

Thick ferromanganese deposits from the Dampier Ridge and the Lord Howe Rise off eastern Australia

B.R. Bolton[1], N.F. Exon[2] & J. Ostwald[3]

Chemical and mineralogical data are presented for four ferromanganese samples (two nodules and two crusts) from two stations of the West German vessel *Sonne*. Three samples came from a dredge on the flanks of the Dampier Ridge in water 2400–2700 m deep. One came from a core on the Lord Howe Rise in water 1549 m deep. Thick ferromanganese deposits overlie a variety of substrates including granite, gabbro and feldspathic sandstone. The ferromanganese deposits, which are up to 20 cm thick, range from round mononucleate nodules with small volcanic nuclei, to polynucleate nodules, to nodules bound together as crusts, and to laminated crusts. Both nodules and crusts are hydrogenetic in origin and have low contents of Ni, Cu and Co, and low Mn:Fe ratios of 0.48–0.91. A comparison of these results with those from three deeper water stations of *Galathea* and *Tangaroa* indicates that Mn:Fe ratios, Ni% and Cu% increase markedly in deeper water, where Mn:Fe ratios exceed 2.5, and Ni+Cu+Co values exceed 1.25%. Any future search for nodules of economic significance should be concentrated in the even deeper water areas (>5000 m) east and southeast of Gascoyne Seamount.

Introduction

In this paper we present geochemical and mineralogical data for four ferromanganese samples (nodules and crusts) collected from two stations on the flanks of the Dampier Ridge and the Lord Howe Rise in the Tasman Sea during the 1985 cruise of the R.V. *Sonne*, involving scientists from the Bundesanstalt fuer Geowissenschaften und Rohstoffe (BGR) and the Australian Bureau of Mineral Resources (SO-36C; Roeser & others, 1985) (Fig. 1). We also discuss the origin of the ferromanganese deposits and compare them with similar deposits from elsewhere.

Bulk compositions of samples were determined using X-ray fluorescence or atomic absorption techniques and quoted as elemental values. Mineralogies were determined using X-ray diffraction or an electron microprobe; compositions derived from microprobe analyses are quoted as oxides.

Little is known of the nature, distribution and abundance of ferromanganese deposits in the Tasman Sea region (Jones, 1980; Glasby, 1986). Manganese nodules from three sites in the Tasman Sea southeast of Sydney, New South Wales, have been described by Exon, Moreton & Hicks (one site, 1980) and Glasby & others (two sites, 1986). Manganese nodules, often forming extensive pavements, have also previously been described from the South Tasman Sea and parts of the South Tasman Rise by Goodell, Meylan & Grant (1971), Watkins & Kennett (1971, 1972, 1977), Conolly & Payne (1972), Payne & Conolly (1972) and Glasby (1973).

The ferromanganese crusts and nodules described here were taken from two deep-water stations from offshore continental blocks: the Lord Howe Rise and Dampier Ridge (Fig. 1; Roeser & others, 1985). The Lord Howe Rise is a very large feature in water 1000–2500 m deep, which extends about 2000 km from the Coral Sea region to the Challenger Plateau off New Zealand; it averages 400 km in width. The general structure of the rise (Fig. 1) has been described in detail by Willcox & others (1980) and Roeser & others (1985). The eastern part of the rise has continental basement rocks relatively close to outcrop, but there is a series of basins, apparently containing 3000 m and more of Mesozoic and Cainozoic rocks, on the western flank.

The Dampier Ridge is a much smaller feature in water 2000–3000 m deep, and lies between Australia and the Lord Howe Rise (Fig. 1). Dredging of granite and gabbro by the R.V. *Sonne* showed that the ridge is a continental sliver (Roeser & others, 1985; Symonds, Willcox & Kudrass, 1988).

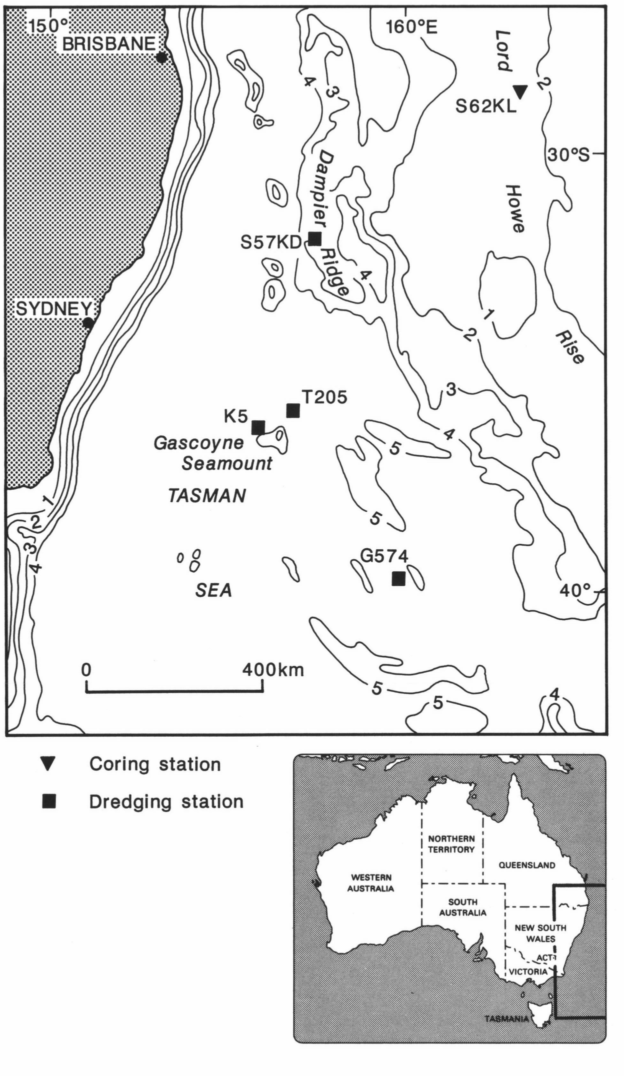

Figure 1. Location map showing sampling stations and major bathymetric features.
S, T, K and G denote *Sonne, Tangaroa, Kimbla* and *Galathea* stations, respectively.

[1] Department of Geology and Geophysics, University of Adelaide, PO Box 498, Adelaide, SA 5001
[2] Marine Geosciences and Petroleum Geology Program, Bureau of Mineral Resources, GPO Box 378, Canberra City, ACT 2601
[3] Central Research Laboratories, Broken Hill Proprietary Co. Ltd, PO Box 188, Wallsend, NSW 2287

Regional setting and descriptions of samples

Two dredge and five core stations were occupied by R.V. *Sonne*, and ferromanganese nodules and crusts were recovered at both dredge stations and in one core (Roeser & others, 1985). Station 57, a dredge (Fig. 1), was sited on a scarp on the western side of Dampier Ridge, on BMR seismic profile 15/058. The dredge returned small fragments of granite, gabbro, microdiorite and feldspathic sandstone, and abundant ferromanganese nodules and crusts up to 20 cm thick, from water 2600–2400 m deep. There was a full range from round mononucleate nodules with small volcanic nuclei, to polynucleate nodules, to nodules bound together as crusts, and to laminated crusts (Fig. 2). One particularly spectacular crust (Fig. 2B) consisted of a lower 5 cm of layered crust (assumed to have formed on basement rocks) and an upper 10 cm of nodules bound together. The ferromanganese layers varied from relatively hard and very dark, with a metallic lustre on newly cut surfaces, to yellowish brown and highly porous. Some deposits contained thin layers of clayey volcaniclastic debris.

One other *Sonne* dredge station (63) recovered ferromanganese from an embayment within the eastern Lord Howe Rise marking the western end of the Vening-Meinesz Fracture Zone, in a position where seismic profiles suggest basement is at the surface. The dredge returned a large block of calcareous limestone, thickly encrusted with ferromanganese, and numerous nodules with cores of sandstone, quartzite, limestone, phyllite and granite. Roeser & others (1985, p. 162)

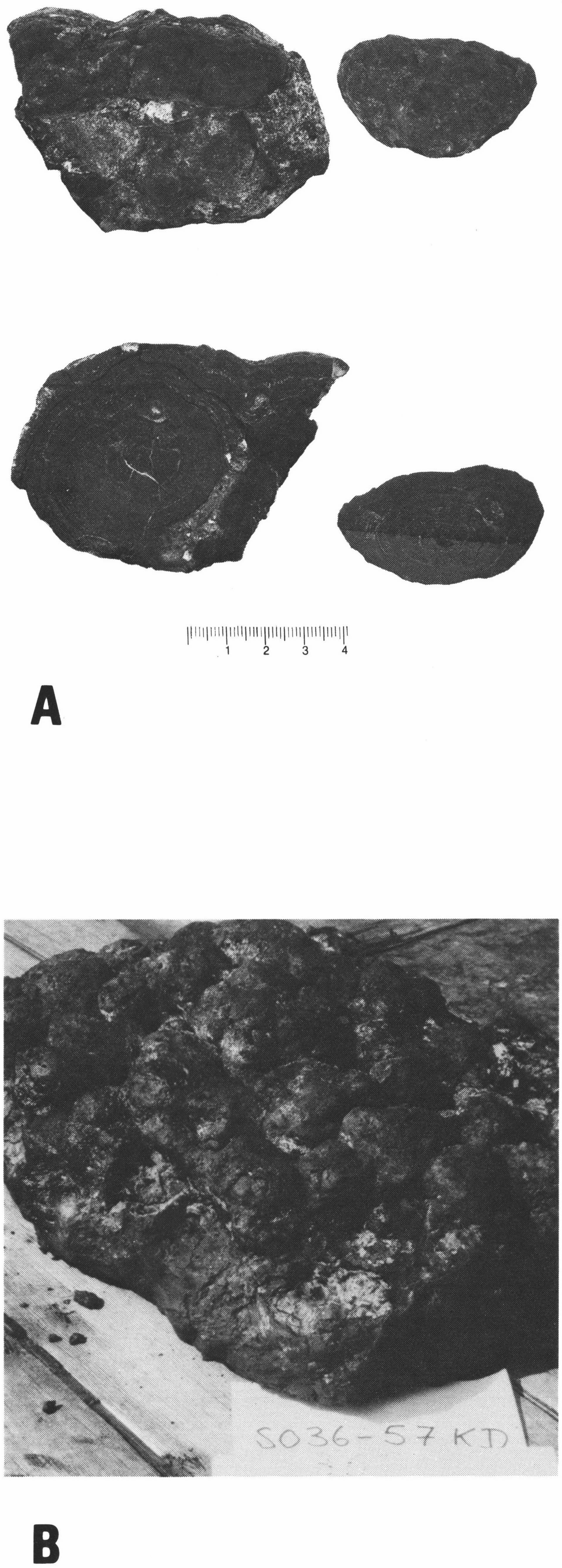

Figure 2.
A. External and internal features of nodules from station 57 (36-57KD5.1 and 36-57KD5.3). Scale is in centimetres.
B. Layered ferromanganese crust at bottom and bound nodules at top. Scale below sample identification is 22 cm long.

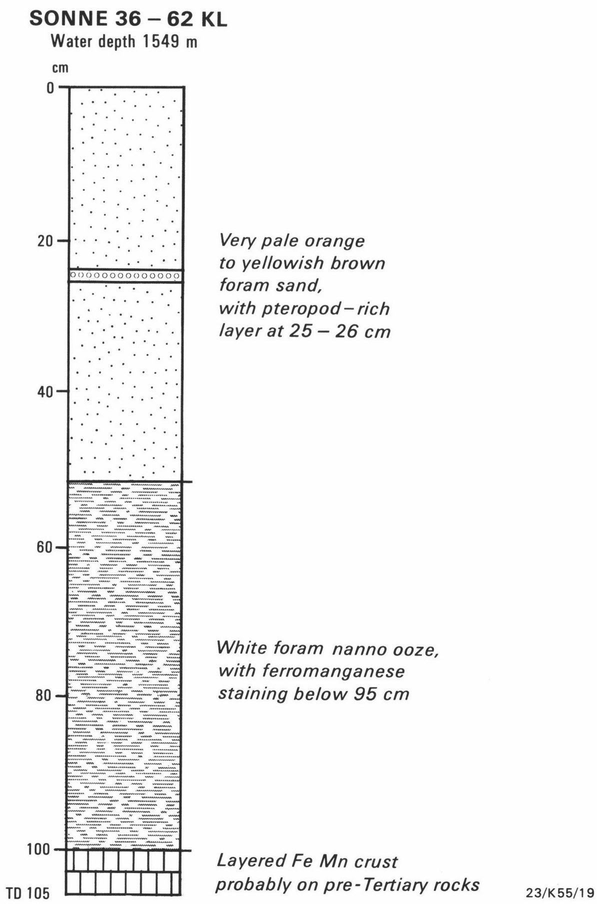

Figure 3. Log of *Sonne* core 36-62KL, which recovered ferromanganese deposits from the eastern flank of Lord Howe Rise. Sediments overlying ferromanganese deposits are of Pleistocene and Holocene age.

stated that 'the presence of intercalated ore mineral layers within an unsually complex stratigraphy of dark and dense Mn/Fe crusts at this locality suggests that past hydrothermal activity associated with the Vening-Meinesz Fracture Zone at least partly influences the growth of these crusts'. This deposit is the subject of a separate publication currently in preparation and is not dealt with further in this paper.

At station 62, a core taken near station 63 on the Lord Howe Rise penetrated a metre of Pleistocene and Holocene foram-nanno ooze and foram sand before striking virtually impenetrable ferromanganese crust, of which 5 cm was recovered (Fig. 3). It is likely that the black, laminated crust formed on a pre-Tertiary unconformity. Four other *Sonne* cores were taken towards the centre of the Lord Howe Rise about 220 km northwest, in areas of thick sediments, and recovered Pleistocene–Recent nanno-foram and foram-nanno oozes with no associated ferromanganese (Roeser & others, 1985).

Composition of ferromanganese deposits

Mineralogy

The ferromanganese crusts and nodules were analysed by X-ray diffraction, and the results are summarised in Table 1. The dominant mineral in the samples (crusts and nodules) was ferruginous vernadite with broad peaks at 2.45 and 1.42 angstroms. Todorokite was present in one of the four samples examined and here was subordinate to vernadite. Birnessite was not identified in any of the samples. Other common minerals included quartz and feldspar, while calcite was identified in core 62 in minor quantities. Non-manganiferous phases occurred mostly as entrapped detrital grains and as nuclei (Fig. 2).

Polished sections of nodules from station 57 indicated the existence of finely-laminated ferruginous vernadite, recognised by its low reflectance in optical images (reflectance of about 9% for 500–650 nm, Ostwald, 1984) and low electron backscatter in polished sections under the scanning electron microscope, owing to its high hydration (Fig. 4). Laminae of todorokite occur rarely in the polished specimens examined, as 0.01 mm layers of higher optical reflectance and higher electron backscatter (lower hydration) than the vernadite. Microanalyses of both phases are given in Tables 2 & 3. It will be seen that the todorokite contains 6.6% to 1.2% NiO, but very low to zero Cu and Co. Vernadite contains very little Ni, Cu and Co.

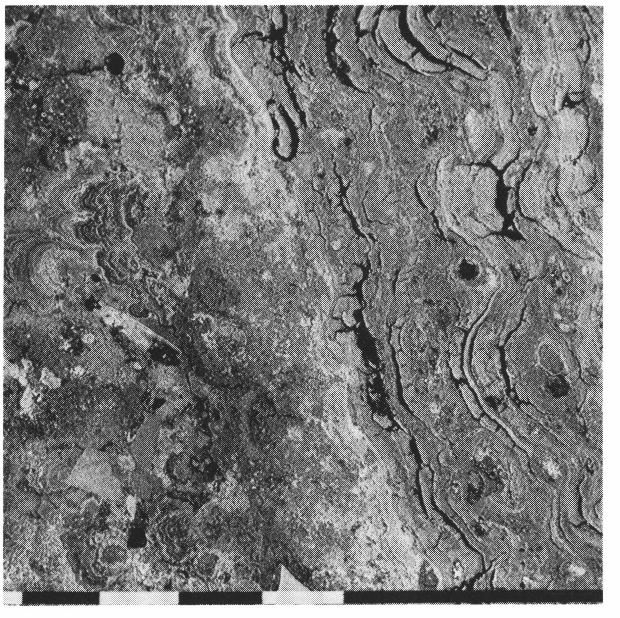

Figure 4. Scanning electron microscope (SEM) micrograph of polished section of Dampier Ridge ferromanganese oxides (Station 57), showing complex layering of ferruginous vernadite (dark) containing thin layers of todorokite (light).
White scale bar is 0.1 mm.

Table 1. Location, physical characteristics and mineralogy of ferromanganese deposits.

Sample number	*Latitude & longitude*	*Location*	*Water depth (m)*	*Substrate lithology*	*Deposit type*[1]	*Deposit thickness or diameter (cm)*
Dredged surface deposits						
57KD 5.1	31°51.8′S 157°22.6′E	Upper part, west-facing slope of Dampier Ridge	2370–2530	metamorphosed granite and microdiorite	N[P]	13.0
57KD 5.2	31°51.8′S 157°22.6′E	Upper part, west-facing slope of Dampier Ridge	2370–2530	metamorphosed granite and microdiorite	C	8.0
57KD 5.3	31°51.8′S 157°22.6′E	Upper part, west-facing slope of Dampier Ridge	2370–2530	metamorphosed granite and microdiorite	N[P]	5.0
Cored sub-surface deposits						
62KL 8.2 100–105 cm	28°35.8′S 163°05.4′E	Upper part, west-facing slope of Lord Howe Rise	1549	not known	C	5.0

Sample number	*Physical characteristics* *Surface texture*	*Internal structure*	*Mineralogy*[2]
Dredged surface deposits			
57KD 5.1	smooth	fine concentric lamination; minor radial cracks; nodule fragment comprises small nucleus	A: vernadite C: quartz
57KD 5.2	smooth, dense, gently undulating	fine wavy lamination	A: vernadite C: quartz, plagioclase
57KD 5.3	smooth, slightly gritty in places	fine concentric lamination, vertical growth structures in thicker laminae	A: vernadite, todorokite C: quartz
Cored subsurface deposits			
62KL 8.2 100–105 cm	not known	black, massive, porous	A: vernadite M: quartz, calcite

[1] C crust, N nodule, [P] polynucleate
[2] A abundant, C common, M minor

In one section the laminated manganese oxides contained rare grains of silver (Fig. 5) which was identified by its X-ray energy spectrum. Irregular particles up to 0.01 mm were detected. These are morphologically similar to silver grains reported by Bolton, Ostwald & Monzier (1986) from the South Rennell Trough–Loyalty Islands zone of the southwest Pacific, although the latter were typically situated in clays associated with ferromanganese crusts, rather than in the manganese oxides. A genetic relationship between the silver in the Dampier Ridge ferromanganese oxides and the previously reported silver occurrence appears likely.

Polished sections of the sub-surface manganese crust (core 62) showed it to be a dense mass of ferruginous vernadite columns (Fig. 6) containing disseminated quartz and carbonate debris.

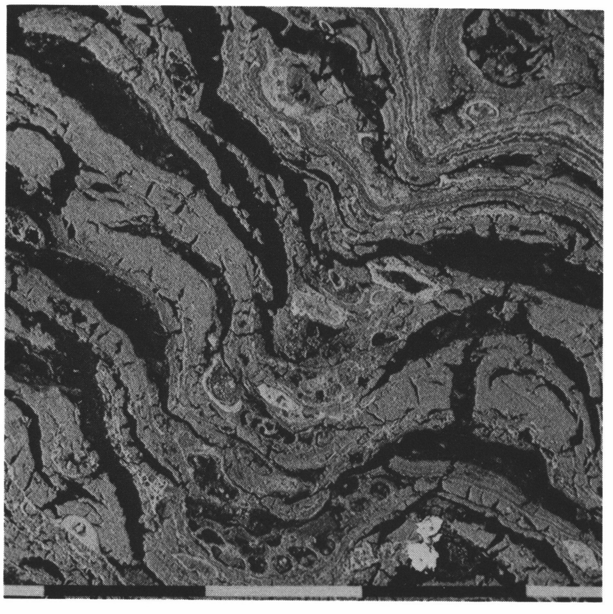

Figure 5. SEM micrograph of polished section of Dampier Ridge layered ferruginous vernadite (Station 57), showing desiccation fracturing and silver grains (white) near base of micrograph.
White scale bar is 0.1 mm.

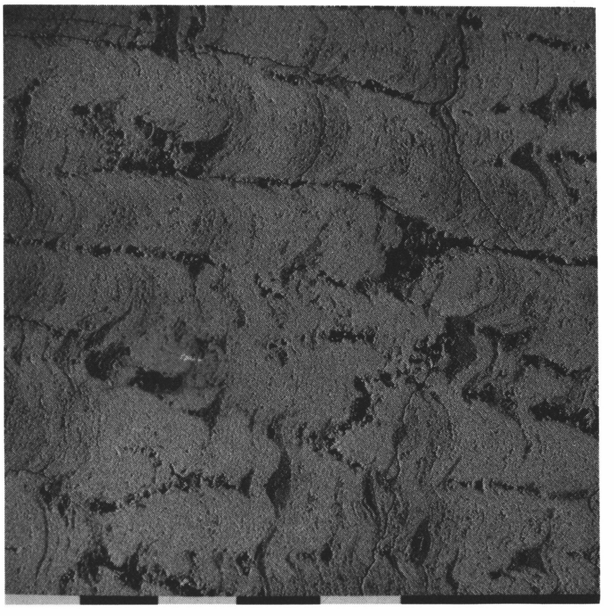

Figure 6. SEM micrograph of polished section of subsurface ferruginous vernadite crust (Station 62), Lord Howe Rise.
White scale bar is 0.1 mm.

Table 2. Microanalysis of ferruginous vernadite from the Dampier Ridge and Lord Howe Rise (weight per cent).

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
MnO_2	16.3	17.6	16.9	20.9	17.8	18.4	32.0	28.5	37.9	31.5	39.2	36.6
Fe_2O_3	39.1	35.0	34.6	38.4	29.2	38.6	34.3	26.7	27.8	27.5	28.4	26.3
CaO	1.3	1.5	1.3	1.0	1.7	1.6	2.6	2.9	2.9	2.6	2.4	3.3
MgO	1.3	1.6	1.4	4.4	2.4	1.6	1.7	1.5	1.9	1.8	1.3	2.2
Na_2O	2.2	2.2	1.2	2.0	4.0	nd	1.8	1.9	2.2	1.5	1.0	2.5
K_2O	0.5	0.4	0.2	0.3	0.5	0.2	0.3	0.4	0.4	0.3	0.3	0.4
P_2O_5	1.3	1.4	1.2	1.7	1.9	1.5	1.6	1.4	1.6	1.5	1.5	1.7
Al_2O_3	2.2	2.3	2.2	5.1	3.4	2.8	1.3	1.1	1.5	1.5	1.3	1.4
SiO_2	8.0	7.9	7.9	7.4	9.1	10.6	6.6	5.3	5.7	5.2	5.5	5.5
NiO	0.3	0.1	nd	0.7	nd	0.3	0.4	0.2	0.3	0.2	0.4	0.6
CuO	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
CoO	nd	nd	nd	nd	0.1	nd	0.2	nd	0.3	0.5	0.4	0.5
Total	72.5	70.0	66.9	81.9	70.1	75.6	82.8	79.9	82.5	74.1	81.7	81.0

Analysis 1–6, Dampier Ridge, Station 57 (dredge); 7–12, Lord Howe Rise, Station 62 (core)
nd not detected

Table 3. Microanalysis of todorokite from Station 57 on Dampier Ridge (weight per cent).

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
MnO_2	52.4	56.1	57.6	53.2	58.5	56.3	57.4	58.2
Fe_2O_3	1.7	4.8	6.6	2.4	2.8	2.1	7.1	4.2
CaO	0.5	0.7	1.2	0.7	0.8	0.4	1.3	0.6
MgO	10.9	8.8	8.3	9.2	9.9	8.8	7.2	9.8
Na_2O	nd	nd	nd	0.1	0.1	nd	nd	nd
K_2O	0.2	0.3	0.2	0.3	0.3	0.2	0.2	0.4
P_2O_5	0.6	0.6	nd	nd	nd	nd	0.1	nd
Al_2O_3	9.1	5.7	4.7	6.3	8.7	7.9	8.3	7.7
SiO_2	3.6	3.1	1.4	1.7	2.3	2.1	1.7	2.3
NiO	6.6	4.8	4.7	3.2	2.1	1.4	1.6	1.2
CuO	nd	0.1	0.6	0.1	0.2	nd	nd	nd
CoO	0.2	nd	0.2	0.1	0.1	nd	nd	nd
Total	85.8	85.0	85.5	77.3	85.8	79.2	84.9	84.0

nd not detected

Microanalyses on the vernadite (Table 2) indicate a maximum of 0.5% CoO and 0.6% NiO. Todorokite was not detected in the Lord Howe Rise material.

The Mn:Fe ratio of the ferruginous vernadite appears to be much higher in the Lord Howe Rise crust than in the Dampier Ridge specimens, a fact indicated by bulk analyses. This may be due to decreasing amounts of terrigenous ferruginous material available for co-precipitation with manganese in the offshore direction.

Bulk chemical composition

Major and minor element concentrations in all samples were determined by X-ray fluorescence and atomic absorption spectroscopy, and the results are summarised in Table 4. Summary statistics for selected metals and elemental ratios are compared in Table 5 with results from nodules recovered at *Kimbla* Station 5 (36° 15′S, 155° 35′E), with results from nodules recovered at *Galathea* Station 547, with results from 9 nodules recovered from the Tasman Sea, with average values for ferromanganese deposits from the southwest Pacific, and with average values for south Pacific nodules.

The most significant feature of the data shown in Table 4 is the generally marked difference in metal values between the two sites sampled. Samples from station 57 are generally depleted in Mn (Mn:Fe ratio of 0.59) compared with those from station 62 (Mn:Fe ratio of 0.91), and slightly depleted in combined content of the metals Ni, Cu and Co (0.75, compared with 0.81 from station 62).

Discussion and origin of deposits

Our samples (Table 5) are broadly similar in composition to the nodules from the *Kimbla* station, southwest of the study area and in water 4300 m deep, and to the crusts and nodules from the southwest Pacific as a whole. In particular, they are comparable in having low values of Mn, a low Mn:Fe ratio, and low values of Ni, Cu and Co. They are markedly different from abundant nodules recovered east of the *Kimbla* station by R.V. *Tangaroa* at two stations (Glasby & others, 1986). Station U205 was at 36°48.6′S, 156°31.8′E in water 4548–4714 m deep, and U206 was at 35°33.3′S, 155°40.4′E in water 4408–4418 m deep. U205 had an Mn:Fe ratio of about 2.5, and combined Ni+Cu+Co content of about 1.30% (Ni 0.85%, Cu 0.40%, Co 0.05%). Our values are also in marked contrast to the analyses from the thin crusts on a whale's earbone and on pumice recovered by *Galathea* at 39°45′S, 159°39′E in a greater water depth of 4800 m (Ahrens, Willis & Oosthuizen, 1967). These had Mn:Fe ratios of about 3.4, and combined Ni+Cu+Co content of about 2.05% (Ni 1.27%, Cu 0.60%, Co 0.18%).

The reasons for the differences between the metal values in the *Sonne* and *Kimbla* samples (low Mn:Fe, and low Ni and Cu) and the *Galathea* and *Tangaroa* samples (high Mn:Fe, and moderately high Ni and Cu) are no doubt

Table 4. Bulk chemistry of ferromanganese deposits from the Dampier Ridge and Lord Howe Rise (weight per cent; dried at 110° C).

Sample number	*Deposit type*[1]	*Mn*	*Fe*	*Ni*	*Cu*	*Co*	*Zn*	*Pb*	*%Ni+Cu+Co*	*Mn:Fe*
Surface deposits from Dampier Ridge										
57KD-5.1	Ns	11.37	23.91	0.46	0.12	0.19	0.11	0.11	0.77	0.48
57KD-5.2	Cs	12.02	20.03	0.21	0.09	0.19	0.07	0.11	0.49	0.60
57KD-5.3	Ns	13.98	20.44	0.57	0.14	0.28	0.09	0.13	0.99	0.68
Subsurface deposits from Lord Howe Rise										
62KL (100–105 cm)	C	21.28	23.28	0.32	0.06	0.43	0.10	0.20	0.81	0.91
Surface deposits from Dampier Ridge										
		Si	*Al*	*Ti*	*Mg*	*Ca*	*Na*	*K*	*P*	*L.O.I.*
57KD-5.1	Ns	12.72	4.94	0.34	1.45	1.01	0.3	0.47	0.36	11.63
57KD-5.2	Cs	14.7	5.81	0.54	1.67	1.44	0.38	0.43	0.38	11.59
57KD-5.3	Ns	12.37	5.94	0.52	1.70	1.13	0.45	0.51	0.34	12.01
Subsurface deposits from Lord Howe Rise										
62KL (100–105 cm)	C	3.12	2.65	0.71	1.20	3.39	0.24	0.30	0.58	16.2

[1] C crust, N nodule, r rough, s smooth

Note: All samples were dried at 110°C. Loss on ignition (L.O.I.) was measured at 960°C. Mn, Fe, Ni, Cu, Zn, Pb and Na were measured by atomic absorption spectrography. All other elements were measured using X-ray fluorescence spectrography.

Table 5. Average metal contents and Mn:Fe ratios for ferromanganese deposits from the Dampier Ridge, the Lord Howe Rise, and elsewhere in the South Pacific. All data are in weight per cent.

	This study	*Kimbla Stn 5 Exon & others (1980)*	*Galathea 574 Ahrens & others (1967)*	*Tasman Sea Glasby & others (1986)*	*Southwest Pacific*	*S Pacific nodules Cronan (1972)*
Number of analyses	4	2	2	9	70	ng
Element						
Mn	14.66	5.9	26.8	19.89	14.2	16.6
Fe	21.92	15.8	7.76	8.13	16	13.9
Ni	0.39	0.26	1.28	0.85	0.22	0.43
Cu	0.31	0.18	0.60	0.40	0.08	0.19
Co	0.27	0.06	0.19	0.06	0.27	0.6
Zn	0.14	ng	ng	0.14	0.05	ng
Pb	0.14	ng	ng	0.22	n.g.	0.07
%Ni+Cu+Co	0.92	0.49	2.06	1.31	0.57	1.22
Mn:Fe	0.66	0.37	3.46	2.45	0.9	1.19

ng not given

complex. However, it does appear that Mn:Fe ratio increases and Ni and Cu percentages increase with increasing water depth in the Tasman Sea, the normal situation in the world ocean. The depression containing the *Galathea* and *Tangaroa* samples is more than 4400 m deep; it is far from land, accessible to Antarctic deep water and below the carbonate compensation depth, so sedimentation rates are low and oxidising conditions prevail. Such conditions are favourable to the development of nodule fields and of high grade nodules. Any future search for nodules of economic significance should probably be concentrated in waters more than 5000 m deep southeast and east of Gascoyne Seamount (Fig. 1), although four Kimbla grabs in that area (Exon, 1979) did not recover nodules.

The ferromanganese deposits examined in this study were formed predominantly by slow precipitation of ferromanganese phases (mainly vernadite) directly from near-bottom seawater (i.e. hydrogenetically) which contains Mn and Fe mainly in colloidal solutions (Halbach & Ozkara, 1979; Cronan, 1984). They all fall within the area of hydrogenous deposits (Fig. 7) as defined by Bonatti, Kraemer & Rydell (1972). There is no evidence either of direct hydrothermal contribution, or of significant accumulation of metals following diagenetic remobilisation from underlying substrates. The variations of composition observed in our samples are interpreted as reflecting different degrees of dilution by aluminosilicates and biogenic detritus, rather than two different sources of metals or environments of growth. The close similarity in mineralogy, chemistry and physical appearance of our samples to typical, deep-water, hydrogenetic ferromanganese deposits described elsewhere appears to support this interpretation (Halbach & Ozkara, 1979; Cronan, 1980; Usui, 1983).

Acknowledgements

We are grateful to BGR Chief Scientist K. Hinz and geologists H.R. Kudrass and M. Wiedicke, who acquired the material on the 1985 *Sonne* cruise in which Exon also participated. Geoff O'Brien of BMR is thanked for reviewing the manuscript.

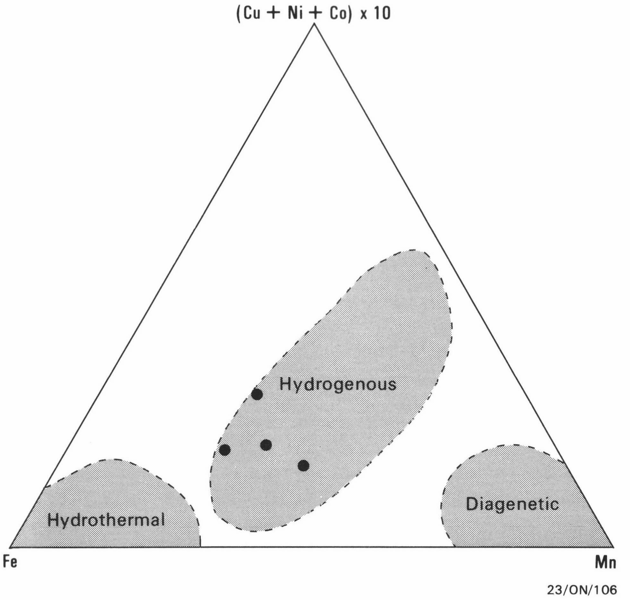

Figure 7. Ternary diagram of Mn/Fe/Cu+Ni+Co concentrations for samples from this study, compared with deep-sea ferromanganese nodules of hydrogenous, hydrothermal, and diagenetic origin.
Outlines of fields from Bonatti & others (1972).

References

Ahrens, L.H., Willis, J.P., & Oosthuizen, C.O., 1967 — Further observations on the composition of manganese nodules with particular reference to some of the rarer elements. *Geochemica et Cosmochimica Acta*, 31, 2169–2180.

Bolton, B.R., Ostwald, J., & Monzier, M., 1986 — Precious metals in ferromanganese crusts from the south-west Pacific. *Nature*, 320, 518–520.

Bonatti, E., Kraemer, T., & Rydell, H., 1972 — Classification and genesis of submarine iron-manganese deposits. *In* Horn, D.R., (editor), Conference on ferromanganese deposits on the ocean floor. *Office of the International Decade of Ocean Exploration, National Science Foundation, Washington DC*, 149–166.

Conolly, J.R., & Payne, R.R., 1972 — Sedimentary patterns within a continent–mid-oceanic ridge–continent profile: Indian Ocean south of Australia. *In* Hayes, D.E., (editor), Antarctic Oceanology 11: The Australian-New Zealand sector. *Antarctic Research Series, 19, American Geophysical Union, Washington DC*, 295–315.

Cronan, D.S., 1972 — Regional geochemistry of ferromanganese nodules in the world ocean. *In* Horn, D.R., (editor), Conference on ferromanganese deposits on the ocean floor. *Office of the International Decade of Ocean Exploration, National Science Foundation, Washington, DC*, 19–29.

Cronan, D.S., 1980 — Underwater minerals. *Academic Press, London*, 362 pp.

Cronan, D.S., 1984 — Criteria for the recognition of areas of potentially economic manganese nodules and encrustations in the CCOP/SOPAC region of the central and southwestern tropical Pacific. *South Pacific Marine Geological Notes*, 3, 1–17.

Exon, N.F., 1979 — Deepsea sediments and manganese nodules from the southern Tasman Sea. *Bureau of Mineral Resources, Australia, Record* 1979/62.

Exon, N.F., Moreton, D., & Hicks, G., 1980 — Manganese nodules from the Tasman Sea off Sydney. *BMR Journal of Australian Geology & Geophysics*, 5, 67–68.

Glasby, G.P., 1973 — Manganese deposits in the southwest Pacific. *In* Inter-university program of research on ferromanganese deposits of the ocean floor, Phase 1. Report sponsored by Seabed Assessment Program, International Decade of Ocean Exploration, *National Science Foundation, Washington DC*, 137–169.

Glasby, G.P., 1986 — Hiatuses in manganese nodule growth: relation to bottom current activity? *Geo-marine Letters*, 5, 247–252.

Glasby, G.P., Stoffers, P., Grapes, R.H., Pluger, W.L., McKnight, D.G., & Main, W.deL., 1986 — Manganese nodule occurrence in the Tasman Sea. *New Zealand Journal of Marine and Freshwater Research*, 20, 489–494.

Goodell, H.G., Meylan, M.A., & Grant, B., 1971 — Ferromanganese deposits of the South Pacific Ocean, Drake Passage, and Scotia Sea. *In* Reid, J.L., (editor), Antarctic Oceanology, 1. *Antarctic Research Series*, 15, 27–92.

Halbach, P., & Ozkara, M., 1979 — Morphological and geochemical classification of deep-sea ferromanganese nodules and its genetical interpretation. *In* Lalou, C., (editor), Colloques Internationaux du C.N.R.S. No. 289, La genese des nodules de manganese. *C.N.R.S., Paris*, 77–88.

Jones, H.A., 1980 — Deepsea manganese nodules in the Australian region — a review. *Australian Mineral Industry Quarterly*, 33(1), 1–14.

Ostwald, J., 1984 — Vernadite — a possible hybrid structured mineral. *Australian Mineralogist*, July, 269–271.

Payne, R.R., & Conolly, J.R., 1972 — Pleistocene manganese pavement production: its relationships to the origin of manganese in the Tasman Sea. *In* Horn, D.R., Delach, M., & Horn, B., (editors), Conference on ferromanganese deposits on the ocean floor. *Office of International Decade of Ocean Exploration, Washington DC*, 81–92.

Roeser, H.A., & others, 1985 — Geophysical, geological and geochemical investigations on the Lord Howe Rise. Final Report on the R/V 'Sonne' Cruise, SO-36, Part 2, *Bundesanstalt fuer Geowissenschaften und Rohstoffe Cruise Report*, 193 pp.

Symonds, P.A., Willcox, J.B., & Kudrass, H.R., 1988 — Dampier Ridge in the Tasman Sea — a continental fragment. *9th Australian Geological Convention, Geological Society of Australia, Abstract Volume* 21, 393–394.

Usui, A., 1983 — Regional variation of manganese nodule facies on the Wake–Tahiti transect: Morphological, chemical and mineralogical study. *Marine Geology*, 54, 27–51.

Watkins, N.D., & Kennett, J.P., 1971 — Antarctic bottom water: major change in velocity during the late Cenozoic between Australia and Antarctica. *Science*, 173, 813–818.

Watkins, N.D., & Kennett, J.P., 1972 — Regional sedimentary disconformities and Upper Cenozoic changes in bottom water velocities between Australasia and Antarctica. *In* Hayes, D.E., (editor), Antarctic Oceanology II: The Australian-New Zealand sector. *Antarctic Research Series*, 19, *American Geophysical Union, Washington DC*, 273–293.

Watkins, N.D., & Kennett, J.P., 1977 — Erosion of deep-sea sediments in the Southern Ocean between longitudes 70° E and 190° E and contrasts in manganese nodule development. *Marine Geology*, 23, 103–111.

Willcox, J.B., Symonds, P.A., Hinz, K., & Bennett, D., 1980 — Lord Howe Rise, Tasman Sea — preliminary geophysical results and petroleum prospects. *BMR Journal of Australian Geology & Geophysics*, 5, 225–236.