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Marine Manganese Crusts Around New Zealand : A Preliminary Assessment

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ABSTRACT

As part of an ongoing evaluation of the marine mineral resources of the New Zealand Exclusive Economic Zone, the distribution and composition of marine manganese crusts have been assessed based on both existing data and the results of a 1988 cruise of R.V. *Rapuhia.*

Hydrogenous manganese crusts thicker than 20 mm have been located at a number of sites, including the SW flanks of the Campbell Plateau, Three Kings Ridge, Aotea Seamount, and three seamounts north of New Zealand. The most prospective area for Co-rich manganese crusts appears to be the crest of the Three Kings Ridge where three samples with a manganese-crustal thickness greater than 30 mm and an average Co content of 0.58% were recovered. Although subeconomic, these crusts can be considered to be shallow-water (< 2000 m) Co-rich manganese crusts.

Hydrothermal manganese crusts have been recovered from the flanks of the Tonga–Kermadec Ridge and possibly the Colville Ridge. Such crusts require further evaluation in view of the insight that they give to local geological processes.

This preliminary assessment indicates that further studies of manganese crusts would be worthwhile not only as part of a resource assessment but also to aid the understanding of palaeoceanographic and tectonic processes around New Zealand.

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INTRODUCTION

The possible economic potential of shallow-water (1000–2500 m) manganese crusts containing in excess of 1% cobalt was first demonstrated by the 1981 R.V. *Sonne* Midpac '81 cruise (Halbach *et al.* 1982). This cruise stimulated much interest in these deposits and led to several further cruises to survey these so-called cobalt-rich manganese crusts. A considerable literature on this topic has now developed (e.g., Aplin & Cronan 1985; Hein *et al.* 1985, 1987, 1988, 1990; Chave *et al.* 1986; Halbach 1986; Manheim 1986; Mangini *et al.* 1987; Pichocki & Hoffert 1987; Ritchey 1987; Bolton *et al.* 1988, 1990; De Carlo *et al.* 1988; Koski 1988; Manheim & Lane-Bostwick 1988, 1989; Puteanus & Halbach 1988; Halbach *et al.* 1989, 1990; Le Suavé *et al.* 1989; Meylan *et al.* 1990; De Carlo 1991; Hodkinson & Cronan 1991). In fact, Hein *et al.* (1988) have listed eleven criteria for the location and possible exploitation of these deposits. These are 1) large volcanic edifices shallower than 1500–1000 m, 2) substrates older than 20 m.yrs, 3) areas of strong current activity, 4) volcanic structures not capped by large modern atolls or reefs (*see*, however, Le Suavé *et al.* 1989), 5) a shallow and well-developed oxygen-minimum zone, 6) slope stability, 7) absence of local volcanism, and 8) areas isolated from input of abundant fluvial and aeolian debris. Exploitation criteria include 9) average cobalt content > 0.8%, 10) average crustal thickness > 40 mm, and 11) subdued small-scale topography.

Prior to this study, very little information was available on the distribution and characteristics of manganese crusts in the New Zealand region. Manganese-coated slabs of rock were reported at NZOI Stn D169 on the Macquarie Ridge and a small fragment of thin manganese crust at Stn F133 on the Campbell Plateau by Summerhayes (1967, 1969) and Glasby and Summerhayes (1975). Phosphatised limestone of Late Oligocene to Late Miocene age which had been almost completely replaced by manganese oxides was recovered from Aotea Seamount (Brodie 1965; Glasby 1972). Hydrothermal manganese crusts were dredged from the Tonga-Kermadec Ridge by Cronan *et al.* (1982) and Moorby *et al.* (1984).

The object of this report is to bring together information on manganese crusts around New Zealand. The report consists of two parts. The first part describes manganese crusts that existed in the NZOI collection prior to 1988. The second part presents the results of the 1988 R.V. *Rapuhia* cruise to the Bellona Trough and Three Kings Rise to search for these deposits. A summary of the data on manganese crusts and nodules within the New Zealand EEZ has recently been given by Glasby and Wright (1990).

STUDIES OF CRUSTS COLLECTED PRIOR TO 1988 *RAPUHIA* CRUISE

During previous cruises in the New Zealand region by the N.Z. Oceanographic Institute and other organisations, a number of manganese-crust samples had been collected. These samples are described briefly in Appendix 1 and their chemical composition presented in Table 1.

Manganese crusts from the island of 'Eua in Tonga have previously been described by Hein *et al.* (1990) and have been shown to be of hydrothermal origin and Miocene in age. The composition presented in Table 1, however, differs significantly from those presented by Hein *et al.* (1990). It corresponds to a Mn/Fe ratio of 0.71 and a Co content of 0.32%. This is typical of manganese deposits of hydrogenous origin. This suggests that the deposition of manganese deposits on 'Eua may be more varied than suggested in the work of Hein *et al.* (1990). In fact, crusts of hydrogenous origin have previously been reported from the Tonga Platform by Koski *et al.* (1985).

Manganese crusts from the Tonga-Kermadec Ridge have previously been studied by Cronan *et al.* (1982, 1984), Moorby *et al.* (1984), Glasby (1988), and Hein *et al.* (1990). Deposits believed to be of hydrothermal origin have been recovered from a number of sites spread over a distance of 1800 km on the Ridge. The high fractionation of Mn from Fe (Mn/Fe ratios of 21.9 and 175), the very low Pb, Co, Ni, and Cu contents and the presence of birnessite as the principal manganese-oxide mineral in crusts from Stns U40 and U189 confirm their hydrothermal origin and emphasise the wide distribution of hydrothermal manganese crusts on the Tonga-Kermadec Ridge.

Manganese crusts and nodules from the Three Kings Ridge (Stns S575, S576) represent thick (up to 40 mm) manganese deposits. As such, they were formed on relatively old seafloor under stable conditions. It is possible that crust formation was initiated with increased Antarctic glaciation at about 12 Ma. This would give a growth rate for the crusts of about 3.3 mm/10^6 yrs. The crusts and nodules show compositions typical of hydrogenous manganese deposits. Crust S576, for example, displays a Mn/Fe ratio of 1.15 and a Co content of 0.53% for the total crust. This crust is also relatively uniform in composition throughout its 38-mm thickness confirming relatively uniform conditions of deposition throughout its history. Mineralogically, the crusts consist of quartz, feldspar, and δ MnO_2 with some todorokite. Apatite, feldspar, and quartz are found in substrates.

The Colville Ridge manganese boulder (*Volcanolog* sample B30/29/1) was so badly broken after collection that a proper description was not possible. However, this sample displays a relatively high Mn/Fe ratio (2.8) together with a very low Co content (0.02%). Mineralogically, it consists of todorokite and birnessite. These features suggest that this deposit may have a significant hydrothermal component to its formation, although the Ni (0.20%) and Cu (0.05%) contents are more indicative of a hydrogenous origin. This is important in view of the finding of Wright *et al.* (1990) that volcanism on the southern Colville Ridge may be younger than 5 Ma.

The Southern Havre Trough sample (S800) represents a thin (2 mm) coating of manganese

Table 1 — Chemical composition of selected manganese crusts from around New Zealand collected prior to the 1988 *Rapuhia* cruise.. Samples were analysed by atomic-absorption analysis following drying at 110°C overnight (Mn and Fe as %, Co, Ni, Cu, Zn, and Pb parts per million).

	Fe	Mn	Co	Ni	Cu	Zn	Pb
'Eua	15.7	11.2	3249	1559	339	558	1357
U40	1.1	24.8	25	200	33	141	15
U189	0.3	45.4	18	159	107	109	12
S575	18.1	10.7	3556	3239	1110	739	1779
S576	17.5	20.2	5337	4136	692	700	1990
B30/29/1	14.4	40.7	229	2003	537	1313	155
S800	17.4	13.3	1739	2142	339	650	1330
4608	14.2	23.7	6963	5838	972	932	1931
67	17.9	18.4	6127	3335	893	730	1842
S100	15.5	9.4	2110	2484	777	641	1057

oxides on boulders. The composition (average Mn/Fe ratio 0.76, average Co content 0.17%) confirms a dominantly hydrogenous origin. The thinness of the crust confirms that it is relatively young (< 1 Ma).

The nodules dredged from near the crest of a seamount situated east of the North Island (4608) are typical hydrogenous deposits (Mn/Fe ratio 1.67, Co content 0.70%).

The manganese crust collected from the flanks of the Bellona Trough (Stn 67) is also of hydrogenous origin (average Mn/Fe ratio 1.07, average Co content 0.65%).

The crust from the flanks of the SW Campbell Plateau (S100) is of typical hydrogenous origin. It is thick (up to 90 mm) and the total crust sample displays a Mn/Fe ratio of 0.61 and a Co content of 0.21%. A profile taken to 60 mm in one of the crusts revealed a fairly uniform composition throughout with the exception of Co and Ni which were enriched in the outer 3 mm. Mineralogically, the crust consists of quartz, feldspar, and δ MnO_2, with apatite, quartz, and feldspar in the substrate. A previous analysis of a manganese nodule from this haul by electron-microprobe analysis has been presented by Challis *et al.* (1982). The geological structure of the SW Campbell Plateau has been reported by Davey (1977).

From the above data, it will be noted that the only samples which display elevated Co contents (> 0.5%) are from the crest of the seamount east of New Zealand (4608), the flanks of the Bellona Trough (Stn 67), and possibly the Three Kings Ridge (S576).

Outside the New Zealand EEZ, Hein *et al.* (1990) have reported on the occurrence of hydrogenous manganese crusts from the Tonga and Lau Ridges with an average thickness of 10 mm and an average Co content of 0.25%, and on hydrothermal crusts from the Valu Fa Ridge in the Lau Basin, the Tonga-Kermadec Ridge, and Tonumea and 'Eua islands in Tonga. The Tongan deposits are further augmented in Mn by supergene enrichment. Bolton *et al.* (1990) have also reported on a 50-mm-thick crust with a Co content of 0.43% from the Lord Howe Rise, and crusts up to 130 mm thick containing 0.19–0.28% Co from the Dampier Ridge. These authors also mention a manganese crust from Lord Howe Rise where past hydrothermal activity associated with the Vening-Meinesz Fracture Zone may have partly influenced the growth of these crusts.

Manheim and Lane-Bostwick (1989) have produced a map of Co concentration in Pacific manganese crusts. They found an area southeast of New Zealand characterised by high Co contents (0.8% on a normalised basis). This high Co region is based on the data of Summerhayes (1967), however Glasby and Summerhayes (1975) commented on the possible analytical errors in the data of Summerhayes (1967) and, in particular, obtained a much lower Co content (0.19 vs 0.6%) for one sample (F129). In addition, sample S100 from the SW Campbell Plateau studied in this work has a Co content of only 0.21%. These two observations suggest that the high-Co region southeast of New Zealand reported by Manheim and Lane-Bostwick (1989) may not be as extensive as shown by these authors. Nonetheless, the recent finding by Bolton

Table 2 — Contents of major and minor elements (including REE) in selected manganese crusts from around New Zealand collected prior to the 1988 *Rapuhia* cruise. Samples were analysed by instrumental neutron activation (method described by Glasby *et al.* 1987). Na, K, Ca, and Fe as %, the remaining elements as parts per million. A dash = not detected or not analysed.

Element	'Eua	U40	U189	S575/1	S575/2	S575/3	S575/4	S576	B30/39/1
Na	0.56	3.70	3.22	0.87	0.84	1.07	0.60	0.99	1.44
K	0.09	–	–	–	–	–	–	–	1.25
Ca	11.4	2.11	1.25	–	3.82	4.40	0.90	1.38	0.87
Fe	14.7	1.19	0.90	18.60	18.50	9.06	10.00	13.40	0.65
Sc	8.4	6.1	0.2	9.3	8.8	5.7	5.5	6.8	1.0
Cr	51.3	3.1	–	32.1	25.3	28.3	20.7	–	1.6
Co	2940	16.0	3.4	3150	3680	690	3430	3610	39.1
Zn	689	–	96	1260	895	948	604	865	865
As	270	59.7	164	138	139	61.5	159	151	51.8
Se	–	–	–	–	–	–	–	–	–
Br	20.0	–	12.7	–	–	5.9		25.6	18.7
Sb	43.6	5.1	6.7	39.9	38.0	10.7	28.9	25.6	68.2
Cs	–	0.6	0.5	–	–	–	–	–	0.8
Ba	1850	–	–	1030	1110	3440	4810	–	2580
Hf	6.2	1.6	–	16.5	16.7	1.8	4.4	5.7	0.2
W	58.1	–	–	–	–	–	–	–	268
Au	–	–	–	–	–	–	–	–	–
Th	11.6	0.5	–	28.0	30.2	6.0	28.0	23.6	0.6
U	–	–	–	–	–	–	–	–	–
La	186	3.6	0.7	135	140	43.3	93.5	196	8.2
Ce	501	9.6	1.1	1300	1350	167	769	920	9.9
Nd	118	–	–	127	139	67.6	–	222	–
Sm	31.6	3.3	0.5	31.8	31.1	9.3	20.9	37.8	1.5
Eu	7.5	0.5	0.1	6.3	6.0	1.5	3.4	7.0	0.40
Tb	4.0	0.4	0.1	4.9	5.8	2.0	2.7	4.1	0.35
Yb	16.8	2.2	0.2	14.1	10.7	6.5	11.5	19.6	2.7
Lu	2.4	0.4	0.2	3.2	2.6	1.2	1.8	2.8	0.3
Ce/La	2.7	2.7	1.6	9.6	9.6	3.9	8.2	4.7	1.2

Table 2 — cont'd

Element	S800 MC4	S800 MC5	S800 MC6	Stn 67 /B	Stn 67 0–5	Stn 67 5–15	Stn 67 15–25	S100 /1	S100 /2	S100 /P	S100 /L	S100 /R
Na	1.63	1.89	1.77	0.76	0.98	0.59	0.52	1.88	1.20	1.11	2.21	2.04
K	0.39	0.30	0.41	–	–	–	–	–	–	–..	–	–
Ca	2.33	2.86	1.80	–	–	1.05	–	1.75	–	1.18	1.61	1.06
Fe	17.0	16.1	17.5	13.90	13.70	13.70	14.00	15.40	12.30	17.00	12.00	12.30
Sc	12.8	10.5	11.6	5.7	5.5	5.6	4.5	8.3	5.4	9.3 –	8.8	10.2
Cr	57.4	48.7	49.4	–	–	–	–	35.6		48.7 –	77.5	63.3
Co	1150	1650	1550	4120	4900	4550	5240	2550	5390	1840	212	405
Zn	737	703	673	–	–	–	–	–	–	–	–	–
As	211	218	238	231	179	175	180	156	224	134	66.9	74.8
Se	–	–	–	–	–	–	–	–	–	–	–	–
Br	45.8	51.8	55.7	–	–	–	–	–	–	23.2	17.8	16.8
Sb	17.3	17.7	19.4	31.6	25.9	26.3	31.4	25.5	23.8	31.2	15.7	16.3
Cs	–	–	–	–	–	–	–	–	–	–	1.5	1.7
Ba	1580	1540	1540	1700	1390	940	1260	965	–	1010	631	345
Hf	–	7.4	7.4	8.2	3.6	8.0	5.3	13.6	5.6	15.3	14.0	13.6
W	26.0	30.4	33.4	–	–	–	–	–	–	–	–	–
Au	–	–	–	–	–	–	–	–	–	–	–	–
Th	16.8	21.4	23.3	40.0	28.9	31.5	39.7	27.6	31.3	28.4	12.4	13.7
U	–	–	5.2	–	–	–	–	–	–	–	–	–
La	150	180	203	186	197	173	212	128	146	129	66.8	79.3
Ce	485	512	544	1880	1250	1480	1760	1020	662	1100	457	453
Nd	87.5	123	133	268	222	212	288	202	169	111	99.0	75.5
Sm	27.6	33.3	36.5	41.2	41.0	40.9	54.1	34.0	30.0	32.5	21.2	25.6
Eu	6.3	7.6	8.4	6.4	7.1	6.3	8.2	4.7	5.3	6.2	3.2	3.8
Tb	5.1	5.9	6.3	3.9	4.0	–	5.7	2.9	4.3	4.6	2.6	3.3
Yb	17.3	15.6	29.5	14.6	19.6	15.3	15.7	12.7	18.6	12.4	4.9	8.1
Lu	2.5	7.9	3.2	2.1	2.8	2.3	2.4	2.3	2.7	2.7	1.5	1.2
Ce/La	3.2	2.8	2.7	10.1	6.3	8.5	8.3	8.0	4.5	8.5	6.8	5.7

et al. (1988) of a manganese crust from a seamount on the South Tasman Rise (latitude 42°S, depth 1700 m) with a Co content of 0.8–1.0% indicates that Co-rich manganese crusts can occur at these southerly latitudes.

Manheim and Lane-Bostwick (1988) have proposed using a normalised cobalt content (equivalent to the % Co x 50 / % Mn + % Fe) as an indicator of the influence of hydrothermalism on manganese crust formation. Values < 0.3% are taken to indicate a hydrothermal input. Such an approach supports the Tonga-Kermadec Ridge and Colville Ridge samples as having a hydrothermal input. The Southern Havre Trough sample may have a minor hydrothermal component.

Table 2 presents additional data for major and minor elements (including the rare-earth elements) in the crusts based on instrumental neutron-activation analysis. Figure 1 shows the North American Shale Composite (NASC)-normalised plots of the REE data.

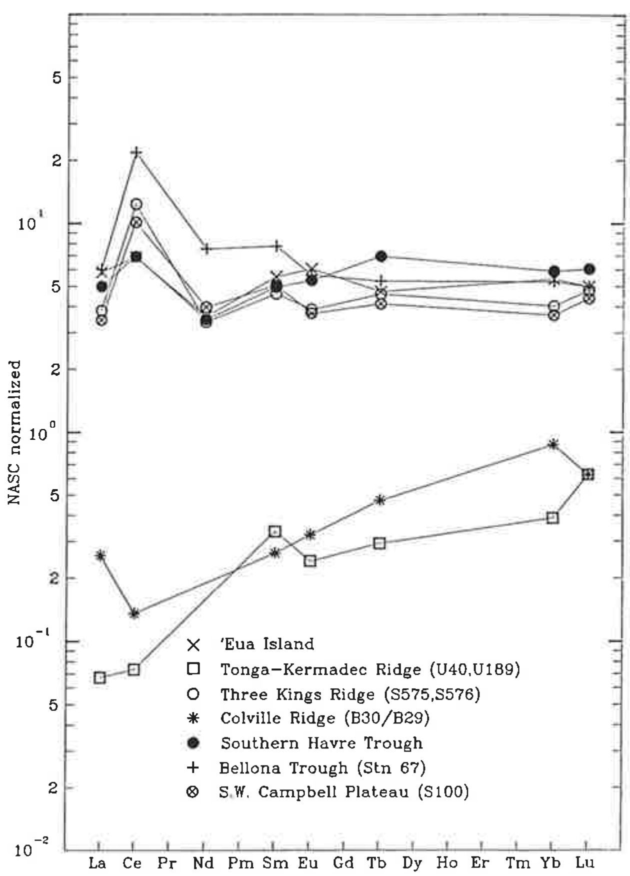

Fig. 1. Plots of North American Shale Composite (NASC)-normalised rare-earth-element distribution for previous manganese-crust data. Data are averaged for each geographic area.

The results confirm the dominantly hydrogenous origin for the 'Eua island, Three Kings Ridge (S575, S576), Southern Havre Trough (S800), Bellona Trough (Stn 67), and SW Campbell Plateau (S100) samples. This is based on the relatively high REE contents and high Ce/La ratios of these samples (Glasby *et al.* 1987). Nonetheless, significant variations in the Ce/La ratios occur in all the above crusts except 'Eua island and S576. These variations may reflect variations in the depositional conditions of the crusts or more likely dilution by terrigenous material. The high Ce/La ratios (> 8.0) of some of the samples from the Three Kings Ridge, Bellona Trough, and SW Campbell Plateau may indicate that these samples have been in the path of strong bottom-water flows (Glasby *et al.* 1987), although there are significant differences in the REE abundances and Ce/La ratios of the Three Kings Ridge and Bellona Trough samples presented here and those collected during the *Rapuhia* cruise (*see* later), making interpretation difficult.

Samples from the Tonga-Kermadec Ridge (U40, U189) and the Colville Ridge (B30/29/1), on the other hand, display a hydrothermal origin as shown by their low REE abundances and low Ce/La ratios (Fleet 1983; Kunzendorf *et al.* 1988; Hein *et al.* 1990). These samples also show low concentrations of Fe, Sc, Cr, Co, Hf, and Th, again compatible with the fractionation of Mn from Fe and a range of minor elements and therefore a hydrothermal origin. These samples contain higher contents of Na and comparable contents of Ce and Br compared to the hydrogenous samples. A similar trend for Na and Ce was noted by Moorby *et al.* (1984) for other manganese crusts from the Tonga-Kermadec Ridge.

R.V. *RAPUHIA* CRUISE, 1988

On the basis of the previous investigations and the general knowledge of the bathymetry and geology of the New Zealand offshore region, the most promising areas for further investigations appeared to be the Three Kings Rise, Bellona Trough, and Campbell Plateau. The R.V. *Rapuhia* cruise was undertaken to follow up these preliminary findings. The cruise investigated the Bellona Trough, Norfolk Ridge, Reinga Ridge, Three Kings Rise, and Aotea Seamount. In all, 80 rock-dredge stations were occupied during the period 27 Jan.—16 Feb. 1988. Each rock dredge was fitted with two capped core-liner tubes to retain sediment samples. A station list, including station co-ordinates and depth plus a brief description of the dredge contents, is given in Appendix 2. A detailed description of the geological material collected at each station constitutes Appendix 3. Table 3 summarises these data by area and, in particular, gives details of manganese-crust thickness, rock types, and associated sediment types. Figure 2 is a schematic cruise track. In the following section, a brief overview of the material collected in each area is presented. The reader should consult the appendices and tables for fuller descriptions of the material.

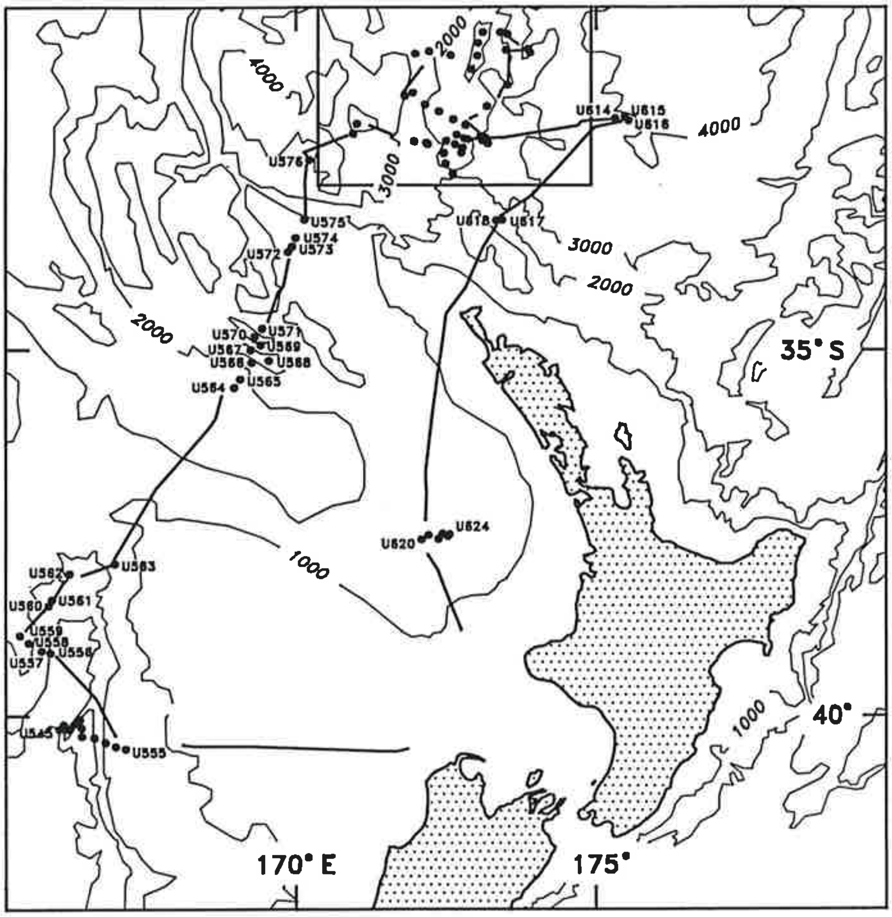

Fig. 2a. Schematic map showing the cruise track and locations of stations taken during the 1988 R.V. *Rapuhia* cruise, plus generalised bathymetry with a contour interval of 1000 m.

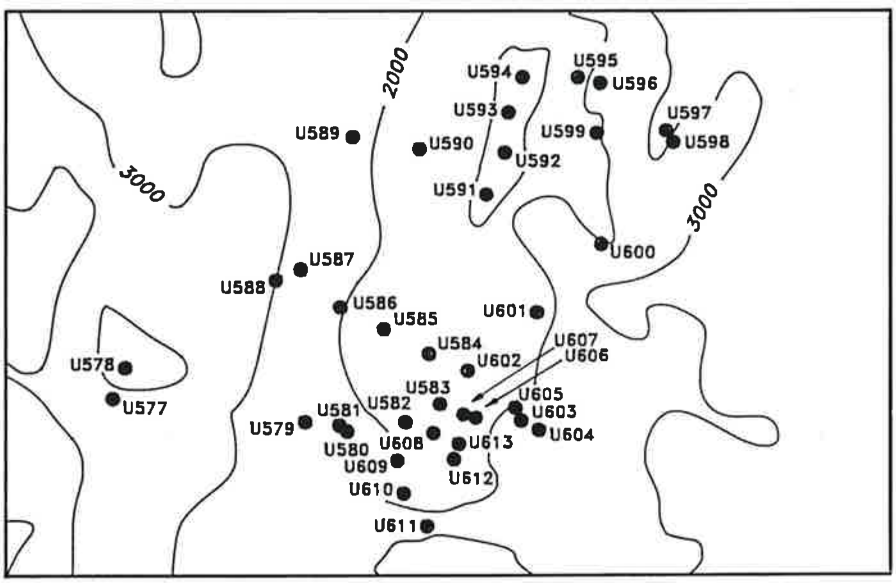

Fig. 2b. Inset from 2a showing the locations of stations taken on the Three Kings Ridge and adjacent seamounts during the 1988 R.V. *Rapuhia* cruise.

Table 3 — Summary of geological material by area collected during the 1988 *Rapuhia* cruise. The figures in the columns for Mn-crustal thickness refer to the number of stations.

Area	No. of Stns	Depth Range (m)	Mn Crust >30 mm	Mn Crust 20–29 mm	Mn Crust 10–19 mm	Mn Crust 2–9 mm	Mn Staining	Substrates and Unencrusted Rocks	Mn-stained Biota	Associated Sediments
Bellona Trough	19	1298–3354	–	–	1	–	1	Rhyolite, andesite, limestone, indurated carbonate ooze	Coral	Carbonate ooze
West Norfolk Ridge	5	865–1890	–	–	–	–	1	Ferruginised limestone, indurated limestone, pumice, cetacean bone	Barnacle plates, coral	Carbonate ooze, carbonate sand
Norfolk Ridge	3	627–1210	–	–	–	–	–	Pumice, volcanic rock	–	Carbonate sand
Reinga Ridge	4	570–2129	–	–	–	–	2	Indurated limestone, ankeritic sandstone and mudstone, limestone, carbonate mudstone, cetacean bone, pumice	–	Carbonate sand, coarse shelly sand
Seamount I	1	2260–2340	–	–	–	1	–	Basalt	–	–
Seamount II	2	2570–3120	–	1	–	–	–	Palagonite, pumice	–	Carbonate ooze, carbonate sand
Three Kings Ridge	23	406–3220	2	–	2	1	7	Porphyritic and flow-banded andesite, feldspathic sandstone, tuff, basalt, tuffaceous mudstone, algal deposits, cetacean bone, pumice	Barnacle plates, coral, brachiopods	Carbonate sand, carbonate ooze
Tui Seamount	3	406–2110	–	–	–	–	1	Algal carbonate, calcareous grit, pumice	–	Carbonate sand, coarse shelly sand
Kiwi Seamount	2	1335–2970	–	–	–	–	–	Pumice	–	Carbonate ooze, carbonate sand
Seamount III	1	590–640	–	–	–	–	–	Coralline limestone	–	Carbonate sand

Seamount IV	1	620	–	–	–	–	–	Pumice	–	Carbonate sand
Seamount V	1	1216–1385	–	–	–	–	–	Limestone, pumice	–	Carbonate sand
Seamount VI	3	1578–1782	–	–	2	–	1	Basalt, pumice	Barnacle plates, echinoid plates, coral	Carbonate sand
Seamount VII	1	1470–1560	–	–	–	1	–	Porphyritic basalt	Coral	–
Devonport Seamount	3	1028–3700	–	–	1	1	–	Calcarenite, pumice	Coral, molluscs, barnacle	–
Seamount VIII	2	1670–1690	–	–	–	–	–	Pumice	–	Carbonate ooze
Aotea Seamount	6	984–1380	–	–	1	–	5	Tuff, picrite, basalt, volcaniclastic sandstone	Coral, bivalves	Carbonate sand, coarse shelly sand

Bellona Trough

A manganese crust (25–50 mm thick) overlying altered volcanic rock was collected by R.V. *Acad. Nesmeyanov* at Stn 67 (40°15.98'S, 165°58.57'E) on a spur adjacent to the Bellona Trough. The depth of the station was not given. In order to investigate the distribution of crusts in this area in more detail, 19 stations were occupied in the Bellona Trough. The stations were located mainly on submarine slopes where outcrops might have been expected.

In fact, one fragment of Mn crust 11 mm thick was recovered from the crest of the spur (Stn U547) from which the above Mn crust was derived. Crust at this station was extremely difficult to remove from the substrate which may account for the limited haul. Mn-stained cobbles were also recovered from the flanks of this spur at Stn U550. The associated biota at Stn U547 may indicate strong bottom currents at the crest of the spur which may favour Mn crustal growth. The other slopes of the Bellona Trough all consist of thick carbonate ooze with limited biota and outcrops.

Our studies thus confirm the occurrence of limited amounts of Mn crusts on the spur previously dredged by R.V. *Acad. Nesmeyanov*. The other slopes of the Bellona Trough appear to be barren of Mn crusts. It therefore appears that the Bellona Trough has very limited potential for Mn crusts.

West Norfolk, Norfolk, and Reinga Ridges

Twelve stations were taken on a transect across the West Norfolk, Norfolk, and Reinga Ridges in which ridge slopes and crests were sampled.

The most interesting rock type recovered is the ferruginised, ?phosphatised limestone from Stns U566, U572, and U574. The fragments tend to be tabular (presumably reflecting their bedded structure) and heavily burrowed. The upper surfaces of some of the larger slabs are smooth, in contrast to the rough undersides, and this is thought to reflect erosion of upper surfaces. In some cases, the fragments are coated with Mn oxides or even partially replaced by Mn oxides.

Othe rock types dredged include limestone (U566, U567, U573, U574), mudstone (U575), indurated calcareous concretions (U572), cetacean bone fragments (U566, U572), pumice (U565, U568, U571, U572, U573), and barnacle plates (U566, U567).

No volcanic rocks or thick manganese crusts were recovered in the region. The associated sediments are coarse shelly sand (U574), carbonate sand (U565, U566, U568, U569, U571, U572, U574), and carbonate ooze. The sediment type reflects the depth (current regime) of the environment. The region is characterised by abundant biota, possibly reflecting local upwelling over these shallow (< 1000 m) ridges.

Three Kings Rise and adjacent seamounts

Forty-six stations were occupied on the Three Kings Ridge and adjacent seamounts, and crests and slopes were dredged. Interest in this region stemmed from the two previously reported hauls of manganese crusts from the Three Kings Rise (Stns S575 and S576) (*see* earlier). The geology of the Ridge has been described by Davey (1982), Kroenke and Eade (1982), Launay *et al.* (1982), Cole (1986), and Korsch and Wellman (1988), and the nature of the sediments on the Ridge by Nelson *et al.* (1982).

This region appeared to be the most promising one sampled with regard to manganese crusts. Crusts thicker than 2 mm were found at Stns U576, U583, U611, crusts thicker than 10 mm at Stns U603, U605, U606, U608, and U616, and crusts thicker than 20 mm at Stns U578, U607, and U611. They appear to be normal hydrogenous crusts with substrates of andesite, dacite, basalt, tuff, palagonite, and calcarenite. The thickest crusts were recovered from Seamount II and the southern end of the Three Kings Ridge. Crusts thicker than 10 mm were dredged in the depth range 1085–2620 m.

Other rock types dredged include lithified carbonate (U580, U584, U594, U595, U599, U601, U602, U606), mudstone (U581), cetacean bones (U582, U584), and barnacle plates (U580, U604, U608, U609). Pumice appeared to be ubiquitous in the area.

The associated sediments are coarse shelly sands (2), carbonate sands (18), and carbonate oozes (8). With the exception of four samples of carbonate ooze in the depth range 1680–1960 m (U612, U613, U617, and U618), carbonate oozes are found at depths greater than 3000 m and carbonate sands at shallower depths. The two samples of coarse shelly sand (U595 and U599) were found at 1474 m and 620 m respectively. Again, the sediment distribution appears to be largely controlled by depth. This possibly reflects current winnowing on elevated portions of the sea floor.

Abundant biota was recovered at several stations (*see* Appendix 2).

Manganese crusts thicker than 10 mm are associated either with no sediment or with carbonate sand and generally limited biota. It is felt that strong bottom currents may account for these associations. The northern end of the Three Kings Rise, on the other hand, is characterised by abundant biota but no manganese crusts. It should be noted, however, that many attached coelenterates (such as gorgonians, sea pens, and anemones) are influenced by strong bottom currents (Heezen & Hollister 1971).

Aotea Seamount

Five samples of foraminiferal limestone of Late Oligocene to Late Miocene age almost completely replaced by manganese oxides have previously been reported from Aotea Seamount (Glasby 1972). For this reason, six dredge stations were occupied along the crest of the seamount in an attempt to recover more of this material. In fact, it was discovered that the seamount is actually about 6 km north of its charted position (van der Linden 1968). The geological structure of Aotea Seamount has been reported by Davey (1973).

Manganese crust greater than 10 mm thick overlying weathered tuff was obtained at one station (U620). Other rock types include basalt, tuffaceous mudstone, volcaniclastic sandstone, and phosphatised limestone; much of this rock is stained (< 1 mm thick) with manganese oxides. Manganese-stained coral and bivalves were also recovered at two stations, as well as a limited biota at a number of stations. Carbonate sand is the dominant sediment type with coarse shelly sand obtained at one station (U619).

GEOCHEMISTRY

The composition of selected crusts collected during the R.V. *Rapuhia* cruise is presented in Table 4. These crusts have an average composition of Mn 16.3%, Fe 14.6%, Co 0.50%, Ni 0.38%, Cu 0.06%, Zn 0.07%, and Pb 0.17%. This composition is typical of shallow water (average depth 1707 m) hydrogenous manganese crusts with a Mn/Fe ratio of about unity (average value 1.12), elevated Co and Ni contents, but low Cu contents. This composition is very similar to the average for shallow-water Pacific hydrogenous crusts presented by Hein *et al.* (1987)

Table 4 — Chemical composition of selected manganese crusts from around New Zealand collected during the 1988 *Rapuhia* cruise.. Samples were analysed by atomic-absorption analysis following drying at 110°C overnight (Mn and Fe as %, Co, Ni, Cu, Zn, and Pb parts per million).

	Fe	Mn	Co	Ni	Cu	Zn	Pb
U576	13.5	20.8	8035	4498	499	575	1359
U578	14.3	14.2	4290	2382	559	447	1025
U583	11.7	19.1	4825	5701	763	797	1797
U603	13.5	17.3	5620	3906	827	661	1708
U605	18.3	14.8	3172	2701	482	794	1906
U606	12.7	21.4	4185	3873	565	1071	298
U607	15.1	18.4	6306	3775	580	614	2059
U610	14.6	17.8	5663	3365	476	586	2016
U615	17.0	22.0	7061	4246	420	587	3572
U616	16.8	17.3	3681	2693	359	603	1769

indicating similar controls on crust composition. Within the limited subset considered here, however, there appears to be no correlation of Co content with water depth. Mineralogically, the samples tend to contain quartz and δ MnO_2 with occasional todorokite and calcite.

Table 5 presents additional data for major and minor elements (including the rare earth elements) in the crusts based on instrumental neutron-activation analysis. The average analysis of deep-sea manganese nodules from Area K (Aitutaki Passage) in the SW Pacific is given for comparison (Glasby *et al.* 1987). Figure 3 shows the North American Shale Composite (NASC)-normalised plots of the rare-earth-data.

These data confirm that the manganese crusts studied here display a limited compositional range. Compared to Area K nodules, the crusts have lower concentrations of Na, K, Fe, Sc, Cr, Br, Hf, Th, and REE (with lower Ce/La ratios), and higher concentrations of As, Sb, Ba, and W. Previously, it has been shown that a number of these elements (e.g., Sc, Hf, Th, and REE) are associated with the iron-oxyhydroxide phase of ferromanganese deposits (Glasby *et al.* 1987). These crusts are therefore somewhat depleted in the iron-oxyhydroxide phase compared to deep-sea nodules from the SW Pacific. Na, K, and Cr are probably associated with the detrital phase.

Based on their REE abundances and their Ce/La ratios, the crusts have a hydrogenous origin. The relatively low Ce/La ratios (2.2–6.4) of the crusts

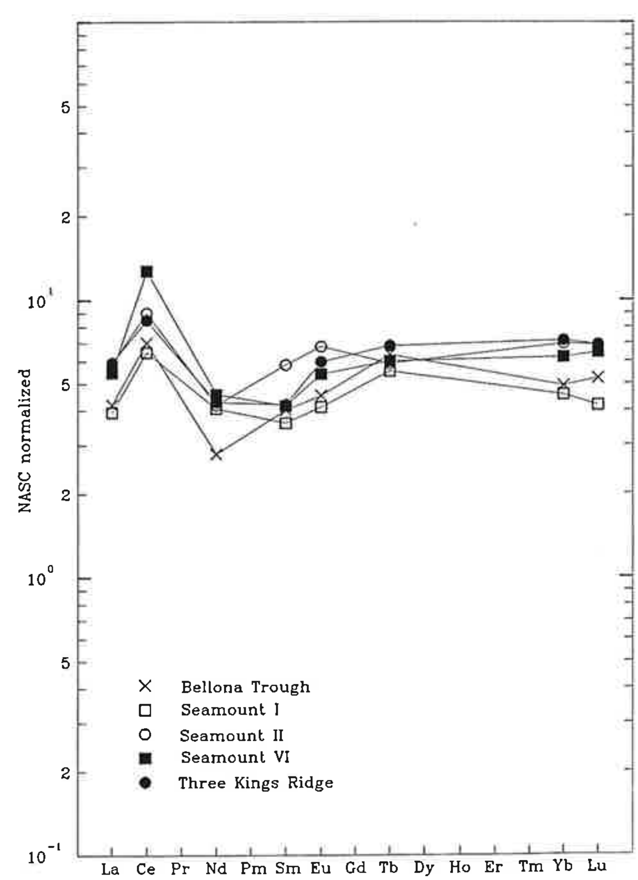

Fig. 3. Plots of North American Shale Composite (NASC)-normalised rare-earth-element distribution for manganese crusts taken during the 1988 R.V. *Rapuhia* cruise. Data are averaged for each geographic area..

Table 5 — Contents of major and minor elements (including REE) in selected manganese crusts from around New Zealand collected during the 1988 *Rapuhia* cruise. Samples were analysed by instrumental neutron activation (method described by Glasby *et al.* 1987). Na, K, Ca, and Fe as %, the remaining elements as parts per million. A dash = not detected or not analysed.

Element	U547	U576	U578	U583	U603	U605	U606	U607	U610	U615	U616	Average Area K nodules
Na	1.45	1.49	1.39	1.17	1.34	0.95	1.19	1.24	1.28	1.19	1.17	1.59
K	0.50	0.40	0.44	0.33	0.28	0.24	0.33	0.24	0.29	0.28	0.24	0.61
Ca	2.06	2.23	1.14	3.01	–	0.98	5.05	–	2.44	2.20	1.48	–
Fe	14.4	9.22	15.4	13.5	15.2	18.9	18.9	14.9	14.1	19.4	16.1	16.3
Sc	8.1	5.6	9.4	6.7	8.0	9.4	9.4	7.4	7.5	6.8	8.9	13.7
Cr	39.9	–	27.6	14.1	14.3	59.1	16.7	–	–	–	14.3	69
Co	3300	3660	3810	5040	4930	2990	2990	5570	5520	3370	2920	4200
Zn	992	726	679	1030	1040	968	1040	1000	815	809	786	307
As	207	132	185	248	216	215	169	256	257	393	248	139
Br	29.1	51.1	14.9	38.4	33.0	22.0	39.5	36.8	17.1	45.0	19.7	18
Sb	31.2	16.6	25.0	30.5	38.5	48.0	15.8	41.8	33.3	40.3	29.5	27.4
Cs	5.0	–	–	–	2.0	–	2.0	–	–	–	1.4	–
Ba	1220	571	956	1150	1500	1890	1500	808	–	989	1310	594
Hf	6.9	4.9	9.5	–	9.1	11.1	11.4	–	–	–	5.3	16
W	72.4	36.4	40.3	8.35	67.5	62.1	27.8	78.9	86.8	88.0	68.2	38
Au	–	–	35.7	–	–	–	–	–	–	–	–	–
Th	17.8	17.0	21.9	23.7	24.1	18.6	19.1	24.7	25.4	20.6	17.2	54
U	–	5.1	6.4	12.3	–	9.9	–	11.6	10.4	9.9	10.6	–
La	134	126	188	165	186	165	–	201	204	205	226	169
Ce	512	473	656	489	810	1050	1050	691	670	577	495	1360
Nd	92	134	138	112	149	153	100	233	76.8	203	180	173
Sm	22.8	20.5	33.2	20.6	28.3	18.8	3.2	24.6	26.4	27.0	28.7	35.1
Eu	5.6	5.1	8.4	7.0	7.2	6.2	6.4	7.6	7.6	7.7	9.0	8.9
Tb	5.4	4.7	5.0	5.8	5.3	4.9	5.6	–	–	9.1	7.5	45
Yb	15.2	14.1	21.5	19.7	19.7	18.7	3.9	23.2	23.3	25.3	23.9	17.8
Lu	2.5	2.0	3.3	3.3	3.2	3.0	0.5	3.4	3.3	3.4	3.6	2.7
Ce/La	3.8	3.8	3.5	4.4	6.4	3.0	6.4	3.4	3.3	2.8	2.2	8.0

suggest that the areas in which they occur are not swept by strong bottom currents. This is in accord with the known flow path of Antarctic Bottom Water which is to the east of the New Zealand continental platform (Nemoto & Kroenke 1981). It should be noted, however, that there are significant differences in the REE abundances and more particularly the Ce/La ratios of the Three Kings Ridge and Bellona Trough samples collected during the R.V. *Rapuhia* cruise and the previously collected samples from these areas (*compare* Tables 2 and 5).

SUMMARY

An attempt has been made to characterise the distribution of marine manganese crusts around New Zealand with a view to establishing whether potentially economic-grade manganese crusts occur.

A preliminary survey of the existing collection of manganese deposits revealed thick crusts (90 mm thick) on the flanks of the SW Campbell Plateau. This sample has a Co content of only 0.21%. Thick crusts (up to 40 mm thick) were found on the Three Kings Ridge. These crusts have an average Co content of 0.53%.

In addition, hydrothermal manganese crusts were obtained from the western flanks of the Tonga-Kermadec Ridge and possibly the Colville Ridge. The Colville Ridge requires further investigation to see if it is indeed a site of active hydrothermalism. On the other hand, a thin manganese crust from the seamount in the Southern Havre Trough appears to be hydrogenous in origin with perhaps a minor hydrothermal component.

On the basis of this compilation of data, a study of the distribution of manganese crusts west and north of New Zealand was undertaken in 1988 using R.V. *Rapuhia*. During this cruise, 80 dredge stations were occupied. Sample substrates were varied and biota were common. For the manganese crusts, only Seamount II, Three Kings Ridge, Seamount VI, Devonport Seamount, and Aotea Seamount yielded manganese crusts thicker than 20 mm. The crust of the Three Kings Ridge appears to be the most prospective. Two samples with manganese crusts greater than 30 mm thick and with an average Co content of 0.60% were found (U607, U610) in addition to the earlier discovery of such thick crusts at the crest of the Ridge (S576). These thick crusts reflect the deposition of manganese oxides from seawater over a relatively long time. Data on the REE abundance and Ce/La ratios of these crusts are ambiguous so that no definite statement can be made on their relationship to bottom-current activity. Although these crusts are not thick enough and do not have a high enough Co content to be considered economically attractive, nonetheless the processes controlling their formation are typical of these for Co-rich manganese-crust formation.

Rare-earth-element analysis confirms a dominantly hydrogenous origin for all samples, except those from the Tonga-Kermadec Ridge and possibly the Colville Ridge.

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REFERENCES

APLIN, A.C.; CRONAN, D.S. 1985: Ferromanganese oxide deposits from the Central Pacific Ocean, I. Encrustations from the Line Islands Archipelago. *Geochimica et Cosmochimica Acta 49* : 427–436.

BOLTON, B.R.; EXON, N.F.; OSTWALD, J. 1990: Thick ferromanganese deposits from the Dampier Ridge and the Lord Howe Rise off eastern Australia. *BMR Journal of Australian Geology and Geophysics 11* : 421–427.

BOLTON, B.R.; EXON, N.F.; OSTWALD, J.; KUDRASS, H.R. 1988: Geochemistry of ferromanganese crusts and nodules from the South Tasman Rise, southeast of Australia. *Marine Geology 84* : 53–80.

BRODIE, J.W. 1965: Aotea Seamount, eastern Tasman Sea. *N.Z. Journal of Geology and Geophysics 8* : 510–517.

CHALLIS, G.A.; GABITES, J.; DAVEY, F.J. 1982: Precambrian granite and manganese nodules dredged from Southwestern Campbell Plateau, New Zealand (Note). *N.Z. Journal of Geology and Geophysics 25* : 493–497.

CHAVE, K.E.; MORGAN, C.L.; GREEN, W.J. 1986: A geochemical comparison of manganese oxide deposits of the Hawaiian Archipelago and the deep sea. *Applied Geochemistry 1* : 233–240.

COLE, J.W. 1986: Distribution and tectonic setting of Late Cenozoic volcanism in New Zealand. *In* Smith, I.E.M. (ed.) "Late Cenozoic Volcanism in New Zealand". *Bulletin of the Royal Society of N.Z. 23* : 7–20.

CRONAN, D.S.; GLASBY, G.P.; MOORBY, S.A.; THOMSON, J.; KNEDLER, K.E.; McDOUGALL, J.C. 1982: A submarine hydrothermal manganese deposit from the south-west Pacific island arc. *Nature, London 298* : 456–458.

CRONAN, D.S.; MOORBY, S.A.; GLASBY, G.P.; KNEDLER, K.; THOMSON, J.; HODKINSON, R. 1984: Hydrothermal and volcaniclastic sedimentation on the Tonga-Kermadec Ridge and in its adjacent marginal basin. Pp 137–149 *in* Kokelaar, B.P.; Howells, M.F. (eds) "Marginal Basin Geology". *Geological Society of London Special Publication 16* : 322 p.

DAVEY, F.J. 1973: Gravity and magnetic measurements over Aotea Seamount, eastern Tasman Sea (Note). *N.Z. Journal of Geology and Geophysics 16* : 1047–1054.

DAVEY, F.J. 1977: Marine seismic measurements in the New Zealand region. *N.Z. Journal of Geology and Geophysics 20* : 719–727.

DAVEY, F.J. 1982: The structure of the South Fiji Basin. *Tectonophysics 87* : 185–241.

DE CARLO, E.H. 1991: Paleoceanographic implications of rare earth element variability within a Fe-Mn crust from the central Pacific Ocean. *Marine Geology 98* : 449–467.

DE CARLO, E.H.; PENNIWELL, P.A.; FRALEY, C.M. 1988: Geochemistry of ferromanganese deposits from the Kiribati and Tuvalu region of the West-Central Pacific Ocean. *Marine Mining 6* : 301–321.

FLEET, A.J. 1983: Hydrothermal and hydrogenous ferromanganese deposits. Do they form a continuum? The rare earth element evidence. Pp 535–555 *in* Rona, P.A.; Boström, K.; Laubier, L.; Smith, K.L. (eds) "Hydrothermal Processes at Seafloor Spreading Centers". Plenum Press, New York. 796 p.

GLASBY, G.P. 1972: Manganese deposits in the Southwest Pacific. *Hawaii Institute of Geophysics Report HIG-72-23* : 59–72.

GLASBY, G.P. 1988: Hydrothermal manganese deposits in island arcs and related to subduction processes : a possible model for genesis. *Ore Geology Reviews 4* : 145–153.

GLASBY, G.P.; GWOZDZ, R.; KUNZENDORF, H.; FRIEDRICH, G.; THIJSSEN, T. 1987: The distribution of rare earth and minor elements in manganese nodules and sediments from the equatorial and S.W. Pacific. *Lithos 20* : 97–113.

GLASBY, G.P.; SUMMERHAYES, C.P. 1975: Sequential deposition of authigenic marine minerals around New Zealand : Paleoenvironmental significance. *N.Z. Journal of Geology and Geophysics 18* : 477–490.

GLASBY, G.P.; WRIGHT, I.C. 1990: Marine mineral potential in New Zealand's Exclusive Economic Zone. *Marine Mining 9* : 403–427.

HALBACH, P. 1986: Cobalt-rich and platinum-bearing manganese crusts — Nature, occurrence, and formation. Pp 137–160 *in* Johnson, C.J.; Clark, A.L. (eds) "Pacific Mineral Resources Physical, Economic, and Legal Issues". East-West Center, Honolulu. 639 p.

HALBACH, P.; MANHEIM, F.T.; OTTEN, P. 1982: Co-rich ferromanganese deposits in the marginal seamount regions of the central Pacific Basin — results of the Midpac '81. *Erzmetall 35* : 447–453.

HALBACH, P.; PRAUSE, B.; KOCH, K.; WESTHOLT, M. 1990: Platinum and palladium in Co-rich ferromanganese crust deposits. *Marine Mining 9* : 117–126.

HALBACH, P.; SATTLER, C.-D.; TEICHMANN, F.; WAHSNER, M. 1989: Cobalt-rich and platinum-bearing manganese crust deposits on seamounts : Nature, formation, and metal potential. *Marine Mining 8* : 23–29.

HEEZEN, B.C.; HOLLISTER, C.D. 1971: "The Face of the Deep". Oxford University Press, New York. 659 p.

HEIN, J.R.; MANHEIM, F.T.; SCHWAB, W.C.; DAVIS, A.S. 1985: Ferromanganese crusts from the Necker Ridge, Horizon Guyot and S.P. Lee Guyot : Geological considerations. *Marine Geology 69* : 25–54.

HEIN, J.R.; MORGENSON, L.A.; CLAGUE, D.A.; KOSKI, R.A. 1987: Cobalt-rich ferromanganese crusts from the Exclusive Economic Zone of the United States and nodules from the oceanic Pacific. Pp 753–771 *in* Scholl, D.W.; Grantz, A.; Vedder, J.G. (eds) "Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins — Beaufort Sea to Baja California". Circum-Pacific Council for Energy and Mineral Resources, Houston. [Earth Science Series, Vol. 6.] 799 p.

HEIN, J.R.; SCHULZ, M.S.; KANG, J.-K. 1990: Insular and submarine ferromanganese mineralization of the Tonga-Lau region. *Marine Mining 9* : 305–354.

HEIN, J.R.; SCHWAB, W.C.; DAVIS, A.S. 1988: Cobalt- and platinum-rich ferromanganese crusts and associated substrate rocks from the Marshall Islands. *Marine Geology 78* : 255–283.

HODKINSON, R.A.; CRONAN, D.S. 1991: Regional depth variability in the composition of cobalt-rich ferromanganese crusts from the SOPAC area and adjacent parts of the central equatorial Pacific. *Marine Geology 98* : 437–447.

KORSCH, R.J.; WELLMAN, H.W. 1988: The geological evolution of New Zealand and the New Zealand region. Pp 411–482 *in* Nairn, A.E.M.; Stehli, F.G.; Uyeda, S. (eds) "The Ocean Basins and Margins, Vol. 7B, The Pacific Ocean". Plenum Press, New York. 642 p.

KOSKI, R.A. 1988: Ferromanganese deposits from the Gulf of Alaska Seamount Province : mineralogy, chemistry, and origin. *Canadian Journal of Earth Sciences 25* : 116–133.

KOSKI, R.A.; HEIN, J.R.; BOUSE, R.M.; SLINEY, R.E. 1985: Composition and origin of ferromanganese crusts from Tonga Platform, Southwest Pacific. Pp 179–186 *in* Scholl, D.W.; Vallier, T.L. (eds) "Geology and Offshore Resources of Pacific Island Arcs — Tonga Region". Circum-Pacific Council for Energy and Mineral Resources, Houston. [Earth Science Series, Vol. 2.] 488 p.

KROENKE, L.W.; EADE, J.V. 1982: Three Kings Ridge : west-facing arc. *Geo-Marine Letters 2* : 5–10.

KUNZENDORF, H.; STOFFERS, P.; GWOZDZ, R. 1988: Regional variations of REE patterns in sediments from active plate boundaries. *Marine Geology 84* : 191–199.

LAUNAY, J.; DUPONT, J.; LAPOUILLE, A. 1982: The Three Kings Ridge and the Norfolk Basin (Southwest Pacific) : An attempt at structural interpretation. *South Pacific Marine Geological Notes 2(8)* : 121–130.

LE SUAVÉ, R.; PICHOCKI, C.; PAUTOT, G.; HOFFERT, M.; MOREL, Y.; VOISSET, M.; MONTI, S.; AMOSSÉ, J.; KOSAKEVITCH, A. 1989: Geochemical and mineralogical study of Co-rich ferromanganese crusts from a submerged atoll in the Tuamotu Archipelago (French Polynesia). *Marine Geology 87* : 227–247.

MANGINI, A.; HALBACH, P.; PUTEANUS, D.; SEGL, M. 1987: Chemistry and growth history of Central Pacific Mn-crusts and their economic importance. Pp 205–220 *in* Teleki, P.G.; Dobson, M.R.; Moore, J.R.; von Stackelberg, U. (eds) "Marine Minerals Advances in Research and Resource Assessment". D. Reidel, Dordrecht. 588 p.

MANHEIM, F.T. 1986: Marine cobalt resources. *Science 232* : 600–608.

MANHEIM, F.T.; LANE-BOSTWICK, C.M. 1988: Cobalt in ferromanganese crusts as a monitor of hydrothermal discharge on the Pacific sea floor. *Nature, London 335* : 59–62.

MANHEIM, F.T.; LANE-BOSTWICK, C.M. (eds) 1989: Chemical composition of ferromanganese crusts in the World Ocean : A review and comprehensive database. *U.S. Geological Survey Open-File Report 89-020* : 200 p., 3 app.

MEYLAN, M.A.; GLASBY, G.P.; HILL, P.J.; McKELVEY, B.C.; WALTER, P.; STOFFERS, P. 1990: Manganese crusts and nodules from the Manihiki Plateau and adjacent areas : results of HMNZS Tui cruises. *Marine Mining 9* : 43–72.

MOORBY, S.; CRONAN, D.S.; GLASBY, G.P. 1984: Geochemistry of hydrothermal Mn-oxide deposits from the S.W. Pacific island arc. *Geochimica et Cosmochimica Acta 48* : 433–441.

NELSON, C.S.; HANCOCK, G.E.; CAMP, P.J.J. 1982: Shelf to basin, temperate skeletal carbonate sediments, Three Kings Plateau, New Zealand. *Journal of Sedimentary Petrology 52* : 717–732.

NEMOTO, K.; KROENKE, L.W. 1981: Marine geology of the Hess Rise 1. Bathymetry, surface sediment distribution, and environment of deposition. *Journal of Geophysical Research 86* : 10734–10752.

PICHOCKI, C.; HOFFERT, M. 1987: Characteristics of Co-rich ferromanganese nodules and crusts sampled in French Polynesia. *Marine Geology 77* : 109–119.

PUTEANUS, D.; HALBACH, P. 1988: Correlation of Co concentration and growth rate — A method for age determination of ferromanganese crusts. *Chemical Geology 69* : 73–85.

RITCHEY, J.L. 1987: Assessment of cobalt-rich manganese crust resources on Horizon and S.P. Lee Guyots, U.S. Exclusive Economic Zone. *Marine Mining 6* : 231–243.

SUMMERHAYES, C.P. 1967: Manganese nodules from the South-western Pacific. *N.Z. Journal of Geology and Geophysics 10* : 1372–1381.

SUMMERHAYES, C.P. 1969: Marine geology of the New Zealand subantarctic sea floor. *Memoirs. N.Z. Oceanographic Institute 50* : 92 p.

VAN DER LINDEN, W.J.M. 1968: Cook Bathymetry. *N.Z. Oceanographic Institute Chart, Oceanic Series 1:1,000,000.*

WRIGHT, I.C.; CARTER, L.; KEWIS, K.B. 1990: GLORIA survey of the oceanic-continental transition of the Havre Taupo back-arc basin. *Geo-Marine Letters 10* ; 59–67.

APPENDIX 1 — Locations, depths, and brief descriptions of existing manganese deposits in the N.Z. Oceanographic Institute collection.

'Eua Island, Tonga

Mn crust 65 x 45 x 15 mm. Crust consists of 2-mm- thick layer of hard black Mn oxides with smooth surface texture overlying 13-mm-thick layer of brown-ish Mn crust incorporating iron oxides and clay minerals.

Tonga-Kermadec Ridge

U40 (25°03.3'S, 176°49.3'W, 1773 m)
Thin fragments of laminated manganese crusts (3–5 mm thick).

U189 (30°44.3'S, 178°48.0'W, 1777 m)
Hard, black, lustrous, somewhat-curved, manganese crusts 12–45 mm thick. Internal banding common but subdued. No evidence of detrital minerals in the crusts and no attached substrate. Some surfaces display micropitting whereas others, particularly around the periphery of the crusts, display metallic lustrous sheen. These crusts correspond to the massive layered material described by Moorby *et al.* (1984). Sample also includes pumice fragments.

Three Kings Ridge

S575 (31°52.0'S, 172°09.6'E, 1380–1280 m)
Flattened manganese nodues 15–60 mm in diameter; evidence of *in situ* fracturing of nodules on sea floor common. Generally smooth surface texture; some botryoidal development. Highly altered volcanic core almost completely interpenetrated by manganese oxides. Thin (1 mm) outer layer of manganese oxides.

S576 (32°24.8'S, 172°24.5'E, 1950–1600 m)
50 x 30 x 15 mm Mn crust and numerous fragments of crust. Upper crust up to 40 mm thick, lower crust up to 30 mm thick. Crust layered with botryoidal surface texture. Core highly altered material. Sharp contacts between Mn crust and core.

Colville Ridge

B30/29/1 (35°13.9'S, 177°26.5'E – 35°15.7'S, 177°21.7'E, 1500 m)
Collected by Russian vessel R.V. *Vulcanolog.*
Mn boulder 900 x 400 x 400 mm. Sample so badly broken on deck that a proper description not possible. However, the shipboard description was of a massive manganese boulder incorporating altered volcanic material, unidentified creamy-white minerals and limited brown iron-oxide staining. The outer manganese layer probably overlies a highly altered volcanic core.

The deposit had a smooth manganese surface on all sides. Parts of the surface were botryoidal, parts soft. Ash was found in the centre and in cracks of the fragments. Several botryoidal layers. Several generations of manganese deposits.

Southern Havre Trough

S800 (36°43.4'S, 177°27.7'E, 2180–2000 m)
Northeastern flank of Whakatane Seamount; fresh to highly altered andesite, ?dacite and pumiceous subrounded to angular cobbles. Manganese coatings < 2 mm thick in upper cobble surfaces and cavities.

Seamount east of North Island

4608 (38°42'S, 177°02'W, 2200 m)
Spheroidal nodules; one 50 x 30 mm with a fragmented, altered volcanic core 15 x 5 mm; the other 20 mm in diameter.

Flanks of Bellona Trough

Stn 67 (40°15.98'S, 165°58.57'E)
Collected by Russian vessel R.V. *Acad. Nesmeyanov* (from Far East Science Centre). Sample No. 67-22. Manganese crust (25–50 mm thick) overlying altered volcanic rock.

SW Campbell Plateau

S100 (54°51.4'S, 165°13.5'E, 2370–2400 m)
Abundant nodules ranging in size to 80 mm. Variety of shapes (flattened, angular, spheroidal). Botryoidal surface texture. Nodules extremely hard, showing evidence of concentric banding around a small nucleus.

Mn crusts up to 90 mm thick. Replacement structure. Botryoidal texture on upper surface — botryoids 5–20 mm in diameter. Burrow structures (diameter up to 5 mm) on underside.

APPENDIX 2 — N.Z. Oceanographic Institute station data for the 1988 *Rapuhia* cruise.

Stn No.	Latitude (°S)	Longitude (°E)	Depth (m)	Setting	Description
Bellona Trough					
U545	40 16.5'	165 59.7'	3304	Western slope of spur	Carbonate ooze; biota
U546	40 14.2'	166 02.6'	3270	Western slope of spur	Carbonate ooze; biota
U547	40 15.3'	166 07.1'	2250	Crest of spur	Manganese crust; carbonate ooze; biota
U548	40 11.1'	166 11.8'	2270	Crest of spur	Biota
U549	40 09.7'	166 14.0'	2257	Crest of spur	Carbonate ooze
U550	40 11.9'	166 18.4'	2952	Eastern slope of spur	Mn-coated andesite cobbles; biota
U551	40 15.7'	166 20.7'	3354	Eastern slope of spur	Carbonate ooze; biota
U552	40 16.4'	166 34.5'	3000–2950	Eastern slope of Bellona Trough	Carbonate ooze; 1 small rhyolite pebble; biota
U553	40 18.9'	166 43.7'	2450–2375	Eastern slope of Bellona Trough	Carbonate ooze; biota
U554	40 20.8'	166 50.3'	2000–1904	Eastern slope of Bellona Trough	Carbonate ooze
U555	40 20.0'	167 00.2'	1536–1517	Eastern slope of Bellona Trough	Carbonate ooze
U556	39 06.5'	165 41.8'	2992–2982	SE tip of Dolphin Spur	Carbonate ooze; biota
U557	39 05.0'	165 36.2'	2731–2670	SE tip of Dolphin Spur	Carbonate ooze; biota
U558	38 57.7'	165 27.5'	2018–1990	SE tip of Dolphin Spur	Carbonate ooze
U559	38 51.9'	165 20.4'	1842	Dolphin Spur	Carbonate ooze; biota
U560	38 32.3'	165 39.9'	2330–2300	Seapeak	Carbonate ooze
U561	38 26.1'	166 48.1'	1890–1884	Seapeak	Carbonate ooze; biota
U562	38 06.2'	166 08.1'	2342–2352	Bellona Trough	Carbonate ooze; biota
U563	37 55.8'	166 55.3'	1308–1298	Head of Bellona Trough	Carbonate ooze; biota
West Norfolk Ridge					
U564	35 17.9'	165 58.8'	1890–1700	Southern slope of West Norfolk Ridge	Carbonate ooze; biota
U565	35 14.7'	169 00.7'	1610–1560	Southern slope of West Norfolk Ridge	Pumice; carbonate sand; biota
U566	35 05.0'	169 09.7'	979–974	Crest of West Norfolk Ridge	Pumice; Mn crust on indurated foram ooze; carbonate sand; dead shells; biota
U567	35 00.3'	169 09.7'	1480–1050	Northern slope of West Norfolk Ridge	Dead coral and dead shells; shelly limestone; biota
U568	35 08.4'	169 28.4'	867–865	Crest of West Norfolk Ridge	Pumice; carbonate sand; coral; biota
Norfolk Ridge					
U569	34 55.5'	169 22.4'	1210	Southern slope of Norfolk Ridge	Carbonate sand; biota
U570	34 48.9'	169 17.6'	691–627	Crest of Norfolk Ridge	Biota
U571	34 44.1'	169 25.0'	1123–1064	Northern slope of Norfolk Ridge	Pumice; carbonate sand; biota
Reinga Ridge					
U572	33 36.7'	170 02.0'	1679–1660	Southern slope of Reinga Ridge	Spheroidal calcareous nodules; ?phosphatised limestone slabs; pumice; carbonate sand; biota including phosphatised bone fragment

Stn No.	Latitude (°S)	Longitude (°E)	Depth (m)	Setting	Description
U573	33 32.0'	170 06.4'	1260	Southern slope of Reinga Ridge	Pumice; limestone; shelly sand; biota
U574	33 19.6'	170 06.9'	570–580	Crest of Reinga Ridge	Mn-coated consolidated ankeritic mudstone and saccharoidal limestone; coarse shelly sand; biota
U575	33 07.9'	170 08.7'	2129–2070	Northern slope of Reinga Ridge	Indurated mudstone fragments; siliceous breccia; carbonate sand; biota
Seamount I					
U576	32 14.5'	170 14.2'	2340–2260	Near crest of seamount (peak at 2050 m)	Fragments of manganese crust with basalt cores; biota
Seamount II					
U577	31 50.2'	170 52.6'	3120	Lower flank of seamount	Pumice; carbonate ooze
U578	31 42.5'	171 05.0'	2620–2570	Near crest of seamount	Mn crust; pumice; carbonate sand
Three Kings Ridge					
U579	31 51.5'	171 57.6'	2109	Western flank of Three Kings Ridge	Mn-coated fragments of ferruginised feldspathic sandstone; pumice; carbonate sand; biota
U580	31 51.2	172 10.2'	1270–1286	Crest of Three Kings Ridge	Calcareous mudstone; barnacle plates
U581	31 51.3'	172 08.8'	1170–1180	Crest of Three Kings Ridge	Mn-coated foram ooze with volcanic microclasts; mudstone; Mn-stained barnacle shells and coral; carbonate sand; biota
U582	31 51.7'	172 26.0'	790–780	Crest of Three Kings Ridge	Phosphatised cetacean bones; pumice; carbonate sand; coral; biota
U583	31 38.1'	172 30.2'	1127	Crest of Three Kings Ridge	Mn crust; pumice; pumiceous sandstone
U584	31 26.3'	172 35.6'	1137–1150	Crest of Three Kings Ridge	Pumice; lithified carbonate sand; biota including phosphatised cetacean bone
U585	31 21.1'	172 26.1'	1730–1702	Western slope of Three Kings Ridge	Pumice; carbonate sand; biota
U586	31 17.1'	172 07.9'	2060–2065	Western slope of Three Kings Ridge	Pumice; carbonate sand; biota
U587	31 12.8'	172 00.9'	2463–2430	Western slope of Three Kings Ridge	Carbonate ooze; biota
U588	31 11.7'	171 52.6'	3220–3210	Western slope of Three Kings Ridge	Pumice; carbonate ooze; biota
U589	31 47.4'	172 08.5'	2030–2010	Western slope of Three Kings Ridge	Pumice; carbonate sand
U590	30 48.8'	172 22.7'	1515–1498	Western slope of Three Kings Ridge	Pumice; carbonate sand; biota
U591	30 50.6'	172 48.3'	486	Crest of Three Kings Ridge	Indurated tuff; coral fragments; pumice; carbonate sand; biota
U592	30 41.3'	172 54.0'	1067–1058	Crest of Three Kings Ridge	Pumice; carbonate sand; biota
U593	30 32.3'	172 55.3'	1097–1082	Crest of Three Kings Ridge	Pumice; carbonate sand; biota
Tui Seamount					
U594	30 20.1'	172 59.6'	406	Crest of Tui Seamount	Fragment of algal carbonate; pumice; carbonate sand; biota

Stn No.	Latitude (°S)	Longitude (°E)	Depth (m)	Setting	Description
U595	30 21.5'	173 08.7'	1474–1365	Eastern slope of Tui Seamount	Pumice; fragments of algal carbonate; coarse shelly sand; biota
U596	30 25.0'	173 17.9'	2100	Eastern slope of Tui Seamount	Pumice; coral; carbonate sand
Kiwi Seamount					
U597	30 40.6'	173 44.7'	2960–2970	NW slope of Kiwi Seamount	Pumice; carbonate ooze; biota
U598	30 40.9'	173 51.5'	1335–1520	Northern slope of Kiwi Seamount	Pumice; brachiopod shells; carbonate sand
Seamount III					
U599	30 43.0'	173 16.9'	640–590	Crest of seamount	Coralline limestone; pumice; coarse shelly sand; biota
Seamount IV					
U600	31 01.7'	173 22.7'	620	Near crest of seamount	Pumice; carbonate sand; biota
Three Kings Ridge					
U601	31 19.9'	173 05.1'	1570–1563	Eastern slopes of Three Kings Ridge	Pumice; carbonate sand; biota
Seamount V					
U602	31 30.7'	172 49.8'	1216–1385	Crest of seamount	Pumice; carbonate sand; biota
Seamount VI					
U603	31 53.6'	173 08.6'	1780–1782	Crest of seamount	Pumice; Mn-coated basalt; carbonate sand; biota
U604	31 57.2'	173 11.0'	1560–1570	Crest of seamount	Mn crusts on basaltic blocks; carbonate sand; biota
U605	31 52.1'	173 06.4'	1640–1578	Crest of seamount	Mn-encrusted basalt
Three Kings Ridge					
U606	31 54.7'	172 47.4'	1100–1085	Eastern slope of Three Kings Ridge	Mn-encrusted andesite; calcareous fragments; black coral; biota
U607	31 53.1'	172 39.9'	1550–1400	Crest of Three Kings Ridge	Mn crust on indurated foram ooze
U608	31 53.5'	172 31.9'	1520–1600	Crest of Three Kings Ridge	Mn fragments; pumice; biota
U609	32 01.7'	172 23.2'	1680–1520	Crest of Three Kings Ridge	Mn-coated (< 1 mm) corals, ?tuff; barnacles and molluscs
U610	32 13.4'	172 24.1'	1500–1504	Crest of Three Kings	Mn crust; coral
Seamount VII					
U611	32 24.2'	172 24.4'	1560–1470	Southern end of Three Kings Ridge	Mn-coated basalt; coral
Three Kings Ridge					
U612	32 01.2'	172 36.7'	1911	Crest of Three Kings Ridge	Pumice; carbonate ooze
U613	31 57.5'	172 41.5'	1960–1955	Crest of Three Kings Ridge	Carbonate ooze; biota

Stn No.	Latitude (°S)	Longitude (°E)	Depth (m)	Setting	Description
Devonport Seamount					
U614	31 35.1'	172 17.2'	3700–3600	Western slope of seamount	Pumice; carbonate ooze; biota
U615	31 32.8'	175 23.4'	1028–1068	Near crest of seamount	Mn-coated calcarenite; Mn-stained coral fragments; fragments of Mn crust
U616	31 32.8'	175 24.6'	1900–2100	Western slope of seamount	Mn crust; shell; biota
Seamount VIII					
U617	33 05.1'	173 21.4'	1680–1687	Eastern slope of seamount	Pumice; carbonate ooze; biota
U618	33 06.9'	173 18.1'	1690–1670	Western slope of seamount	Pumice; carbonate ooze; biota
Aotea Seamount					
U619	37 32.8'	171 59.0'	1112–1044	Crest of seamount	Coarse shelly sand and carbonate sand; Mn-stained coral; biota
U620	37 28.9'	172 32.0'	1350–1380	Crest of seamount	Mn crust on ?weathered tuff; biota
U621	37 29.8'	173 26.6'	1232–1295	Crest of seamount	Mn-stained coral and Bivalvia; carbonate sand
U622	37 31.2'	172 19.6'	1113–1170	Crest of seamount	Tuffaceous mudstone and basalt; carbonate sand; biota
U623	37 30.7'	172 12.4'	1040–1060	Crest of seamount	Volcaniclastic sandstone and breccia a fragments; biota
U624	37 32.7'	172 07.1'	984	Crest of seamount	Tuff pebble; carbonate sand; biota

Appendix 3 — Description of rocks and crusts collected by rock dredge on the 1988 *Rapuhia* cruise.

Bellona Trough

U547 2 larger pieces of Mn crust plus several smaller fragments.
1 piece 70 x 50 x 20 mm — altered rhyolite with reddish tinge of iron oxides, upper surface 11 mm thick. Mn crust with botryoidal surface texture; undersurface of Mn oxides 1 mm thick.
1 piece 70 x 50 x 20 mm. Sample is a limestone almost completely replaced by Mn and Fe oxides. Within the lime-stone, there is a cavity lined with botryoidal crystalline calcite. Outer Mn crust is up to 8 mm thick.
Smaller fragments, as above, Mn crust up to 7 mm thick with altered rhyolitic or calcitic core.
In each case, Mn crust is difficult to remove from the substrate.
1 small piece of indurated foraminiferal ooze.
1 dead solitary coral with Mn-oxide staining (< 1 mm).

U550 About 50 subrounded to subangular cobbles with Mn-oxide staining, the largest 80 mm across. The cobbles are up to 35 mm thick and are fragments of highly altered (palagonitised) andesite with Mn coatings — the upper surface with a 1-mm coating of Mn oxides; the lower surface with a thin staining of Mn oxides ranging up to 1 mm. Most samples are discrete cobbles; only a few have been dredged from outcrop. Many samples have faecal casts (1 mm thick) on surface.
1 fragment of indurated carbonate ooze.

U552 1 small angular pebble (8 mm across) of altered rhyolite with thin (< 1 mm) oxide coating.

West Norfolk Ridge

U565 8 pieces of pumice up to 30 mm.

U566 8 pieces of pumice up to 30 mm.
2 larger and 8 smaller slabs.
2 larger slabs (400 x 250 x 60 mm; 400 x 270 x 60 mm) of indurated, ferruginised, phosphatised, foraminiferal "ooze". The crusts are lightly burrowed with burrows up to 10 mm diameter. The substrate is extensively replaced by Mn oxides; the upper surface is more strongly coated by Mn oxides than the lower surface. The upper surfaces are smoother and rounder (perhaps due to the influence of currents), the underside is rougher and darker but with moderate-yellowish-brown (10YR 5/4) areas. The interior of these crusts contains moderate-yellowish-brown (10YR 5/4) zones strongly replaced by Mn oxides.
The smaller slabs are up to 130 mm across and several are flattened. They are heavily bored, with burrows up to 10 mm in diameter. Some epifauna on the surfaces, but not as abundantly as on larger slabs. These smaller slabs are dominantly greyish-red (5R 4/2) with minor areas of moderate-yellowish-brown (10YR 5/4). This colouration suggests that they are not extensively coated by Mn oxides.
2 cetacean bone fragments, ferruginised and possibly phosphatised.
2 slabs of indurated limestone with minor ferruginisation.
Abundant barnacle plates.

U567 4 small pieces of shelly limestone; barnacle plates and coral, some with thin (< 1 mm) staining of Mn oxides.

U568 2 small pumice pebbles (up to 20 mm).

Norfolk Ridge

U571 18 pieces of pumice (up to 40 mm) plus one volcanic fragment.

Reinga Ridge

U572 20 hard, dense spheroidal and elongated concretions principally consisting of indurated, partly recrystallised fine-grained foraminiferal "ooze", with core of crystalline (bladed) barite. Concretions are creamy with dark areas, and range up to 50 mm in diameter. One soft concretion consists of limestone almost completely replaced by Mn oxides.
Abundant irregular, tabular, elongated and angular-to-subrounded fragments of ferruginised, phosphatised? "ooze". The slabs are 2–7 mm thick and up to 50 mm across.
2 pieces of pumice (up to 35 mm).
1 piece of phosphatised bone fragment.

U573 1 piece of pumice 65 mm across.
1 bored slab of limestone 2 mm thick (60 mm across).

U574 Slab 600 x 400 x 35–50 mm of consolidated ankeritic mudstone with a thin (< 1 mm) coating of Mn oxides, heavily bored (bores up to 15 mm diameter) and encrusted with worm tubes 3 mm in diameter plus other biota. One surface has relatively few borings and little biota, whereas the other surface is heavily bored with abundant biota. Surface is hard and black.
Slab 290 x 250 x 80 mm of ankeritic mudstone. Upper surface black and burrowed, with some light-brown areas in vicinity of burrows, and encrusting organisms; lower surface with larger light-brown area, less burrowed but with more encrusting organisms.
Slab 200 x 120 x 90 mm ankeritic mudstone very similar to that described above.
Number of small fragments similar to that described above.
Slab 130 x 55 x 20 mm ankeritic sandstone. Thin Mn coating (< 1 mm) on exposed surfaces.
2 slabs of lithified carbonate mudstone 170 x 135 x 25–10 mm and 70 x 60 x 20–5 mm with numerous small (1 mm in diameter) burrows on one side but far fewer on the other side. On side with fewer burrows, some evidence of darker brown staining (ferruginisation).

U575 Abundant small (up to 30 mm) angular, irregular fragments of indurated mudstone; smooth with thin (up to 1 mm) coating of Mn oxides plus fragments of cemented, indurated, siliceous breccia with thin (< 1 mm) coating of Mn oxides.

Seamount I

U576 9 small fragments of Mn crust up to 25 mm across. Mn crust up to 7 mm thick. Altered basaltic cores in some.

Seamount II

U577 5 pieces of pumice (up to 70 mm).

U578 3 slabs of Mn crust.
310 x 280 x 80 mm — Mn crust 18–20 mm thick overlying palagonite which has been bored and infilled with Mn oxides; bores up to 5 mm in diameter; sharp contacts between Mn crust and substrate; iron oxides in substrate near contact with crust. Crust material hard and lustrous in section with low detrital-mineral content; no marked banding in the crust. Surface of crust microbotryoidal on upper surface ranging to botryoidal on sides. Limited number of worm tubes on surface of crust.
330 x 180 x 65 mm — Mn crust 25 mm thick; description as above.
170 x 160 x 40 mm — Mn crust 25 mm thick; description as above.
Several palagonite fragments with Mn crusts of various thicknesses; some pieces not bored (2–20 mm); several pieces show heavy boring by organisms; bores up to 5 mm and coated with Mn oxides.
1 piece of pumice (25 mm).

Three Kings Ridge

U579 Numerous pieces of pumice (up to 140 mm).
Many irregular fragments of ferruginised foraminiferal feldspathic sandstone, with abundant zeolite. Fragments are up to 30 mm across and 10 mm thick and display a thin (< 1 mm) coating of Mn oxides on all surfaces.

U580 Small pieces of calcareous mudstone (up to 40 mm). Samples are bored; bores are up to 1 mm across; faint Mn staining around bores; some rounding of the fragments.
Thin calcareous plates 2 mm thick with thin layer (< 1 mm) of Mn oxides on upper surface.
Barnacle plates with a thin (< 1 mm) staining of Mn oxides.

U581 5 large slabs plus a number of smaller slabs of foraminiferal "ooze" containing volcanic microclasts (? pyroclasts). Coated with thin layers (< 1–2 mm) of Mn oxides on all sides. Mn dendrites and Mn interpenetration along fracture zones in ooze. Worm tubes up to 4 mm diameter plus biota on surface of slabs; limited burrow markings up to 5 mm diameter on lower surface of slabs. Dimensions of larger blocks : 500 x 360 x 100 mm; 400 x 260 x 70 mm; 180 x 160 x 50 mm; 260 x 200 x 25 mm; 210 x 130 x 16 mm
6 smaller slabs up to 130 mm across and up to 15 mm thick of tuffaceous mudstone; extensively bored (bores up to 2 mm diameter); some Mn penetration into bores; samples have Mn coating on one side only; some lack a Mn coating entirely.
Abundant barnacle shells with lesser amount of coral stained black by thin layer (< 1 mm) of Mn oxides.

U582 1 bored (bores up to 5 mm) phosphatised cetacean bone (130 x 50 x 10 mm). Minor Mn staining around edges.

1 heavily bored (bores up to 15 mm diameter) phosphatised cetacean bone (110 x 60 x 40 mm); **Mn staining on** surface.
3 pieces of pumice (up to 35 mm).

U583 Large slab 260 x 200 x 80 mm. Crudely bedded pumiceous silty sandstone, coated by 4–10 mm of Mn oxides. Mn oxides on upper surface smooth with limited worm tubes (up to 1 mm diameter). Pumiceous sandstone with brown (iron oxide) and black (manganese oxide) staining on side and lower surfaces. Heavily bored on side and underside (bores up to 10 mm diameter).
Several smaller fragments showing some features as noted above.
4 samples of incipient nodules.
1 piece of pumice (20 mm).

U584 Lithified carbonate sand (up to 45 mm).
2 small phosphatised cetacean bone fragments, one bored.
Pumice (up to 80 mm).

U585 Abundant pumice (up to 130 mm).

U586 4 pieces of pumice (up to 40 mm).

U588 8 pieces of pumice (up to 40 mm).

U589 c. 40 pieces of pumice (up to 40 mm).

U590 Numerous pieces of pumice (up to 140 mm).

U591 1 slab of indurated tuff (90 x 60 x 30 mm) with Mn staining (< 1 mm).
Several heavily bored tabular coralline fragments; bores up to 2 mm diameter.
1 piece of pumice (40 mm).

U592 Abundant pumice (up to 60 mm).

U593 Pumice (up to 50 mm).

Tui Seamount

U594 1 intensively bored fragment of algal? carbonate.
1 piece of pumice (15 mm).

U595 25 bored fragments of algal? carbonate with Mn staining (< 1 mm) (up to 55 mm).
4 pieces of consolidated calcareous grit and sand containing algal? fragments (up to 60 mm). 1 piece of sponge.
Pumice (up to 40 mm).

U596 Pumice (up to 140 mm).

Kiwi Seamount

U597 Pumice (up to 35 mm).

U598 Pumice (up to 45 mm).

Seamount III

U599 1 piece of indurated coralline limestone (80 mm).

Seamount IV

U600 2 pieces of pumice (up to 45 mm).

Three Kings Ridge

U601 1 piece of Mn-cemented foram sand (30 mm).
1 piece of sponge.
Abundant pumice (up to 50 mm).

Seamount V

U602 1 Piece of pumice (35 mm) containing dark "xenoliths".
1 rounded piece of limestone (20 cm).

Seamount VI

U603 c. 60 small fragments of Mn crust up to 12 mm thick, overlying highly altered basaltic fragments in some cases. Sharp contact between crust and substrate. Crust surface slightly mammillated with microbotryoidal surface texture. Mn oxides are black and lustrous. Many of the Mn crusts have no attached substrate. Some are slightly rounded reflecting curvature of host rock.
5 pieces of siliceous sponge.
Few bored mollusc shell fragments and algal platelets (up to 20 mm).
Abundant pumice (up to 40 mm).

U604 Mn crusts (150 x 95 x 80 mm; 140 x 100 x 70 mm; 105 x 80 x 75 mm). Subangular to subrounded blocks of palagonitised glomero-porphyritic basalt with Mn crust 1–2 mm thick. Surface texture of Mn crust smooth. Limited number of worm tubes and coral on surface of sample. Some spallation of outer Mn crust. 2 Mn crusts (105 x 80 x 50 mm; 105 x 80 x 35 mm). Irregularly shaped, rounded concretions of Mn with palagonite core heavily interpenetrated by Mn. Mn crust as above.
Barnacle plates, echinoid spines, and corals all covered with thin layer of Mn oxides (< 1 mm).

U605 Altered vesicular basalt (200 x 150 x 60 mm) with Mn crust 4–20 mm thick. Mn crust has mammil-lated surface with microbotryoidal surface texture. Basalt has yellowish to reddish-brown iron-oxide staining on broken surfaces. Vesicles in basalt up to 10 mm; some vesicles and veins filled by fine-grained foraminiferal "ooze".

Three Kings Rise

U606 3 large angular blocks plus 50 smaller samples. Largest blocks 800 x 340 x 250 mm; 350 x 230 x 250 mm; 310 x 300 x 120 mm.
15 subangular to subrounded sample of porphyritic andesite with thin patchy Mn coating (< 1 mm).
26 smaller subangular to subrounded flow-banded andesite samples with thin patchy Mn coating (< 1 mm).
17 smaller fragments of bored algal calcareous deposits; mostly with limited Mn coating but one sample having Mn crust 15 mm.
2 pieces of Mn crust 10 mm thick.

U607 10 Mn crusts (330 x 100 x 80 mm; 170 x 160 x 85 mm; 160 x 130 x 95 mm; 160 x 150 x 70 mm). Mn crust 30–50 mm thick; mammillated surface with microbotryoidal surface texture. Substrate of ferruginised foraminiferal "ooze". Some infilling of veins and cavities in substrate by fresh foram "ooze". Substrate generally of limited thickness. Internally, Mn crust black, lustrous with little structure, somewhat blocky. Limited biota on surface of crust (e.g., corals, worm tubes, bryozoans).

U608 4 small fragments of Mn crust (2–9 mm thick).
Pumice (up to 30 mm).
Dead coral, brachiopods, barnacle plates, pteropods, and mollusc with light Mn staining on some specimens.

U609 Mn-coated (< 1 mm) corals, barnacle plates with minor molluscs and echinoids.
1 small fragment of ?silicified tuff.

U610 6 Mn crusts plus a number of small fragments (280 x 220 x 100 mm; 280 x 160 x 85 mm; 270 x 150 x 50 mm; 130 x 65 x 35 mm; 115 x 70 x 50 mm; 100 x 60 x 65 mm).
280 x 220 x 100 mm crust. Mn crust 40 mm thick. Hummocky upper surface with microbotryoidal surface texture. Limited fauna on upper surface (worm tubes, polychaetes, coral). Mn oxides on underside are mammillated with botryoidal surface texture. Limited bryozoans on lower surface. Substrate highly altered tuff weathered red by iron oxides. Internally, the crust shows some banding with iron oxide.
130 x 65 x 35 mm crust. As above but has a large (120 mm long, 50 mm diameter) coral block on one side. The crusts follow above description. The crusts are mainly discrete blocks with Mn growth on all sides (i.e., not ripped directly off the substrate). Mn crusts are in range of 20–50 mm thick with a typical thickness of 40 mm. The crusts are dense with a limited fraction (20% by weight) of substrate material.
1 large piece of coral.

Seamount VII

U611 1 large rounded fragment (300 x 190 x 150 mm) of relatively fresh vesicular porphyritic basalt, with thin (1–4 mm) Mn coating. Sample obviously broken off substrate. Limited biota (corals, bryozoans) on surface of Mn oxides. Limited iron-oxide staining on broken surfaces of basalt.
1 smaller piece (120 x 75 x 35 mm) as above.
2 pieces of coral, one with Mn staining (< 1 mm), one without Mn staining.

Three Kings Ridge

U612 1 piece of pumice (25 mm).

Devonport Seamount

U614 15 pieces of pumice (up to 15 mm), some stained slightly black.

U615 6 pieces of Mn-coated rock. Largest is 200 x 170 x 60 mm. The rock is calcarenite, with coral/molluscan fragments cemented in a carbonate-sand matrix. Mn coating thicker on upper surface than on lower surface. Mn oxide thickness < 1 mm.
Coral fragments with few mollusc and barnacle fragments stained with Mn oxides (< 1 mm).
2 small fragments of Mn crust (4 mm thick).

U616 12 small fragments of Mn crust 5–16 mm thick with no visible substrate. Crusts slightly rounded with microbotryoidal surface texture.
1 fragment of coral with thin (< 1 mm) Mn coating.

Seamount VII

U617 10 pieces of pumice (up to 35 mm).

U618 3 pieces of pumice (up to 20 mm).

Aotea Seamount

U619 Dead coral stained black by Mn oxides (< 1 mm).

U620 20 small pieces of Mn crust (2–15 mm thick) overlying a thin substrate of weathered tuff. Mn crust has microbotryoidal surface texture.

U621 Dead coral and bivalves with thin staining of Mn oxides (< 1 mm).

U622 15 pieces of tuffaceous mudstone (up to 95 mm) with thin (< 1 mm) coating of Mn oxides.
9 pieces of picrite-basalt (up to 100 mm), with olivine mostly replaced by iddingsite. Thin (< 1 mm) coating of Mn oxides.
1 piece of siliceous sponge.

U623 19 pieces of volcaniclastic sandstone and breccia (up to 70 mm), characterised by calcite and zeolite cement. Thin coating of Mn oxides (< 1 mm). Surfaces encrusted with worm tubes (up to 5 mm in diameter).

U624 1 pebble of Mn-impregnated tuff up to 30 mm with thin (< 1 mm) coating of Mn oxides.

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