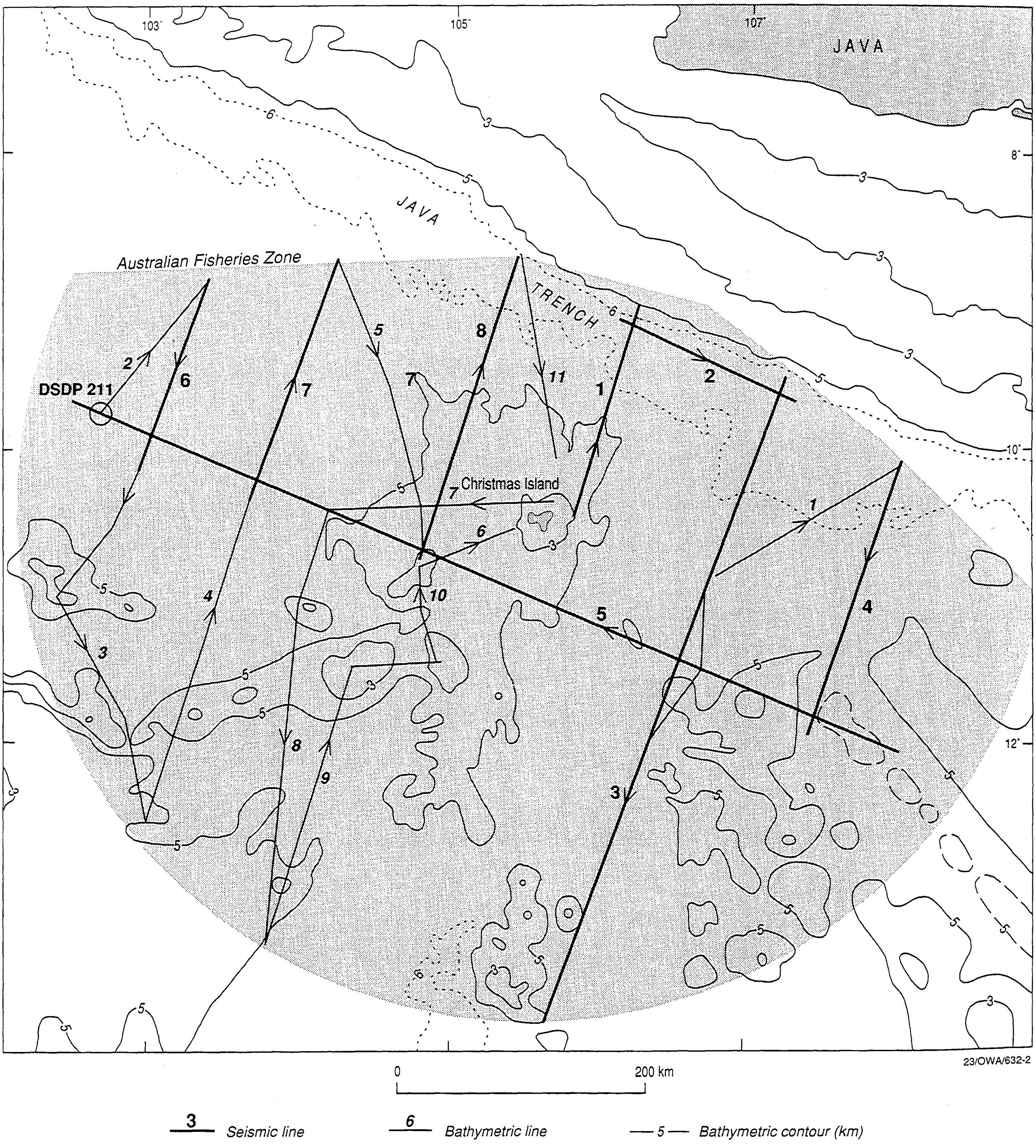

Figure 2: Map of Christmas Island region, showing bathymetry and geophysical profiles recorded on BMR Cruise 107.

pedestals consist of alkali-olivine basalt and trachyte, and are typical intraplate lavas. Associated rocks are mixed sediments consisting of rounded hyaloclastic and volcaniclastic grains set in carbonate; the grains were probably rounded by stream or wave action and then swept into deeper water by storms. The shallow water carbonates are of varied grainsize and contain red algae, larger foraminiferids, and bryozoan, molluscan, and echinoderm debris. The deeper water carbonates are largely chalks dominated by nannofossils and planktic foraminiferids.

Ages obtained from igneous rocks in DSDP Site 211 and from Christmas Island indicate that there were volcanic episodes in at least Late Cretaceous and Eocene/Oligocene times. The ages of sediments dredged from the seamounts, as defined by nannofossils and foraminiferids, include Campanian, Maastrichtian, Paleocene, Eocene, Miocene and Pliocene. We see the seamounts as possibly forming over a hotspot as the crust moved slowly northeast in Late Cretaceous and Palaeogene times. When fast spreading started in the Eocene, and the crust moved rapidly northward, the region was separated from the hotspot and volcanism soon ceased. The shallow-water carbonates and volcaniclastics formed around volcanic islands and on shallow seamounts. They sank well below the surface as the underlying crust cooled and sank, and pelagic carbonates were laid down.

Most of the core attempts (Fig. 3) were on the tops of seamounts and were designed to obtain carbonate oozes for palaeoceanographic studies. Unfortunately recovery was generally very poor, probably because current action had winnowed the surface sediment to a foraminiferal sand, not easily penetrated by gravity or piston corer. Two deepwater cores were taken away from seamounts (P5 and G4) and these were successful. Cores from seamount crests are of apparently unbedded Quaternary, cream nannofossil-foraminiferal ooze, containing well-preserved microfossils, and have $CaCO_3$ contents of 75-90%. Deepwater Core GC04, from 3665 m, is a medium-bedded, pale brown, grey and olive sediment, consisting of nannofossil-foraminiferal ooze and carbonate-rich siliceous ooze, with very variable $CaCO_3$ contents of 6-68%. Core PC05, from 4564 m, is poorly bedded, carbonate-bearing siliceous ooze, with the upper 65 cm yellow brown and the remainder various shades of grey; $CaCO_3$ content is low at 3-39%. These cores clearly fit the regional picture of decreasing planktonic carbonate downward as the Calcite Compensation Depth (5000 m) is approached, and of an increase in resistant components such as clay, zeolites, diatoms and radiolaria.

Free-fall grabs were deployed at 28 stations, generally in groups of three, variably spaced and in water depths of 4500-6000 m. The aim of the sampling was to investigate the manganese nodule potential of the region, which has considerable similarities to the Indian nodule mining site some 3000 km to the west. Almost all grabs returned successfully, most with sediment and some with nodules. Nodules were recovered at nine stations (22 deployments of 73) and average abundance there was 3.0 kg/m^2 (maximum 12), which is below the economic cutoff grade of 5 kg/m^2. Average

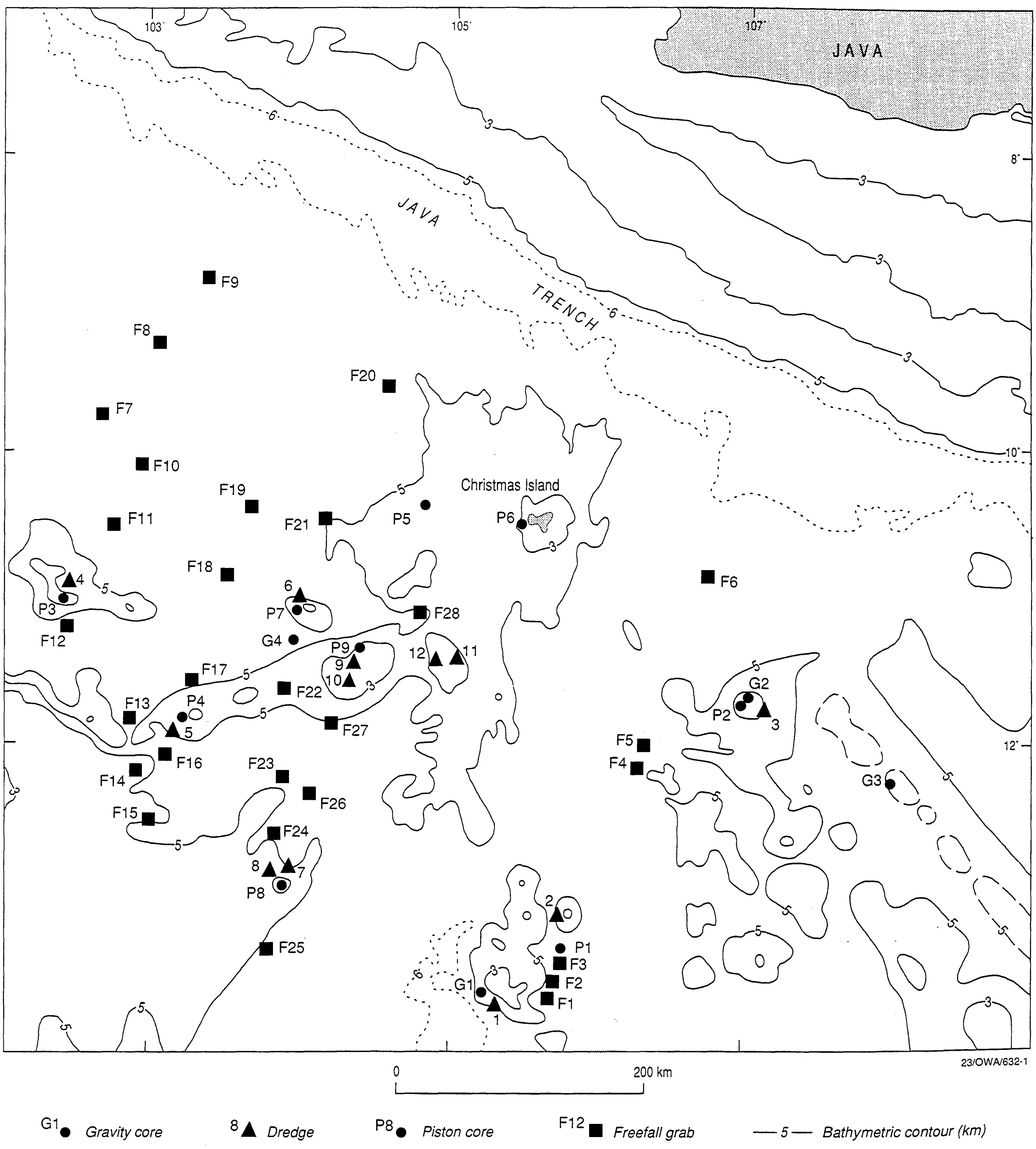

Figure 3: Map of Christmas Island region, showing bathymetry and seabed sampling carried out on BMR Cruise 107.

nodule grades are listed in Table 14, which shows that Cu+Ni+Co%, at 1.13%, is far lower than in the leased areas in the Central Indian Basin and the North East Pacific Ocean, and the economic cutoff grade of 2%. The results show that the Christmas Island offshore area has no potential for economic nodule fields.

Manganese crusts, individually up to 6 cm thick, and often forming multiple crusts twice as thick, were recovered from a number of dredge hauls in water depths of 1500-3700 m. Average metal values are presented in Table 14, which shows that they are somewhat less than Pacific Ocean values, at 0.44% Co compared to 0.63%. The results are not encouraging as regards the possible occurrence of Co-rich manganese crusts with economic potential, but the samples have come from below the optimum depths for Co-rich crusts.

The geological history of the area started with the formation of oceanic crust in the Cretaceous. In Late Cretaceous to Eocene times, volcanic islands probably developed over a hotspot that moved (relatively) southwest with time, subsided, were eroded by wave action, and sank beneath the sea. On them were deposited first shallow water carbonates and later pelagic carbonates, starting in the Late Cretaceous. At the same time hemipelagic and pelagic sediments were laid down on the deep sea floor.

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-north west 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. 4), 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 Rise, which extends south-south west for 700 km (Fig. 1). The Java Trench to the north is more than 6500 m deep, and the abyssal plains around the Christmas 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 until 1987 when mining ceased. Mining resumed at a smaller scale in 1991.

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 work arose from the request, and started in January 1992, using R.V. *Rig Seismic*. A cruise narrative is provided in Appendix 7.

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Geology technicians:	J. Stratton
	P. Davis
Electronics technicians:	L. Miller
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Mechanical technicians:	R. van der Graaf
	M. James
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	A. Radley
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Outside participants:	G. Moss (University of Adelaide geology student)
	S. Williams (ANU geology student)

Ship's Crew List

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Chief officer:	T. Walters
Second officer:	C. Hellier
Second engineer:	Ian McCarthy
Electrician:	W. Hanson
E.A./seaman:	P. Hutchinson
ABs:	T. Dale
	D. Kane
	G. Pretsel
Cooks:	W. Fowler
	G. Conley

Stewards: M. Perrett
M. Cumner

Acknowledgements

Special thanks are due to Peter Gifford, the Administrator of Christmas Island, who provided us with valuable assistance when *Rig Seismic* first berthed at Christmas Island, and entertained us on a memorable Chinese New Year at the end of the cruise. Ian Roach toiled manfully on tabulating and figuring the chemical analyses, Jenny Bedford helped with the plates, and Joy Manly and Philippa Wright with the word processing.

Dr. David Haig and Greg Milner, Department of Geology, University of Western Australia, helped with the identification of many of the planktic foraminiferids and in the assessment of the age of the parent samples.

CRUISE OBJECTIVES

This was 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 its tectonic, volcanic and sedimentary history.

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 onshore phosphate was poor.

CHRISTMAS ISLAND GEOLOGY

An excellent review of the natural history of Christmas Island is provided by Gray (1981). In it, he describes the sea cliffs 10 to 50 m high of uplifted coralline limestone, the shore terrace 50 to 200 m wide, and the central plateau, again bounded by limestone cliffs. The central plateau consists of shallow valleys, and low hills with ridges of coralline limestone. Most geological studies on the island have been related to assessment of its phosphate deposits. Andrews (1900) wrote a monograph 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 (1976) carried out a geophysical investigation using magnetic, electrical, gravity and refraction techniques. Adams and Belford (1974) reported on the foraminiferids 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; they 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) believed 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, foraminiferids 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, half going to Australia and supplying about a quarter of its needs. Production is now much less, and confined to existing stockpiles. 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. 4), and virtually all of it occurs as phosphate rock between limestone pinnacles, 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

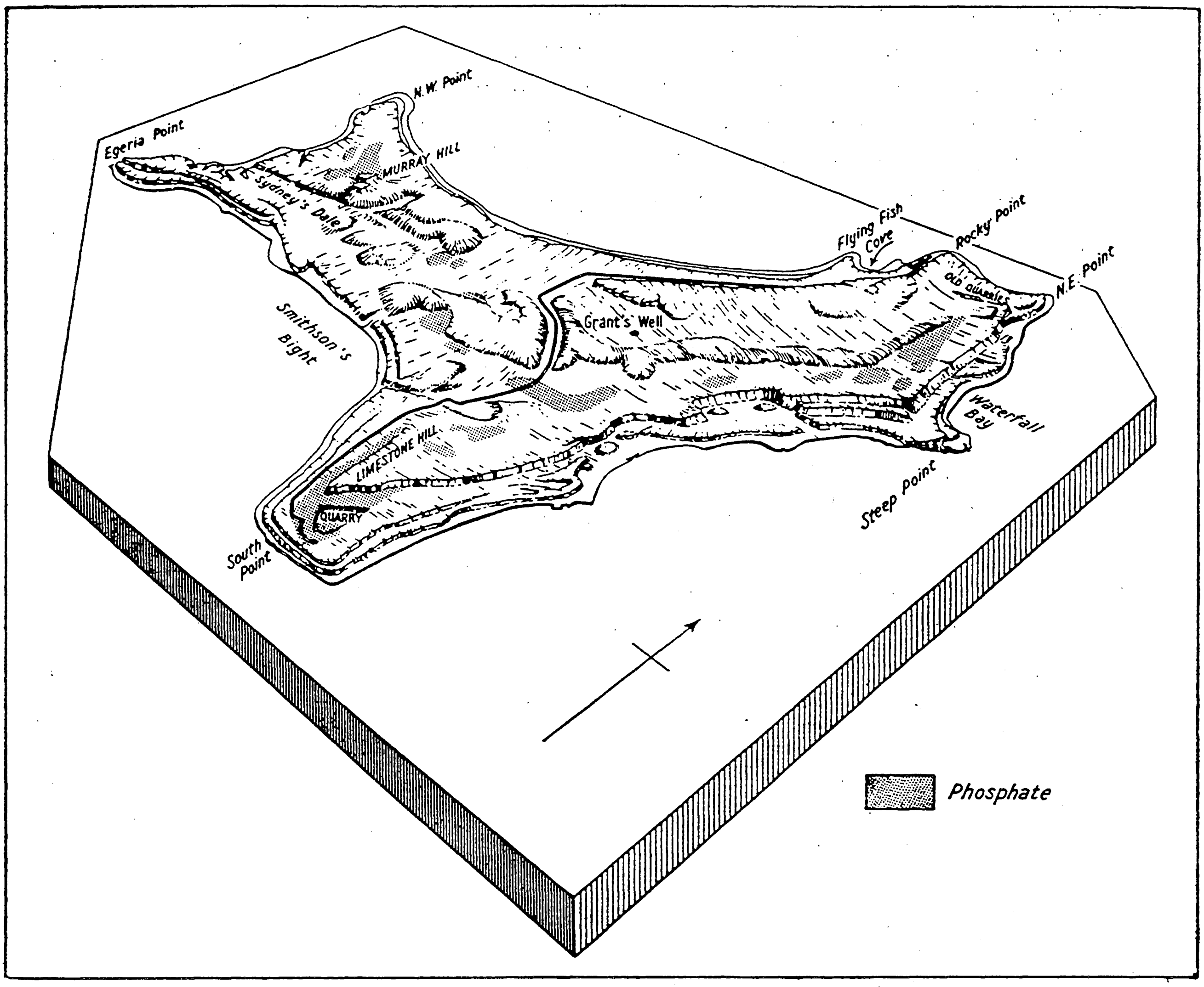


Figure 4. Physiographic sketch of Christmas Island. After White & Warin (1964).

superficial layer of brown, mottled and white, soft, earthy and granular phosphate which mantles the plateau and terrace surfaces.

Barrie (1967) envisaged 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 sea floor 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 formed.

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).

Figure 1 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-north east (e.g. Horizon Ridge), or north east (e.g. Christmas 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 south west of Christmas Island from 2700 to 2800 m.

The highly exaggerated seismic profile shown in Figure 5 (from Veevers, 1974; location in Fig. 4) gives a general impression of the bathymetry in the

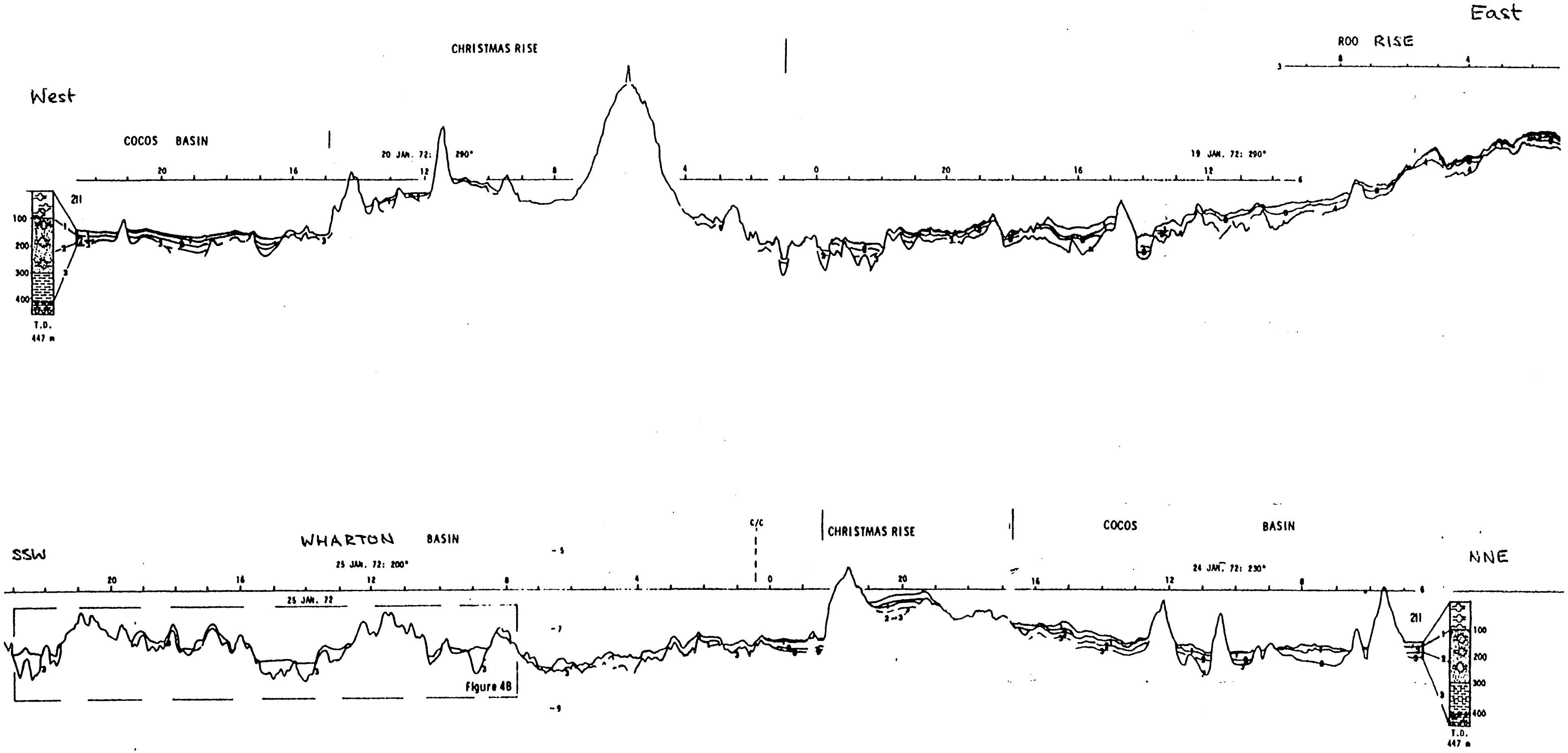


Figure 5. Line drawings of DSDP seismic profiles near Christmas Island. Locations in Figure 1. After Veevers (1974).

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.

OCEANOGRAPHY

The best regional oceanographic data were gathered by the International Indian Ocean Expedition in the 1960s (Wyrtki, 1971), and the GEOSECS Indian Ocean Expedition in the 1970s (Weiss et al., 1983; Spencer et al., 1982). Wytrki (1971) in his Sections 16 and 17, shows north-south oceanographic profiles recorded in February and July 1963, from 9° S, 110° E to 30° S, 110° E, that is a little east of Christmas Island. They go to a depth of 5000 m, and illustrate potential density, potential temperature, salinity, and contents of oxygen, phosphate and nitrate. At the latitude of Christmas Island, in February, the temperature data show a strong thermocline between 200 and 400 m, an oxygen minimum zone (less than 2 micromoles/kg) between 400 and 1000 m, and a phosphate maximum zone (more than 2.4 micromoles/kg) between 700 and 2000 m. The July profiles are different only in detail below the surface zone.

The relevant GEOSECS data were recorded along a north westerly profile from Perth to the Bay of Bengal, west of Christmas Island. Station and cast descriptions are given by Weiss et al. (1983), and sections and profiles by Spencer et al. (1982). As well as the data presented in Wyrtki (1971), silicate, alkalinity, and total CO_2 are included. At similar latitudes the results are similar. The alkalinity data for 9° 21' S, 95° 02' E show jumps in delta CO_2 at certain depths that should be related to lysoclines and compensation depths: aragonite positive to negative at 600 m (aragonite lysocline?), jump in negative at 3200 m; calcite positive to negative at 3400 m (calcite lysocline?), jump in negative at 5000 m (calcite compensation depth?).

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 (Udintsev 1975, 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 (Udintsev 1975, 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. 1,7), 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. 5). 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 (which might possibly extend down into the Miocene, depending on what palaeontological evidence one believes), reflector 2 is a surface within the turbidite sequence (at about 225m), and reflector 3 (seismic basement) is an andesine diabase sill, 10 meters thick (top at 401.5 m), 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 to middle 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.

The marine gravity data from the area have been summarised by Udintsev (1975). An averaged Bouguer gravity anomaly map (Udintsev 1975, 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 south west. 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 north west-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 (McDougall, 1974) 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 (Fig. 6). Dredging of seamounts and ridges has been carried out by R.V. *Vityaz* (Bezrukov and Andrushchenko, 1974; Skornyakova et al., 1980), R.V. *Argo* (Appendix 6), and R.V. *Franklin* (Falloon et al., 1989). The *Franklin* locations are given in Table 2 and the *Vityaz* locations in Table 4. 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., 1989). In addition, shallow marine limestone has been recovered in a number of dredges. For example, *Vityaz* recovered pelagic and shallow-water limestones of Oligocene and Eocene age from Shcherbakov Seamount south west of Christmas Island, at a depth of 1445 m (Bezrukov, 1973). Manganese crust was present in many dredge hauls.

TABLE 2. SUCCESSFUL DREDGES OF R.V. *FRANKLIN* CRUISE FR9/87

Dredge location	Latitude (S)	Longitude (E)	Water depth(m)	Sample Recovery
3 SW slopes of Christmas Island offshore from Egeria Point	S 10° 28.57' F 10° 29.00'	105° 29.99' 105° 31.30'	1900-1700	Small pieces of basalt and limestone
4 as for dredge 3 above	S 10° 28 .57' F 10° 29.00'	105 29.99' 105 31.30'	1900-1700	Full bag of limestone and basalt
7 Scherbakov Seamount	S 10° 49.10' F 10° 50.29'	104° 44.46' 104° 46.21'	2200-2000	Full bag of reefal limestone with some basalt fragments
8 Vening Meinesz Seamount "1341m"	S 11° 20.75' F 11° 18.96'	104° 47.96' 104° 47.91'	2100-2000	Small fragments of mudstone and manganese crust
9 Vening Meinesz Seamount "1341m"	S 11° 17.92' F 11° 17.54'	104° 45.29' 104° 48.03'	2500-2400	Small fragment of altered manganese crusted basalt
11 Vening Meinesz Seamount "1344m"	S 11° 44.09' F 11° 44.44'	103° 16.51' 103° 17.04'	2000-1500	Two small rock fragments
14 Vening Meinesz Seamount "1763m"	S 11° 37.60' F 11° 38.12'	103° 38.40' 103° 41.63'	2000-1500	Two small rock fragments
15 Vening Meinesz Seamount "1763m"	S 11° 37.78' F 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.)

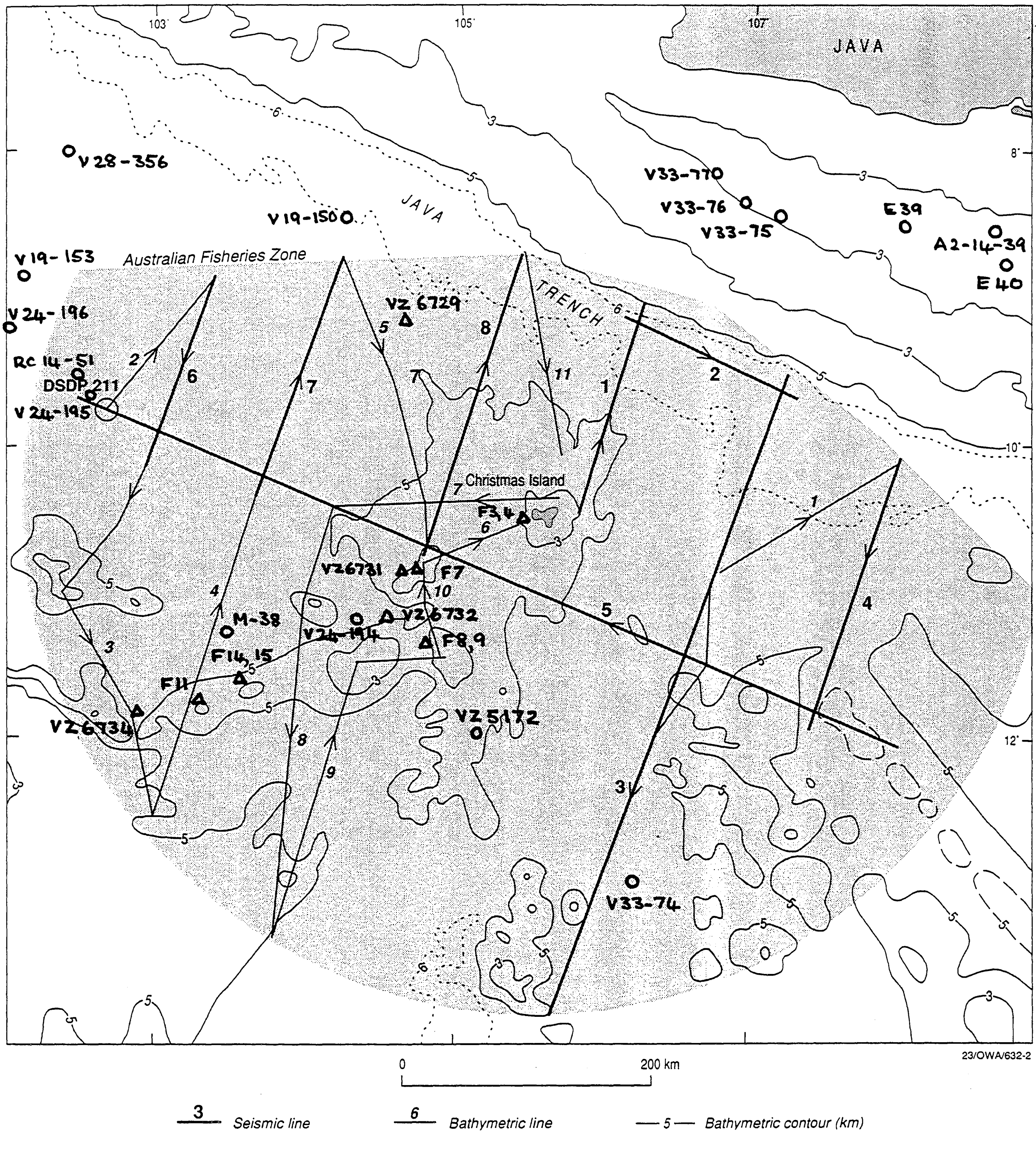


Figure 6. Map showing location of previous sampling in Christmas Island region. A2 = "Atlantis 2", F = "Franklin", RC = "Robert Conrad", V = "Vema", VZ = "Vityaz", E = "Thomas Washington" EURYDICE program. Triangles represent dredge hauls and circles represent cores.

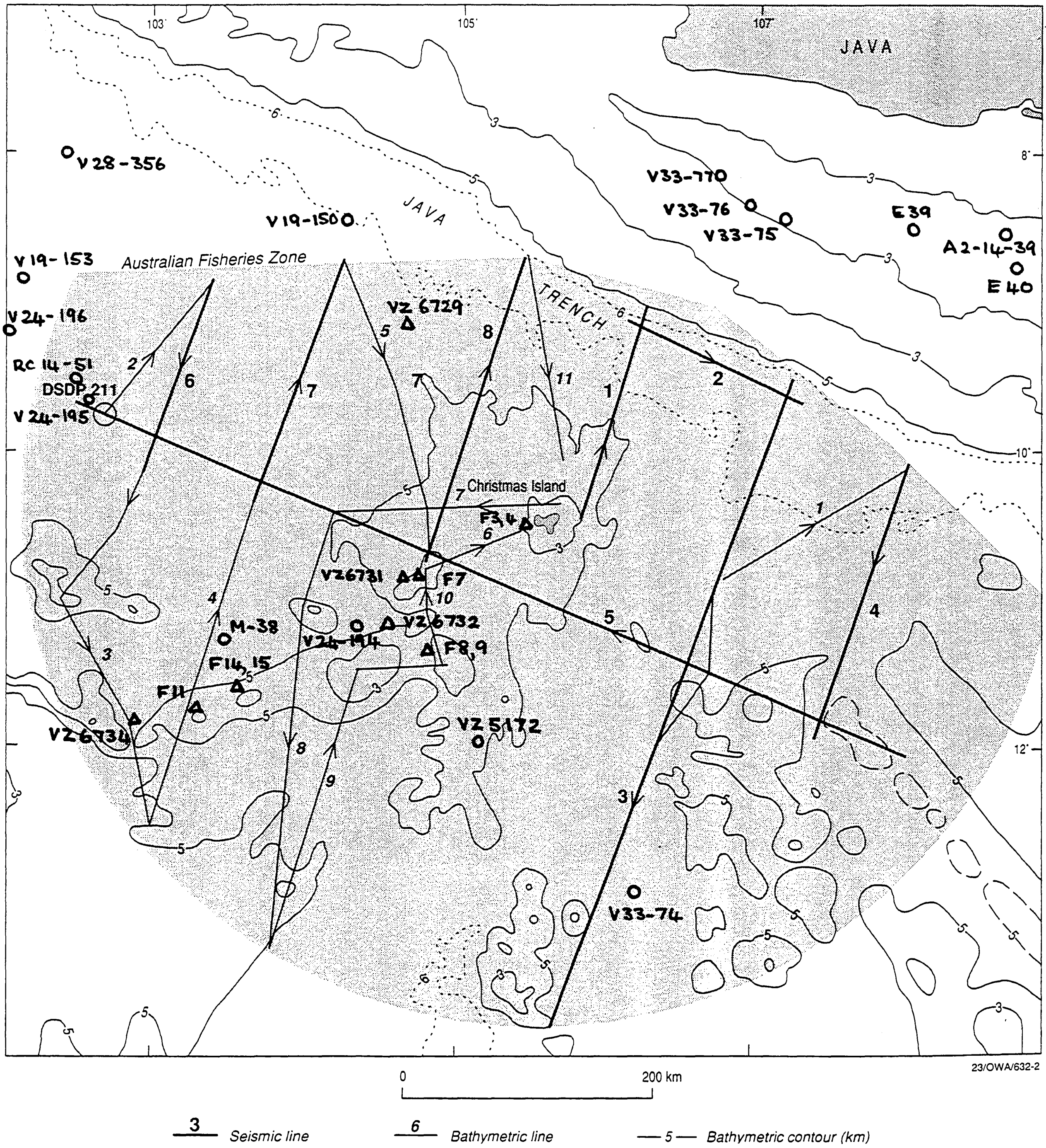


Figure 6. Map showing location of previous sampling in Christmas Island region. A2 = "Atlantis 2", F = "Franklin", RC = "Robert Conrad", V = "Vema", VZ = "Vityaz", E = "Thomas Washington" EURYDICE program. Triangles represent dredge hauls and circles represent cores.

Sediment cores taken by *Argo*, *Atlantis II*, *Vityaz*, *Vema*, *Thomas Washington* and *Robert Conrad* are listed in Tables 3 and 4, and Appendix 6, and are plotted in Figure 6. Shipboard descriptions by Lamont-Doherty Geological Observatory (Table 3) indicate that above the 5000 m isobath the surface sediments are foraminiferal ooze and marl, but that in deeper water these give way to radiolarian (siliceous) clay. Volcanic glass shards form a number of sandy layers and were 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 deep sea 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. 7) indicates that 428.6 m of pelagic sediment, the oldest being Campanian, probably late Campanian, overlies amphibole-bearing basalt intruded by amphibolite. Two samples of coarse-grained dolerite from a sill about 12 m thick (ca. 400-411.5 m), above sediments dated by nannofossils as late Campanian to early Maastrichtian, were dated by McDougall (1974) using the Ar^{40}/Ar^{39} technique as 71±2 m.y. (Campanian-Maastrichtian boundary).

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 fragments make up less than 10% of the siliceous oozes. The volcanic ash is mostly (50%-90%) made up of fresh clear

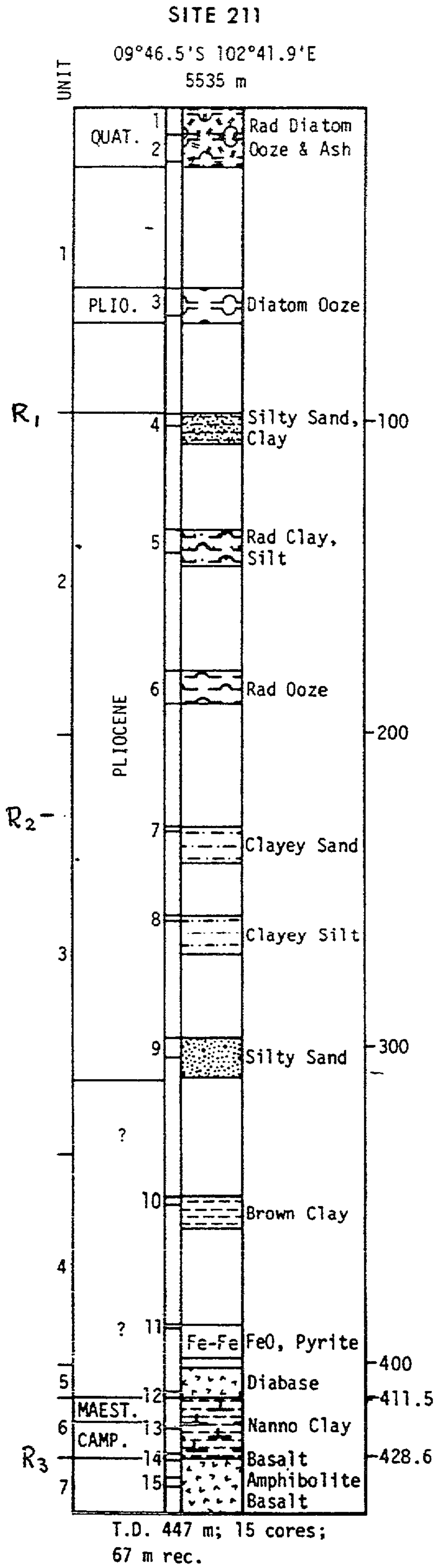


Figure 7. Lithologic units at DSDP Site 211, 250 km west of Christmas Island. Location in Figure 1. After von der Borch, Sclater et al. (1974).

TABLE 3. CORES TAKEN BY LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

Number	Latitude Longitude	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 greyish 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, planktic foraminiferids 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 greyish-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 planktic and benthic foraminiferids, Radiolaria, volcanic glass shards, diatoms, fish teeth, dark minerals, sponge spicules, echinoid spines, fragments of indurated clay, palagonite, basic and acidic rock fragments, Mn micronodules, quartz, ostracods, magnetite, 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 Mn nodule (analysed).

TABLE 3. CORES TAKEN BY LAMONT-DOHERTY GEOLOGICAL OBSERVATORY (CONTINUED)

Number	Latitude Longitude	Depth (m) Recovery (cm)	Description
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, Mn-cemented clay aggregates, Mn micronodules and glass shards. Mn nodules are abundant at 258-275 cm and 388 cm (analysed).

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° S (Site 215) to the eastern Argo Abyssal Plain at 13° 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/m.y., considerably more than the rates calculated by Udintsev (1975) for Holocene sediments, of about 5 m/m.y.

MANGANESE NODULES AND CRUSTS

Possible long-term resources in the Christmas Island offshore area could be 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 south west 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/m.y. 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 made 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 (Lenoble, 1992a & b). 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, south east 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.

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 zone. A fascinating display of co-operation led to agreed boundaries separating the claims of all the groups, and there are now eight nodule mining lease areas in the Clarion-Clipperton zone (Lenoble, 1992b) and one in the Indian Ocean.

In considering all the above information, and especially the potential value 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 recognised 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 South west Pacific under the auspices of the South Pacific Applied Geoscience Commission (SOPAC) and other research organisations. 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° N and 40° S.

A detailed study of the crusts in the Marshall Islands EEZ in the Pacific from 6° N to 14° 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) found that several seamounts in the Marshall Islands EEZ have crusts of over 100 mm thick and average thicknesses 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 km^2 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-south east 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 4800-5500 m, below the local CCD. The paper by Sudhakar (1989) summarises 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 characterised by high Mn/Fe ratios (mean 3.77), high percent Ni+Cu content (mean 2.41%) and high abundance (mean 7.48 kg/m^2). Area R is a zone of red clay where the nodules are characterised by low Mn/Fe ratios (mean 2.24), low percent Ni+Cu contents (mean 1.61%), and low abundance (mean 4.68 kg/m^2). The mean Cu and Ni values are 1.19% and 1.22%, respectively, in Area S nodules, whereas Area R nodules show relatively lower concentrations of Cu (mean 0.68%) and Ni (0.92%), 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%, at 1.8% Ni+Cu cutoff, and > 5 kg/m^2 abundance are recovered. Early diagenetic processes are predominant in the zone of siliceous sediment between 10° S to 15° S, whereas red clay nodules are more hydrogenous than diagenetic in nature. The sedimentary boundary between siliceous and red clays exists around 15° S, which may be the boundary delimiting ore grade nodules to the north of 15° S. It is evident from the Pioneer Area allocated to India by the United Nations that more than 95% of it (150,000 km^2) encompasses the region between the latitudes 10° to 15° S."

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 and 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).

Martin-Barajas et al. (1991) studied box cores gathered on two cruises of the *Marion Dufresne,* with the aim of relating sedimentary history, nodule accretionary processes, and the late diagenetic enrichment that forms nodules rich in nickel and copper. The diagenetic nodules, associated with young siliceous ooze that is more than 17 m thick in places, are smaller (2-5 cm diameter) and less abundant than the hydrogenetic nodules associated with the unconformably underlying red clay of probable Miocene age. Nodule nuclei are predominantly from the Indonesian volcanic arc, and such volcanic fragments first appeared in the local sediment in the late Miocene according to Ninkovitch and Donn (1977). The central deep was the focus of red clay deposition at that time, and hydrogenetic nodules started to form. The oldest siliceous sediments are early Pliocene, using Radiolaria for dating, and high grade nodules started to form in the late Pliocene. Most diagenetic nodules in the deep basins are even younger, being present beneath the sediment/water interface in the upper 40 cm of sediments that are less than 400,000 years old. If the nodules have been moved upward with the sediment, unlikely for buried nodules, they could have started to form 3 million years ago, and average growth rates would be about 10 mm/Ma. If they have formed *in situ*, then growth rates would be ten times as great at about 100 mm/Ma. This compares with rates for the associated hydrogenetic nodules of about 5 mm/Ma, and for average Pacific Ocean Clarion-Clipperton Zone nodules of 1-3 mm/Ma.

As regards metal tonnages, 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.

TABLE 4. PREVIOUS STATIONS WITH MANGANESE NODULES AND CRUSTS

Number	Latitude (° S)	Longitude (° E)	Depth (m)	Equipment (Recovery in cm)	Surface lithology	Coverage
Vityaz 6729-1	9.133	104.667	5530	Bottom scoop		
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

Christmas Island offshore area

Direct information published on manganese nodules and crusts for the area around Christmas Island is very limited. Key papers include Bezrukov and Andruschenko (1974), Udintsev (1975), Noakes and Jones (1976), Skornyakova et al. (1980), Skornyakova (1984), Frazer and Wilson (1980) and Cronan and Moorby (1981). Table 4 lists the stations at which manganese nodules and crusts were found. Table 5 shows all external 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 and Jones (1976) and Jones (1980) listed analyses for 5 deepwater stations to the south (15-17° S, 104-106° 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%).

TABLE 5. PREVIOUS ANALYSES OF MANGANESE NODULES AND CRUSTS

Metal content by weight percentage

Number	Sample	Depth (m)	Mn	Fe	Cu	Ni	Co	Cu+Ni+Co
Vema 24-193	Nodule	4513	11.40	13.50	0.19	0.23	0.28	0.70
	Micronodule	4513	5.00	7.00	0.01	0.18	0.10	0.29*
Vityaz 5172	Nodule	4993	15.73	15.70	0.19	0.30	0.12	0.61
Vityaz 6729-1	Crust (1)	5330	18.50	10.15	0.23	0.55	0.08	0.86*
	Crust (2)	5330	15.24	11.76	0.26	0.58	0.09	0.93*
Vityaz 6731-5	Crust	3850	10.62	14.28	0.12	0.18	0.27	0.57*
Vityaz 6731-6	Nodule	4940	20.90	7.09	0.35	0.59	0.09	1.03
Vityaz 6732-1	Nodule (no nucleus)	1585	19.09	13.09	0.06	0.33	0.37	0.76
	Nodule nucleus	1585	10.94	7.49	0.04	0.18	0.26	0.48*
Vema 24-194	Buried nodule (1)	5256	6.70	7.90	0.07	0.06	0.04	0.17*
	Buried nodule (2)	5256	2.20	3.40	0.08	0.06	0.02	0.16*
	Buried nodule (3)	5256	1.50	7.10	0.03	0.06	0.02	0.11*
Vityaz 6734	Crust	5078	15.75	12.77	0.27	0.51	0.11	0.89*
	Nodule	5078	21.79	10.09	0.85	0.92	0.10	1.87
RC 14-49	Nodule (1)	5273	20.40	14.20	0.48	0. 69	0.12	1.29
	Nodule (2)	5273	19.80	11.80	0.51	0.71	0.12	1.44
	Nodule (3)	5273	17.30	13.10	0.32	0.41	0.16	0.89

Average for surface nodules, excluding * samples	18.30	14.72	0.17	0.52	0.37	1.07
Average for surface nodules in depth range 5078-5273 m	19.82	9.80	0.13	0.68	0.54	1.35
Wharton Basin average (39 stations)**	17.5	11.9	0.18	0.55	0.41	1.14
Wharton Basin siliceous ooze (10 stations)**	20.3	11.4	0.17	0.70	0.56	1.43
Indian Ocean average (324 stations)**	15.4	14.8	0.23	0.46	0.27	0.96

** After Cronan and Moorby (1981)

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 5). Frazer and Wilson (1980) pointed out that the generalised 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 5000-5500 m), 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 sea floor 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 distant future".

However, Frazer and Wilson (1980) did 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 was to occupy many more bottom stations to better map sediment and nodule distribution.

Cronan and Moorby (1981) listed 39 analyses from the Wharton Basin (Table 5) 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 5). 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 5 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.

GEOPHYSICAL PROFILING

Survey 107 was quite successful in carrying out its geophysical program, and the data gathered, together with existing data from the US National Geophysical Data Centre (NGDC), will enable the Christmas Island offshore area to be mapped. The NGDC data come from parts of some 30 cruises involving US, Soviet, Japanese and French vessels. Our own data are yet to be fully processed, but amount to about 2100 km of six-channel seismic profiles, and 3500 km of bathymetry, gravity and magnetic data. The tracks on which the data were acquired are shown in Figure 2. Full reports on the seismic and mechanical systems are presented in Appendices 4 & 5.

ACQUISITION SYSTEMS

The various geophysical systems functioned well, with no more than a normal number of problems, and only the seismic system caused any down time at all. Given that we were experimenting with a new, relatively high-speed towing configuration the results were gratifying. More details of the geophysical systems are given in Appendix 4.

TABLE 7. REFLECTION SEISMIC PROFILES: BMR CRUISE 107

Line	Start	End	Heading	Length (km)
1	10° 26.42' S	9° 02.51' S	16°	70.7
	105° 49.56' E	106° 14.28' E		
2	9° 11.54' S	9° 40.55' S	116°	103.0
	106° 10.00' E	107° 11.43' E		
3	9° 29.64' S	13° 52.43' S	200°	519.7
	107° 14.90' E	105° 34 .87' E		
4	10° 09.25' S	11° 57.61' S	200°	214.0
	108° 00.32' E	107° 19.76' E		
5	12° 06.56' S	9° 45.09' S	294°	628.7
	107° 56.24' E	102° 38.77' E		
6	8° 50.24' S	10° 09.37' S	200°	149.6
	103° 28.64' E	102° 59.49' E		
7	10° 16.99'S	8° 45.77' S	20°	176.7
	103° 47.03' E	104° 20.66' E		
8	10° 52.32' S	8° 44.77' S	20°	233.4
	104° 47.16' E	105° 31.99' E		
			Total	2095.8

Seismic acquisition system

The seismic system consisted of two 150 cubic inch HGS airguns and a 600 m long 24 channel GECO analogue seismic streamer. The airguns were towed about a metre below the surface so that they blew out at the surface, in order to remove the bubble pulse and improve the gun signature. The cable and guns were towed at speeds ranging from 6.5 to 9 knots, depending on weather conditions and the depth of sediment seen above basaltic basement. the aim was to record the data as quickly as possible commensurate with acceptable data quality, and that was continuously monitored. Preliminary seismic processing of part of a line indicates that the data quality is quite acceptable. The main problem with equipment was with the newly constructed tail buoy, which sprang a leak and had to be repaired. Altogether seismic data were acquired for a total of 8 days, with 10% down time. The eight profiles acquired are summarised in Table 7.

Non-seismic acquisition system

The magnetometer was deployed on all long profiles, but was dispensed with on some short transits during the sampling program. The first head deployed gave some problems and was eventually replaced. Thereafter the equipment worked very well indeed. The gravity meter worked flawlessly throughout, but unfortunately it was impossible to make gravity ties to Christmas Island. The performance of the 12 KHz and 3.5 KHz echo sounders was tolerably good, probably because the sea was remarkably calm. The 3.5 KHz instrument gave good seabed penetration in some areas.

Navigation system

The prime navigation system was differential GPS (provided by Racal), with the key base stations in Broome and Singapore. Despite the extreme distance to the stations, differential GPS coverage was maintained for 95% of the cruise, and non-differential coverage for almost all the remaining 5%. Consequently, navigational accuracy was excellent, seldom being worse than 30 m.

SEISMIC PROFILE DESCRIPTIONS

(N.F. Exon and T.L. Graham)

The eight seismic profiles acquired on this cruise are listed in Table 7 and located by Figure 2. They were designed to allow fairly detailed mapping of the Australian Fisheries Zone, in conjunction with profiles recorded by other institutions, and in addition to provide two regional lines, one north-south and the other east-west. In this report we will not attempt to do any more than to describe the profiles and to draw some general conclusions. In general, three sequences can be identified on the highly exaggerated seismic profiles, and these correspond with those identified by Veevers (1974) and tied to DSDP Site 211. The sequences are summarised in Table 8.

Total sediment thickness is about 0-200 m on the Christmas Island Rise and 250-400 m on the abyssal plain. Older basement (R4) appears in the east according to Veevers (1974). This may well be somewhat younger (Albian?) than the Aptian sea floor identified on the basis of sea floor magnetic lineations further east again (Scheibner et al., 1991).

TABLE 8. SEISMIC SEQUENCES IN CHRISTMAS ISLAND REGION

R0-R1	Transparent Quaternary to Miocene siliceous ooze and ash, 95 m thick in DSDP Site 211 (110 milliseconds). Elsewhere in region 50-200 m thick (60-220 ms).
R1-R2	Well-bedded Neogene turbidites and siliceous ooze, 130 m thick in DSDP 211 (130 ms). Elsewhere 50-250 m thick (50-250 ms). (This sequence is stippled in all line drawings)
R2-R3	Variably bedded Palaeogene to Campanian turbidites, siliceous ooze and brown clay on oceanic basalt, 200 m thick in DSDP 211 (200 ms). Elsewhere 100-200 m thick (100-200 ms)

East-west Profile 107/5

This profile is 630 km long and extends right across the Australian Fisheries Zone (AFZ) about 60 km south of Christmas Island, in a WNW direction (Fig. 2). A line drawing from the monitor section (Plate 1) shows that the profile can be separated into three roughly subequal parts. The central part is the Christmas Island Rise, with only a thin sedimentary sequence (ca. 200 m thick) above fairly rough volcanic basement that lies about 5 km below sea level. The three seismic sequences of Table 8 all appear to be present. The massive Shcherbakov Seamount rises 3 km above the rise. To the east of the rise, volcanic basement lies considerably deeper, beneath the abyssal plain at about 5.5 km below sea level. The sedimentary cover is somewhat thicker than on the rise (200-300 m) and again all three sedimentary sequences are present. Two massive seamounts rise above the plain, the larger more than 4.5 km high. The western part has volcanic basement at nearly 6 km below sea level, and sedimentary cover of 200-400 m that generally includes the three sequences. Several basement highs penetrate the sediment and, west of the westernmost high near DSDP Site 211, the middle, well-bedded sequence (R1-R2) is not identifiable, perhaps because massive turbidites have not reached this depocentre and the pelagic sediments are homogeneous.

The gravity profile (Plate 1) is quite unexceptional, simply showing the seamounts as highs. The magnetic profile shows most of the seamounts as highs, suggesting that they are normally polarised, but Shcherbakov Seamount as a low, suggesting that it is reversely polarised and hence of a different age. The general impression given is that there may be identifiable magnetic anomalies east of the rise, but not west of it. This would support the interpretation that anomalies are normal to the track in the east but parallel in the west, because of the different ages of spreading. There is little difference in elevation in the east and west, despite the difference in assumed crustal ages of about 25 m.y.

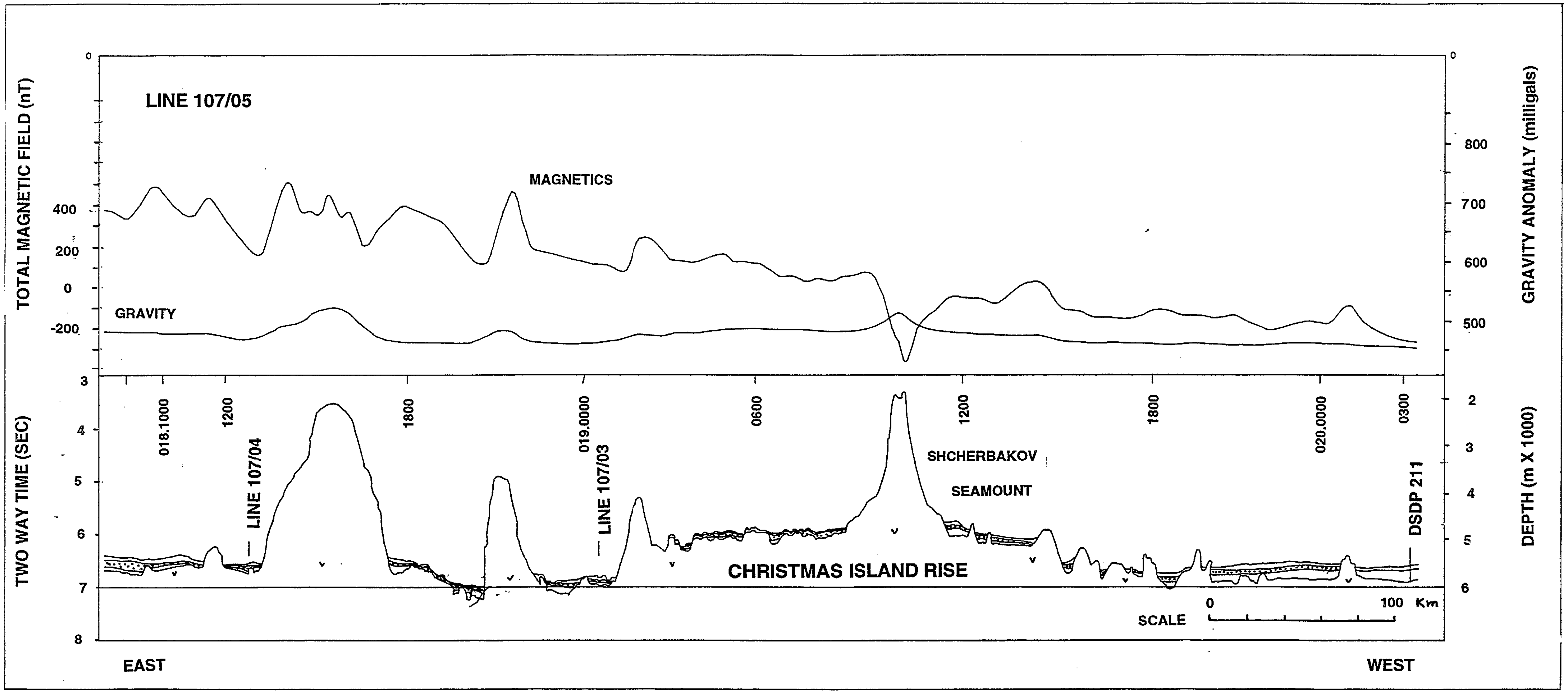


Plate 1. Line drawing of regional east-west seismic profile 107/5. Location in Figure 2. On seismic profile upper sequence is R0-R1, middle stippled sequence is R1-R2, and lower sequence is R2-R3. V = volcanic basement.

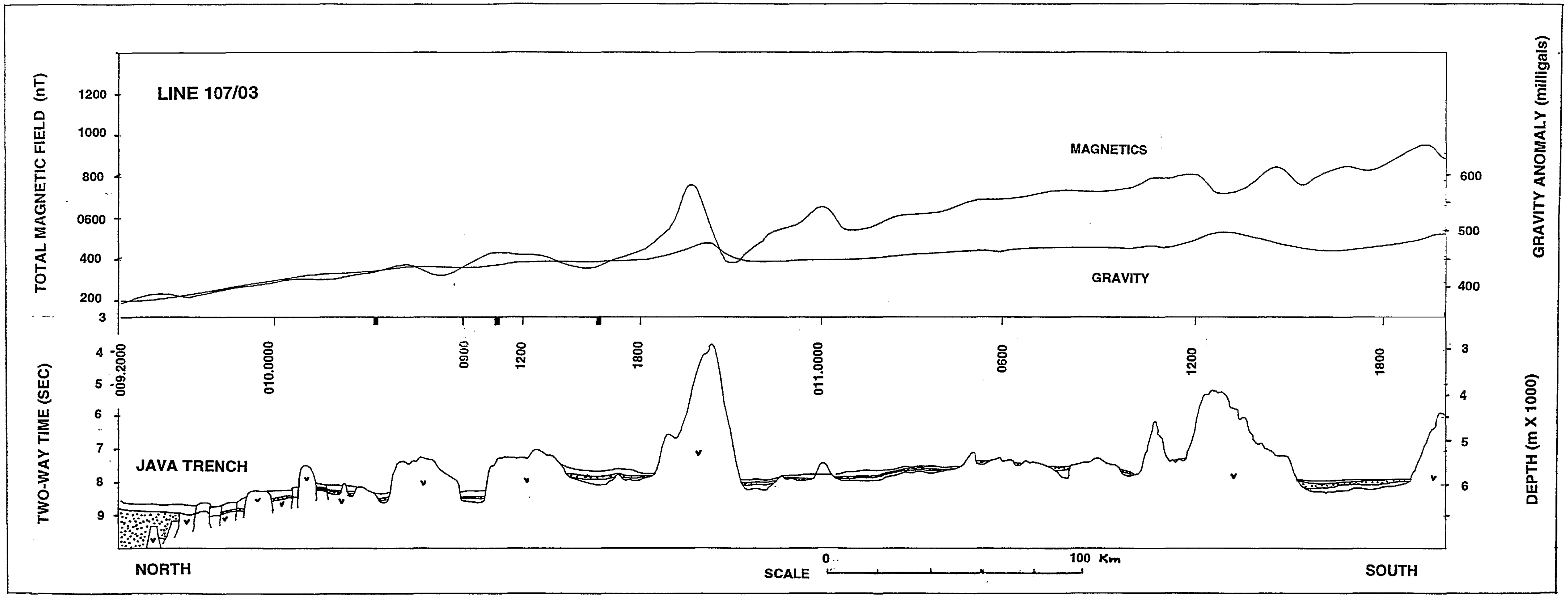


Plate 2. Line drawing of regional north-south seismic profile 107/3. Location in Figure 2. On seismic profile upper sequence is R0-R1, middle stippled sequence is R1-R2, and lower sequence is R2-R3. V = volcanic basement.

North-south Profile 107/3

This profile is 520 km long, extends NNE across the AFZ about 120 km east of Christmas Island, and crosses the axis of the Java Trench. It is located on Figure 2 and shown as a line drawing in Plate 2. The line drawing shows that the rough volcanic basement generally falls northward, from about 5.5 km below sea level in the south to about 6.3 km just south of the flank of the Java Trench. Beneath the trench it lies at least 8 km deep and beneath more than 1 km of sediment. Sedimentary cover averages about 200 m, although volcanic highs are free of sediment, and the usual three sequences are generally present. There are a number of seamounts along the profile, the largest rising 3 km above the sea bed south east of Christmas Island. The basement drops away into the Java Trench by general bowing, and this bowing is aided by a number of normal faults. Fault blocks can be seen beneath the highly stratified sediments in the trench, which are largely turbidites from the Indonesian volcanic arc.

The gravity profile (Plate 2) falls steadily toward the trench, and seamounts show as highs on it. Magnetic values also decline northward, with seamounts creating dipoles with the 'high' offset to the north. It is possible that the anomalies at the southern end of the line might be related to sea floor magnetic lineations, although the profile is believed to be parallel to the lineations.

Short north-south profiles

There are five short north-south profiles across the northern area (Fig. 2) and they show changes from east to west (Figs. 8-13). Profiles 6 and 7 are on the western abyssal plain that is not disturbed by major seamounts, although the basement surface is rather irregular (Figs. 8 and 9). Neither profile extends to the Java Trench, so there are no major changes in elevation. Volcanic basement (oceanic crust) lies 6 km below sea level on Profile 6 and a few hundred metres shallower on Profile 7. Volcanic ridges are buried on Profile 6 but do rise above the sediment cover on Profile 7; on both profiles all three sedimentary sequences are present. On both profiles the lowest sequence fills the topographic lows, but it is much thicker (about 300 m) on the western one. The middle, well-bedded, turbidite-rich sequence dominates the sedimentary succession, averaging 400 m thick on the western profile and 200 m on the eastern one. The uppermost transparent ooze sequence is less than 100 m thick. The total sediment thickness averages 400 m on the western profile and 200 m on the eastern one, the difference being caused by much thicker turbidite deposition in sequence R1-R2 in the western part of the abyssal plain, that was deeper at the time. With the sediment fill the elevation of the plain is now the same on both profiles. A gravity profile (Fig. 8) shows a decline in values northward. The corresponding magnetic profile also shows declining values northward and

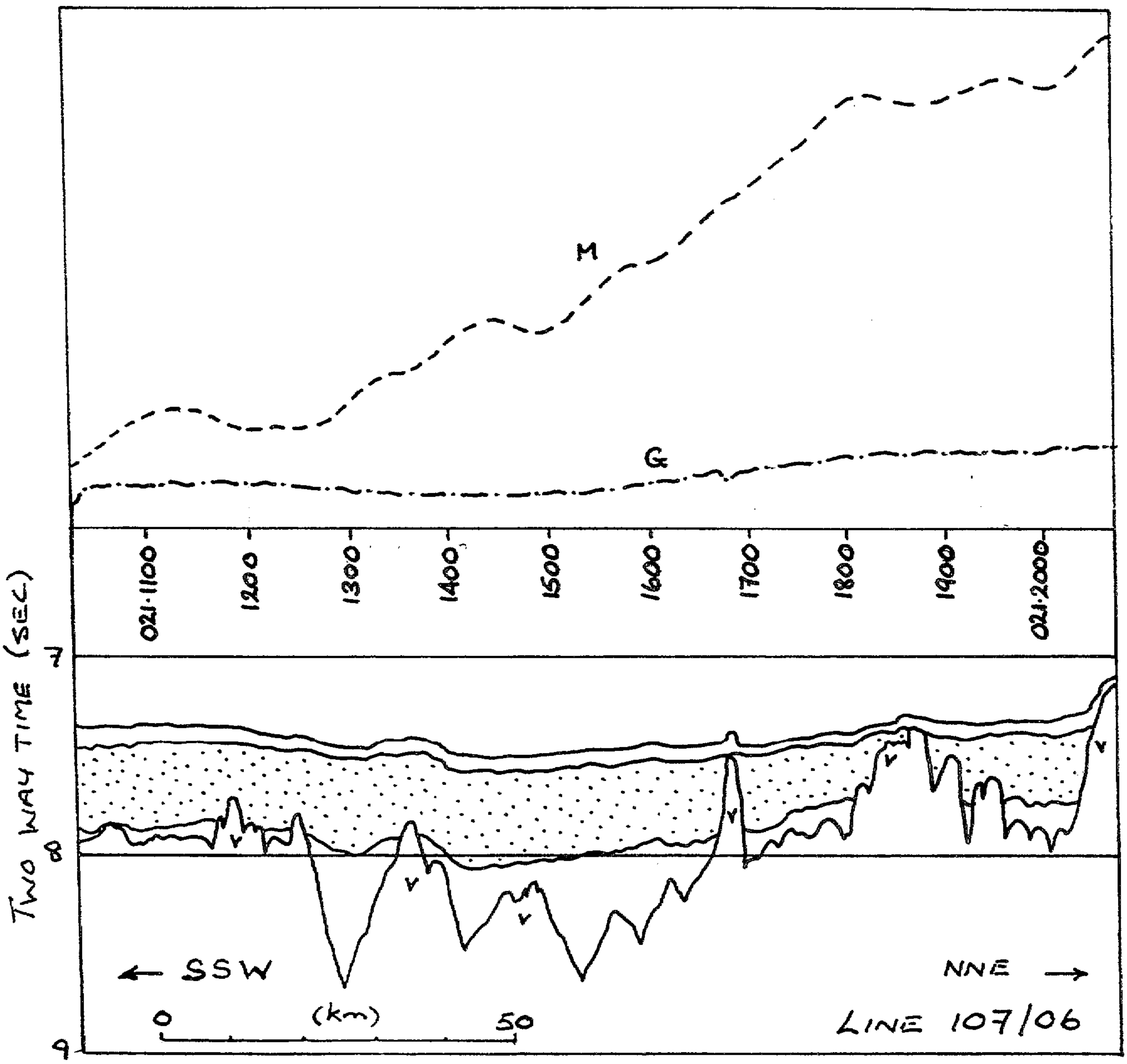
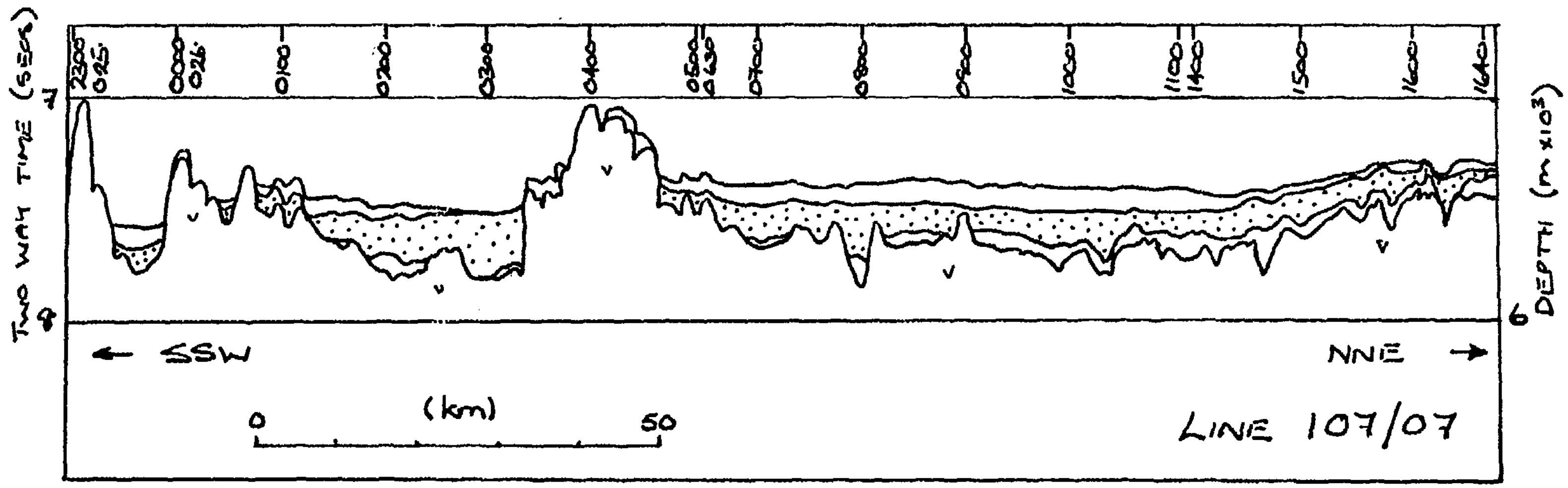


Figure 8. Line drawing of seismic profile 107/6. Location in Figure 2. On seismic profile upper sequence is R0-R1, middle stippled sequence is R1-R2, and lower sequence is R2-R3. V = volcanic basement. M = total magnetic intensity and G = gravity anomaly.

Figure 9. Line drawing of seismic profile 107/7. Location in Figure 2. On seismic profile upper sequence is R0-R1, middle stippled sequence is R1-R2, and lower sequence is R2-R3. V = volcanic basement.



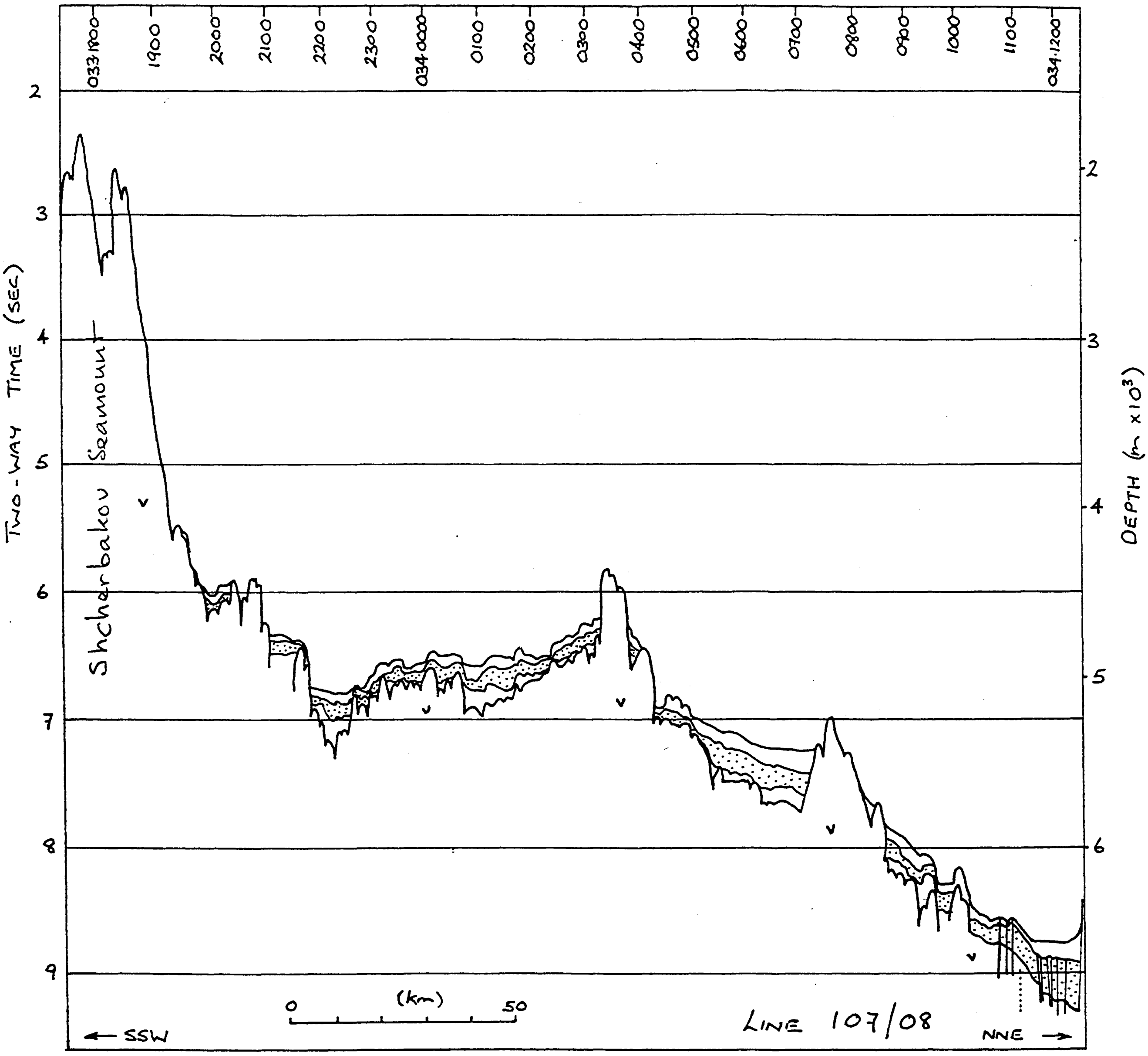


Figure 10. Line drawing of seismic profile 107/8. Location in Figure 2. On seismic profile upper sequence is R0-R1, middle stippled sequence is R1-R2, and lower sequence is R2-R3. V = volcanic basement.

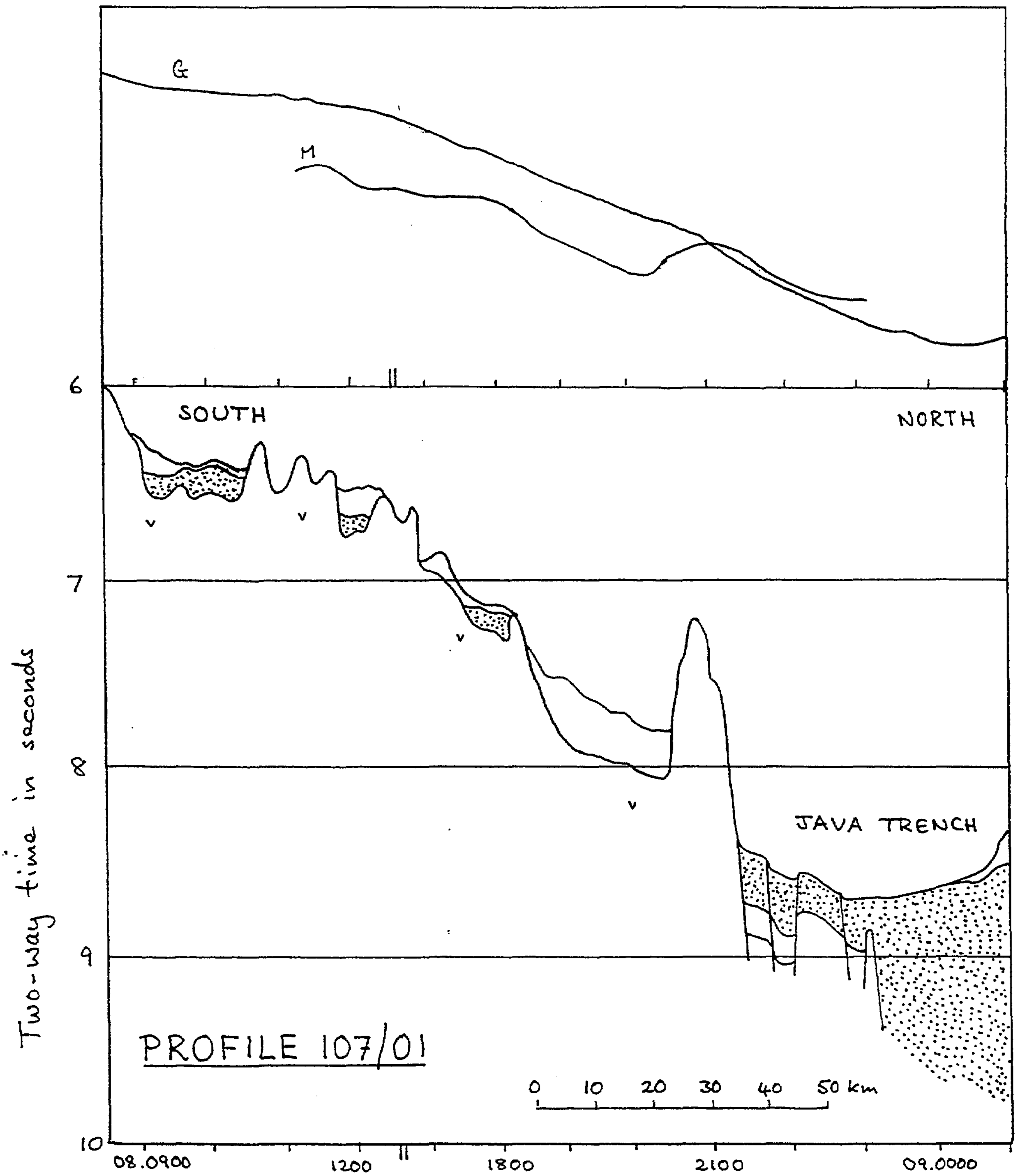
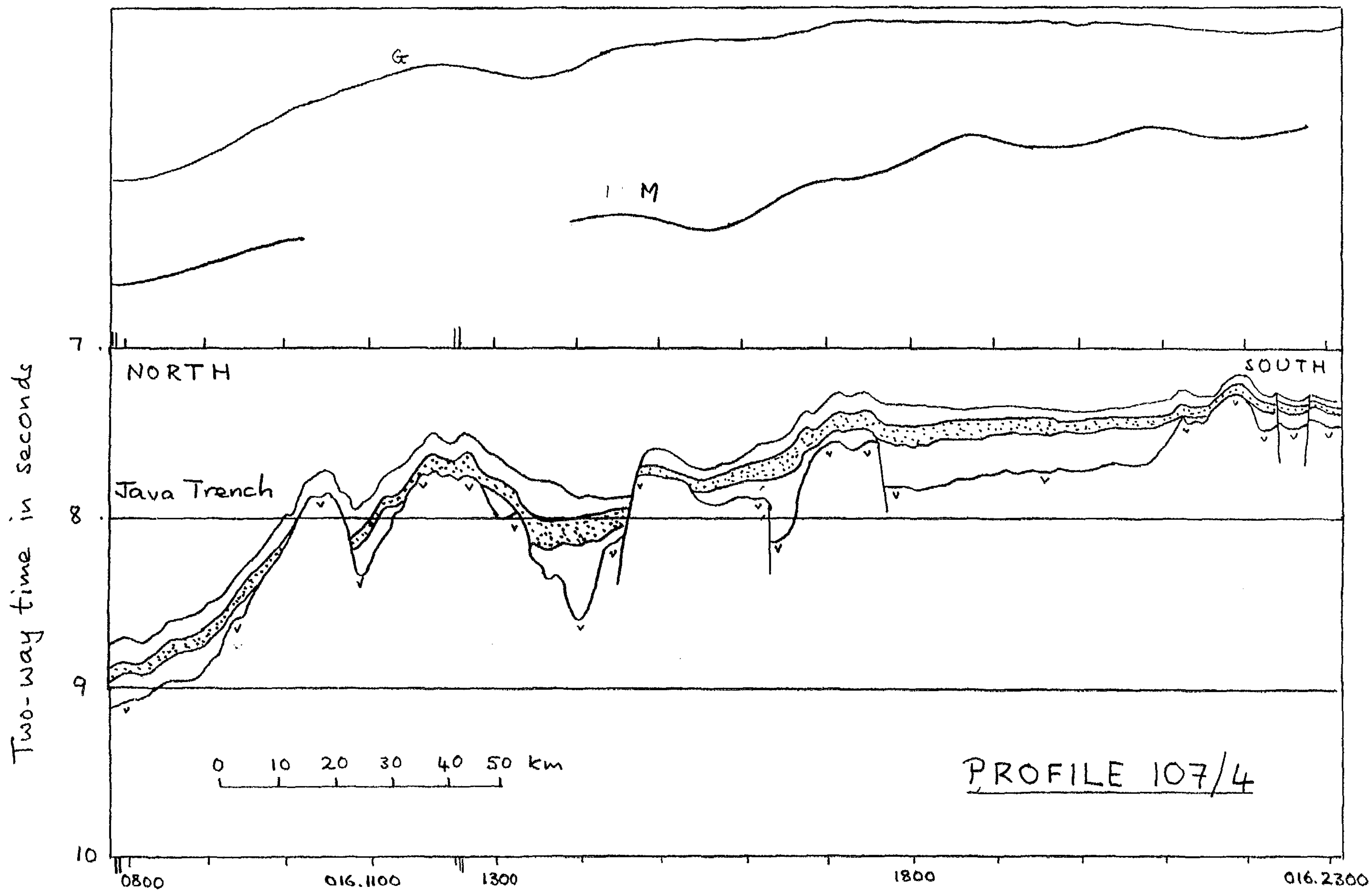


Figure 11. Line drawing of seismic profile 107/1. Location in Figure 2. On seismic profile upper sequence is R0-R1, middle stippled sequence is R1-R2, and lower sequence is R2-R3. V = volcanic basement. M = total magnetic intensity and G = gravity anomaly.

Figure 12. Line drawing of seismic profile 107/4. Location in Figure 2. On seismic profile upper sequence is R0-R1, middle stippled sequence is R1-R2, and lower sequence is R2-R3. V = volcanic basement. M = total magnetic intensity and G = gravity anomaly.



shows that basement highs generally correspond to dipoles with the 'high' offset to the north.

Profiles 8 and 1, which come down off the Christmas Island Rise into the Java Trench, are quite similar to each other (Figs. 10 and 11). The basement surface is irregular and highs are generally sediment-free. Except in the trench, the sedimentary cover is less than 200 m thick. The three sedimentary sequences are recognisable on Profile 8, although well-bedded turbidites rest directly on basement on the flank of the trench. Profile 1 does not show a typical R2-R3 sequence at all; well-bedded sediments sit directly on basement on the Christmas Island Rise, but transparent sediments (no turbidites) form the entire sequence just above the trench. A gravity profile (Fig. 10) shows a steady decline of values northward down the slope, and basement highs correspond with magnetic dipoles with the 'high' offset to the north.

The easternmost profile, Profile 4, is in an area of abyssal plain with no major seamounts Figs. 2 and 12) and extends some distance down the slope of the Java Trench. Basement lies at 5.5 km at the southern end of the profile, and descends northward to 6 km just above the trench. It is broken into a number of blocks of relatively low relief and all the highs are sedimented. The total sequence averages 300 m thick, all three sequences are generally present, and the lowest sequence is generally thickest. Gravity values decline toward the trench and basement highs generate gravity highs. Basement highs generate magnetic dipoles with the 'highs' offset to the north.

Java Trench profiles

As described above, several north-south profiles enter the Java Trench (Figs. 2, 8-13; Plate 2). These profiles show bowing of oceanic crust down into the trench and associated normal faults. They also show that the sediment in the trench is largely well-bedded, suggesting that it consists largely of turbidites. Sediment thicknesses in the trench axis greatly exceed the depth of penetration possible from our seismic system, our monitors being limited to about 1.5 seconds of penetration (TWT). Profile 2 runs along the trench axis and shows wedges of sediment that are probably largely turbidites. It is not figured because areas of very poor data quality make interpretation of the monitor record an unprofitable exercise. Hopefully the stacked version will be considerably better.

Conclusions

The three sequences of Table 8 are present across most of the region. The area can be divided into three areas: the Christmas Island Rise that is about

150 km wide and extends across the area in a NNE direction, and eastern and western provinces. The rise has basement about 5 km below sea level and is overlain by a sedimentary sequence that is 0-200 m thick. It falls toward the Java Trench, with basement about 6 km deep just south of the trench's flank. The eastern province generally has basement at about 5.5 km, but it deepens to 6 km just south of the trench. Sedimentary cover is 200-300 m. The western province has basement at about 6 km and our profiles do not approach the trench. Sediment cover in the western province, of 200-400 m, is generally thicker than elsewhere. Seamounts are abundant in the south of the area, but no large seamounts are known north of Christmas Island. Volcanic crust is bowed down into the Java Trench and there are numerous associated normal faults. The trench is full of well-bedded lens-shaped sequences, assumed to consist largely of volcaniclastic turbidites.

Gravity values fall toward the trench and large seamounts cause local 'highs'. Magnetic values also fall toward the trench, and most dipoles caused by seamounts have magnetic 'highs' displaced to the north. However, at least one major seamount (Shcherbakov) appears to be reversely polarised on the evidence of an east-west profile.

GEOLOGICAL SAMPLING

During the cruise a great deal of bottom sampling was carried out for geological and resource assessment purposes, using dredges, corers, and Benthos free-fall grabs (Fig. 3). Despite the early loss of 4500 m of wire from the deep sea winch during dredging operations (which constrained future dredging to water less than 3500 m deep, and coring operations to depths of less than 4600 m), the sampling program was quite successful (Table 9).

TABLE 9. SUMMARY OF SAMPLING RESULTS: BMR CRUISE 107

Equipment	Water (m)	Stations	Success	Recovery
Dredge	1600-3700	12	9	Basalt, trachyte, volcaniclastics, hyaloclastics, shallow and deepwater carbonates, Mn crusts
Piston core	453-4564	10	7	10.7 m: ooze, marl, clay
Gravity	1993-3665	6	2	10.15 m: ooze, marl
Freefall grab	4574-5929	28 (84 *)	27 (82*)	Clay, volcanic pebbles, Mn nodules (8 stations)

* deployments

The performance of the **deep-sea winch** was hampered by the failure of the tension readout and an inadequate tension graph, which meant that sometimes we had to gravity core or even dredge "blind". The rather unpredictable control system for the winch clearly requires upgrading. The coring operations proved to be rather unsatisfactory, with total recovery very low as shown in Table 8. More information on the performance of geological equipment is provided in Appendix 5.

Nodules were sought at 28 stations, with 85 deployments of *Benthos Boomerang* **freefall grab samplers** (Fig. 3 and Table 12). Sediment was recovered by a sampling tube included within the jaws of the grab, and once it was realised that nodules tended to be small a fine mesh was placed inside the coarser one (1 or 2 cm) provided by *Benthos*. Location was by means of radio (generally one per station), aided by flags or lights on all samplers depending on whether recovery was to be in the day or night. The technique proved to be very successful and only two grabs were lost. In all cases the grabs were deployed along bathymetric lines that had just been run, and usually the deployments (usually three) at each station were about a kilometre apart. The time spent at each station averaged 4-5 hours, including the bathymetric profiling. Water depths varied from 4618 m to 5929 m, and locations from the flanks of seamounts to well out on the flat abyssal plain were sampled. In general, the best results came from near seamounts and that means that nodule distribution is quite restricted. As shown in Table 12, nodules were recovered by 21 of the 83 successful deployments (25% recovery).

ROCKS AND SEDIMENTS DREDGED FROM SEAMOUNTS

(S.M. Williams and N.F. Exon)

The dredging program was confined to the seamounts. It was designed to elucidate their geological history and to sample any Mn crusts in order to assess their economic potential. A chain bag dredge and two small pipe dredges were dragged up the slope of the seamounts targeted. In all, nine seamounts were dredged with 12 deployments, ten of which were successful (Fig. 6 and Table 10). The dredge material was studied aboard ship in hand specimen, with the aid of sawn material and a few thin sections. It was then classified into various groups for each dredge haul before specialist sampling began. Each group in each dredge was assigned a number, and individual samples were given a suffix in the form of a letter; further subsamples were designated by another suffix in the form of numbers. Thus a typical number for a subsample from group 3, from dredge 2 might be 107/DR02/3A-2.

This report provides onboard lithological descriptions of the samples obtained in each dredge haul, slightly modified in the light of post-cruise thin section petrology, and also details any problems encountered during the sampling process. More detail is provided in Appendix 1. Further studies by Williams (1992) provided more detailed descriptions, and facies interpretation and facies assemblage for each dredge site, culminating in a model for the history of volcanism and sedimentation on the seamounts.

TABLE 10. SUMMARY OF DREDGE RESULTS: BMR CRUISE 107

Dredge	Latitude/ Longitude	Seamount top/ Dredge depth	Rock types recovered/comments
1	13° 43.2' S 105° 24.1' E **to** 13° 42.8' 105° 23.5'	2300 m 2800 m	Basalt; hyaloclastite; volcanic breccia; Maastrichtian, late Paleocene and early Eocene shallow -water limestone; pelagic limestones; pelagic ooze
2	13° 09.2' 105° 46.2'	2200 m 3000 m	No recovery; lost dredge and 4500 m dredge wire
3	11° 46.4' 107° 05.0'	1950 m 2200-2400 m	Volcaniclastics; Late Cretaceous shallow -water limestone; pelagic ooze
4	10° 58.3' 102° 25.8' **to** 10° 58.8' 102° 25.3'	1800 m 2800-2300 m	Basalt; trachyte; hyaloclastite; volcaniclastics; Maastrichtian shallow -water limestone; pelagic ooze
5	11° 48.0' 103° 14.8' **to** 11° 46.6' 103° 15.2'	1500 m 2800-1900 m	Basalt; trachyte; early, middle and late Eocene shallow-water limestone; early Eocene pelagic limestone; pelagic ooze
6	11° 02.0' 103° 58.1' **to** 11° 02.0' 103° 56.7'	2500 m 3300-2800 m	Basalt; trachyte; claystone; late Campanian, middle Maastrichtian, late Paleocene, late Eocene and late Miocene pelagic limestone and phosphorite
7	12° 48.1' 103° 57.1'	2720 m 3400 m	No recovery; lost dredge and 80 m of dredge wire
8	12° 50.2' 103° 53.4' **to** 12° 50.7' 103° 53.4'	1750 m 3700-3300 m	Basalt; trachyte; hyaloclastite; volcaniclastics; Late Cretaceous shallow -water limestone
9	11° 27.4' 104° 24.6' **to** 11° 27.3' 104° 24.4'	1200 m 1800-1600 m	Basalt; late Miocene pelagic limestone; pelagic ooze
10	11° 27.3' 104° 24.4' **to** 11° 26.8' 104° 24.3'	1200 m 1520-1450 m	Basalt; volcaniclastics; Maastrichtian, late Paleocene, middle Eocene, early and late Oligocene, and Pliocene pelagic limestone; pelagic ooze
11	11° 25.1' 105° 02.1' **to** 11° 25.2' 105° 00.7'	1500 m 2800-1800 m	Mn crust and pelagic ooze
12	11° 25.7' 104° 51.8' **to** 11° 25.7' 104° 53.4'	1500 m 1500-1800 m	Pelagic ooze

Many rock types are present; the main lithologies are listed by dredge site in Table 1 and expanded on below:

1. Basalts, including some pillow basalts
2. Trachytes

3. Volcaniclastics, mainly coarse grained sands, grits and breccias, with varied proportions of igneous and calcareous clasts.
4. Carbonates including breccias, grainstones, wackestones, calcilutites, mudstones and chalks.
5. Unconsolidated foraminiferal sands and oozes

Other minor lithologies are mentioned only under the specific dredge haul (Table 3) in which they were found. At ten sites manganese crusts, up to 5 cm thick, and impregnations were found. The crusts formed at least a thin veneer on some of the specimens in each haul; they are described under "Manganese nodules and crusts" later in this report.

Site Summary, Site DR01

Latitude: 13° 43.08' S; Longitude: 105° 23.60' E. Water Depth: 2800 m.
Recovery: 163 kg.

General Description:

1. 46% *Hyaloclastite breccia:* Abraded and altered hyaloclastite clasts in coarse sandy to gritty pale grey matrix, largely of molluscan debris.
2. 18% *Volcanic breccia:* Thick beds, calcite cemented, with coarser and finer mixtures of dark brown, angular basalt clasts and olive sand.
3. 12% *Volcanic breccia:* Thick bedded, with carbonate clasts, corals and algal balls, and angular basalt clasts.
4. 18% *Volcanolithic breccia:* Olive to grey, unsorted, with a variety of igneous and calcareous clasts.
5. *% *Basalt:* Brown, microcrystalline, plagioclase phenocrysts.
6. 1% *Phosphatic breccia:* Pinkish white, phosphatised and volcanic.
7. *% *Silty sandstone:* Brown, massive, poorly to moderately lithified, some specimens bored.
8. *% *Algal limestone:* Vuggy, laminated, porous. Calcite vugh infillings.
9. *% *Manganese crusts and impregnations:* Black, up to 1.5 cm thick.
10. 3% *Foraminiferal sand:* Cream, fine-grained.

*% Note that the combined total of those lithotypes listed with this percentage is 2%

Ten separate lithologies were recognised. They are commonly poorly sorted and thickly bedded to massive. Most samples contain at least some small angular basalt fragments and calcareous fragments. The main bioclasts are molluscs, bivalves, algal material, and minor coralline material. Altered hyaloclastite clasts are present in sample DR01/1. Unfragmented basalt, a silty sandstone, and a phosphatised micritic breccia were also sampled. Calcite cementation of coarse clasts is common. Manganese crusts have formed on various substrates. Recent foraminiferal sand is present.

Interpretation:

Coral and algal material are indicative of shallow water (photic zone) activity, possibly in a fringing reef development. Calcareous clasts are fragmented and therefore reworked under high energy conditions, whereas basalt clasts are angular and therefore relatively unworked. Material from a basaltic eruption was rapidly quenched and thus fragmented to produce hyaloclastic debris. Lithology 1 possibly developed as reef talus. Iron enrichment may be the result of vadose weathering during subaerial exposure. Phosphatisation of a volcanic breccia probably occurred post-deposition.

Site Summary, Site DR02

Latitude: 13° 08' S; Longitude: 105° 46' E. Water Depth: 2200 m.
Recovery: none.

4500 m of cable was lost together with the dredges. In total 4860 m of cable was lost or damaged, and 400 m of wire was recovered, leaving a working length of about 4600 m.

Site Summary, Site DR03

Latitude: 11° 46.4' S; Longitude: 107° 05' E. Water Depth: 2200-2400 m.
Recovery: 190 kg.

General Description:

1. 78% *Molluscan grainstone:* Bored, poorly to moderately bedded.
2. *% *Algal boundstone:* Pink, muddy carbonate matrix.
3. *% *Volcanic sandstone:* Phosphatised, bimodal, strongly bioturbated.
4. *% *Pumice:* (5Yr 5/2) Light olive green to pink , highly porous.
5. 16% *Manganese crusts and impregnations:* Black, up to 4 mm thick.
6. 2% *Carbonate grainstone:* Very fine grain carbonate matrix, coarse rounded molluscan fragments and subrounded basalt clasts.
7. *% *Carbonate mudstone:* Fine, sandy, brown mottled, bioturbated.
8. 1% *Carbonate grainstone:* Very coarse grained, porous, coarsely bedded. Molluscan and carbonate mudstone clasts. Geopetal structures.
9. *% *Carbonate grainstone:* Fine grained, thinly bedded with basalt clasts.
10. 1% *Carbonate wackestone:* Fine sand in phosphatic cement.
11. 1% *Foraminiferid-nannofossil ooze:* Fine grained, olive grey.

*% Note that the combined total of those lithotypes listed with this percentage is 1%

Interpretation:

Carbonate grainstones with rare, small, glassy basalt fragments display evidence of shallow water, photic zone deposition. Wackestones formed later in bathyal depths. There is only one sample of volcanic sandstone, and otherwise only sparse evidence of volcanic activity. Post-subsidence there has been coating with manganese crust and sedimentation of Recent foraminiferid-nannofossil ooze.

Site Summary, Site DR04

Latitude: 10° 58.81' S; Longitude: 102° 25.3' E. Water Depth: 2800-2300 m. Recovery: 165 kg.

General Description:

1. 2% *Volcaniclastic calcarenite:* White, thinly bedded, with basalt and calcareous clasts.
2. 6% *Volcaniclastic calcarenite:* Cream, fine-grained, poorly sorted, hard, with volcanic and calcareous clasts
3. 1% *Hyaloclastite breccia:* White calcareous cement with large volcanic clasts; mainly orange, poorly sorted basalt.
4. 25% *Vitric tuff:* pale olive in colour, bioturbated.
5. *% *Volcanic breccia:* Olive in colour with largely sub-rounded pumice clasts.
6. *% *Ironstone:* Very dark brown; jarosite? in cracks.
7. 1% *Scoria:* Strongly vesicular, some layered, green to maroon in colour.
8. *% *Tuff:* very fine-grained, showing weathering zonation.
9. 1% *Ferruginous boxstone or breccia:* dark orange-brown, mottled.
10. *% *Volcaniclastic sandstone:* Poorly sorted, angular, bedded.
11. 31% *Trachyte:* Microcrystalline, grey, moderately fresh, angular blocks.
12. 9% *Basalt*: Dark grey, angular, moderately fresh blocks
13. 5% *Trachyte:* Flow structured, some vesicular.
14. 16% *Weathered volcanics:* Very fine-grained basalts, some vesicular, and scoria.
15. *% *Volcanics:* Very fine-grained, very hard, often platy, light yellow.
18. *% *Nannofossil-foraminiferal ooze:* Cream colour.
19. *% *Nannofossil-foraminiferal ooze:* Light olive-grey colour

*% Note that the combined total of those lithotypes listed with this percentage is 3%

Interpretation:

This site shows the greatest number and variety of lithologies. The samples can be analysed to reveal the complete sequence of seamount development as follows: The basalt, trachyte flows and associated hyaloclastites indicate the building up of a volcanic edifice to sea level. Some of the carbonates formed in the photic zone. Bathyal carbonate deposition points to subsidence, that continued eventually to the present depths. The seamount rocks were coated by manganese crust late in their history.

Site Summary, Site DR05

Latitude: 11° 48.06' S; Longitude: 103° 15.19' E. Water Depth: 2800-1900 m. Recovery: 267 kg.

General Description:

1. 7% *Micritic carbonate wackestone:* White with abundant large foraminiferids.
2. 1% *Algal wackestone:* Algal balls set in a fine white carbonate mudstone.
3. 5% *Foraminiferal chalk:* White, friable, bioturbated.
4. 74% *Carbonate wackestone:* White, heavily bioturbated, hard, with manganese veneer and dendritic impregnations.
5. 11% *Basalt and trachyte:* Fine-grained, homogenous, brown.
6. *% *Sandstone:* One rounded, elongate, dark brown pebble.
7. *% *Calcilutite:* White, very thin-bedded, hard.
8. *% *Nannofossil-foraminiferal ooze:* Pale brown.
9. *% *Manganese crusts:* Less than 5 mm thick, black to dark brown.

*% Note that the combined total of those lithotypes listed with this percentage is 2%

Interpretation:

Bioclasts, such as algal balls, have been reworked and incorporated into deeper water deposits down slope. Other samples are of purely bathyal origin and are commonly strongly bioturbated. The presence of large benthic foraminiferids is evidence of a warm shallow water environment. Basalt and trachyte formed the volcanic edifice.

Site Summary, Site DR06

Latitude: 10° 02' S; Longitude: 103° 56.7' E. Water Depth: 3227-2830 m.
Recovery: 223 kg.

General Description:

1. 45% *Basalt:* Dark brown, vesicular, hard, microcrystalline; some contain subrounded, phosphatised carbonate clasts.
2. 11% *Trachyte:* Manganese encrusted, dark brown, vesicular, hard, with clasts of basalt and/or carbonate.
3. 8% *Manganese crusts and impregnations:* Black, up to 4 cm thick crust with "bubbly" surface texture.
4. 7% *Calcilutite:* Phosphatised, fine-grained pelagic carbonate. Subangular, brown, vesicular basalt clasts.
5. 4% *Carbonate breccia:* Phosphatised carbonate, variable colour from orange to cream, with manganese crust.
6. 1% *Basalt and carbonate:* Highly weathered and manganese impregnated.
7. *% *Claystone:* Well lithified, pale olive, with intermingled pale yellow phosphatised calcilutite.
8. *% *Chalk:* Moderately lithified, heavily weathered, cream colour.
9. *% *Pumice:* Vesicular, dark brown, small subrounded pieces.
10. 11% *Foraminiferid-nannofossil ooze:* Soft, cream colour.
11. 11% *Foraminiferal sand:* Light brownish-grey.
12. 1% *Foraminiferid-nannofossil chalk:* Moderately lithified, cream.
13. *% *Carbonate biomicrite:* Light brownish-grey.

*% Note that the combined total of those lithotypes listed with this percentage is 1%

Interpretation:

There was deepwater deposition of carbonate micrite containing abundant in planktic foraminiferids on a basalt and trachyte volcanic edifice. There is no evidence in this dredge load of shallow water deposition.

Site Summary, Site DR07

Latitude: 12° 48.15' S; Longitude: 103° 57.09' E. Water Depth: 3768-3381m.
Recovery: none.

Dredge, weights and 80 m of cable broken off.

Site Summary, Site DR08

Latitude: 12° 52.51' S; Longitude: 103° 53.22' E. Water Depth: 3700-3300 m.
Recovery: 17 kg.

General Description:

1. 3% *Volcanolithic sandstone and grit:* Olive, with angular fine-grained basalt and poorly sorted carbonate clasts.
2. 1% *Hyaloclastite breccia:* Very hard, olive grey, with angular, concentric clasts.
3. 18% *Porphyritic basalt:* Dark grey, weathered; some samples have a manganese veneer. Contains pyroxene phenocrysts.
4. 47% *Microcrystalline basalt:* One complete rock. Few pyroxene phenocrysts, fresh, homogenous, dark grey.
5. 30% *Basalt and trachyte:* Fine-grained, brown, very weathered; minor vesicular specimens.
6. 1% *Manganese crusts:* Found on volcanics and limestones, up to 5 mm thick
7. *% *Calcarenite:* Medium to coarse-grained. Pale olive.

*% Note that less than 1% of the total is this lithotype.

Interpretation:

Hyaloclastite deposits, both monomict and polymict. Basalt and trachyte form the base of the volcanic edifice. Deep water activity indicated by calcarenite. No evidence of shallow water activity.

Site Summary, Site DR09

Latitude: 11° 27.10 ' S; Longitude: 104° 24.59' E. Water Depth: 1800-1600 m.
Recovery: 21 kg, including soft sediments.

General Description:

1. 72% *Basalt:* Weathered, dark yellowish-brown, microcrystalline, with manganese veneer.
2. 7% *Calcilutite:* Hard, fine-grained, light grey to pale yellow.
3. 7% *Chalk:* Well lithified, foraminiferal-rich, white.
4. 14% *Chalky ooze:* Soft, foraminiferal-rich, white.
5. *% *Foraminiferal ooze:* Unconsolidated, light yellowish-brown.

*% Note that this lithotype is not included in total percentage; totals 20 kg.

Interpretation:

The occurrence only of basalt, calcilutite and chalk at dredge site 9 provides no evidence of shallow water carbonate deposition, hyaloclastite formation or trachyte flows. Only 1 kg of rock was retrieved.

Site Summary, Site DR10

Latitude: 11° 26.46 ' S; Longitude: 104° 24.31' E. Water Depth: 1515-1445m. Recovery: 28 kg.

General Description:

1. *% *Basalt:* Porphyritic, phenocrysts include pyroxene and feldspar, microcrystalline, dark brown, manganiferous veneer.
2. 79% *Carbonate grainstone:* Poorly sorted, coarse carbonate and volcanic clasts set in a fine-grained carbonate matrix.
3. 16% *Chalk:* Fine-grained carbonate with manganiferous veneer and dendritic impregnations. White, with pale brown infillings.
4. 2% *Chalk:* Fine-grained, white carbonate with abundant foraminiferids. Dendritic manganiferous impregnations.
5. 2% *Manganese crust:* Up to 3 cm thick, black, central crust massive, edges foliated.
6. *% *Chalky ooze:* Very fine-grained, white.
7. *% *Nannofossil-foraminiferal ooze:* Pale brown.

*% Note that less than 1% of the total is this lithotype.

Interpretation:

Site DR10 was located on the same seamount as DR09, but in slightly shallower waters, and slightly north of DR09. Retrieved samples include the chalk, basalt and ooze of DR09, and also carbonate grainstone. Again there is no evidence of trachyte or hyaloclastite on this seamount, but in this dredge load the grainstone indicates shallow water.

Site Summary, Site DR11

Latitude: 11° 25.14 ' S; Longitude: 105° 02.10' E. Water Depth: 2850-1718m.

Recovery: 1.41 kg.

General Description:

1. 14% *Foraminiferal-nannofossil ooze:* Pale brown, fine-grained, slightly sandy.
2. 85% *Manganese crust:* Black, up to 3 cm thick, botryoidal and microbotryoidal surface texture. Finely laminated. Some showing clay and carbonate dendrites.
3. 1% *Assorted material*: Assortment from pipe dredge includes Recent foraminiferids and a small starfish.

Note: This dredge probably barely scraped the seamount rocks, as all that was retrieved is Recent ooze and surficial manganese crust.

Site Summary, Site DR12

Latitude: 11° 25.65' S; Longitude: 104° 53.59' E. Water Depth: 1800-1500 m.
Recovery: 2.4 kg.

General Description:

1. 100% *Nannofossil-foraminiferal sand:* Medium to coarse-grained, pale brown.

Note: This dredge only sampled surficial sediments.

CAINOZOIC SEDIMENT CORES

(N.F. Exon and S.M. Williams)

Piston coring was carried out at nine stations and gravity coring at six stations (including two repeats), in water depths of 475-5923 m. The results were generally disappointing with total recovery of only 21 m (Table 11). Part of the problem was clearly due to difficult coring conditions on current-swept seamounts, but the frequent collapse of core liners during piston coring must have been due to rigging miscalculations or faulty materials. Grainsize and carbonate analyses are presented in Appendix 3. The overall coring results are summarised below.

TABLE 11. CORES: BMR CRUISE 107

Core	Latitude (S) Longitude (E)	Depth (m)	Recovery (cm)	Description
PC01	13° 26.18' 105° 44.58'	5923	0	Equipment failure
PC02	11° 42.13' 106° 59.17'	1996	60	Disturbed foraminiferids sand. Imploded core liner
PC03	11° 00.92' 102° 24.86'	1825	140	Sandy nannofossil-foraminiferal ooze
PC04	11° 45.49' 103° 15.59'	1423	5	Hard calcilutite
PC05	10° 26.54' 104° 48.30'	4559	475	Nannofossil-bearing siliceous ooze
PC06	10° 31.24' 105° 31.02'	485	53	Foraminiferal sand and ooze, with manganese coated volcanic cobbles
PC07	11° 02.19' 103° 54.48'	2038	74	Foraminiferal-nannofossil ooze
PC08	12° 54.60' 103° 55.23'	2665	274	Nannofossil-foraminiferal ooze and foraminiferal sand
PC09	11° 02.19' 103° 54.49'	1206	2	Foraminiferal sand
GC01	13° 37.24' 105° 18.26'	2370	620	Foraminiferal-nannofossil ooze
GC01A	13° 37.09' 105° 18.15'	2368	0	No penetration
GC02	11° 42.12' 106° 59.20'	1995	0	No penetration
GC02A	11° 42.09' 106° 59.16'	1997	3	Foraminiferal sand
GC03	12° 16.55' 107° 51.69'	2939	0	No penetration
GC04	11° 17.86' 103° 58.61'	3665	395	56 cm of foraminiferid-nannofossil ooze over siliceous ooze

All the cores from the tops of seamounts were similar, so only two will be described here, GC01 and PC08. In addition two deeper-water cores will be described, GC04 and PC05. Core **GC01**, from a water depth of 2370 m, consists of 6.2 m of light cream to grey nannofossil-foraminiferal ooze, completely bioturbated so that it shows no bedding. Some mottling is apparent. The sand fraction is consistently about 70% and the carbonate content is 85-90%. Core **PC08**, from a depth of 2665 m, consists of 2.74 m of yellow, white, pale brown and light grey nannofossil-foraminiferal ooze, heavily bioturbated with little sign of bedding and minor mottling. The sand fraction varies from about 50%, especially in the lower half of the core, to about 70%. The carbonate content is 75% in most of the core, but rises to 90% in the lower third.

Core **GC04**, from a water depth of 3665 m, came from acoustically transparent (pelagic) sediments on a gentle slope. It is 3.95 m long with 56 cm of foraminiferal-nannofossil ooze overlying foraminiferal and nannofossil-bearing siliceous ooze. The foraminiferal-nannofossil ooze is oxidised, pale brown, and heavily bioturbated, with no bedding and minor mottling apparent. It contains 20-40% sand, largely foraminiferids, and 55-75% carbonate, with nannofossils and foraminiferids in subequal proportions. The siliceous ooze is thinly to medium bedded, and well bedded, with some mottling; in places it is very watery and gelatinous in character . Colours vary from light to dark, in various shades of grey, olive grey, and olive, and indicate the presence of reducing conditions in the sediment. Colour changes may be related to organic and sulphide content. This ooze can be separated into two types, diatomaceous ooze from 56 to 152 cm, and carbonate-rich siliceous ooze from 152 to 395 cm. The diatomaceous ooze contains 50-70% sand and 5-20% carbonate, and is very gelatinous. It is dominated by relatively large diatomaceous sheets, but also contains abundant radiolarians, smaller diatoms, sponge spicules, nannofossils, some fragmented planktic foraminiferids, clay, and light-coloured glass shards. The carbonate-rich siliceous ooze contains 30% sand and 30% carbonate. The constituents are the same as in the diatomaceous ooze, but the proportion of diatomaceous sheets is smaller and of nannofossils is higher. The changes within the siliceous ooze are probably related to changes in the properties of the surface water, and these changes may be relatable to climatic cycles. The overlying carbonate ooze may be a slump from a nearby seamount.

Core **PC05**, from a water depth of 4559 m, sampled 10-15 m of transparent sediment above bedded sediments, forming a pond in rough volcanic basement on the Christmas Island Rise. It is 4.75 m long and consists entirely of carbonate-rich siliceous ooze. The upper 67 cm is oxidised and yellow-brown, and the remainder shows various light to medium tones of grey and olive-grey. Bedding is poorly developed and generally thick, with some thin dark beds and some mottling. The core contains 10-30% sand (much less than in the siliceous ooze of core GC04) and 10-35% carbonate (lowest toward the base). It contains the same constituents as core GC04, but foraminiferal fragments are confined to the upper half of the core, and diatomaceous sheets are not as common (explaining the lower proportion of sand). It is a purely pelagic core, with advanced dissolution of calcareous organisms; the reduced volume of the diaphanous diatom sheets may indicate the onset of solution of siliceous organisms.

In summary, the cores in this area show typical changes in pelagic sedimentation in an oceanic area, from carbonate ooze above 3000 m, to siliceous ooze below. The free-fall grabs returned red clay below 5000 m, where all carbonate is dissolved and also much of the silica.

MANGANESE NODULES AND CRUSTS

(N.F. Exon)

The data base for manganese nodules and crusts in the Christmas Island Australian Fisheries Zone (AFZ) area is dominated by the samples gathered on BMR Cruise 107, with 21 freefall grabs and 7 dredges yielding nodules and/or crusts. Localities of all stations are shown in Figure 3. Nodule data are summarised in Tables 12 and 14, and crust data in Tables 13 and 14. Full analytical information is provided in Appendix 2.

MANGANESE NODULES

Rationale for the study

Previous studies in the Indian Ocean (see "Results of Previous Studies") had shown that manganese nodules are generally quite abundant and of moderate grade, and that they were present in the poorly sampled Christmas Island area with average abundances and grades (Tables 4 and 5). Our hope was that the area would prove to be comparable to the economically more prospective nodule fields of the central Indian Ocean mine site (Sudhakar, 1989; Martin-Barajas et al., 1991), where nodule abundance exceeds 5 kg/m2 over large areas and metal grades on siliceous oozes average a very high 2.41% Ni+Cu. In both 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 and Melguen, 1979; Exon, 1982; von Stackelberg and Beiersdorf, 1991). These include:

1) Low sedimentation rates, which are favoured by distance from major land masses and volcanoes and the 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 and Ulrich, 1968). 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.

TABLE 12. FREE-FALL GRAB STATIONS ON BMR CRUISE 107

Station	Latitude (South)	Longitude (East)	Depth (m)	Recovery	Abundance (kg/m²)
1A	13° 39.72'	105° 39.72'	5888	0.15 kg small smooth nodules	0.675
1B	13° 39.18'	105° 39.92'	5882	nodule fragment	
1C	13° 38.60'	105° 40.12'	5884	nodule fragments, clay	
2A	13° 32.47'	102° 48.22'	5394	clay	
2B	13° 32.26'	105° 42.45'	5894	clay	
2C	13° 31.75'	105° 42.80'	5893	nil	
3A	13° 26.70'	105° 44.68'	5926	clay	
3B	13° 26.12'	105° 44.93'	5928	clay	
3C	13° 25.59'	105° 45.12'	5929	nil	
4A	12° 07.29'	106° 15.34'	5624	pumice, volcanics, clay	
4B	12° 06.85'	106° 15.34'	5622	clay	
4C	12° 06.20'	106° 15.57'	5594	clay	
5A	12° 00.26'	106° 17.89'	5625	clay	
5B	11° 59.71'	106° 18.06'	5604	3 small smooth polynodules, pumice, teeth ,sponge	0.01
5C	11° 59.25'	106° 18.25'	5588	pumice, clay	
6A	10° 58.59'	106° 41.32'	5700	pumice, clay	
6B	10° 57.44'	106° 41.78'	5647	clay	
6C	10° 56.29'	106° 42.24'	5686	pumice, clay	
6D	10° 55.20'	106° 42.65'	5712	nil	
7A	9° 46.33'	102° 41.46'	5479	equipment lost	
7B	9° 46.77'	102° 42.53'	5495	equipment lost	
7C	9° 47.15'	102° 43.45'	5510	clay	
8A	9° 19.30'	103° 05.80'	5476	clay	
8B	9° 19.85'	103° 05.51'	5476	pumice, clay	
8C	9° 20.32'	103° 05.15'	5476	clay	
9A	8° 52.01'	103° 28.01'	5465	pumice, clay	
9B	8° 52.43'	103° 27.67'	5466	clay	
10A	10° 04.38'	103° 01.32'	5429	clay	
10B	10° 04.77'	103° 01.18'	5425	pumice, clay	
10C	10° 05.17'	103° 01.02'	5418	clay	
11A	10° 33.29'	102° 47.79'	5392	pumice, clay	
11B	10° 48.43'	102° 53.65'	5394	clay	
11C	10° 32.89'	102° 48.00'	5397	clay	
12A	11° 12.02'	102° 31.96'	5429	pumice, clay	
12B	11° 11.52'	102° 31.78'	5426	volcanics, clay	
12C	11° 11.11'	102° 31.59'	5400	volcanics	
13A	11° 47.53'	102° 53.11'	5102	0.5 kg small rough nodules, crusts, pumice, clay	2.5
13B	11° 48.43'	102° 53.65'	5105	0.2 kg small smooth nodules, pumice, clay	0.72
13C	11° 49.12'	102° 54.07'	5104	3 small rough nodules, pumice, clay	0.01
14A	12° 10.90'	102° 57.24'	5109	clay	
14B	12° 10.42'	102° 57.20'	5112	clay	
14C	12° 09.92'	102° 57.09'	5105	clay	
15A	12° 30.03'	103° 00.01'	5055	clay	
15B	12° 29.51'	102° 59.92'	5053	clay	
15C	12° 29.03'	102° 59.85'	5057	clay	
16A	12° 01.08'	103° 10.23'	5140	1.55 kg small smooth nodules, pumice, clay	7

TABLE 12. FREE-FALL GRAB STATIONS ON BMR CRUISE 107
(continued)

Station	Latitude (South)	Longitude (East)	Depth (m)	Recovery	Abundance (kg/m²)
16B	12° 01.86'	103° 09.97'	5161	0.8 kg small smooth nodules, pumice, clay,	3.8
16C	12° 02.84'	103° 09.60'	5178	2.65 kg small smooth nodules, pumice, clay	12
17A	11° 32.86'	103° 20.25'	5080	pumice, clay	
17B	11° 33.34'	103° 20.10'	5086	pumice, clay	
17C	11° 33.83'	103° 19.91'	5073	7 small smooth nodules, crust, pumice, clay	0.27
18A	10° 50.39'	103° 35.26'	5717	pumice, clay	
18B	10° 51.12'	103° 35.02'	5716	pumice, clay	
18C	10° 51.81'	103° 34.76'	5706	pumice, volcanics, clay	
19A	10° 22.21'	103° 45.09'	5643	pumice, clay	
19B	10° 22.68'	103° 44.94'	5620	pumice, volcanics, clay	
19C	10° 23.18'	103° 44.79'	5605	pumice, volcanics, clay	
20A	9° 39.36'	104° 37.78'	4896	nil	
20B	9° 38.89'	104° 37.65'	4848	nil	
20C	9° 38.37'	104° 37.47'	4820	pumice, clay	
21A	10° 31.78'	104° 09.84'	4821	Mn crust, pumice, volcanics, clay	
21B	10° 31.04'	104° 10.06'	4839	pumice, burrows, clay	
21C	10° 30.38'	104° 10.25'	4844	pumice, burrows, clay	
22A	11° 40.24'	103° 56.81'	4914	clay	
22B	11° 39.65	103° 56.78	4899	pumice, clay	
22C	11° 38.62'	103° 56.91'	4883	clay	
23A	12° 14.47'	103° 53.74'	4780	1.7 kg small smooth nodules, clay	7.6
23B	12° 13.95'	103° 53.80'	4791	1.6 kg small smooth nodules, clay	7.2
23C	12° 13.45'	103° 53.85'	4778	clay	
24A	12° 36.13'	103° 51.85'	4582	pumice, burrows, clay	
24B	12° 35.64'	103° 51.92'	4576	pumice, clay	
24C	12° 35.16'	103° 51.93'	4574	pumice, clay	
25A	13° 18.91'	103° 48.10'	5712	0.8 kg small rough nodules, crusts, clay	3.6
25B	13° 18.05'	103° 48.17'	5729	0.07 kg small rough nodules, pumice, clay	0.3
25C	13° 17.24'	103° 48.24'	5745	0.17 kg small rough nodules, pumice, clay	0.8
25D	13° 16.44'	103° 48.31'	5750	volcanogenic sandy clay	
26A	12° 15.01'	104° 08.50'	5356	few small nodules, volcanics, clay	0.01
26B	12° 15.50'	104° 08.36'	5373	0.02 kg small rough nodules, volcanics, clay	0.1
26C	12° 15.97'	104° 08.21'	5384	0.07 kg irregular rough nodules, pumice, clay	0.3
27A	11° 51.34'	104° 16.44'	4636	volcanics, pumice, clay	
27B	11° 51.76'	104° 16.39'	4618	volcanics, pumice, clay	
27C	11° 52.16'	104° 16.21'	4633	volcanics, clay	
28A	11° 06.98'	104° 47.05'	4981	0.025 kg small rough nodules, volcanics, clay	0.11
28B	11° 07.74'	104° 47.22'	4975	0.025 kg small rough nodules, volcanics, clay	0.11
28C	11° 08.62'	104° 47.70'	5004	four small rough nodules, volcanics, pumice sand	0.01

4) Sediments with low sedimentation rates, high Ni and Cu content, and high porosity, where bottom waters are oxidising 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.

Previous work in this area had shown that the calcite compensation depth (CCD) lies at about 5000 m, and that the most prospective areas for nodules were south, south east and south west of Christmas Island, where carbonate oozes dominate above 4000 m, and red clay and siliceous ooze below 4000 m (Udintsev, 1975). On this cruise, because sampling density was so low, and sediment patterns thus so uncertain, sediment and nodule distribution were checked by sampling on long profiles across the entire Christmas Island offshore area. Siliceous ooze, the most prospective sediment type for high-grade nodules, is normally transparent on seismic profiles, and this was an aid in planning and interpreting the sampling program.

General techniques and results

Nodules were sought at 28 stations, with 85 deployments of *Benthos Boomerang* freefall grab samplers (Fig. 3 and Table 12). Sediment was recovered by a sampling tube included within the jaws of the grab and, once it was realised that nodules tended to be small, a fine mesh was placed inside the coarser one (1 or 2 cm) provided by *Benthos*. Location was by means of radio (generally one per station), aided by flags or lights on all samplers depending on whether recovery was to be in the day or night. The technique proved to be very successful and only two grabs were lost. In all cases the grabs were deployed along bathymetric lines that had just been run, and usually the deployments (usually three) at each station were about a kilometre apart. The time spent at each station averaged 4-5 hours, including the bathymetric profiling. Water depths varied from 4618 m to 5929 m, and locations from the flanks of seamounts to well out on the flat abyssal plain were sampled. In general, the best results came from near seamounts and that means that nodule distribution is quite restricted. As shown in Table 12, nodules were recovered by 21 of the 83 successful deployments (25% recovery). Both smooth and rough nodules were recovered, generally as small mononodules or polynodules.

Nodule distribution and abundance

Altogether (including 5 earlier stations) nodules have been recovered from 14 stations in the Christmas Island AFZ (Fig. 13). All the known occurrences are south and west of Christmas Island. Nodules were

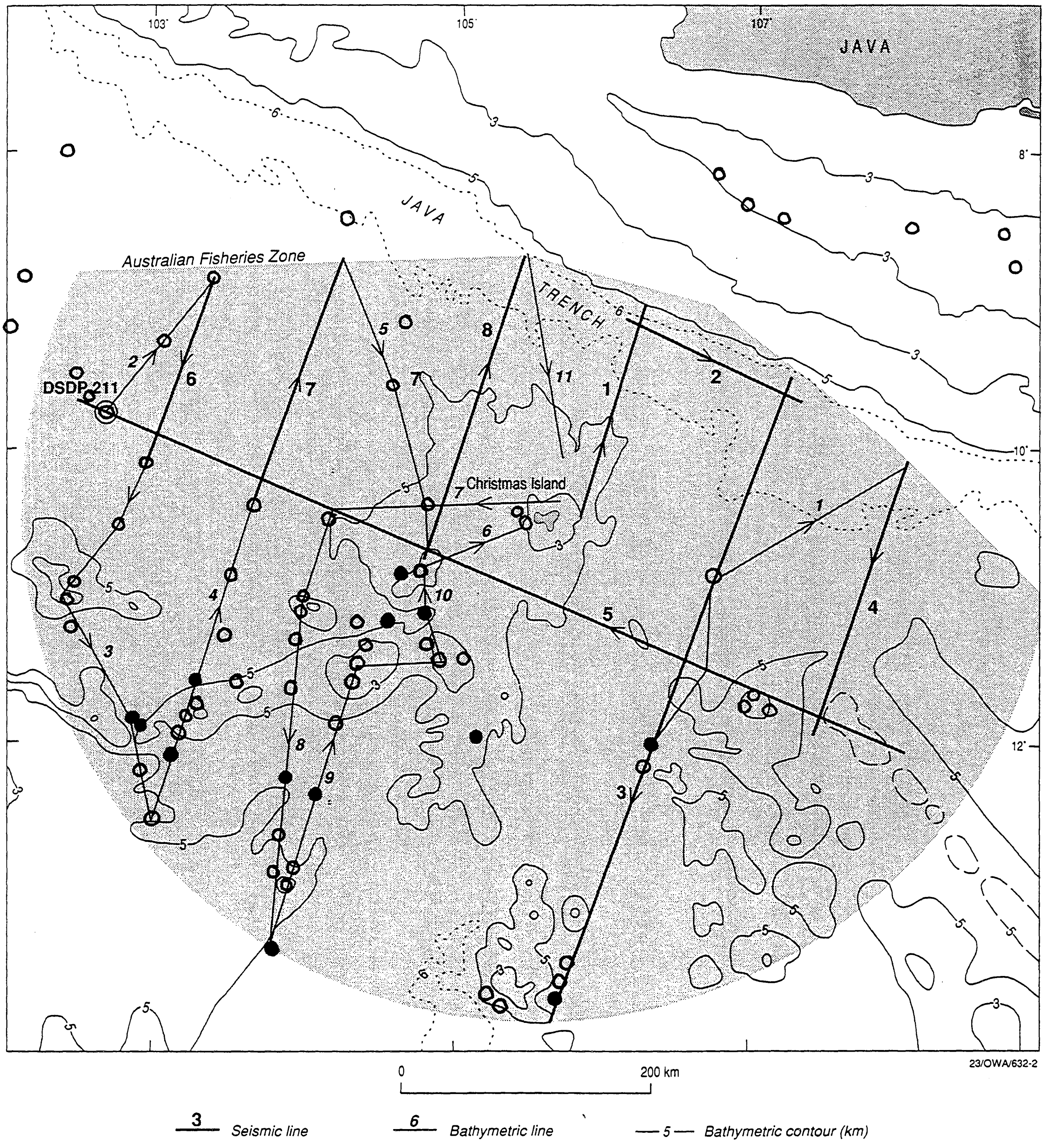


Figure 13. Map of Christmas Island region, showing seabed sample stations which did and did not recover manganese nodules. Solid circles with manganese nodules, open circles without.

recovered at 9 of 28 Cruise 107 stations (32 %) and at 21 of 83 successful deployments (25 %), as listed in Table 12. This compares with percentages of 70-80 % in prospective basins in the Pacific Ocean (Exon, 1983) and probably much the same in the Central Indian Ocean to the west. The shallowest deployment that returned nodules was from water depths of 4780 m (FFG 23 A), and the deepest 5888 m (FFG 1A). Nearly all successful deployments showed that nodules are associated with abyssal clay. The exception is FFG 23 where small rough nodules occur with volcanic fragments.

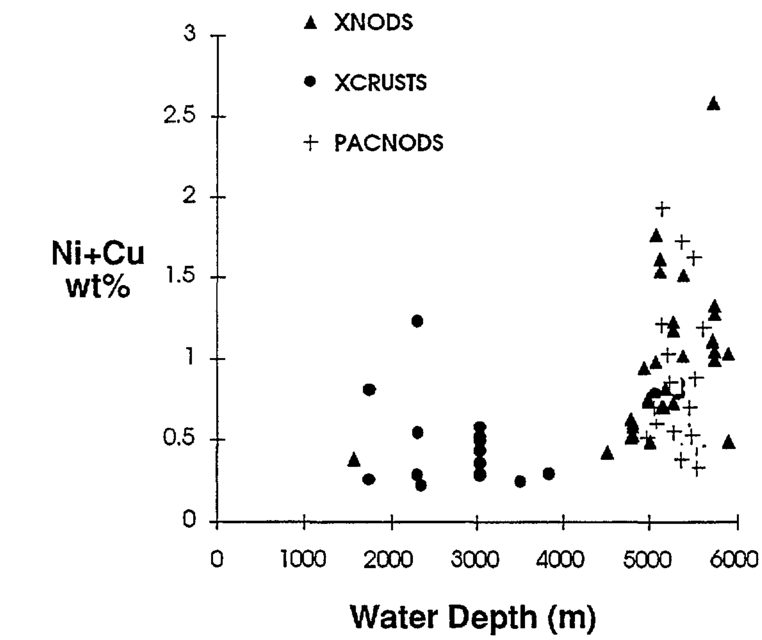
Even where nodules are present they are not particularly abundant, the abundance exceeding the probable economic cut-off of 5 kg/m^2 at only two stations: 16 and 23. This compares with an average abundance in the Indian Ocean mining site of 7.48 kg/m^2 on siliceous ooze and 4.68 kg/m^2 on red clay (Sudhakar, 1989), and higher values in several Pacific Ocean basins (Exon, 1983).

Nodule metal content

Classic Laboratories of Adelaide analysed 24 samples from eight Cruise 107 stations for 32 components, using induction coupled plasma spectrometry on samples dried at 105° C and pulverised using chrome-free steel. The results are listed in full in Appendix 2 and summarised in Table 13. For the key elements, they show averages of Fe 4.66%, Mn 19.68%, Ni 0.51%, Cu 0.49% and Co 0.12%. The average Mn/Fe ratio is a high 5.48. Average Ni+Cu+Co is 1.13% (about world average), with rough nodules averaging 1.30% and smooth nodules 0.92%.

Plots of valuable metal content against water depth (showing also Cruise 107 crusts, and Cook Islands nodules from the Pacific Ocean after Exon (1981) are shown in Figure 14. The nodules alone are taken from only a limited depth range of 4500-6000 m, and show no convincing trend of either Co or Ni+Cu with depth. However, when the Cruise 107 crusts are included, the normal decline in Co values and increase in Ni+Cu values with depth are apparent. The nodules are comparable to the Cook Islands nodules as regards Ni+Cu, but Co values are substantially lower near Christmas Island. A plot of Ni+Cu+Co with water depth (not illustrated) shows values comparable to those in the Cook Islands. A plot of Ni+Cu+Co with latitude (also not illustrated) shows no appreciable trend over the three degrees sampled.

Plots of valuable metals against the Mn/Fe ratio for the Cruise 107 nodules and crusts, and nodules from the Central Indian Ocean (Jauhari, 1990) and Cook Islands (Exon, 1981), are presented in Figure 15. The nodules show the normal situation of increasing Ni+Cu and decreasing Co with increasing Mn/Fe ratio. A flatter slope applies to the Ni+Cu plots from Christmas Island, as compared to the other two areas, which show comparable slopes



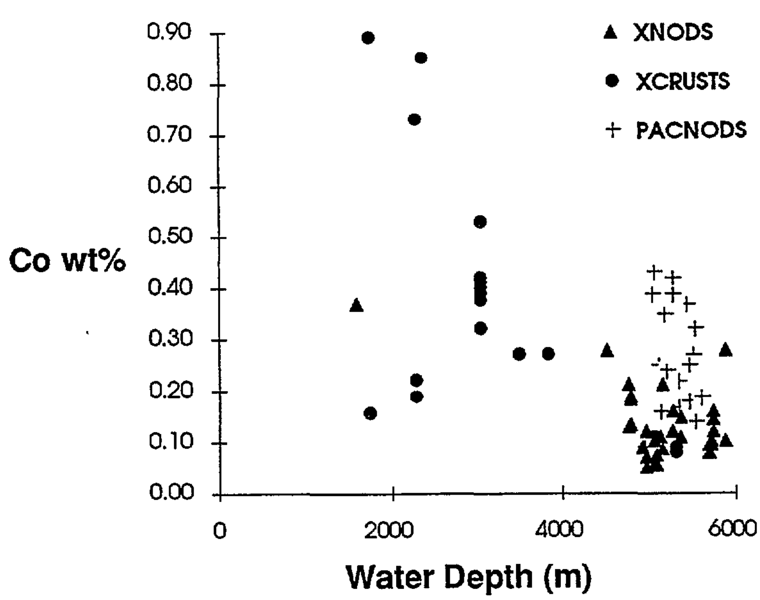
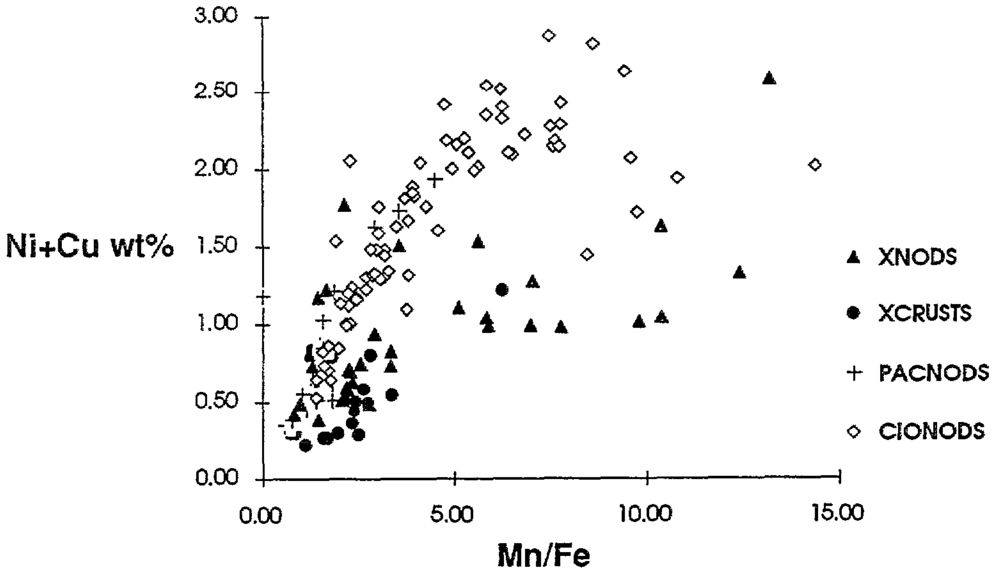


Figure 14. Plots of Ni+Cu% and Co% against water depth for Cruise 107 nodules (XNODS) and crusts (XCRUSTS), and for nodules from Cook Islands (PACNODS: after Exon, 1981).



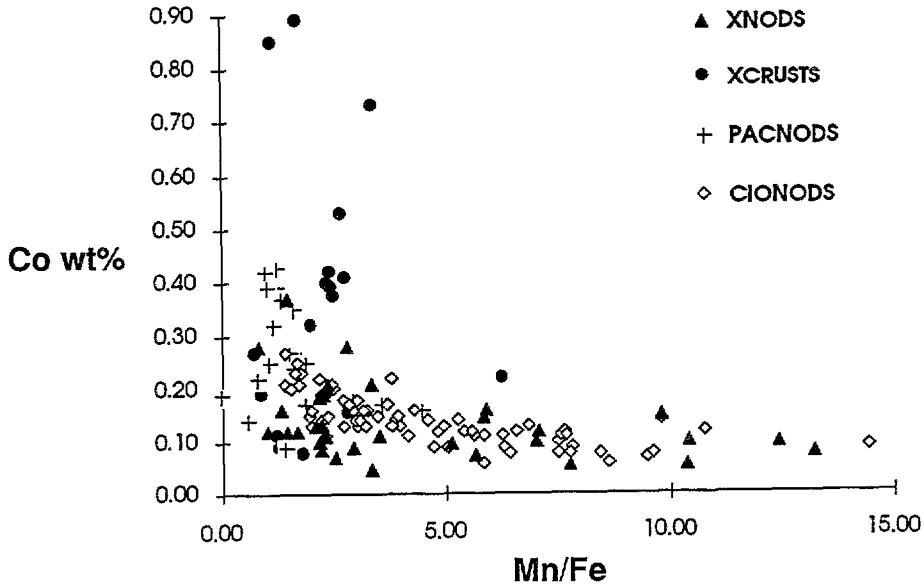


Figure 15. Plots of Ni+Cu% and Co% against Mn/Fe ratio for Cruise 107 nodules (XNODS) and crusts (XCRUSTS), and for nodules from the Cook Islands (PACNODS: after Exon, 1981) and the Central Indian Ocean (CIONODS: Jauhari, 1990).

and higher Ni+Cu at lower Mn/Fe ratios. The Co plot shows a similar slope for all three areas, but the Cook Islands nodules have higher Co values at lower Mn/Fe ratios. These plots clearly show the higher Ni+Cu grades in the Central Indian Ocean mine site area, and the higher Co grades in the Cook Islands.

TABLE 13: NODULES ANALYSED FROM BMR CHRISTMAS ISLAND CRUISE 107

Sample	Latitude (°S)	Longitude (°E)	Type	Water depth (m)	Abundance (kg/m²)	Fe wt%	Mn wt%	Mn/Fe	Ni wt%	Cu wt%	Co wt%	Cu+Ni +Co (%)
1A1	13.6620	105.6620	Ss	5888	0.15	2.39	24.85	10.40	0.52	0.52	0.10	1.14
1B1	13.6530	105.6653	Ir	5882	0.01	5.56	15.48	2.78	0.27	0.23	0.28	0.77
13A1	11.7922	102.8852	Er	5102	2.5	4.00	22.60	5.65	0.84	0.70	0.08	1.62
13A3	11.7922	102.8852	Ss	5102	2.5	2.58	26.70	10.36	0.84	0.78	0.06	1.68
16A	12.0180	103.1705	SPs	5140	7	6.20	14.40	2.32	0.41	0.29	0.11	0.81
16B	12.0310	103.1662	SPs	5161	3.8	6.78	15.09	2.23	0.43	0.28	0.09	0.79
16C	12.0473	103.1600	SPs	5178	12	6.17	20.51	3.32	0.47	0.36	0.21	1.03
17C1	11.5638	103.3318	Ds	5073	0.27	3.29	25.46	7.74	0.51	0.47	0.06	1.03
23A1	12.2412	103.8957	Ss	4780	7.6	7.70	18.19	2.36	0.39	0.25	0.21	0.84
23A2	12.2412	103.8957	Ds	4780	7.6	6.98	14.40	2.06	0.32	0.19	0.13	0.64
23B1	12.2325	103.8967	SPs	4791	7.2	8.31	18.65	2.25	0.36	0.22	0.19	0.77
23B2	12.2325	103.8967	Ds	4791	7.2	6.92	15.25	2.20	0.39	0.21	0.14	0.73
23B3	12.2325	103.8967	SPs	4791	7.2	8.37	18.27	2.18	0.33	0.21	0.19	0.72
25A1	13.3152	103.8017	PEr	5712	3.6	3.63	18.50	5.10	0.57	0.54	0.10	1.21
25A2	13.3152	103.8017	Sr	5712	3.6	2.19	28.87	13.20	1.28	1.30	0.08	2.66
25B1A	13.3008	103.8028	Sr	5729	0.3	2.92	20.43	7.01	0.39	0.61	0.10	1.10
25B2B	13.3008	103.8028	Sr	5729	0.3	2.22	27.55	12.41	0.61	0.72	0.10	1.43
25C1	13.2873	103.8040	Dr	5745	0.8	2.93	20.67	7.05	0.59	0.69	0.12	1.40
25C2	13.2873	103.8040	Dr	5745	0.8	3.39	19.74	5.82	0.43	0.62	0.15	1.20
25C3	13.2873	103.8040	Dr	5745	0.8	3.39	19.89	5.87	0.41	0.59	0.16	1.16
26B	12.2583	104.1393	Sr	5373	0.1	2.63	25.70	9.78	0.39	0.63	0.15	1.17
26C	12.2583	104.1393	IDr	5384	0.3	4.47	15.79	3.53	0.63	0.88	0.11	1.62
28A	11.1163	104.7840	Sr	4981	0.11	4.03	13.39	3.32	0.50	0.24	0.05	0.79
28B	11.1290	104.7870	Sr	4981	0.11	4.71	11.92	2.53	0.40	0.35	0.07	0.82
AVERAGE				5534	3.29	4.66	19.68	5.48	0.5 1	0.49	0.12	1.13

S=spheroidal E=ellipsoidal D=discoidal P=polynodule I=irregular s=smooth r=rough
For rough nodules Cu+Ni+Co=1.30%; for smooth=0.92%
Virtually all nodules were analysed with their volcanic cores.

Plots of Ni+Cu against Co for the same data sets are shown in Figure 16. A clear inverse relationship is shown for the Christmas Island nodules, and also for the other data sets. The triangular plots of Ni:Cu:Co illustrate the same data in another way (Fig. 17). They show that the Christmas Island nodules have roughly equal proportions of Ni and Cu, and are relatively low in Co, as do the Central Indian Ocean nodules. In contrast, the Cook Islands nodules tend to be proportionately higher in Ni and Co, and low in Cu.

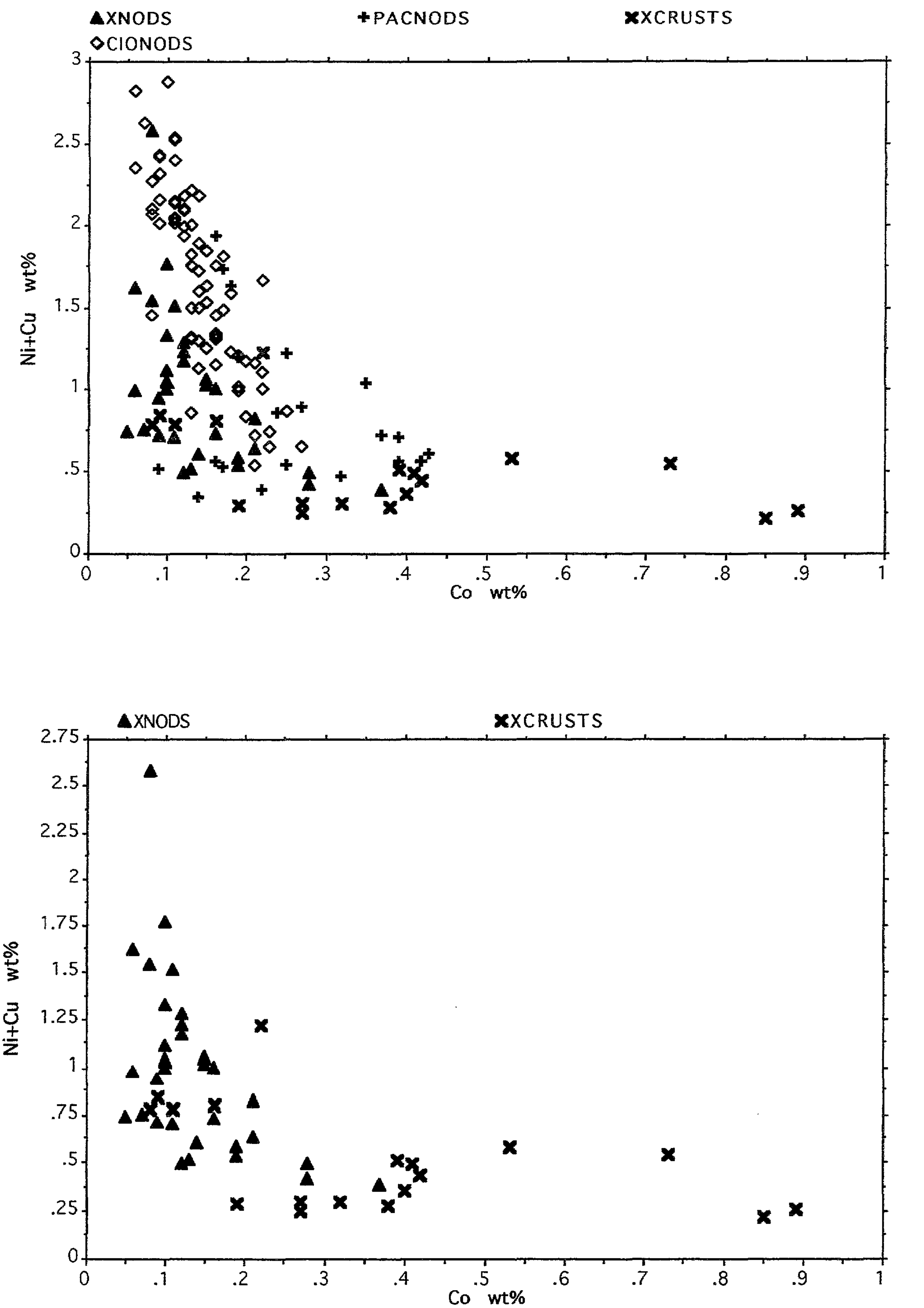
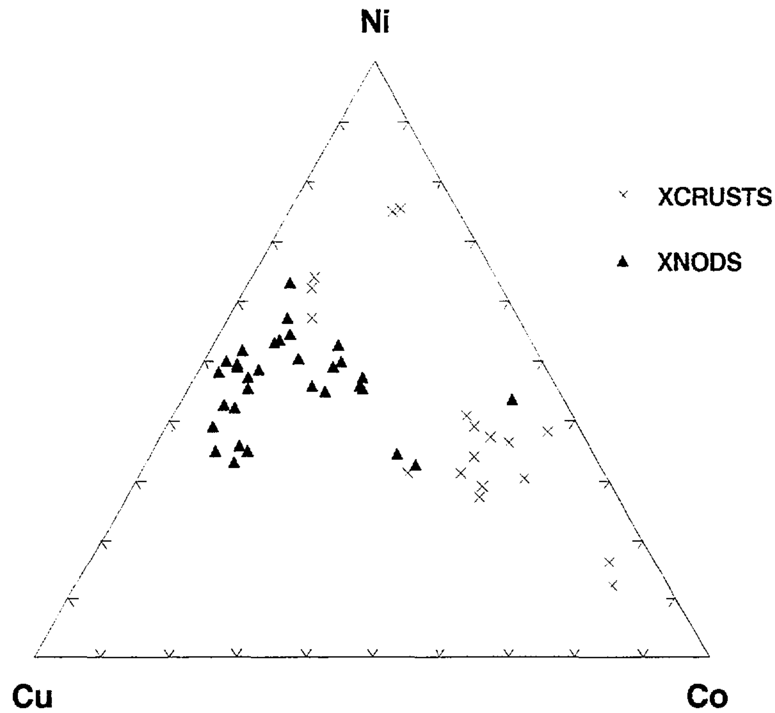


Figure 16. Plots of Ni+Cu% against Co% for Cruise 107 nodules (XNODS) and crusts (XCRUSTS), and for nodules from the Cook Islands (PACNODS: Exon, 1981) and the Central Indian Ocean (CIONODS: Jauhari, 1990).



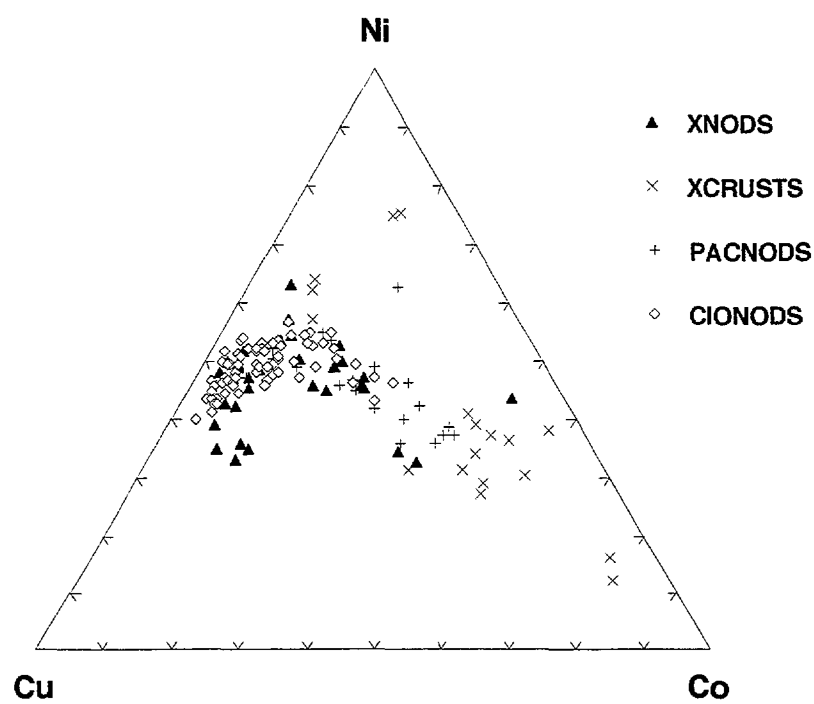


Figure 17 Triangular plots of percentages of Ni, Cu and Co for Cruise 107 nodules (XNODS) and crusts (XCRUSTS), and for nodules from the Cook Islands (PACNODS: Exon, 1981) and the Central Indian Ocean (CIONODS: Jauhari, 1990).

A correlation matrix for Cruise 107 nodules (Appendix 2) shows positive correlations (more than 0.6) between: Mn and Ni and Mo; Fe and V; Ni and Mg; Co and Pb, Ti, Sr, Zr, Y, and La; Zn and Mg; Pb and Ti, Sr, Zr, Y, La, and Ce; Si and Al and K; Al and K; Ti and Sr, Zr, Y, and La; Ca and P; Na and K; Sr and Zr, Y, and La; Zr and La; and Y and La. Moderate negative correlations (less than -0.7) are present between: Fe and Cu and Na; Si and Sr; Al and V; Ti and Mg; Na and V; and K and V. These correlations are not unusual in manganese nodules around the world.

Economic assessment of Christmas Island nodules

Despite the regional character of the sampling in the Christmas Island AFZ, there is now adequate information on which to assess the economic potential of deep sea manganese nodules in the area. Experience elsewhere has shown that such an assessment is unlikely to change substantially with more work. The key elements in any assessment are adequate sampling of both nodule distribution and metal grades, and that has been achieved.

According to the UN Ocean Economics and Technology Branch (1987) the major conditions for a viable nodule mine site are approximately:

Cutoff abundance	5 kg/m^2
Cutoff grade	1.8% Cu plus Ni
Topography	not extreme
Duration of recovery	20 years
Annual recovery	3 million dry metric tons
Efficiency of mining system	20%

Most mine sites declared so far have been about 150,000 km^2 in area.

Nodules are most common in the southwestern sector of the Christmas Island AFZ, furthest from the input of ash from the Indonesian volcanoes but, even there, they probably do not cover 50% of the sea floor. Figure 13 shows that about 40% of sea bottom samples in the sector contained nodules. Of the 23 free-fall grab stations in the sector, deliberately targeted on bathymetrically favourable locations, only 9 returned nodules, and it was unusual to recover nodules from all the deployments (generally three) at the successful stations. Where nodules were present, their abundance was generally not great and their size was not large. The result is that concentrations are mostly under the generally assumed cutoff concentration of 5 kg/m^2 (wet value). Only two stations had concentrations above the cutoff, the highest being 12 kg/m^2. Thus, on the first criterion for economic deposits, the concentration of nodules, the Christmas Island area fails.

The grades of the most valuable metals, Ni, Cu and Co, in the Cruise 107 Christmas Island nodules are listed in Table 13. This shows that Ni+Cu, the critical metals in most areas of the world ocean, average 1.00%, and that Co, of most importance in the Cook Islands, averages 0.12%. Only one sample, FFG25A2, contains more than the cutoff grade for Ni+Cu of 1.8% (value is 2.58%). The highest Co grade of 0.21% is low by world standards. Table 14 compares the Cruise 107 analyses with those from other areas, including those containing deep sea nodule mining leases: the central Indian Ocean and the north east Pacific Ocean. The average grades of Ni+Cu or Ni+Cu+Co are slightly better than those recorded by earlier analyses from near Christmas Island, comparable to grades from the Wharton Basin as a whole, and better than Indian Ocean averages. However, they are substantially worse than values from nodules recovered from areas of red clay and less than half those from areas of siliceous ooze, in the central Indian Ocean lease area. They are also less than half the values from the north east Pacific Ocean area of mining leases. Therefore, the Christmas Island nodules also fail the second criterion for economic fields, suitable metal grade.

TABLE 14. MN NODULE AND CRUST DATA FROM BMR CRUISE 107 AND OTHERS

Samples	Number	Mn (%)	Fe (%)	Cu (%)	Ni (%)	Co (%)	Cu+Ni+Co (%)
Cruise 107 crusts	14	16.2	6.75	0.11	0.35	0.44	0.91
Pacific Ocean crusts	319	22	15	0.08	0.44	0.63	1.15
Central Pacific crusts	311	23	15.7	0.47	0.12	0.79	1.38
Central Pacific outer crusts	102	25.05	14.2	0.06	0.51	1.02	1.59
Marshall Islands crusts		20.3	12.5	0.04	0.39	0.85	1.00
Cruise 107 nodules	24	19.7	4.6	0.49	0.51	0.12	1.13
Other Xmas nodules	8	18.3	14.7	0.37	0.52	0.17	1.07
CIB nodules (Si ooze)	45	26.1	7.7	1.19	1.22	0.14	2.55
CIB nodules (red clay)	44	22.2	10.7	0.68	0.92	0.21	1.81
Wharton Basin nodules	39	17.5	11.9	0.41	0.55	0.18	1.14
Indian Ocean nodules	324	15.4	14.8	0.27	0.46	0.23	0.96
NE Pacific nodules		22.4	8.2	1.02	1.16	0.25	2.43

Cruise 107: Cu+Ni+Co for rough (diagenetic) nodules = 1.30%; for smooth (hydrogenetic) = 0.92%
CIB = Central Indian Ocean nodule lease (after Sudhakar, 1989). Pacific crusts after Hein et al. (1992).

Overall, the Christmas Island nodules can only be regarded as a very long term resource. The relationship of nodule concentration to grade (Table 13) is discouraging, because concentrations of more than 5 kg/m2 coincide with low nodule grades (maximum 1.03% Cu+Ni+Co).

Within the Australian region the most valuable deposits known are those of the Cape Leeuwin nodule field, at 40° S off south west Australia. That field is part of a nodule pavement covering 900,000 km^2, so nodule concentrations are very high, but average grades are unexceptional at 1.15% Ni+Cu and 1.31% Ni+Cu+Co (Exon et al., 1990). The only other

Australian area that warrants further exploration for deep sea nodules is the area around the Cocos-Keeling Group, about 1000 km to the west of Christmas Island and nearer to the central Indian Ocean mining lease. That area shares favourable characteristics of water depth, remoteness from land, and sediment type with the leased area, and is well away from the volcanoes of Indonesia, whose ash may have inhibited nodule formation near Christmas Island.

MANGANESE CRUSTS

Nine of 12 dredge stations occupied on BMR Cruise 107 yielded rocks, and all but two of the dredge hauls with rocks also contained manganese crusts. The thicker crusts obtained from five stations were analysed for a wide range of metals. The analyses are summarised in Table 15 and detailed in Appendix 8. Brief descriptions for each dredge haul are provided under "Rocks and sediments dredged from seamounts" and in Appendix 1. The potential economic value of ferromanganese crusts depends on the thickness of the crusts and their grade of valuable metals, especially cobalt with preferred values of around 1% , and an aim of this work was to assess the economic potential of the crusts in the Christmas Island region.

The crusts occur as multiple layers, up to 20 cm thick, on any hard substrate, and are often interbedded with calcareous or phosphatic sediment, or volcaniclastic carbonate beds. Individual layers are up to five cm thick. The crusts vary from impregnated sediment to massive ferromanganese. Laminated crusts are generally uncommon apart from the uppermost few millimetres. Their surface is frequently microbotrytoidal in character. If these crusts have formed at the average rate prevailing in the Pacific Ocean, of 4.7 mm/m.y. (Hein et al., 1990), the thickest crusts could be as much as 40 m.y. old. However, it should be noted that the range of rates of formation in the Pacific Ocean is 1.5-16 mm/m.y., so the age of our crusts remains an open question.

Table 15 indicates that the average percentages for the main metals are 6.75% Fe, 16.19% Mn, 0.35% Ni, 0.11% Cu and 0.44% Co, and that Cu+Ni+Co averages 0.91%. Compared to central Pacific Ocean crusts (Table 14), probably the crusts with the most economic potential, the average values for all metals other than Ni are low. The oxygen minimum zone in the water column has been proven to coincide with the highest Co values in most parts of the world ocean. In this region the minimum values of less than 2 micromoles/kg lie between 400 m and 1000 m, and values of less than 3 micromoles/kg extend down to 2000 m (see "Oceanography"), and Co values could be expected to drop off slowly as the water deepens. Table 14 and Figure 14 show that the highest Co values of more than 0.8% (DR05/5 and DR 10/5A) are in the shallowest water depths.

Two thick crusts (DR06/2B and DR06/2C) were sampled at three depths below their surfaces, to see whether there were changes with depth in the crust, because it is common for the outer part to be richer in Co than the inner part. In these cases there is no significant decrease with depth in the crust.

TABLE 15. FERROMANGANESE CRUSTS ANALYSED FROM BMR CRUISE 107

Sample	Lat. S	Long. E	Fe wt.%	Mn wt.%	Mn/Fe	Ni wt.%	Cu wt.%	Co wt.%	Cu+Ni +Co%	Thickness cm	Location in crust	Water depth (m)
107/DR05/5	11.79	103.25	9.76	10.99	1.13	0.13	0.09	0.85	1.07	0.5	outer	1900-2800
107/DR06/2B1	10.03	103.94	8.34	20.28	2.43	0.37	0.14	0.39	0.9	0.5	outer	2800-3300
107/DR06/2B2	10.03	103.94	6.78	18.11	2.67	0.38	0.20	0.53	1.11	3.0	middle	2800-3300
107/DR06/2B3	10.03	103.94	5.80	14.40	2.48	0.20	0.08	0.38	0.66	3.0	inner	2800-3300
107/DR06/2C1	10.03	103.94	8.03	19.04	2.37	0.21	0.16	0.40	0.76	0.5	outer	2800-3300
107/DR06/2C2	10.03	103.94	6.92	16.56	2.40	0.32	0.12	0.42	0.86	2.5	middle	2800-3300
107/DR06/2C3	10.03	103.94	5.97	16.49	2.76	0.35	0.14	0.41	0.9	3.5	inner	2800-3300
107/DR06/2A	10.03	103.94	5.63	11.22	1.99	0.18	0.12	0.32	0.62	6.0	all	2800-3300
107/DR008/6	12.53	103.89	6.03	9.75	1.62	0.19	0.06	0.27	0.52	0.5	outer	3300-3700
107/DR10/5A	11.45	104.41	6.75	18.89	2.80	0.72	0.08	0.16	0.96	2.0	inner	1450-1520
107/DR10/5B	11.45	104.41	8.31	14.16	1.71	0.19	0.08	0.89	1.15	1.7	outer	1450-1520
107/DR11/2A	11.42	105.02	7.19	24.3	3.38	0.49	0.06	0.73	1.27	3.0	outer	1800-2800
107/DR11/2B	11.42	105.02	4.37	3.84	0.88	0.15	0.14	0.19	0.48	2.0	inner	1800-2800
107/DR11/2C	11.42	105.02	4.58	28.64	6.26	1.08	0.14	0.22	1.44	1.5	outer	1800-2800
AVERAGE			6.75	16.19	2.49	0.35	0.11	0.44	0.91	2.1		

Crossplots of various metal values against one another show the normal relationships. High Co values and low Ni+Cu values coincide with low Mn/Fe ratios (Fig. 15), and high Co values coincide with low Ni+Cu values (Fig. 16). A triangular plot of Co against Ni and Cu (Fig. 17) shows that all crusts have low proportions of Cu, and that some crusts are relatively rich in Ni and others in Co. There are not enough analyses to be sure whether or not there is a continuum between high Co and high Ni values.

A correlation matrix for 14 analyses from Cruise 107 crusts (Appendix 2) shows strong positive correlations (more than 0.8) between: Mn and Cu and Zn; Fe and Pb, Ti, P, Sr, Zr, Y, La and V; Ni and Cu; Cu and Zn; Co and Ti; Zn and Na; Pb and Sr, Zr, Y, La, and V; Si and Al; Ti and P and Zr; Na and K; P and Zr and La; Sr and Zr, Y, La and V; Zr and La and V; Y and La; and La and V.

Economic potential of Christmas Island crusts

According to Hein (1990) the commonly cited cutoff thickness for manganese crusts is 4 cm, and many of the Christmas Island crusts are thicker than that. The commonly cited cutoff grade is 0.8% Co, and only two of the 14 analyses on crusts from this cruise have higher values (Table 15). The four crusts previously analysed from the region all have Co values well under the cutoff (Table 5). However, most of the crusts dredged on Cruise 107, and all the crusts dredged earlier, come from deeper than the optimum water depth of 500-2000 m (see discussion above). The six crusts from this cruise that could have come from shallower than 2000 m (dredges 5, 10 and 11) include the two values of greater than 0.8%, and their analyses average 0.51% Co.

Given that the oxygen minimum zone in the water column is actually between 400m and 1000 m (see discussion above), optimum water depths for the deposition of Co-rich manganese crusts in the region are probably around 500-1500 m at present, depths shallower than any sampled so far. Although the volcanic pedestals on which the crusts sit, and the oxygen minimum zone, will have moved relative to sea level over time, there is little apparent change in Co values with age in our analyses, as represented by depth in the crusts. This suggests that the present sample depths and oxygen minimum zone are useful indicators of where one should seek higher grade crusts. Including Christmas Island, there are four culminations on volcanic edifices that rise above 1500 m below sea level in the Australian Fisheries Zone, all in the Vening-Meinesz chain, and these should be the primary targets of any future sampling for Co-rich manganese crusts. Secondary targets would be the other eight culminations which rise above 2000 m, all but one of which are south and west of Christmas Island.

In summary, the analyses obtained to date have average values of Co equivalent to those elsewhere in the world. The thickness of the crusts is well above the assumed cutoff value of 4 cm, and two of the analyses are above the cutoff grade for Co of 0.8%. At face value, the results have not been particularly encouraging, but the samples have all come from deeper than the optimum water depths for high Co grades. There are volcanic edifices that lie within the more prospective water depths of 500-2000 m, and they should be sampled when the opportunity arises.

FORAMINIFERAL BIOSTRATIGRAPHY OF DREDGE SAMPLES

(G.C. Chaproniere and P.J. Coleman)

Introduction

Forty seven samples from ten dredge hauls made during Cruise 107, Christmas Island area, yielded foraminiferids with ages ranging from Late Cretaceous to Holocene, with a cluster of samples of late early/earliest middle Eocene age. Some samples are mixtures, suggestive of debris flows and some contain lithologies of differing ages. The depositional environments vary; most were upper to middle bathyal, but some were deep bathyal.

Most dredge hauls were located on, or near, the summits of seamounts in the general area of Christmas Island, north eastern Indian Ocean. The location of the dredge sites are shown in Figure 6 and their depths in Tables 1 and 9.

The samples were selected from each dredge haul on the basis of lithological variation and on subjective estimation of fossil promise. The sample numbering follows that described in "Rocks and sediments dredged from seamounts" earlier in this report.

This study gives the results of foraminiferal analyses of the dredge samples. Most samples were studied by thin-section but a few could be disaggregated, picked over, and specimens obtained for study under the SEM.

The predominant use of thin-sections explains why many of the identifications are hedged by the use of queries or by open nomenclature. A query implies that the identification is reasonably certain but not absolute because among the limited number of random cross-sections no critically diagnostic cross-section was seen. Open nomenclature has the usual connotations. Despite these qualifications, we feel confident that there are no misleading identifications.

The lithology and sedimentary features of the samples are discussed under "Rocks and sediments dredged from seamounts" earlier in this report. In this section, for each sample only a brief summary of the sediment is given, and those features which affect the biostratigraphical conclusions are stressed; for example, some samples consist of lithologies of differing ages.

Samples are discussed in order of dredge number; they are arranged by age in Table 16.

A few samples were quite unproductive of age-diagnostic fossils and lacked noteworthy lithology, but they are included here nevertheless. Other samples produced ages that differ from those obtained using nannofossils (see "Calcareous nannofossil biostratigraphy of rocks from seamounts near Christmas Island", in this report); this difference is almost certainly due to the use of different samples, and to the minute amount of sample required for the study of nannofossils compared with that for foraminiferids.

The Samples

Dredge 1

1/1A - Volcanic breccia with micrite cement. Contains altered molluscan, algal and ?coral fragments. No age-diagnostic fossils.

1/1Bi and ii - Bioclastic grit with igneous clasts, cemented by calcite spar. Bioclasts rounded and recrystallised and include fragments of mollusc, especially bivalve, and echinoids. No age-diagnostic fossils.

1/3A - As for 1/1A above with gastropod and bivalve fragments. No age-diagnostic fossils.

1/6A - volcanic ?breccia - unfossiliferous carbonate clasts with pelagitic micrite, manganiferous and containing specimens of *Morozovella ?caucasica, M. spinulosa* group, "*Globigerina*" sp. cf. *G. senni, Acarinina bullbrooki* group, and ?*Subbotina linaperta.* A deepwater, bathyal sediment mixed with shallow water volcanic debris. Age - Probably Zones P9 to P10, latest Early to earliest Middle Eocene.

1/6B - Lithology and biota similar to 1/6A but with much more manganese and glass, suggestive of derivatives of sea floor eruption. Suggested age: Zones P9 to P10, latest Early to earliest Middle Eocene.

1/6C - Highly recrystallised, unfossiliferous carbonate fragment.

1/7A - Altered limestone with solution cavities filled with planktic foraminiferal ooze, probably modern, with *Globorotalia (Truncorotalia) crassaformis* and specimens of *Globorotalia (Globorotalia) cultrata* group

1/8A - As for 1/1Bi and ii, above. All bioclasts rounded and recrystallised; very small non-diagnostic planktic foraminiferids present.

1/8B - Algal micritic bioclastic grit, somewhat altered, with glassy volcanic clasts, echinoid and bivalve fragments, textulariine foraminiferids and rare planktic foraminiferids -- including *Acarinina* sp., *Morozovella* sp. cf. *M. caucasica* and *Rugotruncana ?subpennyi*. A mixed debris flow including eroded Maastrichtian sediment washed into pelagite of age Zone P8 to P10 (latest Early to earliest Middle Eocene).

Dredge 3

3/1A - Recrystallised micritic limestone with fossiliferous and igneous clasts. Fragments of echinoid, ?rudist mollusc, coralline algae and possible sponge spicules are present, as also a questionable *Globotruncana* sp. Age: possibly Late Cretaceous.

3/1B - Molluscan bivalve grainstone, recrystallised, with small volcanic clasts, algal pieces, molluscan fragments including *Inoceramus* sp., rare echinoid plates, bryozoa, and a piece of a questionable rudist. Foraminiferids are infrequent, generally not diagnostic. Sediment is a gravity flow debris deposit. Age: Probably Late Cretaceous.

3/1C - as for 3/1B above.

3/2 - as for 3/1A but without foraminiferids.

3/3A - Coarse gritty igneous fragments set in a micritic cement. Bioclasts uncommon but include bivalve fragments and the planktic foraminifer *Globotruncana* sp. cf. *G. mayaroensis*. Age: probably late Maastrichtian.

3/5A - Recrystallised micritic limestone with Mn-coating filling cavities. No fauna. Age: indeterminate.

3/5B - Broken micritic limestone, probably a shallow water coquinoidal hash, with coarse fragments, highly altered. Contains dominant bivalve "ghost" fragments with rare echinoid and coralline algal grains. Planktic foraminiferids are rare and indeterminate. Age: indeterminate.

3/6 - Shelly "hash" with bivalves and gastropods, echinoid plates, rare bryozoa, coralline and other algae (often altered) and with rare foraminiferids (not diagnostic). Fairly well sorted with a preferred alignment. Suggest shallow water (<50 m). Age: indeterminate.

3/6A - Carbonate grainstone with volcanic clasts and bioclasts set in a micritic matrix. Bioclasts commonly altered and include abundant algal and bryozoan material, bivalves (including ?*Inoceramus*) and echinoid pieces, and rare foraminiferids (not diagnostic). Shallow water deposit. Age: ?Late Cretaceous.

3/7 - Recrystallised micritic limestones. No fauna. Age: indeterminate.

3/8 - Recrystallised dicrotic limestones. Bioclasts of molluscs (bivalves and ?rudist). Age: indeterminate (possibly Late Cretaceous).

3/9 - As for 3/5A above but with fragments of molluscs and echinoids. Age: indeterminate.

Dredge 4

4/1 - Calcarenite with micritic/sparry cement and with a mixture of coarse and fine lithic and crystalline volcanic grains and bioclasts including larger foraminiferids; these larger grains appear to be derived exotics. Abundant planktic foraminiferids in the finer bands include *Globotruncana ?conica, Globotruncana ?G. contusa (=Rosita contusa), G. ?falsostuarti, G. ?gansseri, G. ?arca, Gublerina cuvillieri, Planoglobulina acervulinoides, Racemiguembelina fructicosa*. The exotic specimens of larger foraminiferids are probably *Lepidorbitoides* sp. cf. *L. socialis*. Also present are coralline algae and molluscan pieces. This sediment is a mixture of worked-over shallow water debris carried into deeper water (?upper bathyal). Age: Late Cretaceous - Maastrichtian.

4/1A - Grainstone mixture with lithic volcanic clasts and bioclasts, comparable with 4/1. Contains *Rosita* sp. cf. *R. contusa*, *Globotruncana arca, G.* sp. cf. *G. aegyptica*, tricarinate *G. ventricosa*, *Planoglobulina acervulinoides*, and *Racemiguembelina fructicosa*. There are also fragments of molluscs (notably *Inoceramus)*, coralline red algae, echinoids, and some bryozoa. This is probably a storm surge deposit, a mixture of shallow water debris carried into deeper water (upper bathyal ?). Age: Late Cretaceous - Maastrichtian (ca. K30-31?).

4/2A - Similar to 4/1 and 4/A above but fewer planktic foraminiferids. Calcareous grainstone with micrite, with sparry cement and with lithic volcanic clasts and bioclasts. Rare planktic foraminiferids also include *G. ?mayaroensis.* Coralline algae are common also molluscan debris (aragonitic fragments altered). Bivalves include *Inoceramus* sp. and also likely rudist pieces. The larger foraminifer *Lepidorbitoides* sp. cf. *L. socialis* is present. This sediment is a mix of high energy shallow and deeper water deposits. Age: Late Cretaceous, possibly late Maastrichtian.

Dredge 5

5/1A - Calcwacke with micrite and sparry cement. Contains bryozoan fragments, echinoid spines, rolled coralline algae. Foraminiferids include *Asterocyclina* sp. cf. *A. matanzensis*, *Heterostegina* sp. cf. *H. saipanensis*, *Operculina pacifica, Discocyclina omphala,* and ? *Rotalia* sp. Planktics include members of *Acarinina bullbrooki* group, *A. ?broedermanni, Morozovella aragonensis, "Globigerina" senni, Subbotina* sp. cf. *S. linaperta* and *S. ?inaequispira*. This is a shallow-water mixed sediment (?lagoonal sludge). Age: Zones P8 to P11 (latest early to earliest middle Eocene).

5/1B - Calcwacke very similar to 5/1A. Similar fauna but with *?Truncorotaloides rohri*, *Subbotina eocaena* group and *Pseudohastigerina micra*. Age: Zones P8 to P11 (latest early to earliest middle Eocene).

5/1Bi and ii - Same as above, but with large oncoliths containing an encrusting foraminiferid *Ladoronia vermicularis*; *Sphaerogypsina globula* and *Morozovella ?spinulosa* are also present. Age: as above.

5/2A - Lithic volcanic algal wacke with micrite. Bioclasts include algal balls, bryozoa, ostracods, echinoid plates. Foraminiferids as for 5/1A. This sediment represents a high-energy shallow water deposit transported down slope to deeper water: (ca. 100 m). Age: Zones P8 to P11 (latest early to earliest middle Eocene).

5/3A - Wacke with micrite, similar to 5/1A. Bioclasts include molluscan remains (altered), bryozoa and also specimens of *Asterocyclina* sp. cf. *A. matanzensis*, *Operculina pacifica, Discocyclina omphala*. These larger foraminiferids are fresh, not eroded or redeposited and probably are synchronous with the planktics. Planktic foraminiferids include *Acarinina bullbrooki* group, *A. ?broedermanni, Morozovella ?aragonensis, M. ?caucasica, M. ?spinulosa, "Globigerina" senni, Subbotina* sp. cf. *S. eocaena* group. Coarse sediment has been transported into a pelagitic host material. Age: Zones P8 to P10, latest early to earliest middle Eocene.

5/3B - as for 5/1B above but biota also includes *Subbotina ?linaperta* and *S. ?inaequispira* and coralline algae. Age: Zones P8 to P11 (latest early to earliest middle Eocene).

5/3C - lithology as for 5/1B. Debris-laden pelagite with exotic larger foraminiferids, bryozoa and echinoid spines; abundant planktic foraminiferids in micrite. Foraminiferids include a few *Discocyclina omphala,* rare *Asterocyclina* sp. cf. *A. matanzensis*, and planktics *Acarinina bullbrooki* group, *A. ?broedermanni, Morozovella ?aragonensis, M. ?caucasica, M. ?spinulosa,* and *"Globigerina" senni.* Age: Zones P8 to P10, latest early to earliest middle Eocene.

5/4A - similar to 5/3C. Pelagite with admixed shallow water debris. Shallow water clasts include echinoid spines, bryozoa fragments and fragments of *Discocyclina* sp. Planktic foraminiferids abundant, with *Acarinina bullbrooki group, A. ?broedermanni, Morozovella ?aragonensis, M. ?caucasica, M. ?spinulosa,* and *"Globigerina" senni.* Age: Zones P8 to P10, latest early to earliest middle Eocene.

5/4B - lithology as for 5/1A above. With *Operculina pacifica, Discocyclina omphala, Asterocyclina ?matanzensis.* Coralline algae and larger foraminiferids are fresh, not eroded or redeposited and probably are synchronous with the planktics. Planktic foraminiferids include *Acarinina bullbrooki* group, *A. ?broedermanni, Morozovella ?aragonensis, M. ?spinulosa, "Globigerina" senni, Subbotina* sp. cf. *S. eocaena* group, *S ?linaperta, S. ?inaequispira* and *Pseudohastigerina micra.* Age: Zones P8 to P11 (latest early to earliest middle Eocene).

5/7 - Calcwacke, with bioclasts set in micrite and sparry cement. Contains large bryozoan fragments, coralline algae and rolled algal balls, rare ostracods and foraminiferids (not diagnostic). Shallow water high-energy deposit. Compare with 5/2A; probably upper to mid-bathyal. Based on this comparison, age may be mid-Eocene.

Dredge 6

6/4A - Pelagite, in part with manganese coating and penetration. Planktic foraminiferids include *Acarinina bullbrooki* group, *A. ?broedermanni, M. ?caucasica, M. ?spinulosa,* and *"Globigerina" senni, ?Subbotina eocaena group.* Deepwater bathyal pelagite. Age: Zones P8 to P10, latest early to earliest middle Eocene.

6/4A-2 - Similar lithology but with planktics of *Dentoglobigerina tripartita* group, ?*Subbotina eocaena* group and ?*Turborotalia centralis*. Age: Zones P12 to P17 (late middle to late Eocene).

6/5 - Brecciated micrite with different lithological types, altered in part and zeolitised. The cavity infill has *Acarinina bullbrooki* group, *Morozovella ?aragonensis, ?Subbotina eocaena* group, *Dentoglobigerina tripartita* group, and ?*Turborotalia centralis*. Two assemblages are present, with ages Zones P8 to P11 (- latest early to earliest middle Eocene) and P12 to P17 (late middle to late Eocene), respectively. The sparry infill has *?Globorotalia (Globorotalia) tumida, ?G. (Globoconella) inflata,* and *Globigerinoides sacculifer* with age of Late Miocene to Holocene. Depositional history complex, possibly with transported Eocene material infilling solution cavities in much younger sediment; alternatively, this sediment might be a polymict breccia (cf. sample 10/2A).

6/5A - Recrystallised micritic limestone. The presence of *Globotruncana ?arca* and *G. ?ventricosa* indicate an age of Late Cretaceous, probably late Campanian to early Maastrichtian.

6/7A - Fractured, recrystallised fine-grained limestone. With molluscan fragments including a possible rudist. Age: Late Cretaceous.

6/8 - Mix of pelagite micrites, manganiferous, with *Globotruncana ?arca, G. ?ventricosa,* and *G. ?lapparenti.* Deepwater, mid-bathyal. Age: Late Cretaceous (late Campanian to early Maastrichtian).

6/13 - Pelagite with volcanic content and manganiferous (cf sample 6/8). Planktic foraminiferids include *Globotruncana ?arca, G. ?ventricosa* and tricarinate, *G. ?lapparenti*. A deepwater, at least mid-bathyal, sediment. Age: late Campanian to early Maastrichtian. A second slide also includes *Globigerinelloides ?ultramicra/praerihillensis, ?Hedbergella holmdelensis* and *?Archaeoglobigerina blowi* and confirms this age.

Dredge 8

8/1A - Debris flow wackestone with micrite, volcanic content; manganiferous. Contains molluscan debris including *Inoceramus* sp. and rudist fragments. Shallow water forms transported into deep water. Age: Late Cretaceous.

8/7 - as for 8/1A above.

Dredge 9

9/2 - Pelagite. Contains spicules and possible radiolarian remains. No age-diagnostic forms. Deepwater, ?lower bathyal. Age: indeterminate.

Dredge 10

10/2A - A complex sediment - turbiditic wacke, layered, with volcanic clasts and bioclasts in a micritic cement. Many bioclasts and other parts have been dissolved and the resultant cavities infilled with presumably younger fine grained sediment with planktic foraminiferids. The original bioclasts are composed mainly of coralline algae, bivalve fragments, echinoids. Planktic foraminiferids include *Globotruncana* sp. cf. *G. arca* and *Rosita contusa* indicating a Maastrichtian age. The solution cavities appear to intersect infill of different ages. The oldest is made up of small globigerine and turborotaline morphology, not very diagnostic of age. These foraminiferids have the appearance of typically middle Oligocene forms, with low species-diversity; they do not include Eocene and Neogene forms. Morphotypes typical of *Tenuitella* spp., *Globigerinita* spp., *Globigerina praebulloides* and *G. ciperoensis* are present but not *Globorotalia (Fohsella) kugleri*. In some of the matrix *Globorotalia (Globorotalia) ?cultrata* group is present indicating a middle Miocene to Holocene age.

10/2B - Turbiditic grainstone, with volcanic clasts and with algae, molluscan (bivalve) fragments including *Inoceramus* sp. and rudists. Also with occasional ostracods, bryozoa. High-energy shallow water material carried down slope as part of a turbidite flow. Age: Late Cretaceous, probably Maastrichtian.

10/3 - Planktic foraminiferal wackestone with common *Turborotalia ?ampliapertura, ?T. euapertura, Dentoglobigerina tripartita* group. *D. ?venezuelana,* small globigerines such as *?Globigerina ciperoensis, G. praebulloides* and *G. officinalis*. Typical late Eocene forms such as *Turborotalia cerroazulensis* group are absent. Deepwater, middle or lower bathyal turbiditic pelagite. Age: probably Zone P19/20 (early Oligocene).

10/4 - Planktic foraminiferal wackestone including *Acarinina* sp. cf. *A. bullbrooki, A. ?broedermanni, Morozovella ?caucasica,* and "*Globigerina*" *senni*. Deepwater, mid-to-lower bathyal. Age: Zones P8 to P10, latest early to earliest middle Eocene. This sample differs markedly from other samples in dredge 10. The assemblage is closest to those from dredges 1 or 6.

10/4A - Planktic foraminiferal wackestone with common *Turborotalia cerroazulensis cerroazulensis, Subbotina eocaena* group, *S ?linaperta,* "*Globigerina*" *senni* and *Globigerinatheka index*. Age: Zones P14 to P16 (late Eocene).

10/6 - Chalky pelagite with frequent planktic foraminiferids including *Globorotalia (Globorotalia) cultrata cultrata, G. (G.) cultrata menardii, G. (Obandyella) scitula, G. (Truncorotalia) crassaformis* group, *?Globigerinoides conglobatus,* and *?Globigerinoides obliquus extremis.* Deepwater mid-bathyal sediment. Age: Zone N19-20 or younger (Pliocene or younger).

TABLE 16. SUMMARY OF BIOSTRATIGRAPHIC RESULTS FOR FORAMINIFERIDS.

Age		Sample
Quaternary		1/7
Pliocene		6/5, 10/2A (both mid/late Miocene to Holocene), 10/6
Miocene		
Oligocene		10/3
Eocene	Late	6/4A, 10/4A
	Middle	1/6, 1/6B, 1/8B, 5/1A, 5/1B, 5/1Bi and ii, 5/2A, 5/3A, 5/3B, 5/3C, 5/4A, 5/4B, 5/7, 10/4
	Early	
Paleocene		
Maastrichtian		4/1, 4/1A, 4/2A
Cretaceous - Late		3/1A, 3/1B?, 3/1C?, 3/6A?, 6/5A, 6/7A, 6/8, 6/13, 8/1A, 8/7

Conclusions

The ages of these samples, as summarised in Table 16, supports the notion that the seamounts had ceased active volcanism before the Late Cretaceous. By the Maastrichtian, water depths had increased sufficiently to attract pelagic sedimentation with component planktic foraminiferids. Some intermittent end-stage volcanism is suggested by the volcanic igneous content of some of the Late Cretaceous/Maastrichtian samples. The absence of Paleocene/earliest Eocene is not explained by our samples (that is, whether this absence is to be explained by erosion or by non-deposition).

Most samples are of latest early to earliest middle Eocene age (Zones P8 to P10 or P11). Most of these indicate deposition at bathyal depths with admixtures of shallower sediments and faunas by way of turbidite and debris flows. Depositional depths appear to have increased during the Neogene, an accompaniment to crustal and subcrustal cooling.

The sedimentary and faunal character of these samples by and large fits the location from which they were dredged, namely near-summit positions on steep-sided volcanic seamounts. The foraminiferids suggest Tethyan warm water environments, at least subtropical e.g. *Morozovella* spp. The area surveyed by Cruise 107 was at a latitude of roughly 38° S during the Early Eocene. The foraminiferids strengthen the notion that early-earliest middle

Eocene oceanic temperatures were warmer at higher latitudes than they are today.

CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY OF ROCKS DREDGED FROM SEAMOUNTS NEAR CHRISTMAS ISLAND

(Samir Shafik)

Introduction

Calcareous nannofossils from dredges obtained during BMR cruise 107 indicate that the sediments on several seamounts in the Vening-Meinesz chain, nearby Christmas Island, range in age from Late Cretaceous to Pleistocene (Table 17). Most of the assemblages are mixed, but not necessarily because of reworking. One possible scenario is that younger unconsolidated nannofossil-bearing sediments infiltrated older sediments where the latter were heavily bored or broken down by subaerial erosion.

Late Cretaceous

Three Late Cretaceous assemblages were identified from dredge 107/DR06 which was obtained from a seamount in the Vening-Meinesz chain at 11° 02.0'S, 103° 58.1'E where waters are 3227 - 2830 m deep. The top of this seamount lies at 2500 m below sea level.

Late Campanian and Maastrichtian

Sample 107/DR06-8A, a moderately lithified chalk, yielded rare, poorly preserved nannofossils. The species *Arkhangelskiella cymbiformis* (small form), *A. specillata*, *Broinsonia parca*, *Chiastozygus litterarius*, *Ceratolithoides aculeus*, *Cretarhabdus surirellus*, *Cribrosphaerella ehrenbergii*, *Eiffellithus eximius*, *Gartnerago obliquum*, *Heterorhabdus sinuosus*, *Lithraphidites carniolensis*, *?Lucianorhabdus cayeuxii*, *Micrarhabdulus decoratus*, *M. helicoideus*, *Micula staurophora*, *Parhabdolithus embergeri*, *Placozygus sigmoides*, *Prediscosphaera cretacea*, *P. grandis*, *P. majungae*, *Quadrum gothicum*, *Q. trifidum*, *Eiffellithus eximius*, *Tetrapodorhabdus decorus*, *Tranolithus exiguus*, *Watznaueria barnesae* and *Zygodiscus bicrescenticus* could be identified.

The co-occurrence of *Broinsonia parca*, *Eiffellithus eximius*, *Quadrum trifidum*, and *Reinhardtites levis* indicates a late Campanian age. The stratigraphic range of *Q. trifidum* straddles the Campanian/Maastrichtian boundary. According to Sissingh (1977), *R. levis* first appears during the late Campanian (his CC22 Zone). Shafik (1990) has used the highest occurrence of *B. parca* to delineate the Campanian/Maastrichtian boundary in the Tropical Province.

The presence of *Gartnerago obliquum* suggests possible reworking from older Upper Cretaceous sediments.

Examination of another preparation from the same sample revealed a similar assemblage, except for the rare presence of the key species *Lithraphidites quadratus,* which is known to range from middle to late Maastrichtian. The presence of species such as *Broinsonia parca, Eiffellithus eximius, Reinhardtites levis* and *Quadrum trifidum* in the assemblage containing the key Maastrichtian *L. quadratus* suggests possible reworking from older sediment or mixing of sediments. The sample contains several lithologies, which probably were deposited at different times.

The absence of cool-water species, recorded from coeval sediments in the onshore Perth and Carnarvon Basins (see Shafik, 1990), and the presence of *Quadrum trifidum, Q. gothicum* and *Ceratolithoides aculeus,* is consistent with a lower latitude position for this assemblage than for assemblages from both the Perth and Carnarvon Basins.

Middle Maastrichtian

Rare, poorly preserved nannofossils suggestive of middle Maastrichtian age were identified in sample 107/DR06-13, a light brownish grey, carbonate mudstone. In addition, rare nannofossil species indicative of a younger age range were identified. Examples include extremely rare *Coccolithus eopelagicus* and *Reticulofenestra scissura,* which suggest an Eocene-Oligocene age range, rare *Calcidiscus leptoporus* and *Discoaster pentaradiatus* which suggest a Quaternary age, and an occasional Quaternary-Holocene *Gephyrocapsa oceanica*. Contamination through sampling is possible, but original mixing of sediments on the seamount cannot be ruled out.

This Maastrichtian assemblage is similar to that recorded from 107/DR06-08A except for the presence of *Actinozygus regularis,* small *Biscutum constans, Bukrylithus hayii, Calculites obscurus, Corolithion signum, Cyclindralithus serratus, Eiffellithus gorkae, E. turriseiffeli, Lithraphidites quadratus, Micula quadratus* and *Prediscosphaera spinosa.* The species *Quadrum trifidum* was not encountered in the 107/DR06-13 assemblage.

The presence of *Lithraphidites quadratus*, in the absence of younger Maastrichtian species such as *Micula murus*, suggests a middle Maastrichtian age, between 68.5 and 67 Ma. The assemblage includes evidence of reworking from older sediments, such as *Bukrylithus hayii* which Perch-Nielsen (1985) restricts to the early Campanian. Other displaced species probably include *Broinsonia parca* and *Eiffellithus eximius,* which are also known from lower Campanian sediments. The tops of the stratigraphic ranges of these species are thought to be near the Campanian/Maastrichtian boundary (Thierstein, 1976; Shafik, 1990).

The presence of reworked *Bukrylithus hayii*, suggests the occurrence of lower Campanian sediments on the seamount, underlying the upper Campanian chalk referred to above.

Marginal marine conditions are indicated by the presence of both *Calculites obscurus* and *Lucianorhabdus cayeuxii* (Thierstein, 1976). The stratigraphic ranges of these two species cover a substantial part of the Late Cretaceous extending into the Maastrichtian, but they may be reworked.

The assemblage lacks the cool-water species recorded from the Maastrichtian of the onshore Perth and Carnarvon Basins (see Shafik, 1990), like the 107/DR06-08A assemblage. The presence of *Quadrum. gothicum Ceratolithoides aculeus* and probably *Micula quadratus* is consistent with a lower latitude compared to assemblages from both the Perth and Carnarvon Basins.

Discussion.

It seems that the sedimentary succession on the seamount dredged at station 107/DR06 includes lower and upper Campanian, and middle Maastrichtian, carbonates which are similar lithologically. Deposition took place in marginal marine environments at palaeolatitudes lower than in the Carnarvon Basin.

To account for the co-occurrence of reworked older species and the much younger Cainozoic species, together with the Maastrichtian elements, recycling and some mixing of these carbonates seem to have occurred during deposition. Also, erosion leading to fragmentation and formation of rocks consisting of mixtures of various fragments seems to have taken place.

Late Maastrichtian

A meagre, monogeneric nannofossil assemblage consisting of *Micula concava, M. murus, M. staurophora, M. swastika* and *M.* sp. aff. *M. murus*, was recovered from sample 107/DR06-04, a phosphatised, fine-grained, pelagic carbonate containing subangular basalt clasts. *Micula murus* indicates late Maastrichtian age, between 67 and 65.5 Ma. The low diversity of the assemblage is probably due to a stressful shallow-water palaeo-environment.

The Maastrichtian assemblages suggest a palaeolatitudinal position north of the Carnarvon Basin, agreeing well with the Campanian assemblage on the same seamount. For example, the late Maastrichtian assemblage (sample 107/DR06-04) lacks the cool-water indicator *Nephrolithus frequens* found in the Carnarvon and Perth Basins, and contains the warm-water species *Micula murus* which is found in the Papuan Basin. These two species co-occur in extratropical assemblages in the Carnarvon Basin: *M. murus* being less frequent than in the tropical assemblages of the Papuan Basin, and *N. frequens* being less frequent than in the austral assemblages in the Perth Basin where other cool-water species are known (e.g. *Cribrosphaerella daniae*) (Shafik, 1990).

Eocene

Two Eocene assemblages were identified. The older, Early Eocene assemblage, was found in three lithotypes from dredge 107/DR05 which was obtained at 11° 48.0'S, 103° 14.8'S, where waters are 2800 - 1900 m deep. The younger, Late Eocene assemblage, came from dredge station 107/DR10 on a seamount at 11° 27.0'S, 104° 24.3'E rising to 1200 m below sea level. The water depth dredged was between 1515 and 1445 m.

Early Eocene

The three lithotypes from dredge 107/DR05, which yielded Early Eocene nannofossils, are (a) white micritic carbonate wackestone with abundant larger foraminiferids (107/DR05-01); (b) white, friable foram chalk (107/DR05-03); and (c) white, heavily bioturbated carbonate mudstone (107/DR05-04). In each, the fossils are rare and poorly preserved. Recrystallisation of coccoliths, and the presence of secondary calcite covering the discoasters, seriously hampered species identification in some cases. Species identified from samples 107/DR05-01B, 107/DR05-03B and 107/DR05-04B are *Chiasmolithus grandis*, *Coccolithus formosus*, *C. pelagicus*, *Cyclicargolithus gammation*, *Discoaster lodoensis*, *Zygrhablithus bijugatus crassus* and unidentifiable species of *Discoaster* and *Micrantholithus*. In addition it was possible to identify *Campylosphaera dela*, *Coccolithus magnicrassus* and *Discoasteroides kuepperi*, *?Pontosphaera plana* and unidentifiable species of *Chiasmolithus* in samples 107/DR05-1A and 107/DR05-03B; *?Calcidiscus protoannulus*, *?Discoaster sublodoensis*, *Sphenolithus moriformis* and *S. radians* in 107/DR05-01A; and *Braaudosphaera bigelowii*, *Discoaster barbadoensis*, *D. lodoensis*, *D. multiradiatus* and unidentifiable species of *Rhabdosphaera* in sample 107/DR05-03B.

The co-occurrence of the key species *Chiasmolithus grandis, Cyclicargolithus gammation* and *Discoaster lodoensis* in all three assemblages indicates a maximum age of Early Eocene. *Discoaster sublodoensis* is known to range into the Middle Eocene, and its association with *Rhabdosphaera inflata* has been used to indicate Middle Eocene age (see, e.g. Okada & Bukry, 1980). The apparent absence of the latter species is consistent with an Early Eocene age, but it could be a preservational artefact as suggested by the poor preservation.

The presence of pentaliths and *Zygrhablithus bijugatus* indicates a marginal marine palaeoenvironment; deposition was probably in shallow water.

Sample 107/DR05-07, a white, hard calcilutite, contains very rare nannofossil specimens. Preservation is very poor, mainly due to diagenetic processes, especially recrystallisation. *Campylosphaera dela*, *Coccolithus formosus, ?C. magnicrassus, C. pelagicus*, *?Discoaster lenticularis,* and small placoliths are present. The age is probably Early Eocene, based on the presence of *C. dela.*

<u>Late Eocene</u>

Carbonates recovered from dredge 107/DR10 contain nannofossils suggestive of Late Eocene and Late Oligocene ages. This dredge was obtained at 11° 27.3'S, 104° 24.4'E, from waters 1515 - 1445 m deep.

Sample 107/DR10-4A , a fine-grained white chalk, yielded abundant poorly-preserved nannofossils. The assemblage identified includes *Bramletteius serraculoides, Coccolithus eopelagicus, C. formosus, Coronocyclus nitescens, Cyclicargolithus floridanus, ?C. reticulatus, Discoaster barbadoensis, D. deflandrei, D. saipanensis, ?Helicosphaera compacta, Lanternithus minutus, Pedinocyclus larvalis, Reticulofenestra scissura, R. scrippsae, R. umbilicus, Sphenolithus moriformis, S. predistentus, S. radians* and *Zygrhablithus bijugatus*. The co-occurrence of *Bramletteius serraculoides, ?C. reticulatus, Discoaster barbadoensis* and *D. saipanensis* suggests a Late Eocene age.

The presence of the holococcoliths *Lanternithus minutus* and *Zygrhablithus bijugatus* suggests marginal marine conditions. That discoasters and sphenoliths are frequent, and chiasmoliths (e.g. *Chiasmolithus oamaruensis*) are virtually absent, indicates that during the Late Eocene, surface waters were warm, consistent with a low-palaeolatitude.

Oligocene

Two lithotypes from dredge 107/DR10, namely white, fine-grained chalky ooze (107/DR10-06), and white chalk (107/DR10-04), were examined. The former yielded Late Oligocene nannofossils, and the latter contains mostly Eocene species. The fossils in sample 107/DR10-06A are abundant and moderately preserved, but in sample 107/DR10-04 they are rare and poorly preserved. It is possible that the Late Oligocene soft chalky ooze of 107/DR10-06A has contaminated the possibly older firmer chalk of

107/DR10-04. The associated sample 107/DR10-04A, discussed above, yielded a poorly preserved Late Eocene assemblage.

107/DR10-06A

The rich assemblage of 107/DR10-06A is dominated by *Cyclicargolithus abisectus*, *C. floridanus*, *Discoaster deflandrei* and *S. predistentus*. Less abundant species (present in appreciable numbers, being frequent to common) include *Coccolithus eopelagicus*, *C. pelagicus*, *Coronocyclus nitescens*, *Sphenolithus ciperoensis*, *S. distentus*, *S. moroformis*, *S. pseudoradians*, *S. radians*, *?Triquetrorhabdulus carinatus*, and *Zygrhablithus bijugatus*. Species which are scarce include *Chiasmolithus altus*, some overcalcified *D. deflandrei* mimicking *D. saipanensis*, *D. tanii*, *Ericsonia subdisticha*, a form mimicking *Hayaster perplexus*, *Helicosphaera compacta*, *H. euphratis*, *H. recta*, *Pedinocyclus larvalis* and *Reticulofenestra scissura*.

The co-occurrence of *Reticulofenestra scissura* and *Sphenolithus ciperoensis* indicates a Late Oligocene age. The presence of the key species *Sphenolithus distentus* suggests an assignment to the NP 24 Zone of Martini (1971). The presence of *Zygrhablithus bijugatus* suggests deposition in shallow water. The abundant occurrence of sphenoliths and the rarity of *Chiasmolithus altus* suggest warm surface waters.

Eocene or Oligocene: 107/DR10-04

The poor assemblage of 107/DR10-4 includes *Bramletteius serraculinoides*, *Coccolithus eopelagicus*, *C. formosus*, *C. pelagicus*, *Coronocyclus nitescens*, *Cyclicargolithus abisectus*, *C. floridanus*, *Discoaster barbadoensis*, *D. deflandrei*, *D. saipanensis*, *?D. tanii*, *?Helicosphaera compacta*, *Lanternithus minutus*, *Pedinocyclus larvalis*, *Reticulofenestra scrippsae*, *R. scissura*, *R. umbilicus*, *?Sphenolithus ciperoensis*, *S. moriformis*, *S. predistenus*, *S. radians* and *Zygrhablithus bijugatus crassus*. It is dominated by only a few species, namely *R. scissura, C. floridanus, D. deflandrei* and *Z. bijugatus*.

Except for *Cyclicargolithus abisectus* and the Late Oligocene key species *Sphenolithus ciperoensis,* most other elements of the assemblage listed above collectively suggest a Late Eocene age. The Late Eocene assemblage recovered from 107/DR10-4A lacks the younger Oligocene elements. It is possible that the presence of *Sphenolithus ciperoensis* is due to contamination during dredging. But if *S. ciperoensis* and *C. abisectus* are *in situ,* then the presence of species such as *Discoaster saipanensis* would mean reworking from Eocene sediments. Evidence of substantial reworking of older nannofossils has been recorded from other material examined from the Christmas Island region, particularly in cores (see, also other contribution by Shafik, this report). Species, such as *Sphenolithus ciperoensis*, indicative of Oligocene age are found, together with other Tertiary and also Neogene species, among the Quaternary assemblage of nanno-foram ooze (107/DR10-07) collected at the same station as sample 107/DR10-4 (see below).

Miocene

Abundant, poorly to moderately preserved nannofossils indicating Miocene age were recovered from dredges 107/DR06 and 107/DR09, which were obtained from sites 3227 - 2830 m and 1800 - 1600 m deep respectively.

Similar assemblages were recovered from three samples examined. These samples are: (a) 107/DR06-12A, a moderately lithified foram-nanno chalk; (b) 107/DR09-03, a white, well-lithified chalk; and (c) 107/DR09-04, a white, soft chalky ooze. The assemblages include the key species *Amaurolithus amplificus, A. delicatus, A. primus, Calcidiscus leptoporus, Coccolithus pelagicus, Discoaster quinqueramus, D. surculus, Hayaster perplexus, Helicosphaera kamptneri, Reticulofenestra pseudoumbilicus, Sphenolithus abies* and *Triquetrorhabdulus rugosus*.

The co-occurrence of species of *Amaurolithus* and *Discoaster quinqueramus* indicates an assignment to the upper part of the NN 11 Zone of Martini (1971), equivalent to the CN 9b Subzone of Okada and Bukry (1980). The age is latest Miocene.

Sample 107/DR06-05, a phosphatised carbonate breccia, is almost barren of nannofossils, except for rare specimens of *Coccolithus pelagicus, Discoaster brouweri, D. pentaradiatus* and *D. quinqueramus* which suggest a Late Miocene age. Even these rare nannofossil specimens could be a result of contamination from the associated sample 107/DR06-12A .

Sample 107/DR10-02, a carbonate grainstone, yielded a very mixed assemblage. Elements indicative of Late Oligocene (such as *Helicosphaera recta* and *Reticulofenestra scissura*), and Early and Middle Miocene (such as *Discoaster deflandrei* 'group', *Sphenolithus heteromorphus* and *Discoaster hamatus*) co-occur with the Late Miocene key species *Discoaster quinqueramus*. The preservation of these various elements differs considerably. Other species identified include *?Amaurolithus primus, Calcidiscus leptoporus, C. macintyrei, Coccolithus miopelagicus, Coronocyclus nitescens*, (reworked) *Cyclicargolithus abisectus,* (reworked) *C. floridanus, Discoaster brouweri,* (reworked) *D. moorei, D. pentaradiatus, D. variabilis, Hayaster perplexus, Helicosphaera kamptneri, Reticulofenestra pseudoumbilicus, Sphenolithus abies,* (reworked) *S. moriformis,* (reworked) *S. predistentus,* (reworked) *Triquetrorhabdulus carinatus* and (reworked) *T. rugosus*.

Pliocene

Sample 107/DR06-10, a foram-nanno ooze, yielded abundant, poorly preserved nannofossils. Signs of partial dissolution are evident, especially among the coccoliths. Calcite overgrowths can be observed on ceratoliths and some discoasters. Species identified include *Calcidiscus leptoporus, C. macintyrei, Ceratolithus rugosus, Coccolithus pelagicus, Discoaster asymmetricus, D. brouweri, D. pentaradiatus, D. surculus, D. tamalis, D. variabilis, Helicoshaera kamptneri, Reticulofenestra pseudoumbilicus, Sphenolithus abies* and *S. neoabies. C. pelagicus, D. asymmetricus* and *D. tamalis* are rare.

The association of *Ceratolithus rugosus, Reticulofenestra pseudoumbilicus, Discoaster asymmetricus, D. surculus,* and *D. tamalis,* in the absence of *Amaurolithus tricorniculatus*, suggests an Early Pliocene age, and assignment to the upper part of NN15 Zone of Martini (1971), equivalent to the CP11b Subzone of Okada & Bukry (1980).

Discussion

Nannofossils recovered from the carbonates obtained in dredge 107/DR06 are Late Cretaceous, Late Miocene and Early Pliocene. Reworked nannofossils indicative of Late Oligocene and Early and Middle Miocene were also found suggesting recycled sediments of these ages. Foraminiferids from the same dredge indicate Late Paleocene and Eocene ages as well (Chaproniere & Coleman, this report). Pelagic carbonate accumulation on the seamount where dredge 107/DR06 was obtained, probably began during the Campanian in a shallow water palaeoenvironment. Deposition continued on during the Tertiary and Neogene. There is evidence for the older sediments being recycled since the Late Cretaceous. The seamount lay in a similar relative position to Australia since the Late Cretaceous, as evidenced by its recovered Maastrichtian nannofossils. Associated rocks in dredge 107/DR06 included basalt and trachytes.

Quaternary

Quaternary nannofossils were extracted from samples collected at several dredge stations. These sample are 107/DR01-10, 107/DR04-18A, 107/DR04-19A, 107/DR05-08, 107/DR06-11, 107/DR09-05, 107/DR10-07, 107/DR11-01, 107/DR12-01. Only assemblages from three dredge stations (107/DR04, 107/DR05 and 107/DR10) are indicated below.

Dredge station 107/DR04

Abundant, moderately preserved nannofossils were extracted from two lithotypes from dredge 107/DR04, which was obtained from waters 2800 - 2300 m deep, on a seamount rising to 1800 m below sea level.

The assemblages from a cream nanno-foram ooze (107/DR04-18A) and a light olive grey, nanno-foram ooze (107/DR04-19A) are similar. They include common to abundant *Calcidiscus leptoporus*, *C. macintyrei*, *Ceratolithus cristatus*, *Florisphaera profunda*, *Gephyrocapsa*, *Hayaster perplexus*, *Helicosphaera kamptneri*, *H. sellii*, *Pseudoemiliania lacunosa*, *Rhabdosphaera stylifer*, *Scapholithus fossilis* and *Umbellicosphaera irregularis*.

The absence of discoasters (particularly *Discoaster brouweri*) and the abundant presence of *Pseudoemiliania lacunosa* suggest an assignment to the lower part of NN 19 Zone of Martini (1971). The age is Early Pleistocene. Abundant *Florisphaera profunda* is consistent with a low palaeolatitude.

Dredge station 107/DR05

Sample 107/DR05-08, a pale brown nanno-foram ooze, yielded a rich Quaternary assemblage with *Ceratolithus cristatus*, *Florisphaera profunda* and *Gephyrocapsa* spp, but includes older species which are important clues to the make-up of the pre-Quaternary sedimentary succession on the seamount. The older species include several age-diagnostic ones indicating reworking from at least four substantially different levels. The oldest is Late Cretaceous in age, based on the presence of *Calculites obscurus*. Other ages are: Paleocene (because of the presence of *Fasciculithus tympaniformis, Chiasmolithus bidens* and *Toweius eminens*); Early Eocene (based on the presence of *Cyclicargolithus gammation*); and younger Eocene and/or Oligocene (on account of *Bramletteius serraculoides, Cyclicargolithus floridanus, Pontosphaera multipora* and *Reticulofenestra scissura*). Of these ages, the Lower Eocene was successfully dredged (samples 107/DR05-01, 107/DR05-03 and 107/DR05-04, discussed above).

Dredge station 107/DR10

Sample 107/DR10-07, a pale brown, nanno-ooze, yielded abundant moderately preserved nannofossils which are dominated by pre-Quaternary species. *Calcidiscus leptoporus, Ceratolithus cristatus, Emiliania huxleyi, Gephyrocapsa* spp. and *Florisphaera profunda* were identified, indicating a Late Pleistocene or Holocene age. The older species suggest mixing of sediments from several levels, prominent among which are Lower and younger Eocene and Upper Oligocene. (The Upper Eocene and Upper Oligocene levels were successfully dredged, see samples 107/DR10-04A and

107/DR10-06A discussed above.) The pre-Quaternary species include several key Eocene species, such as *Discoasteroides kuepperi, Discoaster sublodoensis* and *D. saipanensis,* and others suggestive of younger Eocene and/or Oligocene age, such as *Bramletteius serraculoides, Coccolithus eopelagicus, C. formosus, Cyclicargolithus floridanus, Sphenolithus predistentus, Reticulofenestra scissura, R. umbilicus* and *Zygrhablithus bijugatus.* The Late Oligocene index species *Sphenolithus ciperoensis* is abundant. Also common are *Cyclicargolithus abisectus* and *Triquetrorhabdulus carinatus.* Neogene species such as *Discoaster pentaradiatus* and *Helicosphaera kamptneri* are also present.

Discussion.

Carbonates recovered from dredge 107/DR10 contain *in situ* nannofossils suggestive of Late Eocene (107/DR10-04A) and Late Oligocene age (107/DR10-06A); mixed nannofossil associations of dominantly Eocene and Oligocene age, but also including Neogene elements, within a Pleistocene-Holocene assemblage (107/DR10-07); and planktic foraminiferids indicative of Maastrichtian and Late Paleocene age (Chaproniere & Coleman, this report). Associated rocks in dredge 107/DR10 included basalt and volcaniclastics.

Carbonate accumulation probably began, on the seamount where dredge 107/DR10 was obtained, during the Late Cretaceous and continued on during the Paleocene, Eocene, Oligocene and Neogene. Deposition during the Late Cretaceous and most of the Tertiary was in shallow water. Evidence for warm surface waters in these marginal marine palaeoenvironments, during at least the Late Eocene and Late Oligocene, is noted among the nannofossil assemblages. Recycling of older sediments apparently has taken place recently and is probably continuing to occur.

Undetermined

Examination of preparation from samples 107/DR01-07, 107/DR03-07, 107/DR03-09, 107/DR03-10, 107/DR04-04 and 107/DR06-07 indicated that these samples lack calcareous nannofossils.

Discussion

Late Cretaceous, Eocene and Oligocene assemblages are recorded in carbonates recovered from several seamounts near Christmas Island. These include nannofossil species suggestive of deposition in shallow water palaeoenvironments, probably not deeper than outer shelf and upper slope. They came from dredges taken from depths greater than 1445 m (probably as deep as 2800 m for the Eocene assemblages) on the seamounts. This evidence suggests that the sampled seamounts must have subsided significantly since the Late Cretaceous to early Tertiary.

Since the Late Cretaceous, the seamounts in the Christmas Island region have maintained their relative position to Australia, as indicated by several nannofossil assemblages identified from Upper Cretaceous, Eocene and Oligocene carbonates on these seamounts.

TABLE 17. SUMMARY OF BIOSTRATIGRAPHIC RESULTS FOR NANNOFOSSILS.

Sample	Age	Sample	Age
107/DR01-07	undetermined	107/DR06-07	undetermined
107/DR01-10	Quaternary	107/DR06-10	Early Pliocene
107/DR03-07	undetermined	107/DR06-11	Quaternary
107/DR03-09	undetermined	107/DR06-12A	Late Miocene
107/DR03-10	undetermined	107/DR06-13	Middle Maastrichtian
107/DR04-04	undetermined	107/DR09-03	Late Miocene
107/DR04-18A	Early Pleistocene	107/DR09-04	Late Miocene
107/DR04-19A	Early Pleistocene	107/DR09-05	Quaternary
107/DR05-01B & A	Early Eocene	107/DR10-02	Late Miocene or younger
107/DR05-03B	Early Eocene	107/DR10-04	Eocene or Oligocene
107/DR05-04B & A	Early Eocene	107/DR10-04A	Late Oligocene
107/DR05-07	? Early Eocene	107/DR10-06A	Late Oligocene
107/DR05-08	Late Pleistocene	107/DR10-07	Late Pleistocene - Holocene
107/DR06-04	Late Maastrichtian	107/DR11-01	Quaternary
107/DR06-05	? Late Miocene	107/DR12-01	Quaternary
107/DR06-08A	Early & Late Maastrichtian		

CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY OF SEDIMENT CORES FROM AROUND CHRISTMAS ISLAND

(Samir Shafik)

Introduction

Except for 107PC07, which yielded Early Pliocene nannofossil assemblages, all other cores examined are Quaternary to Holocene in age, based on the occurrence of diagnostic species such as *Gephyrocapsa oceanica*. Some uncertainties in the biostratigraphy of these Quaternary cores are caused by contamination from possible slumping of younger and older sediments, selective dissolution, and reworking. Table 18 lists the samples studied.

Two nannofossil biostratigraphic events were identified in the Quaternary cores: the younger event is the lowest occurrence of *Emiliania huxleyi,* and the older is the highest occurrence of *Pseudoemiliania lacunosa*. Published estimates of the numeric age of these bioevents differ. For example, the lowest occurrence of *E. huxleyi* has been estimated at 0.275 Ma by Berggren

& others (1985), and between 0.279 and 0.251 Ma by Shyu & others (1991). Similarly, the highest occurrence of *P. lacunosa* has been estimated at 0.474 Ma by Berggren & others (1985), and between 0.59 and 0.51 Ma by Shyu & others (1991).

The low-latitude *Florisphaera profunda* was found in most Quaternary samples examined.

Results

Core 107/GC01

Three samples from the bottom part of the core, at 619, 610 and 603 cm, contain abundant *Emiliania huxleyi* based on SEM examination. A sample from 610 cm also contains *Pseudoemiliania lacunosa*. The stratigraphic ranges of *E. huxleyi* and *P. lacunosa* do not usually overlap. *P. lacunosa* is present up the core to the 500 cm level, being without *E. huxleyi* in samples at 600, 550 and 500 cm; optical microscopy suggests that *E. huxleyi* is absent at five levels below 150 cm. *Emiliania huxleyi* reappears in samples from 150 cm and above, and its presence there was confirmed by SEM examination.

It is possible that the samples from the bottom of the core are contaminated from the upper part of the core, which contains *Emiliania huxleyi*. If this is true, then two biostratigraphic events can be identified in this core. The older event is the highest occurrence of *Pseudoemiliania lacunosa* above 500 cm, and the younger is the lowest occurrence of *E. huxleyi* at about 150 cm. Five samples from the section separating the two events were examined. Both *P. lacunosa* and *E. huxleyi* are absent in the biostratigraphic gap represented by these five samples.

Core 107/GC04

This core was deposited subsequent to the important bioevent of the appearance of *Emiliania huxleyi* in the world ocean. Three samples from 390 (bottom of the core), 50 and 30 cm contain *Pseudoemiliania lacunosa* together with abundant *Emiliania huxleyi*. The ranges of these two species do not usually overlap. Optical microscopy suggests that *E. huxleyi* is present throughout the core. Its presence is confirmed at several levels (350, 301, 201, 64.5, 55.5, 50, 46.5, 30 and 1 cm) by SEM examination. The occurrence of *P. lacunosa* is probably a result of reworking. This species seems to be restricted to the bottom of the core, appearing very rarely in the uppermost 50 cm.

Siliceous microfossils and reworked nannofossils are present throughout the core. The reworked nannofossils (such as *Watznaueria barnesae, Chiasmolithus gigas, Discoaster barbadoensis, Coccolithus pelagicus, Sphenolithus predistentus, S. pseudoradianus, Reticulofenestra umbilicus, R. scissura, Sphenolithus ciperoensis, Cyclicargolithus floridanus, C. abisectus, Sphenolithus heteromorphus, S. abies, Reticulofenestra pesudoumbilicus, Discoaster variabilis, D. surculus, D. pentaradiatus, D. brouweri, D. tamalis and Calcidiscus macintyrei*) suggest source sediments of Cretaceous, early Middle and later Eocene, Late Oligocene, Early to Middle Miocene and Pliocene age.

<u>Core 107/PC03</u>

The bottom of the core at 120 cm yielded an abundant Quaternary nannofossil assemblage, which included *Gephyrocapsa oceanica, Pseudoemiliania lacunosa* and *Umbilicosphaera sibogae*. Younger assemblages containing *Emiliania huxleyi* were recovered from samples at 79, 41, 30, 20 and 10 cm levels. *P. lacunosa* was found also at 100 and 20 cm. The higher occurrence of *P. lacunosa* may be the result of contamination by slumping, as *Emiliania huxleyi* was found at the same level; the ranges of these two species do not usually overlap.

The extinction datum of *P. lacunosa* is probably slightly above the 100 cm level, and the lowest occurrence of *Emiliania huxleyi* is probably slightly below the 79 cm level.

<u>Core 107/PC05</u>

The nannofossils are very rare in the bottom sample, at 450 cm. These are severely corroded specimens of *Gephyrocapsa oceanica* and *Calcidiscus leptoporus*. Deposition was near the CCD. Preservation of the nannofossils at most higher levels is poor to very poor. Obvious signs of dissolution abound, and the fossils are usually rare to very rare, suggesting deposition near the CCD for most of the core. Common to abundant nannofossils were recovered from 103 and 50 cm, where preservation is significantly better than at other levels, but sediments at these two levels may have resulted from slumping. Most levels were found to contain reworked nannofossils from Upper Cretaceous (such as *Ceratolithoides aculeus*), upper Palaeogene (such as *Reticulofenestra scissura* and *Discoaster deflandrei*) and Neogene sources (such as *Reticulofenestra pseudoumbilicus, Discoaster variabilis, D. surculus, D. pentaradiatus, D. asymmetricus* and *D. triradiatus*).

The key species *Pseudoemiliania lacunosa* was found at 403 cm, and not at higher levels, except among the abundant and better preserved nannofossils at 103 and 50 cm, which contain younger biostratigraphic evidence. SEM examination revealed the presence of *Emiliania huxleyi* at 250 cm and above.

Accepting that *Pseudoemiliania lacunosa* may have been introduced at 103 and 50 cm by slumping, two biostratigraphic events can be identified in the core. The older event is the highest occurrence of *P. lacunosa* above 403 cm, and the younger is the lowest occurrence of *Emiliania huxleyi* at about 250 cm. The two events are separated by a segment represented by two samples taken from 350 and 303 cm.

Core 107/PC06

Two samples were examined. The assemblages recovered suggest an Early Pliocene age. Sample 107/PC06 from 40 cm yielded *Calcidiscus leptoporus, C. macintyrei, Ceratolithus rugosus, Coccolithus pelagicus, Discoaster asymmetricus, D. brouweri, D. decorus, D. pentaradiatus, D. surculus, D. tamalis, D. triradiatus, Hayaster perplexus, Helicosphaera kamptneri, Pontosphaera* sp., *Reticulofenestra pseudoumbilicus*. The other sample at 8 cm yielded a similar assemblage, minus *Calcidiscus macintyrei*, *Discoaster decorus* and *Coccolithus pelagicus*.

Core 107/PC07

Five samples were studied. The key species *Emiliania huxleyi* was found in the top three samples, down to 30 cm. Samples from 50 and 70 cm yielded Quaternary species including *Gephyrocapsa oceanica*.

TABLE 18. LIST OF SAMPLES EXAMINED FOR NANNOFOSSILS.

Sample	Sample	Sample	Sample
107GC01, 5cm	107GC04, 30cm	107PC03, 41cm	107PC05, 403cm
107GC01, 50cm	107GC04, 46.5cm	107PC03, 50cm	107PC05, 450cm
107GC01, 100cm	107GC04, 50cm	107PC03, 79cm	107PC06, 8cm
107GC01, 150cm	107GC04, 55.5cm	107PC03, 100cm	107PC06, 8cm
107GC01, 250cm	107GC04, 60cm	107PC03, 120cm	107PC07, top
107GC01, 300cm	107GC04, 64.5cm	107PC05, 3cm	107PC07, 10cm
107GC01, 350cm	107GC04, 90cm	107PC05, 50cm	107PC07, 30cm
107GC01, 400cm	107GC04, 101cm	107PC05, 73cm	107PC07, 40cm
107GC01, 450cm	107GC04, 150cm	107PC05, 86cm	107PC07, 50cm
107GC01, 500cm	107GC04, 201cm	107PC05, 103cm	107PC07, 70cm
107GC01, 550cm	107GC04, 250cm	107PC05, 120cm	107PC08, 10cm
107GC01, 600cm	107GC04, 301cm	107PC05, 135cm	107PC08, 50cm
107GC01, 603cm	107GC04, 350cm	107PC05, 150cm	107PC08, 100cm
107GC01, 610cm	107GC04, 390cm	107PC05, 203cm	107PC08, 150cm
107GC01, 619cm	1107PC03, 20cm	107PC05, 250cm	107PC08, 200cm
107GC04, cc	107PC03, 10cm	107PC05, 303cm	107PC08, 250cm
107GC04, 1cm	107PC03, 30cm	107PC05, 350cm	

Core 107/PC08

Two Quaternary biostratigraphic events can be identified in this core. The older event is the highest occurrence of *Pseudoemiliania lacunosa* above 200 cm (this key species was found at 250 and 200 cm only), and the younger is the lowest occurrence of *Emiliania huxleyi* at 100 cm. The two events are separated by a segment represented in this study by one sample from 150 cm.

CONCLUSIONS

General Performance

The cruise successfully carried out most of the (purposely optimistic) cruise plan (Exon, 1991), and met all the cruise objectives (see earlier). As regards the cruise plan:

- About 2100 km of 6 fold seismic data were acquired at relatively high speeds of about 7-8 knots, instead of the hoped-for 2500 km. Seismic quality was adequate for the purpose required. Future high-speed surveys may require the purchase of a special high-speed cable.

- For the assessment of manganese nodules, deepwater core stations and camera stations could not be occupied, because of the early loss of 4500 m of wire from the deepsea winch, which constrained coring and photography to less than 4600 m, too shallow for prospective nodule fields. However, the key element of the assessment operation, the deployment of free-fall grabs, was very successful, and only two grabs were lost from 84 deployments. This was not much less than the planned maximum number of deployments of 104.

- With the reduction of deepsea coring capability, more emphasis was put on shallower coring and dredging. Most of the 15 core stations (planning had been for 13) were on the flat tops of seamounts, where the sediment proved to be sandy and difficult to recover, for both gravity and piston coring. Only 9 cores had any recovery, and only 7 were relatively undisturbed. Especially disappointing were the piston cores, which take considerably longer to rig and deploy than gravity cores, and were plagued with rigging and equipment problems.

- Dredging of seamounts was very successful, despite the loss of wire at two stations where the dredge hung-up on the volcanic pedestals. Of the 12 stations occupied (the plan was for 9), rocks or manganese crusts were recovered from 9.

As regards the cruise objectives:

- There are now adequate bathymetric and seismic profile data to facilitate any deliberations on the seabed boundary between Australia and Indonesia. Suitable maps should have been prepared by late 1993.

- The deepsea manganese nodule resources of the area have been adequately assessed and proven to be of little economic potential. Thick manganese crusts coat rocky outcrops on the seamounts, but the grade of cobalt is unexceptional. However, not enough sampling has been done at the most favourable water depths to completely rule them out as having economic potential.

- The seamounts of the region consist essentially of alkali-olivine basalt and are typical intraplate lavas. Fossil evidence from overlying sedimentary rocks shows that most of the seamounts first formed in pre-Maastrichtian times. In some cases, the oldest sedimentary rocks dredged

Scientific Highlights

The bathymetry of the area is now known in more detail, but there have been no major changes to our general knowledge. The Australian Fisheries Zone (AFZ) consists of four major northeasterly trending provinces, plus part of the Java Trench (Fig. 2). The northwestern province is abyssal plain, with water depths of more than 5500 m and largely more than 6000 m. To its east lies a province consisting of the Christmas Island Rise and the Vening-Meinesz Chain, an area generally shallower than 5000 m, with volcanic seamounts rising commonly to less than 2000 m, and above the surface at Christmas Island. The Christmas Island Rise trends north-northeast and the Vening-Meinesz Chain east-northeast. Further east is a narrow area of abyssal plain, more than 5500 m deep, that is cut by some small seamounts. In the southeast is an area of generally shallower seafloor, and seamounts whose crests lie more than 2000 m deep. The Java Trench, in the north, is as much as 6500 m deep, and is bounded to the south by a seafloor bulge that lifts up all the other structural units by several hundred metres.

Our geophysical profiles show that three sedimentary Cainozoic and Late Cretaceous sequences (R0-R1, R1-R2, R2-R3) are present across most of the region (Table 8). The Christmas Island Rise has basement about 5000 m below sea level and is overlain by a sedimentary sequence that is 0-200 m thick. It falls toward the Java Trench, with basement about 6000 m deep just south of the trench's flank. The deepwater western province has basement at about 6000 m. Sediment cover in the western province, of 200-400 m, is generally thicker than elsewhere. The eastern deepwater province generally has basement at about 5500 m, but it deepens to 6000 m just south of the trench. Sedimentary cover is 200-300 m. Seamounts are abundant in the south of the area, but no large seamounts are known north of Christmas Island. Where volcanic crust is bowed down into the Java Trench there are numerous associated normal faults. The trench is full of well-bedded lens-shaped sequences, assumed to consist largely of volcaniclastic turbidites.

Gravity values fall toward the trench and large seamounts cause local 'highs'. Magnetic values also fall toward the trench, and most of the dipoles caused by seamounts have magnetic 'highs' displaced to the north, suggesting normal polarisation. However, at least one major seamount (Shcherbakov) appears to be reversely polarised (Plate 1).

Six rock types were dredged from the seamounts (Table 1, Fig. 3), many of which have the flat tops characteristic of guyots, suggesting that they were once subject to wave erosion. Their peaks now lie more than 1200 m deep. The volcanic pedestals consist of alkali-olivine basalt and trachyte, and are typical intraplate lavas (see also Williams, 1992). Associated rocks are mixed sediments consisting of rounded hyaloclastic and volcaniclastic grains set in carbonate. The grains were probably rounded in shallow water and then swept into deeper water by storms. The shallow water carbonates are of varied grainsize and contain red algae, larger foraminiferids, bryozoans, molluscs and echinoderms. The deeper water carbonates are largely chalks dominated by nannofossils and planktic foraminiferids.

Radiometric ages from igneous rocks in DSDP Site 211 and from Christmas Island indicate that there were volcanic episodes in, at least, Late Cretaceous and Eocene/Oligocene times. Fossil assemblages in sedimentary rocks dredged from the seamounts are of Campanian, Maastrichtian, Paleocene, Eocene, Miocene and Pliocene ages, as defined by nannofossils and foraminiferids. Rather poor evidence from sea-floor spreading anomalies, and better evidence from DSDP Site 211, suggest that the oceanic crust is slightly older (Campanian) than the seamounts west of a postulated north-south fracture zone at about 103.5°E (Scheibner et al., 1991); poor sea-floor spreading evidence suggests it is substantially older (Albian?) in the east.

We see the seamounts as possibly forming over a hotspot as the crust moved slowly northeast in Late Cretaceous and Palaeogene times. When fast spreading started in the Eocene, and the crust moved rapidly northward, the region was separated from the hotspot and volcanism ceased. The shallow-water carbonates and volcaniclastics formed around volcanic islands and on shallow seamounts. As the underlying crust cooled and sank, these edifices sank into deep water, and pelagic carbonates were laid down.

Most of the core attempts (Fig. 3) were on the tops of seamounts, and gave cores of apparently unbedded Quaternary, cream nannofossil-foraminiferal ooze, containing well-preserved microfossils, and with $CaCO_3$ contents of 75-90%. Two deepwater cores were taken away from seamounts (P5 and G4). Deepwater Core GC04, from 3665 m, is a medium-bedded, pale brown, grey and olive nannofossil-foraminiferal ooze and carbonate-rich siliceous ooze, with very variable $CaCO_3$ contents of 6-68%. Core PC05, from 4564 m, is poorly bedded, yellow-brown to grey carbonate-bearing siliceous ooze; $CaCO_3$ content is low at 3-39%. These cores clearly fit the regional picture of decreasing planktonic carbonate downward as the Calcite Compensation Depth (5000 m) is approached, and of an increase in resistant components such as clay, zeolites, diatoms and radiolarians.

Free-fall grabs were deployed at 28 stations (Fig. 3), and generally small nodules were recovered with deepsea ooze at nine stations (22 deployments of 73). Average abundance was 3 kg/m^2 (maximum 12), which is below the economic cutoff grade of 5 kg/m^2. Average nodule grades are listed in Table 14, which shows that Cu+Ni+Co%, at 1.13%, is far lower than the economic cutoff grade of 2%. The results show that the Christmas Island offshore area has no potential for economic nodule fields.

Manganese crusts, individually up to 6 cm thick (and often in considerably thicker multiple crusts), were dredged from water depths of 1500-3700 m. Average metal values (Table 14) are somewhat less than Pacific Ocean values, at 0.44% Co compared to 0.63%. The thickness of the crusts is well above the assumed cutoff value of 4 cm, and two of the analyses are above the cutoff grade for Co of 0.8%. The results to date have not been particularly encouraging, but the samples all come from deeper than the optimum water depths for high Co grades. There are volcanic edifices that lie within the more prospective water depths of 500-2000 m, and they should be sampled when the opportunity arises.

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APPENDIX 1: SHIPBOARD LITHOLOGICAL DESCRIPTIONS

Samanda Williams and Neville Exon

SITE SUMMARY, SITE DR01

Latitude: 13° 43.08' S
Longitude: 105° 23.60' E
Water Depth: 2800 m
Amount Recovered: 163 kg

Site DR01: Sample 01

75 kg of Hyaloclastite breccia
Thick bedded, brown (7.5YR 4/4), angular to moderately rounded hyaloclastite grit up to 3cms in diameter, set in a coarse sand/gritty pale grey (7.5YRN8 to 7.5YRN6) matrix consisting largely of calcite cemented pale grey molluscan debris and other biolithic fragments (<2mm). Minor indeterminable light yellowish brown zeolitised fragments. Upper surface encrusted by 2mm isopachous manganese veneer.

Site DR01: Sample 02

30 kg of Volcanic breccia
Thickly bedded volcanic breccia with interbedded coarse and fine layers. Dark brown (7.5Y4/2), angular, mostly lath shaped, basalt clasts up to 35 mm long. Some basalt clasts contain fine feldspar shards. Clasts show a small degree of alignment parallel to bedding. Olive (2.5Y 6/4), possibly zeolitised very fine grained glass sand. Calcite cemented. Manganese veneer present.

Site DR01: Sample 03

20 kg of Volcanic breccia
Very thick bedded and poorly sorted volcanic breccia. Carbonate clasts include corals, hexacorals, bivalves, and irregular algal balls up to 1 cm diameter which have formed around volcanic nuclei. Angular to sub-angular, brown to very dark brown (2.5YR3/4 to 2.5YRN2) basalt clasts up to 2 cms diameter set in a fine grained volcanic matrix. Manganese crust about 3 to 4 mm thick.

Site DR01: Sample 04

30 kg of Volcanolithic breccia
Unsorted volcanolithic breccia with a variety of clast shapes and sizes, up to 3 cms diameter. Pale olive (5Y6/4) to grey (N6) in colour probably due to the presence of smectite. Large variety of igneous clasts including pumice and basalt. Basalt clasts are angular or vaguely defined. Minor calcareous clasts which are largely molluscan. No Flow structures; ash fall or slump deposit. Manganese crust 2mm thick at most.

Site DR01: Sample 05

1 kg of Basalt:
Brown (7.5YR5/2), microcrystalline, relatively homogenous basalt. Basalt contains sub-angular, elongate plagioclase phenocrysts and minor Zeolite. Manganese veneered.

Site DR01: Sample 06

1 kg of Phosphatised micritic breccia
Pinkish white (7.5YR8/2) to brown, a number of micrites with various shades of brown. Possibly phosphatised volcanic as its surface does not react with hydrochloric acid. Rare small volcanic clasts and large angular sparse biomicritic clasts up to 5 cms in diameter, otherwise structureless and homogenous. Manganese crust 5mm thick.

Site DR01: Sample 07

2 kg of Silty sandstone
Brown (7.5YR5/2), massive, poorly to moderately lithified silty sandstone. Some specimens intensively bored (1mm diam. fine tubes). Some borings infilled by micrite which contains planktic foraminiferids. Manganese crust 2 mm thick.

Site DR01: Sample 08

One small sample of Algal limestone
Pinkish white (2.5Y8/2) pelmicrite which is vuggy, laminated and porous. Calcite vugh infillings. Small irregularly shaped dark brown volcanic clasts. Manganese encrusted and stained.

Site DR01: Sample 09

Less than 1 kg of Manganese crusts and impregnations
Black thick crusts,up to 1.5 cms thick formed on various substrates.

Site DR01: Sample 10

5 kg of Foram sand
Cream, fine grained form rich sand.

SITE SUMMARY, SITE DR02

Latitude: 13° 08' S
Longitude: 105° 46' E
Water Depth: 2200 m
Amount Recovered: No recovery.

Lost 4500 m of cable and dredge. In total 4860 m of cable was lost or damaged, 400 m of wire was recovered.

SITE SUMMARY, SITE DR03

Latitude: 11° 46.4' S
Longitude: 107° 05' E
Water Depth: 2200 m to 2400 m
Amount Recovered: 190 kg

Site DR03: Sample 01

150 kg of Molluscan Grainstone
Poorly to moderately bedded molluscan grainstone. Most specimens show colour banding (2.5YR6/6, 7.5YR8/2, 5YR5/1) parallel to bands of varying fossil content. Fossils are mainly coarse molluscan fragments, some brachiopods, minor corals, (1cm diameter), minor algae and minor well preserved echinoid spines in a fine lithified carbonate sand matrix. Fairly heavily bored, with some bioclasts removed leaving voids. Small sub-angular hyaloclastite and rounded basalt clasts. Shallow water carbonate assemblage, back beach storm deposit. Colour banding may be due to algal staining or vadose weathering by phreatic groundwaters. Manganese encrusted. Manganese crust ranges in thickness from a thin veneer to a 0.3 mm thick crust.

Site DR03: Sample 02

2 kg of Algal Boundstone
Pink (7.5YR6/2) muddy carbonate blocks bound together, a micritic matrix.

Site DR03: Sample 03

1 kg of Volcanic Sandstone
Bimodal, sub-angular to sub-rounded, medium sand sized, largely basalt grains set in a phosphatised, fine grained, bioturbated matrix and cement. Incomplete cementation. Manganese crust 3 mm thick. Rounding of grains possibly in shallow water, followed by fine grain matrix deposition in deeper water.

Site DR03: Sample 04

1 kg of Pumice
Light olive green to pink, (5Yr 5/2) highly porous pumice.

Site DR03: Sample 05

30 kg Manganese crusts and impregnations
Black crusts, mammilated in part, up to 4 mm thick. Crusts generally on micritic carbonate blocks bound together. Micrites contain various bioclasts including planktic foraminiferids.

Site DR03: Sample 06

4 kg of Carbonate Grainstone
Moderately bedded to thick bedded carbonate grainstone. Sub-rounded, 2 mm diameter basalt clasts and coarse rounded molluscan clasts and red algae debris set in a cream (10YR8/2) very fine grained carbonate matrix. Variable carbonate cement. Manganese veneer.

Site DR03: Sample 07

0.25 kg of Carbonate Mudstone
Fine grained sandy, carbonate mudstone. Mottled brown in colour resulting from bioturbatation. Minor volcanic fragments. Manganese thin veneer and impregnations.

Site DR03: Sample 08

2 kg of Carbonate Grainstone
Coarsely bedded, very coarse grained molluscan fragments and carbonate wackestone to mudstone clasts. Highly porous, pores largely filled with soft mud and rare calcite.
Geopetal structures.

Site DR03: Sample 09

0.25 kg of Carbonate Grainstone
Thinly bedded, light brown, fine grained, slightly sandy. Subrounded basalt clasts.
Porous. Manganese veneer.

Site DR03: Sample 10

2kg of Carbonate Wackestone
Fine sand in phosphatic cement encrusted by ferro-manganese crust.

Site DR03: Sample 10

0.25 kg of Foram-nanno ooze
Fine grain, olive grey foram-nanno ooze.

SITE SUMMARY, SITE DR04

Latitude: 10° 58.81' S
Longitude: 102° 25.3' E
Water Depth: 2800 m to 2300 m
Amount Recovered: 165 kg

Site DR04: Sample 01

3 kg of Calcarenite packestone to grainstone, biosparite.
Very fine grain, white (10YR7/2) calcarenite sand and very coarse to gritty lithic calcarenite with subrounded basalt clasts (10YR4/2), and calcareous clasts including foraminiferids. Uppermost layer is a white(10YR8/2) carbonate mudstone. Thinly bedded, well defined interbeds of foraminiferids

rich micrite interbedded with imbricated layers rich in large bioclasts and rounded volcanic clasts.

Site DR04: Sample 02

10 kg of Calcarenite grainstone. Biosparite.
Poorly to thickly bedded, poorly sorted, cream, fine grained calcarenite grainstone with volcanic clasts. Molluscan fragments and other calcareous debris. One large oyster. Sub-angular basalt clasts, less than 3mm in diameter make up to 20% of the rock.

Site DR04: Sample 03***

2 kg of Hyaloclastite breccia
Fine grained white calcareous cemented. Variety of large volcanic, mainly orange, poorly sorted, subangular basalt clasts and hyaloclastite clasts, up to 1cm diameter. Range of shades of brown, commonly (7.5YR5/4). Spherulites. Vesicular.

Site DR04: Sample 04***

40 kg Vitric tuff (Bentonite)
Pale olive in colour (5Y6/3), altered and bioturbated.

Site DR04: Sample 05

1 kg Volcanic breccia
Jigsaw, cracked in places, breccia of feldspar shard clast, orange brown clasts, mixed vesicular clasts. Sub-rounded largely pumice and some basaltic clasts. Fine grained olive (5Y5/3) coloured matrix.

Site DR04: Sample 06

0.5 kg Ironstone
Description:
Very dark brown with olive green. Nontronite in cracks.

Site DR04: Sample 07 (sub-samples a,b and c)

3 kg of Scoria

Strongly vesicular scoriatious material. Some layered, green (5Y3/1) to maroon (2.5YR2/4).

7a Green-grey, slightly vesicular, aphyric trachyte with 25% dark red-brown inclusions of vesicular basalt.
7b Olivine + plagioclase phyric vesicular basaltic lava. Dark brown, microcrystalline, structureless, aphyric groundmass containing about 30% vesicles.
7c Olivine + plagioclase phyric vesicular basalt. Structureless sample. 25% red brown, altered microcrystalline groundmass.

Site DR04: Sample 08

1 kg of Tuff
Grey (10YR6/1), very fine grain, zoned possibly as a result of weathering. Creamy alteration product 3 mm thick and weathered crust.

Site DR04: Sample 09

1 kg of Ferruginous boxstone or breccia
Dark grey/brown (10YR4/2) boxstone separated by dark orange brown ironstone.

Site DR04: Sample 10

0.5 kg; One water rounded Volcaniclastic sandstone pebble
Poorly sorted, angular sandstone, interbedded with light grey (2.5Y7/2) siltstone.
Siltstone shows soft sediment deformation and is slightly calcareous.
Generally greyish brown (10YR5/3) overall colour.

Site DR04: Sample 11 (sub-samples a, b, c, d and e)

50 kg of Trachyte
Microcrystalline, grey (N5), commonly light green-grey, moderately fresh angular blocks. Some samples show a weak preferred orientation but are generally structureless, non-vesicular and homogenous.
11a Trachyte
11b Sparsely feldspar phyric Trachyte.
11c Mafic Trachyte or Benmoreite.
11d Polymic breccia of trachytic clasts.
11e Trachyte. Quite mafic.

Site DR04: Sample 12 (sub-samples b and c)

14 kg of Alkali olivine basalt
Microcrystalline, dark grey (N4), angular fresh blocks. Phenocrysts of plagioclase up to 1cm long and fine phenocrysts of olivine.
12b Plagioclase, olivine phyric alkali olivine basalt.
12c Alkali olivine basalt.

Site DR04: Sample 13 (sub-samples a, b, c, and d)

8 kg of Trachyte
Flow structured, indistinct layering. Few angular plagioclase feldspars, otherwise no clear crystal shapes. Largely non-vesicular, samples range from microcrystalline to medium grained.

Site DR04: Sample 14

25 kg of Weathered Volcanics
Very fine grain basalts to scoria. Rough surface texture, bubbly scoriation. Various shades of grey and brown.

Site DR04: Sample 15

0.5 kg of Volcanics
Very fine grain, very hard, often platy, light yellow(5Y7/3) volcanics.

Site DR04: Sample 18

1 kg of nanno-foram ooze
Cream to very pale brown (10YR8/3) unconsolidated ooze.

Site DR04: Sample 19

0.1 kg of nanno-foram ooze
Light olive grey unconsolidated ooze.

SITE SUMMARY, SITE DR05

Latitude: 11° 48.06' S
Longitude: 103° 15.19' E
Water Depth: 2800 m to 1900 m
Amount Recovered: 267 kg

Site DR05: Sample 01

20 kg of Micritic carbonate wackestone, biopelmicrite.
Poor to medium bedded with abundant large foraminiferids set in white (2.5Y8/2) carbonate mudstone. Very few other fossil fragments, those present include small branching bryozoan nets and minor abraded red algal fragments and echinoderm spines.

Site DR05: Sample 02

2 kg of Algal wackestone, biomicrite
2cm diameter, asymmetric and abraded algal balls set in a fine, hard, white (5Y8/2) carbonate mudstone. Manganese veneer in parts.

Site DR05: Sample 03

15 kg of Packed biomicrite, wackestone
White (2.5Y8/2), friable, bioturbated packed biomicrite. About 60% planktic foraminiferids and 2% large benthonic foraminiferids. Manganese micro nodules.

Site DR05: Sample 04

200 kg of Packed biomicrite, wackestone.
White (2.5Y8/2), heavily bioturbated, hard micrite with scattered larger benthonic foraminiferids.
Manganese veneer and dendritic impregnations.

Site DR05: Sample 05

30 kg Basalt and trachyte
Dark yellowish brown (10YR3/4), homogenous, microcrystalline, variably vesicular basalt and trachyte with feldspar phenocrysts. Spiratic calcite cementation and some calcareous infillings.Manganese crust up to 1 cm thick.
5c Alkali olivine basalt.

Brown, vesicular, microcrystalline groundmass with 20% feldspar and olivine phenocrysts. Vesicles are spherical or coalesced or more commonly elongate. Direction of elongation of vesicles is parallel to the alignment of lath shaped feldspar phenocrysts.
5d Trachyte.
Red brown, non-vesicular, 10%, 2 mm long equant feldspar phenocrysts and clustered phenocrysts, (glomerocrysts). Dendritic iron-manganese in a 2 cm thick alteration rim.

Site DR05: Sample 06

Less than 100 g of Sandstone.
One rounded, elongate, dark brown (7.5YR4/4) pebble with calcareous oncolites set in clay.

Site DR05: Sample 07

A few chips of Calcilutite.
Very thinly bedded, hard, white (10YR8/2) micrite. Bioclasts include branching bryozoan net fragments, red algae and algal ball fragments.

Site DR05: Sample 08

1 kg of Nanno-foram ooze
Pale brown (10YR6/3) ooze.

Site DR05: Sample 09

Small handfull of Manganese Crusts.
Black to dark brown, less than 5mm thick crust.

SITE SUMMARY, SITE DR06

Latitude: 10° 02' S
Longitude: 103° 56.7' E
Water Depth: 3227 m to 2830 m
Amount Recovered: 223 kg

Site DR06: Sample 01

100 kg of Pillow Basalt
Dark brown, vesicular, hard, microcrystalline background, some samples contain subrounded, oval shaped, phosphatised carbonate clasts. Some samples have a manganese veneer.

Site DR06: Sample 02

25 kg , Trachyte (some Pillow Basalt ?)
Dark brown (10YR5/3 to 10YR3/4), vesicular, hard trachyte. Some samples contain clasts of basalt and/or carbonate and carbonate layers. Manganese encrusted, up to 3 cms thick
and dendritic manganese in part.
2d Trachyte.
Red brown, moderately vesicular, aphyric, microcrystalline groundmass. Spherical vesicles 1mm to 2mm in diameter, some elongated to oval shaped, in an approximately parallel alignment. Vesicles take up 20% of sample.

Site DR06: Sample 03

20 kg of Manganese crusts and impregnations
Black, up to 4 cm thick crust with "bubbly" surface texture.

Site DR06: Sample 04

15 kg of Calcilutite
Phosphatised, cream (5YR8/2), fine grained pelagic carbonate. Some volcanic breccia set in the phosphatised carbonate matrix. Sub-angular, brown, vesicular basalt clasts up to 2 cms diameter. At least two major phases of Manganese crust formation, first up to 3 cm thick, second up to 2 cm thick but generally less than 1 cm.

Site DR06: Sample 05

10 kg of Carbonate breccia
Highly brecciated phosphatised carbonate with variable colour from orange to cream.
Manganese crust 2 mm thick.

Site DR06: Sample 06

2 kg of Basalt

Highly weathered mixed basalt and manganese impregnated phosphatised carbonate.
Manganese crust 0.5 to 1.5 cms thick

Site DR06: Sample 07

200 g of Claystone
Well lithified, pale olive (5Y6/3), intermingled with pale yellow (5Y8/3) phosphatised calcilutite. Some manganese veneer and impregnations.

Site DR06: Sample 08

800 g of Chalk
Moderately lithified, heavily weathered, cream coloured (10YR8/2) chalk. Number of micrites mixed by bioturbation, grey and brown micrite borings. Manganese impregnations and dendrites.

Site DR06: Sample 09

100g of Pumice
Small sub rounded, dark brown (10YR4/3), vesicular pumice pieces up to 5 cm in diameter.

Site DR06: Sample 10

25 kg of Foram-nanno ooze
Soft, cream (5YR8/2) coloured ooze.

Site DR06: Sample 11

25 kg of Foram sand
Light brownish grey (2.5Y6/2) foram sand.

Site DR06: Sample 12

3 kg of Foram-nanno chalk
Moderately lithified, cream (5YR8/2) coloured chalk.

Site DR06: Sample 13

300 g of Carbonate sparse biomicrite
Light brownish grey (10YR6/2) strongly bioturbated multi-micrite. Very small angular feldspar clasts and sub-rounded once glassy clasts.

SITE SUMMARY, SITE DR07

Latitude: 12° 48.15' S
Longitude: 103° 57.09' E
Water Depth: 3768 m to 3381 m
Amount Recovered: No recovery.

Dredge, weights and 80 m of cable broken off. No recovery.

SITE SUMMARY, SITE DR08

Latitude: 12° 52.51' S
Longitude: 103° 53.22' E
Water Depth: 3700 m to 3300 m
Amount Recovered: 17 kg

Site DR08: Sample 01

500 g of Volcanolithic sandstone and grit
Olive (5Y5/4), very coarse to medium grained, very poorly sorted, strongly lithified volcanolithic sandstone and grit. Angular fine grain basalt fragments, pumice, mollusc and unidentified carbonate clasts.

Site DR08: Sample 02

200 g of Hyaloclastite breccia
Very hard, olive grey (5Y/52) in colour, with angular, concentric hyaloclastite clasts less than 2 cm in diameter. Some specimens with glassy pumice. One clast replaced by calcite.
8/2a Monomictic breccia
8/2b Polymictic, diverse lava types
8/2c Originally glassy basaltic hyaloclastite

Site DR08: Sample 03

3 kg of Porphyritic Basalt
Weathered, dark grey (2.5YN4) basalt. Some samples have Manganese veneer.
3a Originally glassy feldspar phyric basalt.
3b Hawaiite

Site DR08: Sample 04

8 kg of Microcrystalline Basalt
One complete fresh, homogenous, dark grey (2.5Y4/0) rock.

Site DR08: Sample 05 ***

5 kg of Basalt and trachyte
Fine grained, brown, (10YR4/3 to 10YR5/2), very weathered samples.
Minor vesicular specimens.
5a Feldspar phyric basalt.
5b Aphyric Trachyte.

Site DR08: Sample 06

200 g of Manganese crusts
Micro-botryoidal, laminated crusts up to 5 mm thick, found on volcanics and limestones.

Site DR08: Sample 07

50 g of Calcarenite fragments
Pale olive (5YR6/3), medium to coarse grained calcarenite.

SITE SUMMARY, SITE DR09

Latitude: 11° 27.10' S
Longitude: 104° 24.59' E
Water Depth: 1800m to 1600 m
Amount Recovered: 21 kg

Site DR09: Sample 01

100 g of Formerly glassy basalt
Weathered, dark yellowish brown (10YR4/4), aphinitic, divitrified glassy olivine basalt.
with manganese veneer.

Site DR09: Sample 02

10 g of Calcilutite
Hard, fine grained. Light grey (10YR7/2) to pale yellow (2.5Y7/4).

Site DR09: Sample 03

10 g of Chalk
White (10YR8/1), weakly lithified, foraminiferids rich chalk.

Site DR09: Sample 04

20 g Chalky ooze
White (2.5Y8/2), soft, foraminiferids-rich chalky ooze.

Site DR09: Sample 05

20 kg of Foram ooze
Unconsolidated, light yellowish brown (2.5Y6/4) foram rich ooze.

SITE SUMMARY, SITE DR10

Latitude: 11° 26.46' S
Longitude: 104° 24.31' E
Water Depth: 1515 m to 1445 m
Amount Recovered: 28 kg

Site DR10: Sample 01

1 kg of Basalt and Trachyte
Microcrystalline, dark brown (10YR4/3), porphyritic, phenocrysts include pyroxene and feldspar. Manganese veneer.

1b Trachyte, a mixed rock.
Dark brown (10YR4/3), microcrystalline groundmass with 20% phenocrysts of olivine, pyroxene and feldspar up to 2mm long.

Site DR10: Sample 02

100 kg of <u>Carbonate Grainstone</u>
Poorly sorted coarse to gritty carbonate and volcanic clasts set in a fine grain carbonate matrix. Carbonate clasts include molluscs, bivalves, echinoids and other carbonate fragments. Volcanic clasts are sub-angular, and are commonly dark brown, fine grained basalt. Thickly to medium bedded. Matrix colour is pinkish white (7.5YR8/2) with some browner and greyer layers. Manganese crust up to 3 mm thick, with only a veneer on some samples.
10/2a
Three main layers are present in the slide, a basal layer rich in red algae fragments and a few sub-angular volcanic clasts in a sparse matrix of planktic foram rich dark grey micrite. The middle layer also has the dark grey globular foram rich micrite but has fewer algal fragments and no volcanic fragments. The upper layer has algal fragments and other bioclasts set in a light yellow micrite.
10/2b
Poorly sorted coarse red algal fragments and molluscan (complicated wall structure) debris
?Inoceramus, a late Cretaceous mollusc, other molluscan fragments include an unusual U shaped fragment.
Occasional ostracods and bryozoan.
Pelloids, possible fecal pellets.

Site DR10: Sample 03 ***

20 kg <u>Chalk</u>
Medium bedded, fine grain bioturbated carbonate. White (10YR8/2), with very pale brown (10YR7/4) infillings. Forams not abundant. Manganese veneer and dendritic impregnations.

Site DR10: Sample 04

3 kg <u>Chalk</u>
Fine grain white (10YR8/2) carbonate with abundant foraminiferids. Dendritic Manganese impregnations.

Site DR10: Sample 05

3 kg of Manganese Crust
Black, up to 3 cm thick. Central crust massive, edges folliated. Bubbled, ropey appearance, smooth on microscopic scale.

Site DR10: Sample 06

100g Chalky ooze
White (10YR8/2), very fine grain chalky ooze.

Site DR10: Sample 07

100 g of Nanno-foram ooze
Pale brown (10YR6/3) ooze.

SITE SUMMARY, SITE DR11

Latitude: 11° 25.14' S
Longitude: 105° 02.10' E
Water Depth: 2850 m to 1718 m
Amount Recovered: 1.41 kg

Site DR11: Sample 01

200 g of Foram-nanno ooze
Pale brown (10YR6/3), fine grain, slightly sandy ooze.

Site DR11: Sample 02

1.2 kg of Manganese crust
Black, up to 3 cm thick. Botryoidal and microbotryoidal surface texture. Finely laminated. Some showing clay and carbonate dendrites.

Site DR11: Sample 03

10 g fine grained material
Assortment from pipe dredge, includes recent foraminiferids and a small star fish.

SITE SUMMARY, SITE DR12

Latitude: 11° 25.65' S
Longitude: 104° 53.59' E
Water Depth: 1800 m to 1500 m
Amount Recovered: 2.4 kg

Site DR12: Sample 01

2.4 kg of Nanno-foram sand
Medium to coarse grained, pale brown (10YR6/3) sand.

APPENDIX 2: CHEMICAL ANALYSES OF MANGANESE NODULES AND CRUSTS FROM BMR CRUISES 107 AND 78

Classic Laboratories, Osman Place, Thebarton, South Australia 5031

After the Christmas Island cruise, 42 samples of manganese nodules and crusts were sent to Classic Laboratories for chemical analysis by the induction-coupled plasma spectroscopy method. The samples were pulverised using chrome-free steel and dried at 105°C. The station data for the 40 Christmas Island samples are given in the body of this report in Tables 10 and 12, and some descriptive information is given in Tables 13 and 15. The station information for three nodules (78/DR04/A-C) and one crust (78/DR05) from West Tasmania is given in BMR Record 1989/12. Station DR04 was at about 44°09'S, 144°47'E, in water 2800-2600 m deep, and DR05 was at about 44° 10.5'S, 144°43'E, in water 3730-3050 m deep.

The results are dislayed in three forms: as oxides, as elements, and as correlation matrixes.

Analysis code IC4A Report 2AD0770 Page I1

NATA Certificate

Sample	CaO	Fe2O3	Na2O	Al2O3	TiO2	K2O	MnO
107/FFG/01A1	2.42	7.05	3.50	6.05	0.500	1.26	32.1
107/FFG/01B1	2.22	16.4	2.36	5.05	0.980	0.880	20.0
107/FFG/013A1	2.12	11.8	2.70	5.55	0.490	1.01	29.2
107/FFG/013A3	2.20	7.60	3.08	5.20	0.370	1.19	34.5
107/FFG/016A	1.95	18.3	2.32	6.60	0.760	0.980	18.6
107/FFG/016B	2.18	20.0	2.34	6.10	0.850	0.980	19.5
107/FFG/016C	2.32	18.2	2.20	3.60	0.770	0.760	26.5
107/FFG/017C1	1.99	9.70	2.72	4.50	0.390	1.20	32.9
107/FFG/023A1	2.34	22.7	2.02	3.48	0.910	0.660	23.5
107/FFG/023A2	2.00	20.6	2.36	5.75	0.820	1.11	18.6
107/FFG/023B1	2.38	24.5	2.02	3.06	0.970	0.620	24.1
107/FFG/023B2	1.90	20.4	2.30	5.35	0.800	0.930	19.7
107/FFG/023B3	2.38	24.7	1.93	3.02	0.960	0.560	23.6
107/FFG/025A1	2.06	10.7	2.78	6.65	0.580	1.19	23.9
107/FFG/025A2	2.00	6.45	2.90	4.86	0.360	0.930	37.3
107/FFG/025B1A	1.68	8.60	2.98	5.90	0.380	1.26	26.4
107/FFG/025B2B	1.87	6.55	3.00	4.26	0.240	1.25	35.6
107/FFG/025C1	1.81	8.65	2.74	6.10	0.440	1.27	26.7
107/FFG/025C2	1.78	10.00	2.76	5.55	0.410	1.30	25.5
107/FFG/025C3	1.78	10.00	3.12	5.35	0.400	1.23	25.7
107/FFG/026B	1.65	7.75	3.74	3.50	0.210	1.18	33.2
107/FFG/026C	1.42	13.2	2.48	7.75	0.750	1.06	20.4
107/FFG/028A	2.52	11.9	3.14	9.75	0.910	1.93	17.3
107/FFG/028B	1.99	13.9	3.06	9.45	0.780	1.81	15.4
107/DR05/5	7.55	28.8	2.28	1.93	2.62	0.500	14.2
107/DR06/2B1	3.00	24.6	1.97	1.28	1.04	0.440	26.2
107/DR06/2B2	2.72	20.0	2.30	3.78	1.42	1.07	23.4
107/DR06/2B3	16.1	17.1	1.81	1.76	1.57	0.590	18.6
107/DR06/2C1	2.88	23.7	2.28	2.20	1.21	0.700	24.6
107/DR06/2C2	2.68	20.4	2.52	4.70	1.55	1.20	21.4
107/DR06/2C3	14.7	17.6	1.87	1.40	1.61	0.520	21.3
107/DR06/ 3A	10.5	16.6	2.26	4.34	1.39	1.15	14.5
107/DR008/6	10.1	17.8	2.56	6.40	1.91	1.36	12.6
107/DR10/5A	4.28	19.9	2.20	2.28	0.380	1.09	24.4
107/DR10/5B	8.75	24.5	2.08	1.77	2.12	0.590	18.3
107/DR11/2A	3.18	21.2	2.12	0.850	1.24	0.440	31.4
107/DR11/2B	9.50	12.9	3.78	9.55	1.04	2.54	4.96
107/DR11/2C	2.32	13.5	2.50	2.78	0.500	0.870	37.0
78/DR05A	2.04	20.0	1.81	5.75	1.22	1.06	15.5
78/DR04/A	2.04	22.9	1.74	2.12	1.05	0.470	20.9
78/DR04/B	5.75	36.2	1.19	3.58	0.380	0.500	12.6
78/DR04/C	3.60	33.5	1.34	4.50	0.510	0.730	11.4
Detn limit	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
Units	%	%	%	%	%	%	%

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Sample	P2O5	MgO	SiO2	LOI	As	Sn	Mo
107/FFG/01A1	0.500	2.60	20.5	19.8	<50	<50	360
107/FFG/01B1	0.450	1.76	26.2	20.4	120	<50	280
107/FFG/013A1	0.380	2.92	19.6	20.3	<50	<50	340
107/FFG/013A3	0.280	2.84	18.6	19.9	60	<50	320
107/FFG/016A	0.510	2.34	22.9	22.0	120	<50	240
107/FFG/016B	0.560	2.26	23.1	20.0	100	<50	200
107/FFG/016C	0.470	2.00	13.7	26.0	60	<50	260
107/FFG/017C1	0.280	3.12	20.0	19.3	<50	<50	280
107/FFG/023A1	0.610	1.94	14.0	25.3	120	<50	280
107/FFG/023A2	0.590	2.14	21.2	23.0	60	<50	220
107/FFG/023B1	0.660	1.94	12.8	25.5	160	<50	280
107/FFG/023B2	0.520	2.36	19.9	23.1	100	60	240
107/FFG/023B3	0.680	1.89	12.5	25.6	80	<50	240
107/FFG/025A1	0.420	2.52	26.3	19.3	<50	<50	340
107/FFG/025A2	0.240	3.06	15.6	20.4	<50	<50	550
107/FFG/025B1A	0.250	2.58	27.9	18.4	<50	<50	360
107/FFG/025B2B	0.210	2.66	20.7	19.4	<50	<50	450
107/FFG/025C1	0.310	2.80	26.7	18.3	<50	<50	340
107/FFG/025C2	0.270	2.78	27.0	18.5	<50	<50	360
107/FFG/025C3	0.230	2.48	27.8	18.3	<50	<50	340
107/FFG/026B	0.180	2.82	21.2	20.8	<50	<50	400
107/FFG/026C	0.370	3.30	26.8	19.4	80	<50	220
107/FFG/028A	0.520	2.08	31.3	16.4	140	<50	220
107/FFG/028B	0.390	2.20	31.3	17.2	180	<50	200
107/DR05/5	4.66	1.66	11.9	21.5	180	<50	<50
107/DR06/2B1	1.01	1.65	7.95	27.0	320	<50	550
107/DR06/2B2	0.780	1.63	15.6	23.6	100	<50	400
107/DR06/2B3	9.15	1.18	6.35	22.1	100	<50	450
107/DR06/2C1	0.800	1.60	10.6	26.8	220	<50	450
107/DR06/2C2	0.750	1.80	17.3	24.9	180	<50	500
107/DR06/2C3	8.30	1.19	5.00	24.0	180	<50	360
107/DR06/23A	6.05	1.25	15.1	23.9	160	<50	300
107/DR008/6	0.700	1.54	20.5	23.7	220	<50	200
107/DR10/5A	2.04	3.10	17.3	20.5	100	<50	360
107/DR10/5B	5.35	1.61	10.8	21.3	220	<50	180
107/DR11/2A	0.890	1.89	5.10	29.7	240	<50	750
107/DR11/2B	5.35	1.41	32.0	16.1	60	<50	<50
107/DR11/2C	0.520	3.72	8.10	24.1	100	<50	450
78/DR05A	0.620	2.02	29.8	18.8	160	<50	280
78/DR04/A	0.730	1.85	18.6	24.8	100	<50	550
78/DR04/B	3.96	2.02	14.8	17.9	160	<50	260
78/DR04/C	2.26	2.14	19.2	18.6	100	<50	220
Detn limit	(0.010)	(0.010)	(0.010)	(0.010)	(50)	(50)	(50)
Units	%	%	%	%	ppm	ppm	ppm

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Sample	Cr	W	Zn	Pb	Cd	Co	Ni
107/FFG/01A1	<50	<100	2200	180	<20	1000	5200
107/FFG/01B1	<50	<100	660	500	<20	2800	2650
107/FFG/013A1	<50	100	1400	600	<20	750	8400
107/FFG/013A3	<50	100	2000	400	<20	550	8400
107/FFG/016A	<50	<100	700	950	<20	1100	4100
107/FFG/016B	<50	100	640	850	<20	850	4300
107/FFG/016C	<50	100	740	1150	<20	2100	4650
107/FFG/017C1	<50	<100	1650	340	20	550	5100
107/FFG/023A1	<50	<100	640	1500	<20	2100	3850
107/FFG/023A2	<50	<100	520	1050	<20	1300	3200
107/FFG/023B1	<50	<100	620	1450	<20	1900	3600
107/FFG/023B2	<50	<100	600	950	<20	1350	3850
107/FFG/023B3	<50	<100	600	1400	<20	1850	3250
107/FFG/025A1	<50	<100	940	400	<20	950	5700
107/FFG/025A2	<50	<100	1250	300	<20	800	1.28%
107/FFG/025B1A	<50	<100	1100	200	<20	1000	3850
107/FFG/025B2B	<50	<100	1400	80	<20	950	6100
107/FFG/025C1	<50	<100	860	280	<20	1200	5900
107/FFG/025C2	<50	<100	1100	260	<20	1450	4300
107/FFG/025C3	<50	<100	1100	280	<20	1600	4050
107/FFG/026B	<50	<100	1750	200	<20	1500	3850
107/FFG/026C	<50	<100	960	550	<20	1100	6300
107/FFG/028A	<50	100	1050	360	<20	500	5000
107/FFG/028B	<50	<100	820	550	<20	700	4000
107/DR05/5	<50	<100	980	2650	20	8500	1300
107/DR06/2B1	<50	<100	800	1550	20	3900	3650
107/DR06/2B2	<50	100	660	1200	<20	5300	3800
107/DR06/2B3	<50	<100	600	1500	<20	3750	2000
107/DR06/2C1	<50	200	580	1500	<20	4000	2050
107/DR06/2C2	<50	100	700	1500	20	4200	3200
107/DR06/2C3	<50	<100	640	1050	<20	4100	3500
107/DR06/23A	<50	<100	540	1150	<20	3200	1800
107/DR008/6	140	200	640	850	<20	2700	1900
107/DR10/5A	<50	100	1150	320	<20	1550	7200
107/DR10/5B	<50	<100	900	2300	<20	8900	1850
107/DR11/2A	<50	200	640	1900	<20	7300	4850
107/DR11/2B	<50	200	380	750	<20	1900	1500
107/DR11/2C	<50	<100	1400	600	<20	2200	1.08%
78/DR05A	<50	<100	560	1050	<20	4250	2950
78/DR04/A	<50	100	800	1300	<20	4550	4250
78/DR04/B	60	100	1100	700	20	1400	3450
78/DR04/C	60	<100	1150	700	20	1550	3300
Detn limit	(50)	(100)	(20)	(50)	(20)	(50)	(50)
Units	ppm	ppm	ppm	ppm	ppm	ppm	ppm

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Sample	Ba	Ta	Nb	V	Be	Cu	La
107/FFG/01A1	880	<50	<50	320	<20	5200	60
107/FFG/01B1	1150	<50	80	440	<20	2250	60
107/FFG/013A1	1150	<50	<50	380	<20	7000	120
107/FFG/013A3	1350	<50	<50	360	<20	7800	80
107/FFG/016A	860	<50	60	440	<20	2900	160
107/FFG/016B	860	<50	60	380	<20	2750	180
107/FFG/016C	1100	<50	80	500	<20	3550	200
107/FFG/017C1	1700	<50	<50	380	<20	4650	80
107/FFG/023A1	1200	<50	80	560	<20	2450	260
107/FFG/023A2	920	<50	60	460	<20	1900	220
107/FFG/023B1	1100	<50	80	560	<20	2150	260
107/FFG/023B2	860	<50	80	460	<20	2100	200
107/FFG/023B3	1100	<50	100	560	<20	2050	280
107/FFG/025A1	900	<50	<50	340	<20	5400	80
107/FFG/025A2	1250	<50	<50	380	<20	1.30%	60
107/FFG/025B1A	1250	<50	<50	360	<20	6100	60
107/FFG/025B2B	1550	<50	<50	400	<20	7200	60
107/FFG/025C1	1550	<50	<50	360	<20	6900	60
107/FFG/025C2	1350	<50	<50	420	<20	6200	80
107/FFG/025C3	1400	<50	<50	360	<20	5900	60
107/FFG/026B	1550	<50	<50	400	<20	6300	<50
107/FFG/026C	900	<50	<50	340	<20	8800	80
107/FFG/028A	740	<50	60	220	<20	2400	100
107/FFG/028B	640	<50	80	240	<20	3500	120
107/DR05/5	3050	<50	200	460	<20	900	380
107/DR06/2B1	1100	<50	100	600	<20	1400	220
107/DR06/2B2	1350	<50	120	460	<20	1950	180
107/DR06/2B3	1800	<50	80	480	<20	800	280
107/DR06/2C1	1900	<50	80	520	<20	1550	200
107/DR06/2C2	1100	<50	100	560	<20	1200	260
107/DR06/2C3	1400	<50	100	440	<20	1400	160
107/DR06/23A	1800	<50	80	480	<20	1150	200
107/DR008/6	580	<50	80	380	<20	600	160
107/DR10/5A	1900	<50	60	340	<20	800	60
107/DR10/5B	3200	<50	160	560	<20	750	450
107/DR11/2A	1300	<50	80	600	<20	550	240
107/DR11/2B	1050	<50	<50	190	<20	1400	100
107/DR11/2C	3150	<50	60	480	<20	1350	60
78/DR05A	920	<50	80	400	<20	950	180
78/DR04/A	1700	<50	120	580	<20	1150	180
78/DR04/B	1500	<50	60	680	<20	700	100
78/DR04/C	1250	<50	80	640	<20	1150	100
Detn limit	(20)	(50)	(50)	(20)	(20)	(50)	(50)
Units	ppm	ppm	ppm	ppm	ppm	ppm	ppm

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Sample	Zr	Sc	Y	Sr	Ce
107/FFG/01A1	170	20	50	360	200
107/FFG/01B1	580	<20	50	740	1300
107/FFG/013A1	300	20	80	560	400
107/FFG/013A3	200	<20	50	500	200
107/FFG/016A	540	30	110	780	700
107/FFG/016B	500	30	90	660	600
107/FFG/016C	440	20	100	880	1100
107/FFG/017C1	200	20	50	560	1600
107/FFG/023A1	620	30	130	1050	1300
107/FFG/023A2	540	30	110	820	900
107/FFG/023B1	680	20	140	1100	1300
107/FFG/023B2	600	30	100	800	900
107/FFG/023B3	700	30	100	800	1400
107/FFG/025A1	280	30	80	480	300
107/FFG/025A2	180	<20	40	420	200
107/FFG/025B1A	360	30	40	360	200
107/FFG/025B2B	130	<20	40	380	100
107/FFG/025C1	220	20	50	380	300
107/FFG/025C2	240	20	60	440	300
107/FFG/025C3	190	20	40	360	300
107/FFG/026B	100	<20	30	360	1400
107/FFG/026C	440	40	40	420	3200
107/FFG/028A	480	<20	60	520	300
107/FFG/028B	620	<20	60	520	400
107/DR05/5	840	<20	340	1400	3600
107/DR06/2B1	620	<20	170	1350	1100
107/DR06/2B2	640	<20	100	1050	1500
107/DR06/2B3	520	<20	200	1250	1700
107/DR06/2C1	520	<20	220	1350	1800
107/DR06/2C2	640	<20	140	1200	1200
107/DR06/2C3	640	<20	90	960	1400
107/DR06/23A	500	<20	220	1100	1600
107/DR008/6	420	<20	100	740	600
107/DR10/5A	300	<20	70	740	200
107/DR10/5B	660	<20	500	1450	2700
107/DR11/2A	520	<20	130	1450	1400
107/DR11/2B	400	<20	110	700	800
107/DR11/2C	300	<20	70	840	400
78/DR05A	560	<20	90	740	1100
78/DR04/A	500	<20	90	980	1300
78/DR04/B	280	<20	110	600	900
78/DR04/C	380	<20	100	600	600
Detn limit	(20)	(20)	(20)	(20)	(100)
Units	ppm	ppm	ppm	ppm	ppm

XMASANAL.XLS

Sample	Mn	Fe	Ni	Cu	Co	Zn	Pb	Si	Al	Ti	Mg	Ca	Na	K	P	Ba	Sr	Zr	Y	La	Ce	V	Mo
107/FFG/01A1	24.86	4.93	0.52	0.52	0.10	0.22	0.02	9.58	3.20	0.30	1.57	1.73	2.60	1.05	0.22	0.09	0.04	0.02	0.01	0.01	0.02	0.03	0.04
107/FFG/01B1	15.49	11.47	0.27	0.23	0.28	0.07	0.05	12.25	2.67	0.59	1.06	1.59	1.75	0.73	0.20	0.12	0.07	0.06	0.01	0.01	0.13	0.04	0.03
107/FFG/013A1	22.62	8.25	0.84	0.70	0.08	0.14	0.06	9.16	2.94	0.29	1.76	1.52	2.00	0.84	0.17	0.12	0.06	0.03	0.01	0.01	0.04	0.04	0.03
107/FFG/013A3	26.72	5.31	0.84	0.78	0.06	0.20	0.04	8.70	2.75	0.22	1.71	1.57	2.28	0.99	0.12	0.14	0.05	0.02	0.01	0.01	0.02	0.04	0.03
107/FFG/016A	14.41	12.80	0.41	0.29	0.11	0.07	0.10	10.71	3.49	0.46	1.41	1.39	1.72	0.81	0.22	0.09	0.08	0.05	0.01	0.02	0.07	0.04	0.02
107/FFG/016B	15.10	13.99	0.43	0.28	0.09	0.06	0.09	10.80	3.23	0.51	1.36	1.56	1.74	0.81	0.24	0.09	0.07	0.05	0.01	0.02	0.06	0.04	0.02
107/FFG/016C	20.52	12.73	0.47	0.36	0.21	0.07	0.12	6.40	1.91	0.46	1.21	1.66	1.63	0.63	0.21	0.11	0.09	0.04	0.01	0.02	0.11	0.05	0.03
107/FFG/017C1	25.48	6.78	0.51	0.47	0.06	0.17	0.03	9.35	2.38	0.23	1.88	1.42	2.02	1.00	0.12	0.17	0.06	0.02	0.01	0.01	0.16	0.04	0.03
107/FFG/023A1	18.20	15.87	0.39	0.25	0.21	0.06	0.15	6.55	1.84	0.55	1.17	1.67	1.50	0.55	0.27	0.12	0.11	0.06	0.01	0.03	0.13	0.06	0.03
107/FFG/023A2	14.41	14.41	0.32	0.19	0.13	0.05	0.11	9.91	3.04	0.49	1.29	1.43	1.75	0.92	0.26	0.09	0.08	0.05	0.01	0.02	0.09	0.05	0.02
107/FFG/023B1	18.67	17.13	0.36	0.22	0.19	0.06	0.15	5.98	1.62	0.58	1.17	1.70	1.50	0.51	0.29	0.11	0.11	0.07	0.01	0.03	0.13	0.06	0.03
107/FFG/023B2	15.26	14.27	0.39	0.21	0.14	0.06	0.10	9.30	2.83	0.48	1.42	1.36	1.71	0.77	0.23	0.09	0.08	0.06	0.01	0.02	0.09	0.05	0.02
107/FFG/023B3	18.28	17.27	0.33	0.21	0.19	0.06	0.14	5.84	1.60	0.58	1.14	1.70	1.43	0.46	0.30	0.11	0.08	0.07	0.01	0.03	0.14	0.06	0.02
107/FFG/025A1	18.51	7.48	0.57	0.54	0.10	0.09	0.04	12.30	3.52	0.35	1.52	1.47	2.06	0.99	0.18	0.09	0.05	0.03	0.01	0.01	0.03	0.03	0.03
107/FFG/025A2	28.89	4.51	1.28	1.30	0.08	0.13	0.03	7.29	2.57	0.22	1.85	1.43	2.15	0.77	0.10	0.13	0.04	0.02	0.00	0.01	0.02	0.04	0.06
107/FFG/025B1A	20.45	6.01	0.39	0.61	0.10	0.11	0.02	13.04	3.12	0.23	1.56	1.20	2.21	1.05	0.11	0.13	0.04	0.04	0.00	0.01	0.02	0.04	0.04
107/FFG/025B2B	27.57	4.58	0.61	0.72	0.10	0.14	0.01	9.68	2.26	0.14	1.60	1.34	2.23	1.04	0.09	0.16	0.04	0.01	0.00	0.01	0.01	0.04	0.05
107/FFG/025C1	20.68	6.05	0.59	0.69	0.12	0.09	0.03	12.48	3.23	0.26	1.69	1.29	2.03	1.05	0.14	0.16	0.04	0.02	0.01	0.01	0.03	0.04	0.03
107/FFG/025C2	19.75	6.99	0.43	0.62	0.15	0.11	0.03	12.62	2.94	0.25	1.68	1.27	2.05	1.08	0.12	0.14	0.04	0.02	0.01	0.01	0.03	0.04	0.04
107/FFG/025C3	19.90	6.99	0.41	0.59	0.16	0.11	0.03	13.00	2.83	0.24	1.50	1.27	2.31	1.02	0.10	0.14	0.04	0.02	0.00	0.01	0.03	0.04	0.03
107/FFG/026B	25.71	5.42	0.39	0.63	0.15	0.18	0.02	9.91	1.85	0.13	1.70	1.18	2.77	0.98	0.08	0.16	0.04	0.01	0.00	-0.01	0.14	0.04	0.04
107/FFG/026C	15.80	9.23	0.63	0.88	0.11	0.10	0.06	12.53	4.10	0.45	1.99	1.02	1.84	0.88	0.16	0.09	0.04	0.04	0.00	0.01	0.32	0.03	0.02
107/FFG/028A	13.40	8.32	0.50	0.24	0.05	0.11	0.04	14.63	5.16	0.55	1.25	1.80	2.33	1.60	0.23	0.07	0.05	0.05	0.01	0.01	0.03	0.02	0.02
107/FFG/028B	11.93	9.72	0.40	0.35	0.07	0.08	0.06	14.63	5.00	0.47	1.33	1.42	2.27	1.50	0.17	0.06	0.05	0.06	0.01	0.01	0.04	0.02	0.02
107/DR05/5	11.00	20.14	0.13	0.09	0.85	0.10	0.27	5.56	1.02	1.57	1.00	5.40	1.69	0.41	2.03	0.31	0.14	0.08	0.03	0.04	0.36	0.05	-0.01
107/DR06/2B1	20.29	17.20	0.37	0.14	0.39	0.08	0.16	3.72	0.68	0.62	1.00	2.14	1.46	0.37	0.44	0.11	0.14	0.06	0.02	0.02	0.11	0.06	0.06
107/DR06/2B2	18.12	13.99	0.38	0.20	0.53	0.07	0.12	7.29	2.00	0.85	0.98	1.94	1.71	0.89	0.34	0.14	0.11	0.06	0.01	0.02	0.15	0.05	0.04
107/DR06/2B3	14.41	11.96	0.20	0.08	0.38	0.06	0.15	2.97	0.93	0.94	0.71	11.51	1.34	0.49	3.99	0.18	0.13	0.05	0.02	0.03	0.17	0.05	0.05
107/DR06/2C1	19.05	16.57	0.21	0.16	0.40	0.06	0.15	4.96	1.16	0.73	0.96	2.06	1.69	0.58	0.35	0.19	0.14	0.05	0.02	0.02	0.18	0.05	0.05
107/DR06/2C2	16.57	14.27	0.32	0.12	0.42	0.07	0.15	8.09	2.49	0.93	1.09	1.92	1.87	1.00	0.33	0.11	0.12	0.06	0.01	0.03	0.12	0.06	0.05
107/DR06/2C3	16.50	12.31	0.35	0.14	0.41	0.06	0.11	2.34	0.74	0.97	0.72	10.51	1.39	0.43	3.62	0.14	0.10	0.06	0.01	0.02	0.14	0.04	0.04
107/DR06/23A	11.23	11.61	0.18	0.12	0.32	0.05	0.12	7.06	2.30	0.83	0.75	7.51	1.68	0.95	2.64	0.18	0.11	0.05	0.02	0.02	0.16	0.05	0.03
107/DR008/6	9.76	12.45	0.19	0.06	0.27	0.06	0.09	9.58	3.39	1.15	0.93	7.22	1.90	1.13	0.31	0.06	0.07	0.04	0.01	0.02	0.06	0.04	0.02
107/DR10/5A	18.90	13.92	0.72	0.08	0.16	0.12	0.03	8.09	1.21	0.23	1.87	3.06	1.63	0.90	0.89	0.19	0.07	0.03	0.01	0.01	0.02	0.03	0.04
107/DR10/5B	14.17	17.13	0.19	0.08	0.89	0.09	0.23	5.05	0.94	1.27	0.97	6.25	1.54	0.49	2.34	0.32	0.15	0.07	0.05	0.05	0.27	0.06	0.02
107/DR11/2A	24.32	14.83	0.49	0.06	0.73	0.06	0.19	2.38	0.45	0.74	1.14	2.27	1.57	0.37	0.39	0.13	0.15	0.05	0.01	0.02	0.14	0.06	0.08
107/DR11/2B	3.84	9.02	0.15	0.14	0.19	0.04	0.08	14.96	5.06	0.62	0.85	6.79	2.80	2.11	2.34	0.11	0.07	0.04	0.01	0.01	0.08	0.02	-0.01
107/DR11/2C	28.66	9.44	1.08	0.14	0.22	0.14	0.06	3.79	1.47	0.30	2.24	1.66	1.85	0.72	0.23	0.32	0.08	0.03	0.01	0.01	0.04	0.05	0.05
78/DR05A	12.00	13.99	0.30	0.10	0.43	0.06	0.11	13.93	3.04	0.73	1.22	1.46	1.34	0.88	0.27	0.09	0.07	0.06	0.01	0.02	0.11	0.04	0.03
78/DR04/A	16.19	16.01	0.43	0.12	0.46	0.08	0.13	8.70	1.12	0.63	1.12	1.46	1.29	0.39	0.32	0.17	0.10	0.05	0.01	0.02	0.13	0.06	0.06
78/DR04/B	9.76	25.31	0.35	0.07	0.14	0.11	0.07	6.92	1.90	0.23	1.22	4.11	0.88	0.41	1.73	0.15	0.06	0.03	0.01	0.01	0.09	0.07	0.03
78/DR04/C	8.83	23.43	0.33	0.12	0.16	0.12	0.07	8.98	2.38	0.31	1.29	2.57	0.99	0.61	0.99	0.13	0.06	0.04	0.01	0.01	0.06	0.06	0.02
	Mn wt%	Fe wt%	Ni wt%	Cu wt%	Co wt%	Zn wt%	Pb wt%	Si wt%	Al wt%	Ti wt%	Mg wt%	Ca wt%	Na wt%	K wt%	P wt%	Ba wt%	Sr wt%	Zr wt%	Y wt%	La wt%	Ce wt%	V wt%	Mo wt%
Detn limit			50.00																				
Units			m ppm																				

Christmas Island Manganese Nodules Correlation Matrix n=27

	Mn	Fe	Ni	Cu	Co	Zn	Pb	Si	Al	Ti	Mg	Ca	P	K	P	Ba	Sr	Zr	Y	La	Ce	V	Mo
Mn	1.000																						
Fe	-0.509	1.000																					
Ni	0.708	-0.435	1.000																				
Cu	0.544	-0.706	0.597	1.000																			
Co	-0.137	0.515	-0.426	-0.539	1.000																		
Zn	0.577	-0.286	0.546	0.507	-0.412	1.000																	
Pb	-0.289	0.630	-0.496	-0.604	0.940	-0.512	1.000																
Si	-0.260	-0.454	-0.023	0.381	-0.589	0.099	-0.609	1.000															
Al	-0.347	-0.448	0.029	0.336	-0.616	-0.042	-0.552	0.888	1.000														
Ti	-0.464	0.436	-0.578	-0.575	0.818	-0.617	0.867	-0.409	-0.280	1.000													
Mg	0.610	-0.468	0.792	0.632	-0.545	0.751	-0.644	0.304	0.198	-0.728	1.000												
Ca	-0.473	0.234	-0.463	-0.462	0.331	-0.478	0.406	-0.437	-0.250	0.599	-0.671	1.000											
Na	0.249	-0.808	0.171	0.518	-0.410	0.275	-0.475	0.563	0.580	-0.300	0.322	-0.272	1.000										
K	-0.250	-0.566	-0.017	0.221	-0.547	-0.051	-0.536	0.796	0.881	-0.259	0.132	-0.141	0.771	1.000									
P	-0.468	0.323	-0.441	-0.445	0.364	-0.406	0.445	-0.452	-0.315	0.515	-0.623	0.927	-0.350	-0.222	1.000								
Ba	0.203	0.236	0.056	-0.225	0.525	0.233	0.456	-0.535	-0.601	0.283	0.076	0.194	-0.211	-0.465	0.330	1.000							
Sr	-0.161	0.584	-0.411	-0.679	0.867	-0.545	0.933	-0.739	-0.649	0.776	-0.640	0.430	-0.487	-0.539	0.449	0.443	1.000						
Zr	-0.477	0.532	-0.517	-0.608	0.724	-0.646	0.823	-0.331	-0.206	0.850	-0.665	0.367	-0.398	-0.260	0.390	0.138	0.762	1.000					
Y	-0.321	0.521	-0.496	-0.484	0.801	-0.328	0.845	-0.486	-0.444	0.754	-0.543	0.465	-0.347	-0.392	0.530	0.632	0.773	0.624	1.000				
La	-0.348	0.550	-0.510	-0.557	0.886	-0.545	0.942	-0.504	-0.436	0.884	-0.662	0.464	-0.461	-0.439	0.487	0.424	0.868	0.821	0.896	1.000			
Ce	-0.273	0.415	-0.417	-0.240	0.696	-0.270	0.746	-0.374	-0.339	0.687	-0.353	0.316	-0.290	-0.431	0.401	0.410	0.594	0.627	0.670	0.663	1.000		
V	0.064	0.720	-0.155	-0.394	0.490	-0.028	0.521	-0.697	-0.748	0.198	-0.257	0.072	-0.772	-0.832	0.159	0.346	0.553	0.215	0.403	0.430	0.284	1.000	
Mo	0.726	-0.138	0.422	0.147	0.028	0.109	-0.037	-0.450	-0.503	-0.284	0.164	-0.288	-0.181	-0.455	-0.304	-0.070	0.170	-0.202	-0.258	-0.106	-0.259	0.427	1.000

Christmas Island Manganese Crusts Correlation Matrix n=14

	Mn	Fe	Ni	Cu	Co	Zn	Pb	Si	Al	Ti	Mg	Ca	Na	K	P	Ba	Sr	Zr	Y	La	Ce	V	Mo
Mn	1.000																						
Fe	-0.730	1.000																					
Ni	0.721	-0.719	1.000																				
Cu	0.800	-0.861	0.962	1.000																			
Co	-0.456	0.605	-0.681	-0.652	1.000																		
Zn	0.898	-0.886	0.715	0.828	-0.602	1.000																	
Pb	-0.513	0.933	-0.526	-0.686	0.541	-0.752	1.000																
Si	-0.235	-0.468	0.066	0.173	-0.280	0.102	-0.695	1.000															
Al	-0.139	-0.523	0.282	0.329	-0.561	0.245	-0.654	0.872	1.000														
Ti	-0.798	0.910	-0.832	-0.894	0.806	-0.874	0.767	-0.243	-0.417	1.000													
Mg	0.681	-0.798	0.782	0.797	-0.891	0.771	-0.706	0.274	0.445	-0.947	1.000												
Ca	0.292	0.146	-0.077	-0.023	0.448	0.131	0.268	-0.573	-0.588	0.262	-0.422	1.000											
Na	0.668	-0.937	0.633	0.772	-0.623	0.904	-0.891	0.440	0.580	-0.836	0.724	-0.049	1.000										
K	0.395	-0.850	0.506	0.618	-0.737	0.673	-0.882	0.685	0.787	-0.801	0.765	-0.475	0.868	1.000									
P	-0.638	0.858	-0.709	-0.788	0.531	-0.679	0.798	-0.421	-0.375	0.843	-0.786	0.382	-0.658	-0.704	1.000								
Ba	0.639	-0.297	0.290	0.337	-0.101	0.395	-0.172	-0.269	-0.463	-0.398	0.392	0.057	0.077	0.037	-0.542	1.000							
Sr	-0.538	0.890	-0.607	-0.736	0.675	-0.770	0.921	-0.576	-0.656	0.795	-0.735	0.188	-0.892	-0.843	0.677	-0.053	1.000						
Zr	-0.780	0.966	-0.756	-0.871	0.702	-0.887	0.857	-0.350	-0.467	0.952	-0.849	0.124	-0.909	-0.842	0.825	-0.322	0.859	1.000					
Y	-0.571	0.841	-0.439	-0.609	0.355	-0.731	0.912	-0.520	-0.394	0.659	-0.569	0.089	-0.769	-0.692	0.769	-0.356	0.853	0.751	1.000				
La	-0.480	0.914	-0.495	-0.667	0.399	-0.699	0.972	-0.707	-0.610	0.700	-0.615	0.226	-0.828	-0.804	0.822	-0.213	0.835	0.807	0.893	1.000			
Ce	-0.236	0.593	-0.656	-0.659	0.590	-0.497	0.544	-0.436	-0.734	0.543	-0.461	0.109	-0.708	-0.633	0.332	0.454	0.668	0.581	0.329	0.485	1.000		
V	-0.422	0.886	-0.597	-0.705	0.711	-0.698	0.940	-0.721	-0.800	0.780	-0.749	0.332	-0.886	-0.929	0.719	0.020	0.935	0.861	0.777	0.877	0.726	1.000	
Mo	0.707	-0.740	0.641	0.760	-0.237	0.733	-0.585	0.106	0.151	-0.627	0.485	0.267	0.712	0.411	-0.498	0.215	-0.556	-0.682	-0.480	-0.617	-0.477	-0.494	1.000

APPENDIX 3: $CaCO_3$ AND GRAINSIZE ANALYSES FROM BMR CRUISE 107

Paul Attenborough

Grain Size Analysis

1. This analysis was carried out at BMR using the wet sieve method. The core was sampled at the required interval of 50 cm or less, and between 10 and 15 grammes of sediment were taken. The sample was transferred to a screw-capped vial, which was filled with distilled water, and numbered with core and depth (sample interval).

2. Sieves used were: + 2.5 and +5 mm = Gravel
   + 63 and + 125 µm = Sand
   The mud fraction was the sample washed through the +63 µm sieve.

3. The sample was placed in an ultrasonic bath for 4 minutes before sieving to assist the dispersion of grain particles. The sample was washed through the set of sieves with distilled water, and each fraction was labelled, dried, weighed and recorded.

4. Each fraction's weight was added together to get a total weight, and then each fraction was expressed as a percentage of the total sample weight.

Carbonate Analysis

1. The sample was labelled and dried in an oven preset to 40° C for 24 hours. When dry the sample was transferred to an agate mortar and pestle and then ground into a fine powder.

2. One gramme of sample was weighed into a special sample container. 10 mls of concentrated hydrochloric acid was dispensed into a reaction pressure vessel (a "carbonate bomb") and the sample container floated on the acid within it. The gas-tight lid was screwed into the reaction vessel and the vessel inverted to allow the acid and sediment to mix.

3. Carbon dioxide gas was generated when the acid reacted with any calcium carbonate present in the sample, and the gas pressure was measured on a gauge. The pressure was read and converted to percentage calcium carbonate by using a standard graph. The graph was made by recording the gas pressure released from pure calcium carbonate in volumes of 0.1 to 1 gms, treated using the same procedures as above.

Survey 107
Christmas Island
Project Scientist: N.Exon

Grain Size/ CaCO3
Analysis Results

Sample I.D.	Depth (Metres)	Weight. Retained (grams) >500uM	>250uM	>125uM	>63uM	<63uM	CaCO3 Content	% Retained >500uM	<500>250uM	<250>125uM	<125>63uM	<63uM	%LOSS	Comments
107GC01	0.05	0.3528	0.5151	0.3042	0.2881	0.6409	85%	15%	21%	13%	12%	35%	5%	
107GC01	0.50	0.4495	0.9635	0.5246	0.4132	0.8627	91%	14%	31%	17%	13%	21%	4%	
107GC01	1.00	0.4940	0.8820	0.4490	0.4701	0.9641	87%	12%	21%	11%	11%	42%	3%	
107GC01	1.50	0.9406	1.7357	1.2736	1.2260	2.1666	70%	13%	25%	18%	17%	23%	3%	
107GC01	2.00	1.1332	1.5025	1.0999	0.6769	1.8101	91%	15%	20%	14%	9%	40%	2%	
107GC01	2.50	1.2205	2.2518	1.2406	1.0943	2.3148	91%	13%	24%	13%	12%	33%	4%	
107GC01	3.00	0.5943	1.2430	1.0049	0.9762	1.5705	91%	9%	20%	16%	15%	37%	2%	
107GC01	3.50	0.4670	0.9755	0.6200	0.7151	1.1821	82%	7%	14%	9%	10%	58%	2%	
107GC01	4.00	0.8050	1.8436	0.8542	0.9390	1.7440	80%	11%	24%	11%	12%	39%	3%	
107GC01	4.50	1.0010	1.6500	0.9190	0.7820	1.7830	85%	11%	18%	10%	8%	51%	2%	
107GC01	5.00	0.7462	1.3742	1.0289	0.7191	1.4653	76%	10%	19%	14%	10%	43%	3%	
107GC01	5.50	0.5080	1.4201	0.7289	0.7100	1.2180	85%	6%	18%	9%	9%	56%	2%	
107GC01	6.00	0.4375	1.4521	0.6930	0.6768	1.1143	91%	11%	26%	10%	13%	40%	1%	Retested
107GC01	6.10	1.0962	1.2655	0.6962	0.6783	1.7745	89%	18%	21%	12%	11%	37%	1%	
107PC03	0.20	0.6415	0.8020	0.4848	0.3125	0.9540	78%	25%	31%	19%	12%	12%	2%	
107PC03	0.50	0.5157	0.9433	0.5080	0.4018	0.9175	80%	16%	29%	15%	12%	25%	3%	
107PC03	1.00	0.2018	0.6686	0.4500	0.3692	0.5710	89%	7%	22%	15%	12%	41%	3%	
107PC03	1.20	0.4689	1.0615	0.4731	0.2720	0.7409	87%	14%	32%	14%	8%	29%	2%	
107GC04	0.01	0.0674	0.0745	0.0691	0.0940	0.1614	68%	3%	4%	3%	5%	81%	4%	
107GC04	0.50	0.1668	0.2028	0.1600	0.1820	0.3488	57%	8%	10%	8%	9%	63%	3%	
107GC04	0.60	0.0681	0.1023	0.1200	0.0390	0.1071	21%	9%	14%	16%	5%	52%	3%	
107GC04	0.90	0.0007	0.0011	0.2794	0.0732	0.0739	8%	0%	0%	43%	11%	43%	3%	
107GC04	1.01	0.0007	0.0051	0.1778	0.0121	0.0128	6%	1%	23%	20%	10%	44%	3%	Retested
107GC04	1.50	0.0540	0.1320	0.1611	0.0456	0.0996	21%	9%	22%	27%	8%	31%	3%	
107GC04	2.01	0.0197	0.1302	0.5658	0.1089	0.1286	32%	1%	6%	24%	5%	62%	3%	
107GC04	2.50	0.0702	0.1548	0.6010	0.2410	0.3112	30%	2%	5%	20%	8%	61%	3%	
107GC04	3.01	0.0021	0.0276	0.4815	0.0958	0.0979	30%	0%	1%	21%	4%	71%	3%	
107GC04	3.50	0.1000	0.1491	0.1486	0.0542	0.1542	33%	8%	12%	12%	4%	62%	2%	
107GC04	3.90	0.0334	0.1362	0.3601	0.1602	0.1936	35%	1%	6%	16%	7%	67%	3%	

Survey 107
Christmas Island
Project Scientist: N.Exon

Grain Size/ CaCO3
Analysis Results

		Weight. Retained (grams)						% Retained						
Sample I.D.	Depth (Metres)	>500uM	>250uM	>125uM	>63uM	<63uM	CaCO3 Content	>500uM	<500>250uM	<250>125uM	<125>63uM	<63uM	%LOSS	Comments
107PC05	0.03	0.0005	0.0030	0.0053	0.0218	0.0223	17%	0%	1%	2%	7%	88%	3%	
107PC05	0.50	0.0165	0.0526	0.0801	0.0462	0.0627	39%	1%	4%	7%	4%	82%	2%	
107PC05	1.03	0.0040	0.0234	0.1215	0.0947	0.0987	28%	1%	3%	5%	17%	71%	3%	Retested
107PC05	1.50	0.0010	0.0120	0.1898	0.1720	0.1730	21%	0%	1%	16%	15%	66%	2%	
107PC05	2.03	0.0045	0.0186	0.0374	0.1378	0.1423	32%	0%	1%	2%	8%	87%	1%	
107PC05	2.50	0.0011	0.0006	0.0772	0.0820	0.0831	24%	0%	0%	4%	4%	92%	1%	
107PC05	3.03	0.0012	0.0031	0.0041	0.1002		13%	0%	0%	0%	10%	87%	2%	
107PC05	3.50	0.0000	0.0241	0.2893	0.3625	0.3625	3%	0%	1%	9%	11%	79%	1%	
107PC05	4.03	0.0043	0.0095	0.0700	0.0572	0.0615	17%	0%	1%	6%	5%	86%	2%	
107PC05	4.50	0.0027	0.0097	0.0291	0.0410	0.0437	6%	0%	1%	2%	2%	92%	3%	
107PC06	0.08	0.4882	1.8282	0.9427	0.8122	1.3004	84%	6%	21%	11%	10%	48%	4%	
107PC06	0.40	0.0366	1.7402	0.8692	0.6609	0.6975	97%	1%	27%	13%	10%	46%	4%	
107PC07	0.00	0.7783	1.4030	1.0928	0.8128	1.5911	87%	15%	28%	22%	16%	17%	2%	
107PC07	0.10	0.8210	1.6547	1.1486	1.2063	2.0273	72%	11%	23%	16%	17%	30%	3%	
107PC07	0.30	1.0283	1.4880	0.8720	0.6881	1.7164	97%	16%	23%	13%	10%	36%	2%	
107PC07	0.50	0.8870	1.3710	0.9803	0.8037	1.6907	74%	14%	22%	16%	13%	33%	2%	
107PC07	0.70	0.7135	1.2852	1.0230	0.8047	1.5182	89%	12%	22%	18%	14%	32%	2%	
107PC08	0.10	0.2032	0.4542	0.2471	0.2221	0.4253	87%	9%	21%	11%	10%	47%	1%	
107PC08	0.50	0.3960	0.8080	0.5916	0.5100	0.9060	85%	12%	25%	18%	16%	28%	2%	
107PC08	1.00	0.2031	0.4481	0.3181	0.2510	0.4541	87%	10%	22%	16%	12%	38%	3%	
107PC08	1.50	0.5281	1.0220	0.5147	0.4207	0.9488	89%	10%	19%	10%	8%	50%	3%	
107PC08	2.00	0.4420	1.2933	0.6004	0.5750	1.0170	95%	8%	22%	10%	10%	48%	2%	
107PC08	2.50	0.5772	1.3360	0.5900	0.5432	1.1204	93%	11%	25%	11%	10%	40%	2%	

APPENDIX 4: CRUISE 107 SYSTEM REPORT

Ed Chudyk

Rig Seismic departed from Christmas Island late on 7 January 1992 for the survey cruise which consisted of high speed seismic, gravity, magnetic and bathymetric profiling and sampling using free-fall grab, dredge, piston and gravity corer. The cruise was concluded on February 1992.

Data Acquisition System (DAS)

The DAS was started as soon as we boarded at Christmas Island. However, in spite of the fast start which was made, the ship sailed before the DAS was fully up. The DAS computer ran faultlessly for the first two weeks of the cruise. Stoppages in the following two weeks were generally controlled shut-downs or controlled crashes after operator errors.

A summary of the DAS equipment and operation on Survey 107 is as follows.

Racal Satellite Navigation System

1. No signal from the Indian Ocean satellite could be detected by the satellite demodulators; a call to Racal Singapore confirmed that data are transmitted by the Indian Ocean satellite on a frequency different from that used by the Pacific satellite.

Indian satellite frequency (Racal dish)	67.960 Mhz
Pacific satellite frequency; (Racal dish new and old)	68.440 Mhz
Marisat dish as per Racal frequencies but minus	2.000 Mhz

2. Due to the extreme distance to base stations in Broome and Singapore DGPS (differential GPS) coverage was sometimes lost. Two additional stations were used to help fill in these gaps. The positions and approximate ranges of stations used on the survey are as follows:

Singapore	100	01° 17.777' N	103° 47.471' E	1488 km
Kota Trengannu	101	05° 19.991' N	103° 08.922' E	1940 km
Miri	103	04° 23.853' N	133° 59.474'E	1944 km
Darwin (seldom used)	202	12° 25.97' S	139° 50.44'E	3025 km
Perth (not used)	204	32° 03' S	115° 44' E	2527 km
Broome	203	17° 53.958' S	122° 15.558' E	1768 km

By using the extra reference stations DGPS coverage was maintained at 90% with only brief periods of T-set or non-differential coverage. DR was used for less than 0.5% of the navigation. Unfortunately the large distances to the reference stations degraded our usually excellent differential positioning somewhat. However, the navigation was quite adequate for a deep water seismic and sampling survey.

3. Operations on Syndays were adversely affected by tests and re-programming of the GPS satellites. At one stage, with 4 good satellites, excellent geometry and differential corrections, the Racal system was defeated by the rapid changes in position given by the satellites.

4. At one stage no differential data were received from Singapore for S.V. 14 for several days. All the other station we were using were sending corrections; after a call was placed to the Singapore monitor, S.V. 14 became available about 20 minutes later.

5. Both the Singapore and Broome stations fell out occasionally. When reference station failures occurred a different station was selected. Generally no record of the length of the downtime was obtained; however Broome was down for 3 hours on 3 February 1992.

6. Differential data were written to optical disk from 028-0249 GMT to the end of the survey. During the night shift the Compaq PC locked up several times when differential corrections were received for seven satellites with eight in view. The problem was initially solved by reducing the amount of data written to the disk, by tracking only the best 5 satellites. On subsequent nights differential data from 7 satellites were processed and written to disk.

7. The Trimble receiver connected to Racal # 2 generally lost track of satellites well before the other receiver. It was noted that Racal # 2 displayed SNR values considerably lower than Racal # 1. The second Racal antenna was found to be connected to the receiver via a thin co-axial cable, RG-58. The thin co-ax was replaced by an RG-213. The SNR values for Racal # 2 then increased about fifty percent and were then fractionally greater than those of Racal # 1. Racal # 2 then tracked satellites to the mask limit in most conditions.

8. The only problem with receivers was with Trimble # 1, which locked up for apparently no reason on 2 February 1992. All attempts to unlock the unit failed. Eventually the memory was erased and the appropriate data re-entered; the Trimble then resumed navigating.

Magnetometer

There were some initial problems with the magnetometer. Less than optimal performance was caused by a small slit in the head diaphragm and corroded inter-connecting cables. The cables were cleaned and a temporary patch put on the diaphragm, but the patch eventually failed. A different head was then attached to the cable, and it worked satisfactorily until the end of the survey.

Gravity

The Bodenseewerk gravity meter performed flawlessly on the cruise. No gravity ties were made to Christmas Island because of the limited amount of time available, and also because of the difficulty in estimating the elevation of the ship as it rode at anchor 150 m from shore.

Hades echo-sounder system

The 12 KHz echo sounder worked well, and the stem was only lowered once when high noise levels, caused by the thrusters, seriously degraded its performance. The 3.5 KHz echo sounder provided sub-bottom profiling in up to the maximum water depth encountered, seafloor sediment conditions permitting. Generally the performance of the unit was as good as we have previously achieved.

Seismic System

The seismic cable consisted of a 24-channel 600-metre transformerless Geco streamer cable, one fore and one aft stretch section, 3 Syntron cable levelers, 200 m of tow rope and a single pontoon aluminium tailbuoy. The seismic source consisted of 2 Haliburton 150 c.i. sleeve guns, with a nominal air pressure of 2000 psi. The guns were towed in a dual array configuration, one gun being deployed from each side of the stern, and were towed about 30 m behind the ship. The guns were each suspended beneath a rigid steel pontoon at depths varying from 1 to 1.5 m, and at speeds of 6.5 and 9 knots. The speed was varied in relation to the thickness of the sediments, the thinner the sediment cover the faster the ship's speed. The data were of a quality to satisfy the cruise requirements and were written into 3480 tape cartridges.

Some relatively minor problems were experienced with the seismic system. The following is a list of the problems and the actions taken to rectify them:

1. Automatic test sequence cutoff filters to 0
   Reset filters back to 24 and 256 Hz
   Performed individual tests instead of the auto sequence

2. System hangs
   These were traced back to faulty cable connections between DRQ3B card, interface box and Phoenix A/D converter

3. IFP errors and data collection errors
   Minimised by reseating all connectors at the back of MVAX3 CPU and all connectors to the Phoenix A/D converter.

4. Automatic tape change failures - usually after a reboot
   Reinitiated auto switch 100-200 shots before the change
   Reduced number of shots from 1048 to 1000
   Reinitialized auto tape change after 400 - 500 shots.

5. Error in attaching Syntron controller
   A new DHQ11 card was installed, the system was run for 24 hours collecting data, writing to tape, running monitors, reading the gun controller and the Syntron with 3 birds attached to a single programming coil in the workshop without any error message. When the cable was deployed and acquisition started the error message came up after only 30 shots. Later when the original DHQ11 board was tested it worked without fault.

The cause of the system hangs has not been determined. Sometimes Mad (the unit that reads Phoenix) could be restarted and sometimes it could not. Examining the event flag status of the programs did not seem to be particularly helpful in tracking the Mad hangs. If the Mad restart failed, then logging out and then back into Music sometimes fixed the problem. However, the programs usually needed to be recompiled and the Music system reloaded.

The system was run for long periods, betwen seismic lines and while carrying out geological sampling, without failure. The only piece of equipment which was not producing its customary data during the tests was the gun controller; for one test 3 birds were read via the program coil.

The play-back system could read tapes, dump data values and do trace statistics but crashed when the plot option was selected.

Seismic Line Summary

line #	start time	stop time	down time	problems
1	008.0626	009.0147	1:00	system hung
			1:18	system hung
			0:39	loose Phoenix cable
2	009.0700	009.1739	1:00	tape switch failed
3	009.1925	011.2010	2:30	added tailbuoy
			----	tape switch failed
			1:17	system hung
			2:12	system hung
4	016.0621	016.2314	1:11	system hung
			0:51	tape switch failed
5	018.0604	020.0341	1:40	system hung
6	021.0800	021.2054	1:30	system hung
7	025.2246	026.1652	2:15	multiple gun failures
			----	tape switch failed
			2:25	retrieved fishermen and repaired bird rings
8	033.1719	034.1242	----	----------------

Total hours shooting seismic = 193.6 hours (total to 034.1200)
Total down time = 19.8 hours (total to 034.0500)

Percent down time = 10%

APPENDIX 5: CRUISE 107 MECHANICAL REPORT

Ray de Graaf

Coring Winch and Power Pack.

The coring winch and spooling gear worked reasonably well throughout the survey. 5000 m of 18 mm diameter wire rope was lost when the dredge hung up on a volcanic seamount. The power pack caused a few minor problems during the survey.

1: A pressure transducer had to be replaced due to tension readings being unavailable at the winch console.

2: High oil temperature problems developed from a sticking thermostatic valve in the heat exchanger lines. The valve was replaced and the old unit was repaired.

3: There was a loss of hydraulic pressure due to a sticking Rexroth proportional speed controlling valve. The valve was serviced, and operations continued.

Core catchers

The new piston coring/gravity coring core catchers worked well, but the previous core catcher design, with the twin rivets and the rivet heads machined off, works as well and is easier to install.

Dredge Bridle

The new dredge bridle with the right angled hollow section tubes worked well, except that a vent hole should have been left in the tubes to prevent collapse under the water pressure (as did happen).

APPENDIX 6: CORES AND DREDGES FROM THE CHRISTMAS ISLAND REGION

(A listing from The United States Marine Core Curators' Data Base)

Institution: Lamont Doherty Geological Observatory (LDGO)

Sample Location: 09° 33' S Latitude, 102° 30' E Longitude; Ship: ROBERT CONRAD; Sampling Device: Piston Core; Core Length: 1501 cm; Cruise I.D.: RC 14; Storage Method: Unknown Storage Code; Sample Number: 060051; Date Collected: 04/20/71; Water Depth: 5550 m.

age= core bottom is upper late Pleistocene
dominant lithology : interbedded clay
accessory lithologies : structureless diatomaceous clay ooze, structureless diatomaceous ooze, interbedded volcanic ash, interbedded diatomàceous clay
mottling: burrowing
palaeontology: radiolaria, diatoms
mineralogy: dissem volc glass shards, mn oxide, ash layer(s)

Sample Location: 12° 53' S Latitude, 103° 40' E Longitude; Ship: ROBERT CONRAD; Sampling Device: Piston Core; Core Length: 579 cm; Cruise I.D.: RC14; Storage Method: Unknown Storage Code; Sample Number: 062053; Date Collected: 04/22/71; Water Depth: 4544 m.

age= unknown
dominant lithology: structureless foraminiferidsl ooze
accessory lithologies: structureless foraminiferidsl diatomaceous marl ooze, structureless foraminiferidsl chalk ooze, structureless foraminiferidsl marl ooze, structureless foraminiferidsl clay ooze, structureless volcanic sand, interbedded sandy clay
dominant lithology: structureless clay
mottling: burrowing
palaeontology: foraminiferids, radiolaria , diatoms, ostracods, echinoid spines, sponge spicules, fish teeth, shell fragments
mineralogy: quartz, dark minerals, mica, sedimentary rock frags, igneous rock frags(basic), igneous rock frags(acidic), dissem volc glass shards, palagonite, Mn nodules, magnetite, sand stringer(s)

Sample Location: 08° 27' S Latitude, 104° 15' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 1228 cm; Cruise I.D.: VM19 Storage Method: Unknown Storage Code; Sample Number: 168150; Date Collected: 07/16/63; Water Depth: 5678 m; Recovery: 1228 cm

age=core bottom age is upper late Pleistocene
dominant lithology: interbedded clay
accessory lithology: graded volcanic sand
mottling: burrowing
palaeontology: foraminiferids, radiolaria, sponge spicules
mineralogy: quartz, dark minerals, mica, dissem volc glass shards, Mn nodules, glauconite

Sample Location: 08° 51' S Latitude, 102° 07' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 749 cm; Cruise I.D.: VM19; Storage Method: Unknown Storage Code; Sample Number: 171153; Date Collected: 07/18/63; Water Depth: 5433 m; Recovery: 749 cm

age=core bottom age is upper late Pleistocene
dominant lithologies: interbedded clay, radiolarian diatomaceous clay
accessory lithologies: graded volcanic sand, interbedded silty clay
mottling: burrowing
palaeontology: radiolaria, diatoms, sponge spicules
mineralogy: quartz, dark minerals, mica, dissem volcanic glass shards, Mn nodules

Sample Location: 11° 09' S Latitude, 104° 21' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 435cm; Cruise I.D.: VM24; Storage Method: Unknown Storage Code; Sample Number: 205194; Date Collected: 09/02/67; Water Depth: 5256 m

age=core bottom age is unknown
accessory lithologies: structureless, diatomaceous marl ooze, structureless radiolarian clay, laminated radiolarian clay, structureless, clayey volcanic sand
dominant lithology: structureless sandy clay
mottling: burrowing
palaeontology: radiolaria, diatoms, fish teeth
mineralogy: dissem volcanic glass shards, pumice, Mn oxide (dissem)

Sample Location: 09° 38' S Latitude, 102° 34' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 930 m; Cruise I.D.: VM24; Storage Method: UNKNOWN STORAGE CODE; Sample Number: 206195; Date Collected: 09/03/67; Water Depth: 5486 m

age=core bottom is upper late Pleistocene
accessory lithologies: interbedded radiolarian diatomaceous clay ooze, interbedded clayey volcanic sand
dominant lithology: interbedded radiolarian clay
accessory lithology: brecciated radiolarian clay

accessory lithologies: laminated radiolarian clay ooze, structureless volcanic sand
mottling: burrowing
palaeontology: radiolaria, diatoms, sponge spicules
mineralogy: mica, dissem volcanic glass shards, Mn oxide (dissem)

Sample Location: 09° 11' S Latitude, 102° 00' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 785 cm; Cruise I.D.: VM24; Storage Method: Unknown Storage Code; Sample Number: 207196; Date Collected: 09/03/67; Water Depth: 5444 m

age=core bottom age is upper late pleistocene
accessory lithologies: structureless volcanic sandy clay, laminated ash
dominant lithology: structureless clay
accessory lithology: laminated clay
mottling: burrowing
palaeontology: radiolaria
mineralogy: igneous rock frags(basic), dissem volcanic glass shards, ash layer(s)

Sample Location: 08° 00' S Latitude, 102° 24' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 469 cm; Cruise I.D.: VM28; Storage Method: Unknown Storage Code; Sample Number: 389356; Date Collected: 11/10/71; Water Depth: 5574 m

age=core bottom is undifferentiated Pleistocene
accessory lithologies: structureless clay, structureless silty radiolarian clay
dominant lithology: structureless diatomaceous ooze
accessory lithology: structureless volcanic ash
mottling: intense burrowing
palaeontology: radiolaria, diatoms
mineralogy: quartz, mica, igneous rock frags(basic), igneous rock frags(acidic), ash layer(s)

Sample Location: 12° 56' S Latitude, 106° 11' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 1129 cm; Cruise I.D.: VM33; Storage Method: Room Temp, Dry; Inside Diameter: 06 cm; Sample Number: 074; Date Collected: 07/11/76; Water Depth: 5633 m

0-150	primary lithology: undiff. terrigenous material subdominant: undiff. biosiliceous mud or ooze comments: MnO2 nodules
150-179	primary lithology: undiff. terrigenous material first: undiff. biosiliceous mud or ooze
179-183	manganese crusts

183-1129 primary lithology: undiff. terrigenous material
subdominant: mud or ooze

Sample Location: 12° 56' S Latitude, 106° 11' E Longitude; Ship: VEMA; Sampling Device: Gravity Core; Core Length: 68 cm; Cruise I.D.: VM33; Storage Method: Room Temp, Dry; Inside Diameter: 03 cm; Sample Number: 074TW; Date Collected: 07/11/76; Water Depth: 5633 m

0-68 primary lithology: undiff. terrigenous material
subdominant: mud or ooze

Sample Location: 08° 25' S Latitude, 107° 11' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 941 cm; Cruise I.D.: VM33; Storage Method: Room Temp, Dry; Inside Diameter: 06 cm; Sample Number: 075; Date Collected: 07/13/76; Water Depth: 3396 m

0-228	primary lithology: calcareous nannofossil mud or ooze subdominant: undiff. terrigenous material
228-232	primary lithology: undiff. biocalcareous material secondary lithology: undiff. biocalcareous material first subdominant: sand second subdominant: sandy mud or ooze
232-321	primary lithology: undiff. terrigenous material secondary lithology: sandy mud or ooze first subdominant: undiff. biocalcareous material
321-330	primary lithology: foraminiferids sand first subdominant: undiff. terrigenous material
330-671	primary lithology: undiff. terrigenous material first subdominant: diatom mud or ooze
671-680	primary lithology: foraminiferids secondary lithology: sand first subdominant: undiff. terrigenous material
680-699	primary lithology: undiff. terrigenous material subdominant: diatom mud or ooze
699-715	primary lithology: undiff. biosiliceous material secondary lithology : sand subdominant: undiff. terrigenous material
715-810	primary lithology: undiff. terrigenous material subdominant: diatom mud or ooze
810-870	primary lithology: diatom mud or ooze subdominant: sponge spicules second subdominant: calcareous nannofossils
870-885	core disturbance
885-919	primary lithology: undiff. biosiliceous material subdominant: calcareous nannofossil mud or ooze
919-925	primary lithology: foraminiferidsl sand subdominant: undiff. terrigenous material

925-980 primary lithology: undiff. biosiliceous material
subdominant: calcareous nannofossil mud or ooze

Sample Location: 08° 25' S Latitude, 107° 11' E Longitude; Ship/Platform: VEMA; Sampling Device: Gravity Core; Core Length: 68 cm; Cruise I.D.: VM33; Storage Method: Room Temp, Dry; Inside Diameter: 03 cm; Sample Number: 075TW; Date Collected: 07/13/76; Water Depth: 3396 m

0-68 primary lithology: undiff. terrigenous material
secondary: mud or ooze

Sample Location: 08° 20' S Latitude, 106° 57' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 1110 cm; Cruise I.D.: VM33; Storage Method: Room Temp, Dry; Inside Diameter: 06 cm; Sample Number: 076; Date Collected: 07/13/76; Water Depth: 3159 m

0-220 primary lithology: undiff. terrigenous material
secondary lithology : sandy mud or ooze
first subdominant: undiff. biocalcareous material
secondary subdominant : undiff. biosiliceous material
220-28 primary lithology : undiff. terrigenous material
secondary lithology : sandy mud or ooze
subdominant : undiff. terrigenous material
282-515 primary lithology : undiff. terrigenous material
secondary : sandy mud or ooze
515-526 primary lithology : volcanic
secondary : mud or ooze
526-700 primary lithology : undiff. terrigenous material
secondary : sandy mud or ooze
subdominant : undiff. biocalcareous material
700-1013 primary lithology : undiff. terrigenous material
secondary : sandy mud or ooze
1013-1020 primary lithology : undiff. terrigenous material
subdominant : foraminiferids muddy sand
1020-1110 primary lithology : undiff. terrigenous material
subdominant : sandy mud or ooze

Sample Location: 08° 20' S Latitude, 106° 57' E Longitude; Ship/Platform: VEMA; Sampling Device: Gravity Core; Core Length: 24 cm; Cruise I.D.: VM33; Storage Method: Room Temp, Dry; Inside Diameter: 03 cm; Sample Number: 076TW; Date Collected: 07/13/76; Water Depth: 3159 m

0-24 primary : undiff. terrigenous material
secondary : mud or ooze

Sample Location: 08° 07' S Latitude, 106° 43' E Longitude; Ship/Platform: VEMA; Sampling Device: Piston Core; Core Length: 1117 cm; Cruise I.D.: VM33; Storage Method: Room Temp, Dry; Inside Diameter: 6 cm; Sample Number: 077; Date Collected: 07/13/76; Water Depth: 3014 m

0-25	primary: undiff. terrigenous material secondary: sandy mud or ooze
25-58	primary : undiff. terrigenous material secondary: mud or ooze
58-83	primary: undiff. biocalcareous material secondary: sandy mud or ooze
83-147	primary : undiff. terrigenous material secondary: sandy mud or ooze
147-250	primary : undiff. terrigenous material secondary: sandy mud or ooze
250-255	primary : undiff. terrigenous material secondary: muddy sand
255-370	primary : undiff. terrigenous material secondary: sandy mud or ooze subdominant: undiff. biocalcareous material
370-385	primary: undiff. biocalcareous material secondary: sand
385-523	primary: undiff. biocalcareous material secondary: sandy mud or ooze
523-583	primary: undiff. biocalcareous material secondary: muddy sand subdominant: undiff. terrigenous material
583-675	primary: undiff. terrigenous material secondary: sandy mud or ooze
675-685	primary: undiff. biocalcareous material secondary: muddy sand subdominant: undiff. terrigenous material
685-1117	primary: undiff. terrigenous material secondary: sandy mud or ooze subdominant: undiff. biocalcareous material

Sample Location: 08° 07' S Latitude, 106° 43' E Longitude; Ship/Platform: VEMA; Sampling Device: Gravity Core; Core Length: 63 cm; Cruise I.D.: VM33; Storage Method: Room Temp, Dry; Sample Number: 077TW; Date Collected: 07/13/76; Water Depth: 3014 m

0-63	primary: undiff. biocalcareous material secondary: sandy mud or ooze subdominant: volcanic:

Institution: Scripps Instutute of Oceanography (SIO)

Sample: Location: Begining - 09° 23.0' S Latitude, 109° 16.0' E Longitude; water depth : 01390 Corrected Meters; Ship/Platform: ARGO; Cruise I.D.: MSN; Sampling Device Used: Dredge; Date Collected: 11/11/60; Sample Number: 020D; Storage Method: Room Temp, Dry. Ending - Latitude: 08° 07' S; Longitude: 106° 43' E; Water Depth: 3014 m

primary : foraminiferidsl sandy mud or ooze
secondary: volcanic breccia
comments : unknown age

Sample Location: 13° 20.0' S Latitude 109° 35.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Gravity Core; Core Length: 114 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 5 cm; Sample Number: 033G; Date Collected: 11/07/60; Water Depth: 4703 m

0-23	primary: undiff. biocalcareous mud or ooze secondary: undiff. biosiliceous mud or ooze comments: Quaternary
23-51	primary: undiff. biosiliceous mud or ooze secondary: undiff. biocalcareous mud or ooze comments: Quaternary, much E. rex
51-70	primary: undiff. biosiliceous mud or ooze secondary: undiff. biocalcareous mud or ooze comments: Quaternary
70-114	primary: undiff. Quaternary biosiliceous mud or ooze

Sample Location: 13° 18.0' S Latitude, 109° 27.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Gravity Core; Core Length: 156 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 5 cm; Sample Number: 033GA; Date Collected: 11/07/60; Water Depth: 4490 m

0-120	primary: undiff. biosiliceous mud or ooze secondary: undiff. biocalcareous mud or ooze comments: Quaternary
120-138	primary: undiff. biocalcareous mud or ooze secondary: undiff. biosiliceous mud or ooze comments: Quaternary
138-156	primary: undiff. biosiliceous mud or ooze comments: unknown age

Sample Location: 11° 38.0' S Latitude, 109° 33.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Gravity Core; Core Length: 116 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 5 cm; Sample Number: 034G; Date Collected: 11/08/60; Water Depth: 4612 m

0-8 primary: radiolarian mud or ooze
secondary volcanic glass shards
comments: Quaternary
8-116 primary: undiff. biosiliceous mud or ooze
secondary: undiff. biocalcareous mud or ooze
comments : Quaternary

Sample Location: 11° 40.0' S Latitude, 109° 32.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Gravity Core; Core Length: 22 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 5 cm; Sample Number: 034GP; Date Collected: 11/08/60; Water Depth: 4604 m

0-04 primary: undiff. biosiliceous mud or ooze
subdominant: undiff. biocalcareous mud or ooze
comments: Quaternary
4-122 primary: undiff. biosiliceous mud or ooze
secondary: undiff. biocalcareous mud or ooze
comments: Quaternary

Sample Location: 11° 40.0' S Latitude, 109° 32.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Piston Core; Core Length: 916 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 6 cm; Sample Number: 034P; Date Collected: 11/08/60; Water Depth: 4604 m

0-762 primary: undiff. biosiliceous mud or ooze
secondary: undiff. biocalcareous mud or ooze
subdominant: undiff. terrigenous material
comments: Quaternary
762-916: sucked in

Sample Location: 10° 28.0' S Latitude, 109° 46.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Gravity Core; Core Lengt: 96 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 5 cm; Sample Number: 035G; Date Collected: 11/09/60; Water Depth: 6550 m

0-55 primary: undiff. biosiliceous mud or ooze
secondary: undiff. terrigenous mud or ooze
subdominant: volcanic
comments: Quaternary
55-70 primary: diatom mud or ooze
secondary: undiff. biocalcareous mud or ooze
comments: Quaternary
70-96 primary: radiolarian mud or ooze
secondary: undiff. terrigenous mud or ooze
comments: mineral grains, Quaternary

Sample Location: 09° 22.0' S Latitude, 109° 17.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Gravity Core; Core Length: 29 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 5 cm; Sample Number: 036GA; Date Collected: 11/10/60; Water Depth: 1582 m

0-01	primary: undiff. biocalcareous sandy mud or ooze secondary: radiolarian mud or ooze subdominant: volcanic comments: Quaternary
1-29	primary: undiff. biocalcareous material mud or ooze secondary: radiolarian mud or ooze subdominant: volcanic comments: Quaternary

Sample Location: 08° 53.0' S Latitude, 109° 36.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Gravity Core; Core Length: 162 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 5 cm; Sample Number: 037G; Date Collected: 11/11/60; Water Depth: 3300 m

0-162	primary: undiff. biosiliceous mud or ooze secondary: undiff. biocalcareous mud or ooze first subdominant: volcanic second subdominant: undiff. terigenous material comments: Quaternary

Sample Location: 08° 48.0' S Latitude, 109° 38.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Piston Core; Core Length: 919 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 6 cm; Sample Number: 037P; Date Collected: 11/11/60; Water Depth: 3210 m

0-919	primary: undiff. biosiliceous mud or ooze secondary: undiff. biocalcareous mud or ooze subdominant: undiff. terrigenous material comments: mineral grains, Quaternary

Sample Location: 08° 48.0' S Latitude, 109° 38.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Gravity Core; Core Length: 93 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Sample Number: 037PG; Date Collected: 11/11/60; Water Depth: 3210 m

0-93 primary: radiolarian mud or ooze
secondary: undiff. biocalcareous mud or ooze
first subdominant: undiff. terrigenous material
second: volcanic
comments: Quaternary

Sample Location: 11° 15.0' S Latitude, 103° 28.0' E Longitude; Ship/Platform: ARGO; Sampling Device: Gravity Core; Core Length: 123 cm; Cruise I.D.: MSN; Storage Method: Refrigerated; Inside Diameter: 5 cm; Sample Number: 038G; Date Collected: 11/20/60; Water Depth: 5527 m

0-123 primary: undiff. biosiliceous mud or ooze
comments: Quaternary

Sample Location: 08° 29.1' S Latitude, 108° 01.4' E Longitude; Ship/Platform: T. WASHINGTON; Sampling Device: Piston Core; Core Length: 270 cm; Cruise I.D.: ERDC; Storage Method: Refrigerated; Inside Diameter: 8 cm; Sample Number: 039P; Date Collected: 02/02/75; Water Depth: 3528 m

0-10 primary: volcanic ash
secondary: undiff. terrigenous sandy mud or ooze
first subdominant: undiff. biosiliceous material
second subdominant: plant debris
comments: Quaternary

10-62 primary: volcanic ash
first subdominant: undiff. biosiliceous material
second subdominant: undiff. terrigenous material
comments: Quaternary

62-67 primary: undiff. terrigenous sandy mud or ooze
secondary: volcanic ash
first subdominant: plant debris
second subdominant: pteropods
comments: cross bedded, Quaternary

67-120 primary: undiff. biosiliceous mud or ooze
secondary: undiff. terrigenous mud or ooze
first subdominant: plant debris
second subdominant: calcareous nannofossils
comments: Quaternary

120-126 primary: undiff. terrigenous sand
comments: cross bedded, unknown age

126-158 primary: undiff. terrigenous mud or ooze
secondary: undiff. biosiliceous mud or ooze
comments: 140-149 missing, Quaternary

158-167 primary: undiff. terrigenous sandy mud or ooze
comments: unknown age

167-177 primary: undiff. terrigenous sand
secondary: undiff. terrigenous muddy sand

first subdominant: plant debris
second subdominant: volcanic
comments: cross bedded, unknown age

177-270 primary: undiff. biosiliceous mud or ooze
secondary: undiff. terrigenous mud or ooze
first subdominant: calcareous nannofossils
second subdominant: volcanics
comments: Quaternary

Sample Location:08° 29.1' S Latitude, 108° 01.4' E Longitude; Ship/Platform: T. WASHINGTON; Sampling Device: Gravity Core; Core Length: 183 cm; Cruise I.D.: ERDC; Storage Method: Refrigerated; Inside Diameter: 4 cm; Sample Number: 039PG; Date Collected: 02/02/75; Water Depth: 3528 m

0-29 primary: volcanic ash
first subdominant: diatoms
second subdominant: undiff. terrigenous material
comments: upper sed lost, Quaternary

29-34 primary: undiff. terrigenous sandy mud or ooze
secondary: volcanic ash
first subdominant: plant debris
second: pteropod
comments: cross bedded, Quaternary

34-68 primary: undiff. biosiliceous mud or ooze
secondary: volcanic ash
first subdominant: undiff. terrigenous material
second: undiff. biocalcareous material
comments: wood, Quaternary

68-75 primary: undiff. terrigenous sand
comments: cross bedded, Quaternary

75-98 primary: undiff. biosiliceous mud or ooze
secondary: volcanic ash
comments: Quaternary

98-104 primary: undiff. terrigenous mud or ooze
secondary: undiff. biosiliceous material mud or ooze
subdominant: volcanic
comments: Quaternary

104-113primary: undiff. terrigenous material sand
secondary: volcanic ash
comments: bedded, Quaternary

113-172 primary: undiff. terrigenous sandy mud or ooze
comments: Quaternary

172-173 primary: undiff. terrigenous sandy mud or ooze
secondary: volcanic ash
comments: turbidite, Quaternary

173-175 primary: undiff. terrigenous sand
secondary: volcanic ash
comments: bedded turbidite, Quaternary

175-181	primary: undiff. terrigenous mud or ooze first subdominant: undiff. biosiliceous material second: volcanic comments: Quaternary
181-183	primary: undiff. terrigenous mud or ooze first subdominant: undiff. biosiliceous material second: volcanic comments: Quaternary

Sample Location: 08° 45.0' S Latitude, 108° 43.9' E Longitude; Ship/Platform: T. WASHINGTON; Sampling Device: Piston Core; Core Length: 333 cm; Cruise I.D.: ERDC; Storage Method: Refrigerated; Inside Diameter: 8 cm Sample Number: 040P; Date Collected: 02/03/75; Water Depth: 3566 m

0-5	primary: volcanic ash secondary: undiff. biosiliceous mud or ooze comments: disturbed, Quaternary
5-125	primary: diatom mud or ooze secondary: undiff. terrigenous mud or ooze first subdominant: volcanic comments: Quaternary
125-127	primary: volcanic ash secondary: undiff. terrigenous sandy mud or ooze first subdominant: undiff. biosiliceous material second: undiff. biocalcareous material comments: Quaternary
127-190	primary: undiff. biosiliceous material mud or ooze secondary: volcanic ash subdominant: calcareous nannofossils comments: 139-150 missing, Quaternary
190-322	primary: undiff. terrigenous mud or ooze secondary: volcanic ash first subdominant: calcareous nannofossils second: plant debris comments: 290-300 missing, Quaternary
322-333	primary: undiff. biosiliceous mud or ooze secondary: undiff. terrigenous muddy sand first subdominant: undiff. biocalcareous material second: pyrite or marcasite comments: Quaternary

Sample Location: 08° 45.0' S Latitude, 108° 43.9' E Longitude; Ship/Platform: T. WASHINGTON; Sampling Device: Gravity Core; Core Length: 153 Cm; Cruise I.D.: ERDC; Storage Method: Refrigerated; Inside Diameter: 4 Cm; Sample Number: 040PG; Date Collected: 02/03/75; Water Depth: 3566 M

0-70 primary: volcanic ash
secondary: undiff. biosiliceous mud or ooze
subdominant: undiff. terrigenous material
comments: Quaternary

70-80 primary: undiff. biosiliceous mud or ooze
secondary: undiff. terrigenous mud or ooze
comments: Quaternary

80-104 primary: undiff. terrigenous mud or ooze
secondary: undiff. biosiliceous mud or ooze
first subdominant: volcanic
second: plant debris
comments: Quaternary

104-106 primary: volcanic ash
secondary: undiff. terrigenous sandy mud or ooze
first subdominant: undiff. biosiliceous material
second: undiff. biocalcareous material
comments: Quaternary

106-153 primary: volcanic ash
secondary: undiff. terrigenous sandy mud or ooze
subdominant: undiff. biosiliceous material
comments: Quaternary

Institution: Woods Hole Oceanographic Institution (WHOI)

Sample Location: 08° 31.6' S Latitude, 108° 39.6' E Longitude; Ship/Platform: ATLANTIS II; Sampling Device: Piston Core; Core Length: 820 cm; Cruise I.D.: A209314; Storage Method: Room Temp, Moisture Sealed; Inside Diameter: 6 cm; Sample Number: 0039; Date Collected: 11/20/76; Water Depth: 3563 m

0-820 primary: undiff. biocalcareous mud or ooze
secondary: undiff. terrigenous mud or ooze
comments: Quaternary

Sample Location: 08° 31.6' S Latitude, 108° 39.6' E Longitude; Platform: ATLANTIS II; Sampling Device: Gravity Core; Core Length: 108 cm; Cruise I.D.: A209314; Storage Method: Room Temp, Moisture Sealed; Inside Diameter: 6 cm; Sample Number: 0039; Date Collected: 11/20/76; Water Depth: 3563 m

0-108 primary: undiff. biocalcareous mud or ooze
secondary: undiff. terrigenous mud or ooze
comments: Quaternary

APPENDIX 7: BMR CRUISE 107 NARRATIVE

Neville Exon

Rig Seismic sailed from Christmas Island at 1800 (local time) on 7 January 1992 with a maritime crew under the command of Captain Lindsay Gillies, and with a scientific contingent of 19 consisting of 17 BMR staff and two university students. At 1830 a briefing and safety meeting was held and at 1930 we had arrived at the beginning of seismic line 1, running northward to the Java Trench. Preparations for running the seismic gear in its new configuration lasted until 1400 on 8 January, when profiling commenced. The system used two sleeve airguns towed a metre below the surface so that the bubble would escape at the surface, thus improving the sharpness of the energy pulse. The seismic cable was 600 m long with 24 channels of hydrophones, and was controlled in depth by 3 depressors ("birds") and stabilised by a relatively small ship-shaped tail buoy.

Line 1 was 170 km long and was completed at 0930 on 9 January. It was run at an average speed of 6.5 knots through the water and included several loops of an hour or so, caused by computer problems. The profile shows an irregular descent from the volcanic pedestal of Christmas Island toward the 6500 m depths of the Java Trench. Sedimentary cover on the volcanic crust is generally less than 200 m, and is absent on the numerous volcanic rises. However, in the Java Trench, volcanic sands and muds have poured in, and their base is beyond the 1500 m penetration of our seismic system. The bedded turbidites near Christmas Island and in the trench are clearly very different from the transparent pelagic oozes at about 5000 m depth.

Toward the end of line 1, Peter Davis injured his right ear when a door slammed against his head, just as he was cleaning his ear with a cotton bud on a wooden stick. The mate examined the wound and the captain radioed the doctor on Christmas Island for advice. The advice was that Davis need not come to hospital because, even if the ear drum were ruptured, no operation would be advisable for several months. Davis said that the wound was not very painful and that he could continue working.

Line 2 was a west-east profile along the axis of the Java Trench, designed to tie the north-south lines 1 and 3 together, and was about 110 km long. We decided to remove the tail buoy to see whether this would enable us to get a good profile at a higher speed. This was done using the rubber boat, and with this and other adjustments it was 1500 on 9 January when profiling recommenced. A number of problems with the computers, including not allowing them quite enough time to write to tape, caused reduction of data quality, but as this was a low-priority profile we continued to its end without stopping. The end of the line was reached at about 0130 on 10 January. The boat speed had been kept at 7-7.5 knots and the section was very noisy. The profile showed a number of sediment wedges and some faulting at depth within the trench, and suggested that sediment was being distributed by mass flows from a number of sources.

Line 3, a 540 kilometre long line to the south, was started at 0330 on 10 January. Data quality on this important line was poor, even at 6 knots, and it was decided to see whether it would be better with the tail buoy attached. Profiling stopped to do this at 1000, and recommenced at 1300. Data quality was greatly improved at 6 knots, showing that the tail buoy damped the cable noise - a useful experiment was ended. By the end of the profile the towing speed had been increased to 7 knots, with acceptable data quality. Line 3 showed the thick section in the Java Trench, a number of seamounts to the south, and rather limited pockets of sediment, less than 300 m thick, between them. The line was completed at about 0400 on 12 January.

Dredge 1, up a 2300 m guyot at 13° 37' S, 105° 18' E, started at 1000 on 12 January and ended successfully at 1500. Various volcaniclastic rocks and detrital shallow-water carbonates were recovered. Gravity core 1A was attempted atop the guyot but a failure of the core catcher led to no recovery. A second attempt, with a cut-off plastic bag outside the core catcher, recovered 6.22 m of foraminiferid-nannofossil ooze as gravity core 1, in 2375 m of water at 2300 on 12 January.

Benthos free-fall grabs formed a vital part of the cruise sampling equipment. They are designed for systematic sampling of manganese nodules and travel rapidly to the bottom, take a sample in a net that collects only grit and coarser material, drop some ballast, and return to the surface for collection. We added small sediment traps to recover some bottom sediment. In the south-eastern region, a series of grabs were taken on the abyssal plain along seismic line 3 in water deeper than 5000 m, to assess nodule prospects. The first group of 3 stations (FFG1A-C), taken from 0330 to 0600 on 13 January, was at about 13° 40' S, 105° 40' E, in water 5880 m deep. We recovered a few very small nodules, some basalt and pumice fragments, and brown clay. The second group (FFG 02A-C), taken from 0815 to 1220 on 13 January, was at about 13° 33' S, 105° 42' E, in water 5890 m deep. No nodules were recovered, only clay. The third group (FFG03A-C), taken from 1330 to 1700 on 13 January, was at about 13° 26' S, 105° 45' E, in water 5930 m deep. Recovery consisted solely of clay.

Work on setting up the piston corer for the first time since 1988 was started at midday on 13 January, while on transit and during deployment of free-fall grabs. A great deal of effort was needed to get all parts to fit and to rig the gear satisfactorily. At 2010 the gear was lowered away at 13° 26' S, 105° 45' S, in 5923 m of water. The corer was recovered at 0130 on 14 January. The corer had reached the bottom, on the evidence of a little adhering sediment , but was empty. The Benthos clamp attached to the trigger arm had slid down the main cable, compressing the free-fall loops, and the trigger-arming device had not worked because of water leakage through an O-ring. As a result the piston had stayed at the bottom of the corer, preventing the entry of any sediment. It was agreed that, in future, the trigger would be armed at the surface unless the weather was bad. The faulty Benthos clamp would be assiduously avoided!

Dredge 2 was taken up a guyot whose top lies 2200 m deep, at 13° 08' S, 105° 46' E. The dredge was deployed at 0500 on 14 January and reached bottom in about 3700 m of water. Dredging north west up the slope led to a number of bites. At 0905 the dredge hung up, possibly on rocks at 2800 m, and could not be freed. The ship turned to the reciprocal course (SE) and wire was payed out in an attempt to get an advantageous position to free the dredge. Unfortunately the dredge wire then tangled on another obstacle further down the slope (water depth 3000-3400 m) about 1200 m from the dredge and, despite attempts to free it by pulling laterally from directly above and from all four points of the compass, with pulls of up to 12 tonnes (safe working load of the wire is 14 tonnes), no progress was made. After 8 hours of attempts to free the wire with no success, the chief scientist decided that sufficient pull must be exerted to either free or break the wire. This was done with the ship vertically above the snag. When the controls prevented the winch exceeding an 18 tonne pull, the winch was locked and the ship moved away from the snag at a propeller pitch of 30°. After some minutes, at 1713, there was an almighty bang and the wire broke about 400 m below the ship. The wire rope leapt off the block and a tangle developed on the winch which badly damaged the wire 400 m above the break. About 4500 m of wire was lost below the break and, with the damaged part, 4860 m was written off. The break was not at a splice.

On the morning of 15 January, the wire was run out during a transit between free-fall grab stations, and the length of the remaining good wire on the drum carefully checked and found to be 4381 m. While this was being done the top of every even layer from the bottom was inscribed on the drum to ensure easier calculations of wire left after any future similar incidents. The remaining 400 m of substandard wire was spliced to the good cable by the ship's crew with the help of the mechanical technicians from 0800 to 1200 on 16 January, to give us a working length of about 4600 m (leaving a safe amount of wire above the lowest wrap). The ramifications of the loss for this cruise are mainly in the limitation in coring depth. This is not a critical part of the AGSO assessment program, but does seriously restrict the university students' programs.

The fourth group of free-fall grabs (FFG 4A-C) was taken in 5620 m of water, from 0125 to 0510 on 15 January, at about 12° 7' S, 106° 15' E. Recovery was limited to brown clay, and a few pebbles of pumice and basalt. The fifth group of grabs (FFG 5A-C) was taken in 5590-5625 m of water, from 0600 to 0920 on 15 January. Recovery consisted of clay, pumice and a shark's tooth 2 cm long. The sixth group (FFG 6A-D) was taken after a long transit, in water 5650-5700 m deep, from 1940 on 15 January to 0020 on 16 January, at about 10° 59' S, 106° 42' E. Recovery again consisted of brown clay and pumice. The six groups of stations in this area south east of Christmas Island were located on narrow strips of abyssal plain between seamounts, and showed conclusively that there are no prospects for large accumulations of nodules in the area.

After a long transit to the north east, which located a new seamount, seismic line 4 was started at 1430 on 16 January. This line is 250 km long and extends southward from the Java Trench, in the north eastern part of the study area.

It was run at 8 knots in good weather and, despite two systems failures, was completed at 0715 on 17 January. It showed that no volcanic seamounts are free of draping sediment, in contrast to the earlier north-south lines, probably because the relief is much less. Depressions between basement blocks are filled with up to one second of sediment; a transparent sequence is everywhere underlain by a bedded sequence, in turn underlain by another transparent sequence above oceanic crust.

Another sampling program in the south east began with a piston core on a guyot at 11° 42' S, 106° 59' E, in water 1990 m deep. The core was deployed from 1140 to 1340 on 17 January. The corer recovered 7 m of calcareous ooze and sand, but much of the core liner imploded, probably because the piston started its stroke 2 m above the seabed rather than at it, resulting in a very disturbed core. Two attempts were made to take a gravity core at the same location (GC 02 and 02A) but almost no recovery resulted. We abandoned our attempts to core at 1940, in the belief that foraminiferidsl sand was stopping penetration, and moved to the south eastern side of the guyot to dredge. Dredge 3 was taken at 11° 46' S, 107° 05' E, from 2050 on 17 January to 0030 on 18 January. A full load of rocks was recovered from depths of 2400-2200 m. The rocks consisted of a superb array of coastal carbonates with reworked volcanic detritus. After a fruitless attempt to find a seamount at 11° 47' S, 107° 32' E, the last station attempted in the south east was gravity core 03, on top of a seamount at a water depth of 2939 m, at 12° 17' S, 107° 52' E. Coring took from 0920 to 1115 on 18 January, but there was again no recovery.

The very poor results with the normally reliable gravity corer, only one success in 5 attempts, are hard to explain. For the first core, when the tension gauge was not working, it is possible that there was no bottom contact. However the gauge was working for the last three attempts and did show a marked release in tension as the corer hit the bottom. It showed no increase of tension beyond the normal winding tension as the corer left the bottom, suggesting that there was no penetration and that the corer had fallen over before or at bottom contact . The evidence of a small amount of foraminiferidsl sand in one core suggests that the latter was the case. Probably the winnowed sediments on the seamounts are so sandy that they refused entry to the relatively slow-falling gravity corer (much as is the case with sands on the continental shelf), but allowed the faster-falling gravity corer to penetrate 7 m at the same site (PC 02). Two alternatives can be tried at future such core sites: a shorter gravity corer run at maximum speed to reduce the chance of toppling, or a shorter piston corer with the piston set to trigger lower.

The 540 km long east-west seismic line 5 was commenced at 1415 on 18 January, and was run at speeds of up to 9 knots, with good results. Three major volcanic build ups, including the Christmas Rise, were separated by areas of sediment up to 0.5 seconds thick. The westernmost end of the line crossed DSDP Site 211, and son after the line ended at 1130 on 20 January. A comparison of the performance of a single water gun with a single sleeve gun ended at 1430. The test indicated that the water gun gave higher resolution but lacked adequate power in water 5500 m deep.

Our next aim was to assess the nodule prospects of the northwestern part of the area by sampling along a profile to the north east. From 1530 to 1600 on 20 January we deployed three free-fall grabs (FFG 7A-C), at about 9° 47' S, 102° 42' E, in water 5500 m deep. All had radios and lights and at 1850 we heard one grab surface. At 2005 we recovered that grab, the easternmost and latest deployed, about 2 km north west of where it was deployed, suggesting a surface current of about a knot.

Using the current information we searched for the other two grabs up to 9 km north west of where they were released, with no avail, and at 2355 we called off the search. Probably neither grab surfaced, suggesting that they had seized upon a rock or a manganese crust too heavy to bring up. The third grab recovered brown clay.

At 0005 on 21 January we commenced bathymetric line 2, running north east from near DSDP Site 211. From 0245 to 0630 on 21 January, three free-fall grabs (FFG 8A-C) were deployed at about 9° 20' S, 103° 5' E, in water 5480 m deep. All three were recovered empty. One recovery was very lucky, because although its light failed it was spotted right next to the ship. Another two grabs (FFG 9A and B) were let fall and recovered from 1120 to 1440 at about 8° 52' S, 103° 28' E, in water 5460 m deep. They contained only pumice and clay. This brief survey showed that nodule prospects are poor in this area relatively near the Sunda volcanic arc.

Seismic line 6, extending 300 km south from the rise south of the Java Trench, started at 1610 on 21 January and finished at 0450 on 22 January, after some computer crashes caused delays early on the line. The line shows nearly 1 second of section above basement over much of its length, with basement rises but no seamounts. The normal three sequences are present: transparent surface layer, well-bedded thick middle sequence, and poorly bedded basal sequence.

We then started a program of bathymetric and magnetic profiling, and geological sampling in the south west of the area, which appears to be the most prospective area for manganese nodules. Three grabs (FFG 10A-C) were released and recovered from 0620 to 1000 on 22 January, in water 5400 m deep at 10° 5' S, 103° 1 minute E. We recovered brown clay and a piece of pumice, but no nodules. Another three grabs (FFG 11A-C) were released and recovered between 1440 and 1650, in water 5400 m deep at 10° 33' S, 102° 48' E. Again only brown clay and a little pumice were recovered.

There followed a transit to a guyot 1800 m deep, on which piston core 3 was taken at 11° 1' S, 102° 25' E, from 2125 to 2345 on 22 January. For this core, suspecting resistant winnowed sand on the bottom, we used only a 6 m barrel. The corer recovered 1.4 m of white Quaternary nannofossil-foraminiferidsl ooze from 1325 m, and this was the first successful core on a seamount for quite some time. The ship then headed down the northern slope of the guyot, and after we had reterminated the winch cable and overcome a problem in the winch power pack, dredge 4 was lowered away at 0400 on 23 January. The dredge was hauled south west up the slope and strong bites were encountered between 2800 and 2300 m. It was brought on board at 0830, and contained a very varied array of volcanics, shallow-water carbonates, and volcaniclastic sandstones often with a carbonate cement.

The ship then headed further south to continue the search for manganese nodules. Three grabs (FFG 12A-C) were dropped and recovered in water 5420 m deep, between 1055 and 1415 on 23 January, at 11° 12' S, 102° 32' E. Recovered were brown clay, a number of pieces of manganese-encrusted volcaniclastics, and a piece of pumice. One of the grabs appears to have fallen onto a volcanic outcrop rather than ooze. Because of our lack of success in finding nodule fields, we next decided to re-sample a Soviet dredge station that had recovered nodules. Three grabs (FFG 13A-C) were dropped and recovered in a water depth of 5100 m onto an irregular seabed between 2040 on 23 January and 0020 on 24 January, at 11° 48' S, 102° 54' E. This was a location where *Vityaz* had dredged nodules and, sure enough, we got nodules in all three dredges. The nodules were mostly small spherical or polynodules, and occurred in abundances of up to 2.5 kg/m^2, together with clay and pumice. Another three grabs (FFG 14A-C) were dropped and recovered in water 5110 m deep, between 0315 and 0845 on 24 January, at 12° 10' S, 102° 57' E. They returned only clay. Three grabs (FFG 15A-C) were dropped and recovered in the far south west of the region in water 5060 m deep, between 0925 and 1240, at 12° 29' S, 103° E. Only clay was collected. The next grab station (FFG 16A-C) was taken on some abyssal hills, 5160 m deep, from 1700 to 2015, at 12° 2' S, 103° 10' E. A large haul of small spherical and polynodules (up to 12 kg/m^2) was associated with pumice and brown clay.

The next program involved the sampling of a 1300 m deep seamount at 11° 45' S, 103° 16' S. A piston core was deployed first, to sample the ooze on top, from 2300 on 24 January to 0055 on 25 January. Unfortunately a storm blew up at the critical time (and a number of boobies took shelter on the ship vomiting up pieces of squid and prawns) and the echo sounder no longer could distinguish soft bottom. The corer smacked into hard carbonates, crumpling the core cutter and turning the 6 m-long steel corer pipe into a strange spiral shape. A very small quantity of carbonates was recovered. Then the southern slope of the seamount was dredged from 2800 to 1900 m, from 0200 to 0610. A large haul of fine grained carbonates with numerous larger foraminiferids, and quite unlike the carbonates recovered in the earlier dredges, was associated with some basalts porphyritic in plagioclase and hornblende.

A grab station (FFG 17A-C) at the northern foot of the seamount in a water depth of 5080 m, was occupied from 0850 to 1150 on 25 January, at 11° 33' S, 103° 20' E. Clay and pumice were present in all three grabs, and a few small nodules were present in the grab furthest upslope. Another station (FFG 18A-C) was occupied from 1730 to 2105, on the slope below a seamount in water 5710 m deep, at 10° 51' S, 103° 35' E. Only pumice and clay were recovered. The last grab station (FFG 19A-C) in this series was occupied from 0140 to

0540 on 26 January, at 10° 23' S, 103° 45' E, in water 5620 m deep. Recovered were pumice, volcanics and brown clay.

Seismic line 7 was run northward in the north west of the area, starting at 0650 on 26 January. This line extended almost to the Java Trench, was 300 km long, and showed that basement was rather shallow. Toward the end of the line we came across a burned-out Taiwanese fishing boat, and we pulled our gear in from 1930 to 2200 while we rescued the six crew members, who were very happy to see us. They had been drifting for 12 days, but were in good health. The seismic profile was completed at 0050 on 27 January.

We started bathymetric line 5 to the south-south east at 0530 on 27 January, and occupied a grab station (FFG 20A-C) from 0745 to 1036, at 9° 39' S, 104° 38' E, in water 4850 m deep. Recovery was of pumice and brown clay. Piston core 5 was taken between 1625 and 2015, at 10° 27' S, 104° 48' E, in 4559 m of water. We recovered 4.75 m of Quaternary grey foraminiferid-nannofossil ooze. After a fruitless attempt to find soft sediments on two seamounts to the south, we headed eastward on bathymetric line 6 toward Christmas Island, starting at 0000 on 28 January. Piston core 6 was taken in shallow water (485 m) just off the south western point of Christmas Island (10° 31' S, 105° 31' E) between 0620 and 0650. Recovered was 53 cm of nannofossil-foraminiferidsl ooze, plus a large basalt cobble and associated manganese crust. At 0830, *Rig Seismic* was lying off Flying Fish Cove on the island, awaiting medical clearance for the six rescued fishermen before they could be put ashore. Clearance was duly given, and they and the ship's electrician were farewelled. *Rig Seismic* departed on a westerly course on bathymetric line 7 at 1030.

Soon after we turned south on bathymetric line 8 at 1900, a suitable target area for a grab station (FFG 21A-C) was identified. The grabs were deployed between 2000 and 2315 on 28 January, at 10° 31' S, 104° 10' E, in a water depth of 4840 m. We recovered pumice, minor manganese crusts and brown clay. We then sampled a seamount 2040 m deep, at 11° 2' S, 103° 52' E, shallower and about 9 miles west of its previously plotted location. Piston core 7 was deployed from 0530 to 0700 on 29 January and managed to cut the wire of the trigger weight, slowing it down and giving only 74 cm recovery. Dredge 6 sampled the slopes at 3300 to 2800 m, from 0830 to 1300, and yielded a large haul of basalt and phosphatised carbonate, both of which bore several generations of manganese crusts up to 3.5 cm thick. Gravity core 4 was taken in 3665 m of water from 1550 to 1800, at 11° 18' S, 103° 59' E. We recovered 421 cm of grey carbonate ooze.

Another series of grab stations was now occupied southward along bathymetric line 8. The first station (FFG 22A-C) was in water 4900 m deep at 11° 39' S, 103° 57' E, and took from 2160 on 29 January to 0030 on 30 January. Recovered were brown clay and a little pumice. The second station FFG 23A-C) was taken in water 4780 m deep in the moat near a seamount, from 0500 to 0810, at 12° 14' S, 103° 54' E. Grabs A and B each recovered about 1.7 kg of small smooth nodules, and the associated sediment was brown foraminiferid-bearing mud. The third grab, taken on the slope of the seamount, recovered only mud. The next station (FFG 24A-C) was in water 4580 m deep, at 12° 36' S, 103° 52' E, and was occupied from 1100 to 1400. Recovered was brown foraminiferidsl-rich mud, a little pumice, and four small nodule pieces that were probably contaminants from the previous station. The last station in the series (FFG 25A-D) was in the extreme south west of the area, at 13° 18' S, 103° 48' E. Water depth was 5730 m and the station was occupied between 1920 and 2340. The location was near a seamount, and the grabs straddled the moat of young sediments and a ridge of older sediments. We recovered small spherical or ellipsoidal polynodules, all rough, from the three shallower stations, with 0.8 kg of nodules in grab A. The associated material was red-brown clay, pumice and sharks' teeth. In grab C the nodules were covered in a rim of stiff light brown clay.

The seamount above the last nodule station, at 12° 54' S, 103° 55' E, was the next target. Piston core 8 was deployed from 0320 to 0600 on 31 January and, despite another imploding liner, recovered 274 cm of cream foraminiferidsl ooze from water 2665 m deep, atop the seamount. Dredge site 7 was occupied from 0750 to 1350, and there were a number of good bites as we dredged southward upslope, before the dredge became hung up at 3400 m. Eventually the wire parted under a vertical pull of about 12 tonnes, about 80 m above the dredge rather than at the 9 tonne shear pin. The weights ahead of the dredge may have become wedged in an outcrop and they too were lost. Dredge 8 was deployed a little west of dredge 7, without weights and with a 7 tonne shear pin, from 1600 to 2100. Unfortunately, the tensiometer ceased to function when it was on the bottom, leaving "wire out" and "winch speed" as the sole surviving controls. We had no other indications of bites while on the bottom but, on retrieval of the dredge, we found that the dredge was very battered, and that the pin had sheared and the dredge had flipped, meaning that no rocks were in the chain bag. Fortunately, the two pipe dredges contained an assortment of basalt and volcaniclastic rocks, which appear to have come from water depths of between 3700 and 3300 m.

On the way north along bathymetric line 9, two free-fall grab stations were occupied. The first (FFG 26A-C) was occupied from 0200 to 0530 on 1 February at 12° 15' S, 104° 8' E, in water 5370 m deep. The location was in a scour channel at the base of a seamount, and small rough nodules and polynodules were recovered in very small amounts, along with volcanic and pumice pebbles in foraminiferidsl-rich brown clay. The second station (FFG 27A-C) was occupied from 0850 to 1140 at 11° 52' S, 104° 16' E, in water 4620 m deep. We recovered volcanic and pumice pebbles, but no nodules, in brown foraminiferidsl-rich clay.

Three stations were occupied on a large 1200 m deep seamount at 11° 23' S, 104° 26' E. The first was piston core 9, taken from 1620 to 1720 in water 1207 m deep. The corer appears to have penetrated 2 m, and the core barrel was bent from the impact, but the core washed out, leaving only a little foraminiferidsl sand in the core catcher. Dredge 9 was attempted from 1830 to 2130 in water 1800 to 1600 m deep. Despite a major bite, recovery was only a few grammes of basalt, calcilutite and chalk. Dredge 10 was attempted nearby in water 2000 to 1500 m deep, from 2300 on 1 February to 0200 on 2 February. It recovered a large amount of shallow marine carbonates, chalk, and some basalt and manganese crust.

After a bathymetric transit to the east, two dredge stations were attempted on a large 1500 m deep seamount, at 11° 25' S, 104° 56' E. The first was dredge 11, on the eastern flank of the seamount from 0700 to 1100 on 2 February, in water 2850-1750 m deep. Only a small amount of manganese crusts and soft sediment was recovered. The second station was dredge 12, on the western flank of the seamount from 1300 to 1700, in water 1800 to 1500 m deep. Only foraminiferidsl sand was recovered.

Bathymetric line 10 to the north was started immediately after dredge 12, but was broken from 1900 to 2245 for the last free-fall grab station (FFG 28A-C), at 11° 7' S, 104° 47' E, in water 4990 m deep. The location was in a depression between two seamounts, and small quantities of manganese polynodules, some clay-coated, were recovered in brown clay.

Seismic line 8 was a northerly line, 70 km long, starting west of Christmas Island over Shcherbakov Seamount, and crossing the Java Trench. It was started at 0100 and completed without any equipment problems at 2100 on 3 February, and it shows the rapid descent from the seamount into the trench. The volcanic basement is quite irregular, and protrudes through the sediment cover in places. Normal faults cut the thick sedimentary section in the trench. Bathymetric line 11 commenced immediately afterward and took us southward to Christmas Island, where the cruise terminated at 0800 on 4 February. The scientific contingent was ashore by 1000 and the *Rig Seismic* then sailed for Fremantle. The cruise objectives generally had been met, although the loss of 5000 m of winch cable had constrained our sampling activities somewhat.