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Publications in this series result from specific enquiries for information. They record and comment on relevant available data.

The N.Z. Oceanographic Institute, through the work of R.V. *Tangaroa* and in collaboration with CCOP./SOPAC and scientists from the Federal Republic of Germany, U.S.A., and France, has carried out exploratory research on the occurrence of manganese nodules in the Southwest Pacific Ocean. This *Summary* describes some of that work and places it in the context of a comparative survey of nodules from the Equatorial and Southwest Pacific regions.

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New Zealand Oceanographic Institute
Division of Marine and Freshwater Science, D.S.I.R.,
P.O. Box 12-346, Wellington North, New Zealand

MANGANESE NODULE STUDIES IN THE EQUATORIAL AND SOUTHWEST PACIFIC: THE I.C.I.M.E. PROJECT

G.P. Glasby†, G. Friedrich*, W.L. Plüger*, T. Thijssen*, H. Kunzendorf**

ABSTRACT

The International Cooperative Investigations of Manganese Nodule Environments (I.C.I.M.E.) Project was an international collaborative effort first formulated in 1975 to study the modes of genesis of manganese nodules in a number of areas of the Equatorial and Southwest Pacific using a range of techniques and approaches. This report gives some indication of the origin of this project and the work carried out at RWTH Aachen between 1978 and 1981. It shows the considerable advantage of using transects to study the distribution and characteristics of manganese nodules in previously little-studied areas of the World Ocean. The success of this project led to a further transect study of manganese nodules from Tahiti - East Pacific Rise - New Zealand in 1981. It is hoped that these studies, taken together, have significantly advanced our understanding of the modes of genesis of manganese nodules in the Pacific Ocean.

INTRODUCTION

Although deep-sea manganese nodules were discovered in 1873 and extensively studied during the H.M.S. *Challenger* expedition of 1872-1876, it was not until the mid-1960s when J.L. Mero (1965) published his classic book "The Mineral Resources of the Sea" that the economic potential of these deposits first became appreciated. This in turn stimulated major activity in manganese nodule research in the 1970s, particularly in the United States, Germany, Japan, and France by academic, governmental, and industrial organisations. Indeed, the 1970s can be considered to be the decade of growth for manganese nodule research. In this regard, the Arden House Symposium held in January 1972 under the auspices of the Lamont-Doherty Geological Observatory in New York State, at which the U.S. I.D.O.E. (International Decade of Ocean Exploration) Ferromanganese Program was formulated (Horn 1972), can be regarded as a turning point in the attention which manganese nodules have received, particularly in the Equatorial North Pacific. The German manganese nodule programme, using F.S. *Valdivia*, also dates from about this time, although its origins were independent.

Although the fundamental geological and chemical characteristics of manganese nodules could be said to be known at the time of the Arden House Symposium, the detailed relationship of manganese nodules to the environment of deposition, and therefore the mode of genesis of these deposits, could not. This has turned out to be the central problem in manganese nodule research in the 1970s culminating in the U.S. MANOP programme to measure *in situ* the environmental parameters controlling nodule genesis in a limited number of areas using a specially developed "bottom lander" (Bender 1983). This problem is important because it is now realised that a number of possible mechanisms may contribute to manganese nodule deposition and trace metal uptake, any one of which may be dominant in a given situation. The relationship of manganese nodules to their environmental parameters - be they geographic, topographic, sedimentologic, or related to such factors as the migration of bottom water currents, the biological productivity of the overlying surface waters or the availability of potential nucleating agents on the seafloor - has therefore been a central theme.

† New Zealand Oceanographic Institute, D.S.I.R., Wellington, N.Z.
* Abteilung fur Angewandte Lagerstättenlehre der RWTH Aachen, F.R.G.
** Risø National Laboratory, Roskilde, Denmark.

By 1975, sufficient work had been carried out to show a clear distinction in characteristics between nodules from the Equatorial North Pacific between the Clarion and Clipperton Fracture Zones where potentially economic-grade nodules were being explored by U.S. and German vessels and those of the Southwest Pacific, particularly the Southwestern Pacific Basin, which had been surveyed using the N.Z. Oceanographic Institute R.V. *Tangaroa*. In particular, nodules from the Southwestern Pacific Basin had lower contents of Mn, Ni, Cu, and Zn, higher contents of Fe and Co, the presence of δ-MnO_2 rather than 10 Å (1.0 nm) manganite as the principal manganese-oxide mineral phase and quite different morphology from those of the Equatorial North Pacific. The idea had been developed, particularly by Greenslate (1975), that the biological productivity of the overlying surface water may be important in cycling certain trace elements, particularly Mn, Ni, Cu, and Zn, to the seafloor as a result of the sinking of planktonic organisms, faecal pellets and other biological debris as part of the natural biological cycle. This followed an earlier suggestion of Correns (1941) of the possibility of biological extraction of manganese from seawater into foraminiferal tests. This idea was later strongly supported by the work of Leinen and Stakes (1979) on the geochemistry of deep-sea sediments from the Equatorial Pacific collected during the Deep Sea Drilling Project.

The realisation that the Pacific can be divided into a zone of equatorial high productivity, with subtropical anticyclonic gyres of low productivity in the temperate regions of both the central North and South Pacific, suggested that this variation in oceanic productivity might be a cause of the difference in nodule characteristics in the Equatorial and Southwest Pacific (Glasby 1976). Virtually all of the work in the Equatorial Pacific had, however, concentrated in the region between the Clarion and Clipperton Fracture Zones because this appeared to be the region where potentially economic-grade nodules occur. It was clear, however, that, in order to further our fundamental understanding of the origin of nodules, the scope of study in the Equatorial Pacific needed to be expanded and that this could best be achieved by means of an Equatorial Pacific transect.

THE I.C.I.M.E. PROJECT

The opportunity to moot this idea first occurred at the CCOP/SOPAC (Committee for Co-ordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas) Workshop held in Suva, Fiji, 1975 (UNESCO 1975; Glasby and Katz 1976). As a result of this workshop, a small group of specialists from Germany, France, U.S.A., U.K., and New Zealand met during the International Geological Congress in Sydney in August 1976 to formulate further ideas on manganese nodule research, the results of this meeting were summarised as follows (Glasby 1978):

"From a consideration of the distribution and geochemistry of manganese nodules throughout the Pacific Ocean, it was decided that the most important problem to be tested is the role of biological productivity and transport in controlling the abundance and metal contents of manganese nodules. In particular, areas of low-metal-content nodules in the Southwest Pacific associated with low biological productivity should be compared and contrasted with areas of high-metal-content nodules in the Equatorial North Pacific associated with high biological productivity in order to assess whether the metal contents of the nodules are diagnostic of the environment of deposition and, in particular, the productivity of the overlying waters.

Therefore it was strongly recommended that a transect between the North and South Pacific be made to test this hypothesis. Two transects were suggested: Honolulu - Tahiti and Tahiti - Rarotonga. These transects should include a series of detailed local surveys of the distribution, geochemistry, mineralogy, morphology, and internal structure of manganese nodules and their relation to the underlying sediments. In addition, assessment of the productivity at each site from nutrient concentrations and plankton abundance in the overlying water column should be made. Chemical data from the GEOSECS cruises should be drawn on wherever possible to supplement these findings. Box coring was considered a particularly suitable technique for this type of survey, and dating of manganese nodules whose position at the sediment-water interface was known and of the associated sediment was recommended. Particular emphasis should be placed on studies of dissolution and diagenetic features in both the nodules and sediments, particularly using scanning electron microscopy."

At this meeting, G. Pautot (C.N.E.X.O.) [Centre National Pour l'Exploitation des Océans, France] presented an outline of a joint programme for a north-south transect across the equator at 134°W in which this problem could be included as part of an overall study of manganese nodule genesis. This plan was adopted. As a result of this meeting, the I.C.I.M.E. Project was born as an international co-operative effort to study manganese nodule genesis in the Equatorial Pacific. The principal organisations involved in this project are RWTH Aachen (principal scientist G. Friedrich), C.N.E.X.O. (principal scientist G. Pautot), the University of Hawaii (principal scientist J.E. Andrews), Imperial College, London (principal scientist D.S. Cronan), and the N.Z. Oceanographic Institute (principal scientist G.P. Glasby).

The programme commenced when the German vessel F.S. *Sonne* sampled Areas C, D, F, G, and K during cruise SO-06 between 25 August and 14 October 1978 and the French vessel N.O. *Suroit* sampled Areas A, B, H, and I during cruises COPANO I and II between 2 August and 7 October 1979 (Fig. 1). One of the

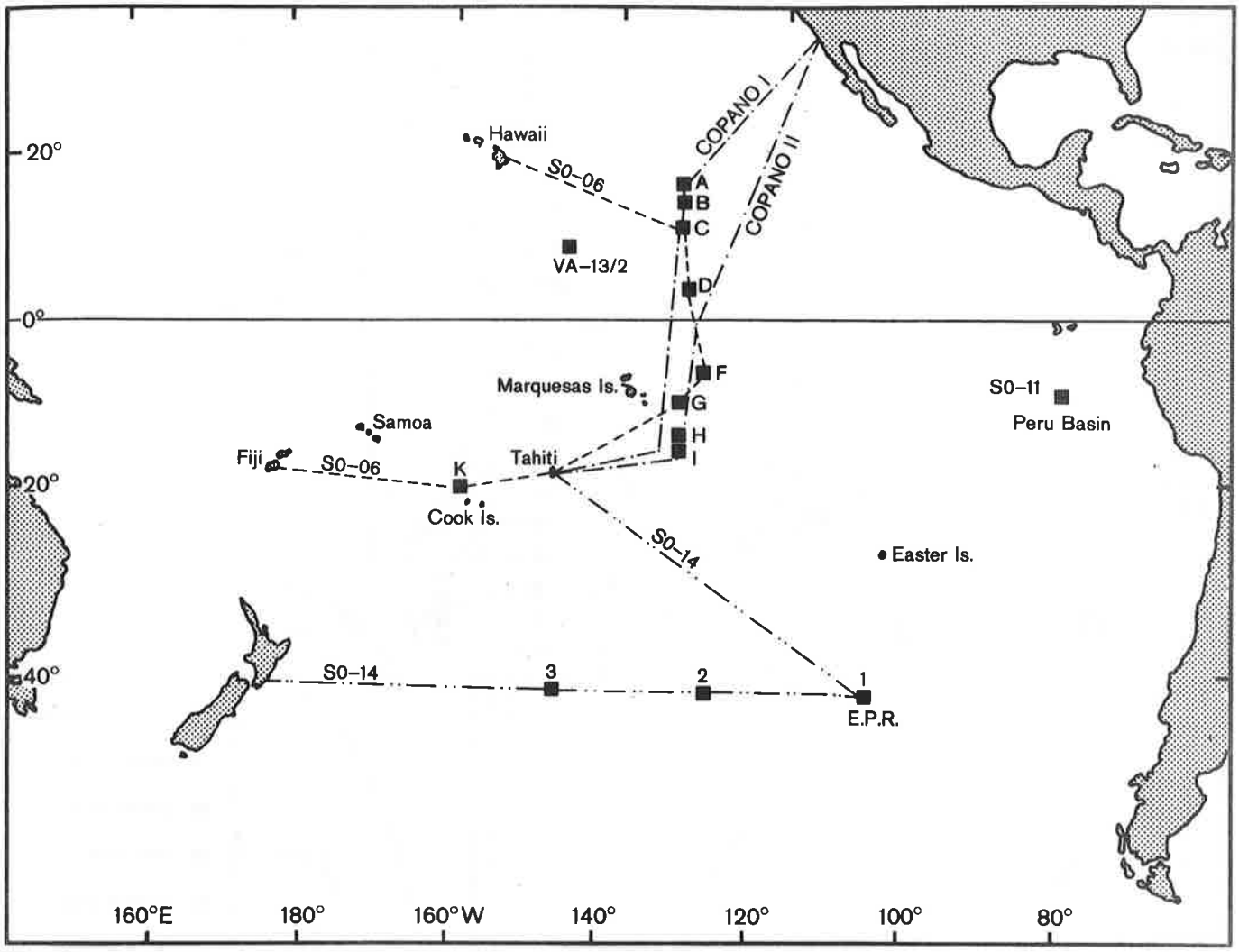

Fig. 1. Schematic map showing the positions of the study areas described here.

authors (G.P.G.) obtained leave of absence from the N.Z. Oceanographic Institute to work at RWTH Aachen for two years (1979–1981) in order to compare Equatorial Pacific nodules with those previously collected from the Southwestern Pacific and Samoan Basins by the N.Z. Oceanographic Institute with a view to attempting to understand the difference in morphology, composition, and mineralogy between nodules from these two regions.

In order to focus the limited resources available, the I.C.I.M.E. Project concentrated on a survey of seven limited areas varying in size from 150–4000 km^2 (the areas sampled by F.S. *Sonne* being much larger than those sampled by N.O. *Suroit*) on either side of the equator from 16°30'N to 15°20'S at 134°W (Fig. 1). In addition, one area (Area K), Aitutaki Passage, was sampled in the Southwest Pacific. In each area, a bathymetric survey was carried out in order to enable the position of samples to be related to bottom topography. In the COPANO cruises, an ATNAV (acoustic transponder navigational) system was used, in which three transponders were lowered to the seafloor and the position fixed relative to them; this ensured greater positional accuracy for these surveys but limited the area of the survey. Nodule and sediment samples were collected by means of free-fall grabs, box cores, and dredges. and bottom photographs were taken to study the *in situ* distribution of the nodules. Surface- and bottom-water samples were collected in order to study the trace metal geochemistry of the seawater. Such detailed surveys enabled a study to be made of the relationship between nodule characteristics and environmental characteristics such as topography or sediment type. Information was therefore obtained from the cruises to characterise, in some considerable

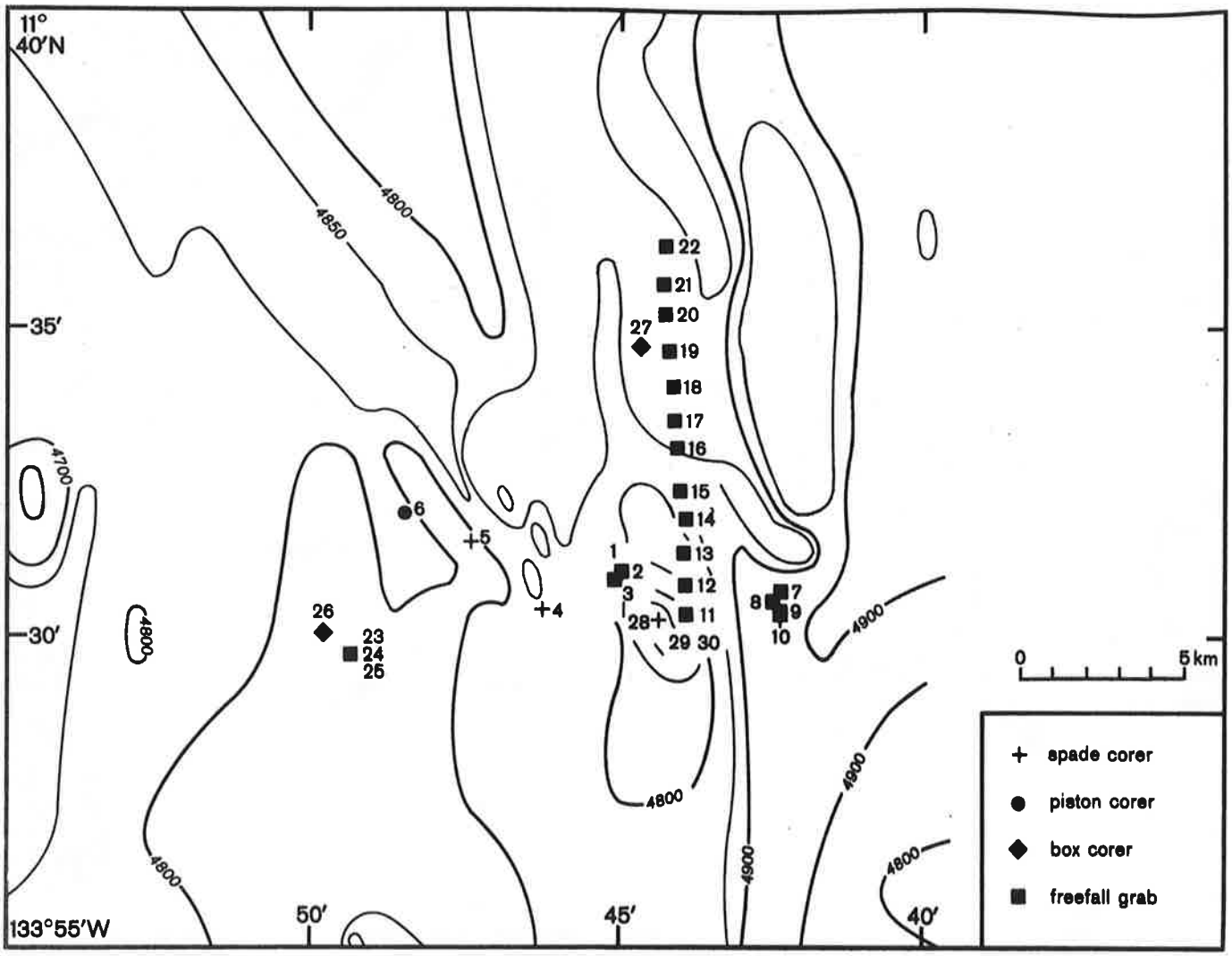

Fig. 2. Schematic map showing the bathymetry and station locations in Area C (*see* Fig. 1). Depths in metres.

detail, the environment of deposition of the nodules from these sites. From this, an overview of the problems of nodule genesis in the Equatorial and Southwest Pacific could be attempted. To show something of the techniques involved, a bathymetric chart of Area C, showing sampling locations, is given in Fig. 2 and an *in situ* and onboard photograph of nodules from one station in Area C is shown in Fig. 3.

Whilst work on the I.C.I.M.E. Project is continuing, it is worth noting some of the principal findings of the project obtained by the RWTH Aachen group to date.

1. 15,089 nodules collected from Areas C, F, G, and K by F.S. *Sonne* have been described by a standard classification scheme developed by M.A. Meylan and J.D. Craig at the University of Hawaii. Of these nodule samples, 398 have been analysed chemically for 12 elements (Mn, Fe, Co, Ni, Cu, Zn, Ba, Si, Al, U, Ce, La) and the mineralogy of selected nodules from each of these areas has been determined. This represents one of the largest collections of nodule data at one institute and has enabled a statistically meaningful comparison of nodule characteristics between areas to be made.

2. 89 composite micronodule samples have been analysed for 7 elements (Mn, Fe, Co, Ni, Cu, Zn, Ba), 228 sediment samples have been analysed for 11 elements (Mn, Fe, Co, Ni, Cu, Zn, Ba, Si, Al, Mg, Ti), and 165 pore-water samples for 7 major elements (Ca, K, Sr, Mg, Si, Cl, S (as sulphate)). These analyses were carried out in conjunction with the Institute for Sediment Research, University of Heidelberg. This extensive collection of geochemical data has enabled a statistical treatment using both correlation matrices and R- and Q-mode cluster analyses and has been

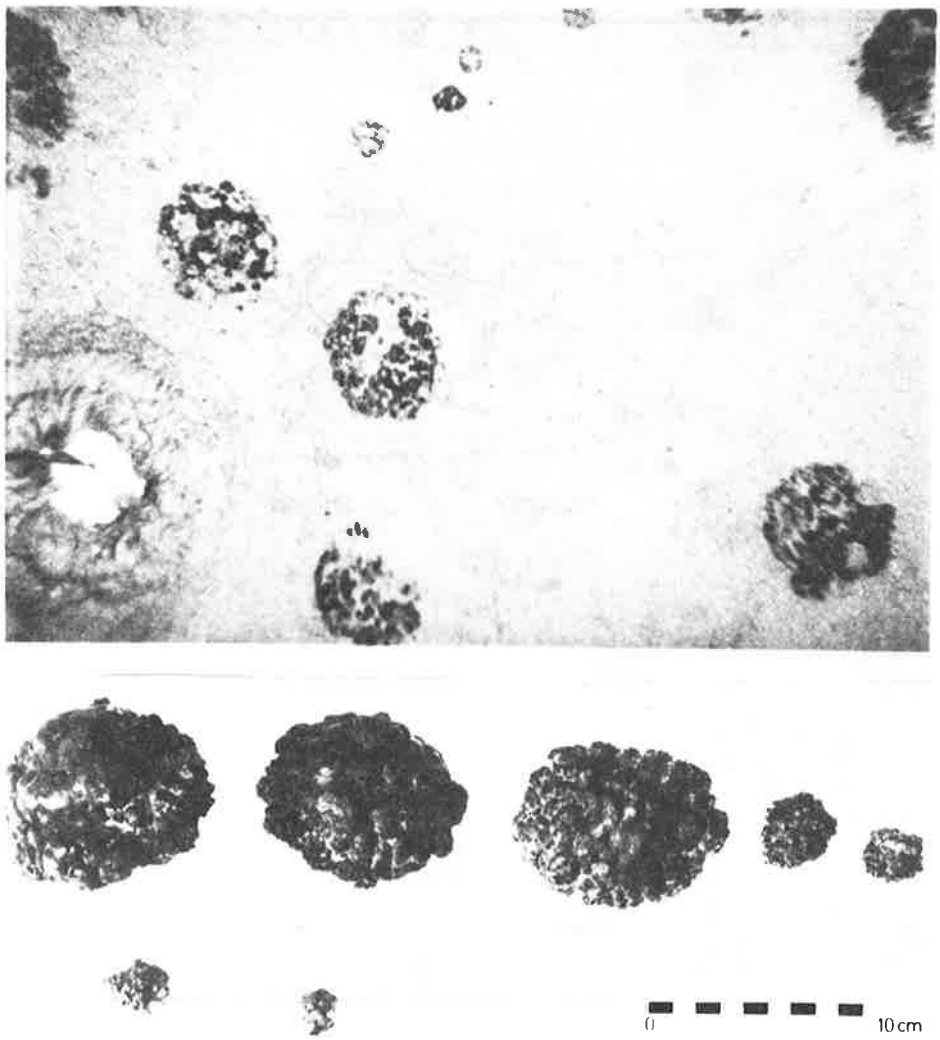

Fig. 3. Photographs showing the nodules from Stn 20 in Area C *in situ* and onboard ship. The *in situ* photograph is approximately 0.4 m across.

important in establishing element pathways in nodules and sediments in each of the areas.

3. Chemical analyses of surface and bottom seawater samples in the ng/kg range for Co, Ni, Cu, Cd, and Pb carried out at the Nuclear Research Centre, Julich, has further demonstrated the role of the biological pathway in cycling elements to the seafloor.

4. Mössbauer studies of selected nodules and sediments carried out at the Department of Chemistry, University of Antwerp, Belgium, have suggested that all deep-sea nodules have an identical iron oxide-hydroxide mineralogy but differences in the iron mineralogy of the associated sediments occur. Sediments from the Equatorial Pacific are, for example, more completely oxidised (only ferric iron present) than those from the Aitutaki Passage (approximately 15% ferrous iron present).

5. Rare-earth analyses of about 50 nodules and sediments carried out at Risø National Laboratory, Denmark, have shown markedly higher contents of the rare-earth elements from the Aitutaki Passage nodules than those from the Equatorial Pacific.

The data collected from these areas have emphasised the difference between nodules from the Equatorial and Southwest Pacific and offer persuasive evidence for the role of biological productivity in controlling these differences. Considering the transect across the equator, nodules are not found in the immediate vicinity of the equator because this region lies

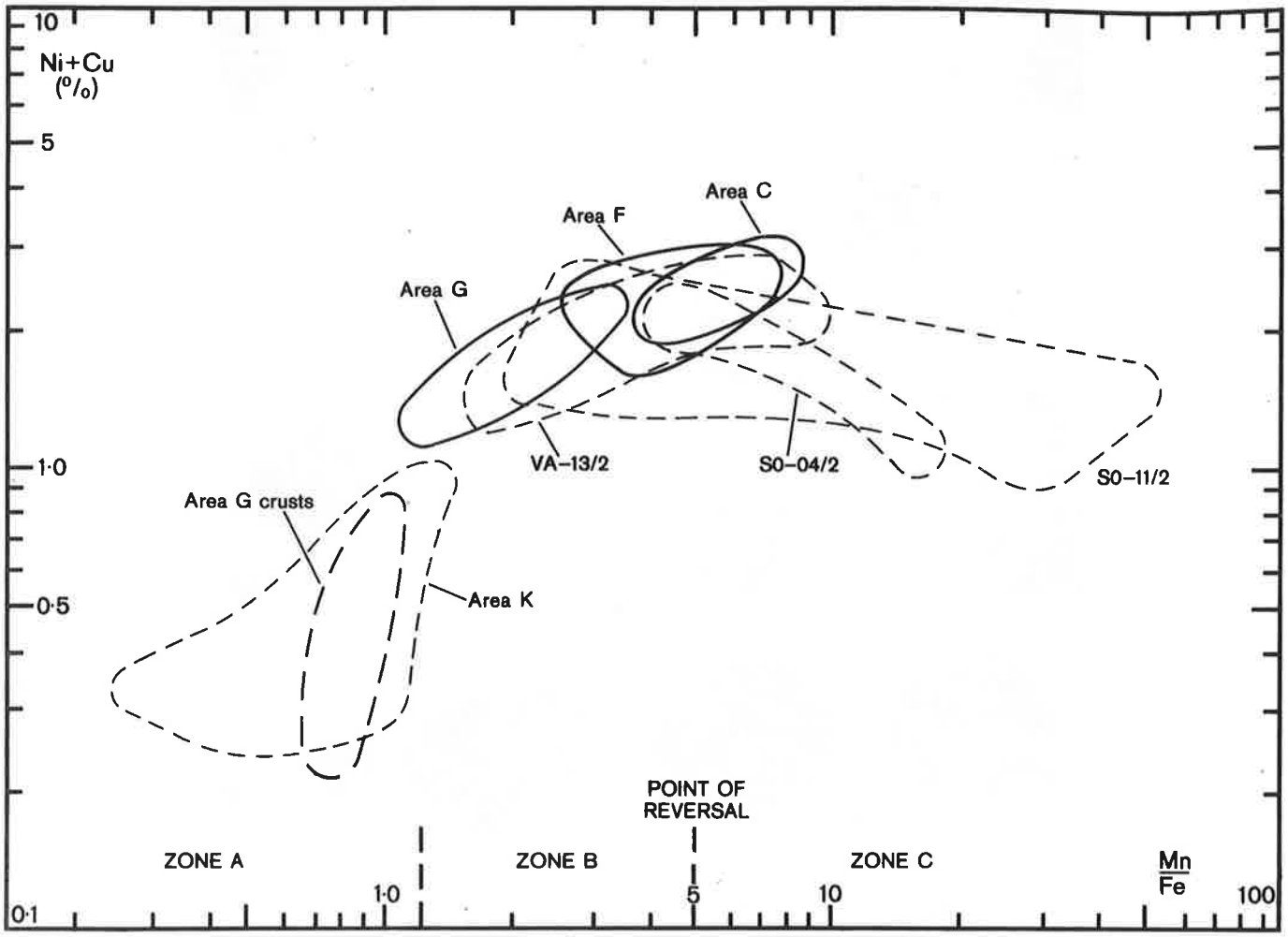

Fig. 4. Graph showing the relationship between the Ni + Cu contents and Mn/Fe ratios of manganese nodules from various areas in the Pacific.

above the Carbonate Compensation Depth. The region is therefore characterised by the occurrence of carbonate sediments and the sedimentation rate is too high for nodule formation. Such a latitudinal variation in abundance of biogenic sediments in the Pacific had previously been reported by Arrhenius (1963) and Greenslate *et al.* (1973). In general, Equatorial Pacific nodules from north and south of the equator display similar compositions characterised by high Mn/Fe ratios and high contents of Ni, Cu, Zn, and Ba compared to those of the Southwest Pacific. These nodules can therefore be considered to belong to one geochemical province. The carbonate sedimentation rate is, however, higher south of the equator than in the region north of the equator between the Clarion and Clipperton Fracture Zones. Nodules south of the equator are therefore smaller and occur in lower abundance than those from between the Clarion and Clipperton Fracture Zones. This difference arises in part from the fact that the region between the Clarion and Clipperton Fracture Zones has been swept by strong bottom currents since the Lower Miocene. The onset of this bottom current has therefore been of considerable importance in the development of these potentially economic-grade nodules characterised by high abundance and high Ni + Cu contents in the Equatorial North Pacific.

In order to demonstrate the various mechanisms controlling nodule composition in the Pacific, a plot of the Mn/Fe ratios of the nodules against the Ni + Cu contents from each of the study areas has been made. Such a plot has recently been used by Halbach *et al.* (1980) to deduce the origin of nodules from the "Sonne Basin". In their graph, the Ni + Cu contents of the nodules first rise with the Mn/Fe ratio to a maximum value of about 3% at a Mn/Fe ratio of about 5 (defined by these authors as the "point of reversal") and then decrease with an increasing Mn/Fe ratio. We have observed a similar trend for nodules from the entire

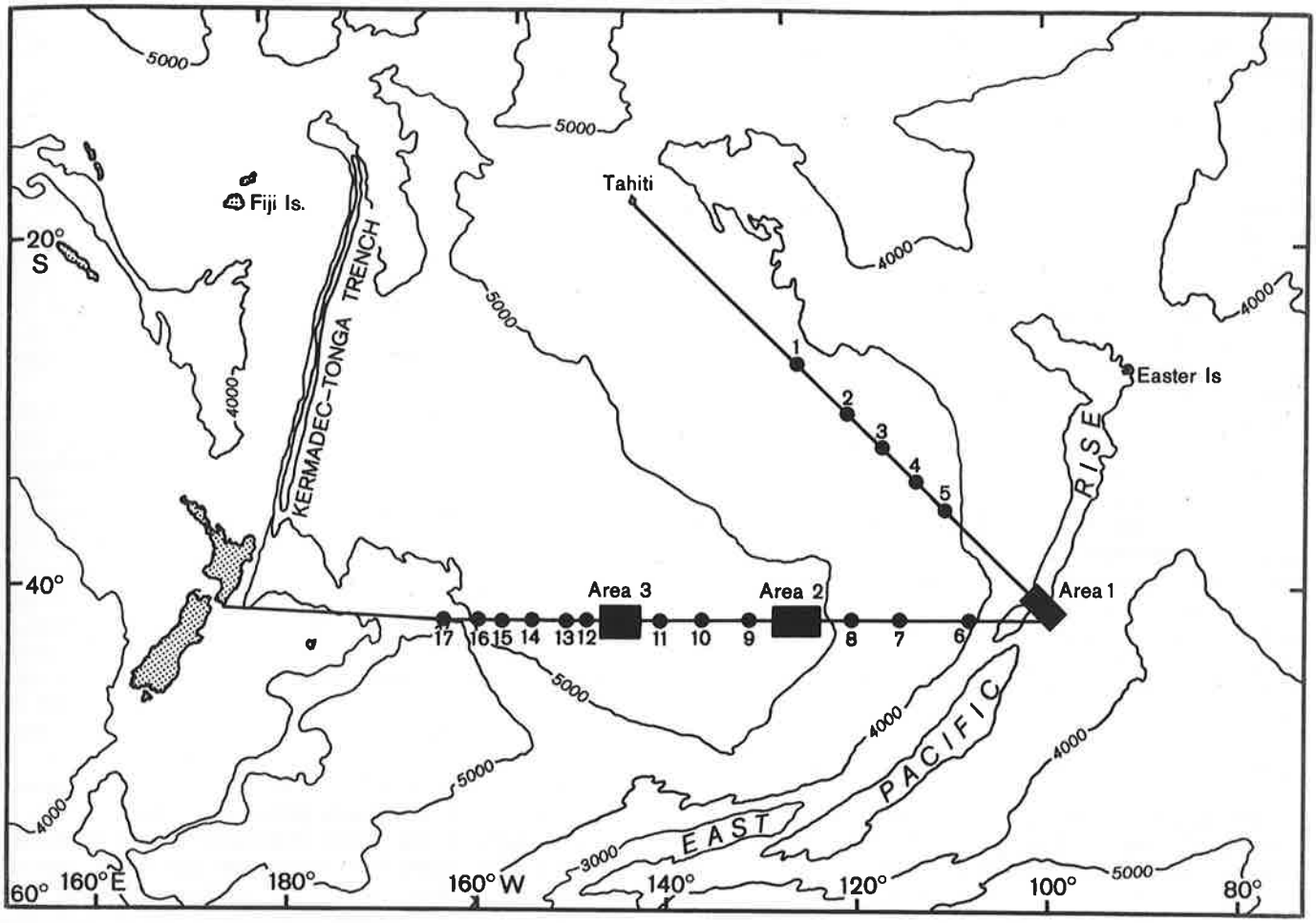

Fig. 5. Schematic map showing track of F.S. *Sonne* during cruise SO-14 with sample locations and study areas marked.

Pacific Ocean (Fig. 4). This graph represents three distinct zones.

Zone A consists of manganese nodules from the Southwest Pacific (Area K) and manganese crusts characterised by low Ni + Cu contents and low Mn/Fe ratios; these values reflect the fact that nodules from the low-productivity zones and manganese crusts are derived principally by direct precipitation of elements from seawater and therefore have a "baseline" composition reflecting this simple mode of formation.

Zone B consists of nodules from the Equatorial Pacific (Areas C, F, G, and *Valdivia* 13/2 area) having higher Ni + Cu contents and Mn/Fe ratios reaching a maximum value of the Ni + Cu content encountered (about 3%) at a Mn/Fe ratio of about 5 (the point of reversal); these nodules are found in the Equatorial Pacific high-productivity belt where there is an additional supply of divalent transition elements such as Ni^{2+}, Cu^{2+}, and Zn^{2+} derived from the *in situ* dissolution of siliceous tests within the sediment column. The incorporation of these divalent metal ions into the nodule structure helps to stabilise the 10 Å manganite structure. Within the nodules, individual laminae probably have the theoretical maximum concentration of these divalent transition metal ions in the 10 Å manganite phase. Additional manganese is also derived from this biogenic source but is incorporated into the nodules in the tetravalent state.

Zone C consists of nodules from the Peru Basin (SO-04 and SO-11/2) having higher Mn/Fe ratios but decreasing Ni + Cu contents; these nodules have an additional source of elements, namely the upward migration of Mn^{2+} in the sediment column due to the development of reducing conditions there. In these nodules, part of the additional manganese is incorporated into the ferromanganese-oxide structure in the divalent state (Mn^{2+}) and stabilises the formation of 10 Å manganite in the same way as Ni^{2+}, Cu^{2+}, and Zn^{2+} in Zone B nodules. In the extreme, the principal manganese-oxide mineral becomes a Mn-rich rather than

a Ni-, Cu-, Zn-rich 10 Å manganite. This is the situation encountered in shallow-water, continental-margin nodules. In fact, Peru Basin nodules show a gradation in composition from one similar to that of normal Equatorial Pacific nodules with similar Mn/Fe ratios and Ni + Cu contents to those with extremely high Mn/Fe ratios and low Ni + Cu contents. Mn/Fe ratios of Peru Basin nodules can in fact exceed 50. In the Peru Basin therefore, the effects of these two processes (biogenic enrichment of divalent transition metal ions such as Ni^{2+}, Cu^{2+}, and Zn^{2+} and the diagenetic enrichment of manganese by remobilisation of this element within the sediment column) play a role in controlling nodule composition, the relative importance of which varies throughout the basin depending on local sedimentation conditions.

In fact, the above nodule types can be classified as follows – Zone A nodules (**halmeic** – derived from seawater, Arrhenius 1963), Zone B nodules (**biogenic**), and Zone C (**diagenetic**). Although there is clearly an overlap between these various nodule types, this classification does help to explain the "end-member" composition of manganese nodules in the Pacific. This graph is therefore important in demonstrating the main process controlling nodule composition in the Pacific. The influence of these elemental supply mechanisms to nodule morphology, composition, mineralogy, and growth rate have been discussed in detail elsewhere.

The results of the *Sonne* work described above have been published by Friedrich (1979), Friedrich *et al.* (1981, 1983), Shrivastava *et al.* (1981), Stoffers *et al.* (1981), Thijs *et al.* (1981), Glasby and Thijssen (1982a, 1982b), Kunzendorf *et al.* (1982), and Glasby *et al.* (1983). Two papers on this work were also presented by the RWTH Aachen group at the International Geological Congress in Paris in July 1980 as part of a special session on the I.C.I.M.E. Project (Friedrich *et al.* 1980a, b).

SO-14 CRUISE

Because of the success of the I.C.I.M.E. Project, a second major transect was planned and undertaken by F.S. *Sonne* to survey the eastern sector of the Southwestern Pacific Basin during the period 1980 as a joint RWTH Aachen – N.Z. Oceanographic Institute programme (Plüger 1981). Because of its remoteness, the area had only rarely been visited by research vessels and the aim of the project was to examine in more detail nodules from the region of low productivity below the subtropical anticyclonic gyre extending into the more productive circumpolar waters. The transect traversed Tahiti – East Pacific Rise – New Zealand and involved a detailed study of three specific areas along the cruise track (Fig. 5).

Cruise SO-14 of F.S. *Sonne* took place between 3 August and 11 September 1980. In all, 3 areas and 17 locations were investigated (Fig. 5). As well as sampling manganese nodules, sediments, and surface and bottom seawater and plankton, bathymetric and seismic profiles were continuously run and photographs of the seafloor taken with a TROIKA camera system. The success of this cruise may be assumed from the fact that 228 kg of manganese nodules and 57 m of sediment core were recovered. The weather conditions during the cruise were poor with an average temperature of 8°C (from 12 August) and an average sea state of 6–7 rising to 10 in some cases. This is to be expected at such southerly latitudes (42°S) in the austral winter.

From the data so far obtained, it is seen that nodules along the transect from Tahiti to the East Pacific Rise are characterised by very low abundances but moderately high Mn/Fe ratios and Ni + Cu contents. The water depth along this transect averages 4,250 m and is above the Carbonate Compensation Depth. The increased rate of sedimentation due to the incorporation of carbonates in the sediments explains the low nodule density. At the crest of the East Pacific Rise itself, a ferruginous calcareous ooze of possible hydrothermal origin similar to that found at the axes of many mid-ocean ridges was discovered. On the transect from the East Pacific Rise to Wellington at 42°S, the water depth increases to a maximum of 5,670 m at Loc. 12 but then shoals to 4,674 m at Loc. 17. The carbonate content of the sediments reflects the water depth so that pelagic brown clays (eupelagic clays) characterised by the absence of carbonate are found only between Area 3 and Loc. 14 in the deepest waters. The Carbonate Compensation Depth is therefore very deep here. Nodule abundance along this transect is difficult to estimate because some of the free-fall grabs returned empty even though the photographs taken by the free-fall grab camera showed the presence of abundant nodules. It is possible that nodule abundance is locally so high that the free-fall grab cannot close properly and returns to the sea surface empty. Even so, at Loc. 13, nodule density averaged 20.2 kg/m^2 and at one station attained the remarkable density 64.2 kg/m^2. Average nodule densities well in excess of 20 kg/m^2 in the region of the eupelagic clays can therefore be expected.

The Mn/Fe ratios and Ni + Cu contents of the nodules along the 42°S transect vary with distance from New Zealand such that the Mn/Fe ratios and Ni + Cu contents of the nodules increase to the pelagic brown clays and then decrease towards the East Pacific Rise (with an increase once again near the East Pacific Rise where nodule abundances are low). The combination of highest nodule abundances and grades are therefore found on the eupelagic clays at Locs 12–13 about 2,300 km east of New Zealand in water depths >5,000 m. At Loc. 12, for example, the nodules have an average Mn/Fe ratio of 3.1 and Ni + Cu content of 1.78%. This area is one of extremely low sedimentation rate being far from any source of terrigenous sediment-

ation and below the Carbonate Compensation Depth. this would explain the extremely high nodule abundances. The high Mn/Fe ratios and Ni + Cu contents of the nodules may reflect the proximity of the region to the high productivity zone associated with the Antarctic circumpolar region.

In terms of morphology, nodules from the western flanks of the East Pacific Rise are dominantly small polynucleate nodules with high coverage on the seafloor whereas those from the eupelagic clay areas tend to be extremely large (exceeding 80 mm diameter in some cases) spheroidal nodules with botryoidal surface texture.

Nodules from the eupelagic clays at 42°S are therefore quite different in size, shape, and composition from those of the Southwest Pacific region near the Cook Islands (Southwestern Pacific Basin, Samoan Basin, south Penrhyn Basin, Aitutaki Passage). Meylan (1978) has already noted the difference in nodule facies between the two areas which he named the Southwestern Pacific Basin Facies and the Cook Island Facies respectively.

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