

RELATIONSHIPS BETWEEN NODULE GENESIS AND TOPOGRAPHY IN THE EASTERN AREA OF THE C-C REGION

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INTRODUCTION

The initiative of the International Seabed Authority (ISA) for the establishment of a geological model of the Clarion-Clipperton region is aimed at, i.a., identifying and exploring regional and local patterns in distribution of nodules as well as those related to the presence and concentration of base metals in them. The long-term comprehensive geological studies, carried out up to date in the region, have elucidated general relationships between distribution and conditions enhancing the presence of nodules as well as relationships between base metal contents and specific morphotectonic features of the C-C zone, the crystalline basement age and tectonic position, structure and development of sedimentary cover, depth and topography of the seafloor, subsidence and sedimentation rates, and the major environmental factors of a key importance for nodule formation (Cronan, 1977; Kazmin, 1984; Korsakov, 1987; Stackelberg, Beiersdorf, 1991; Kotliński, 1999; Andreev, Ed, 2000; Morgan, 2000).

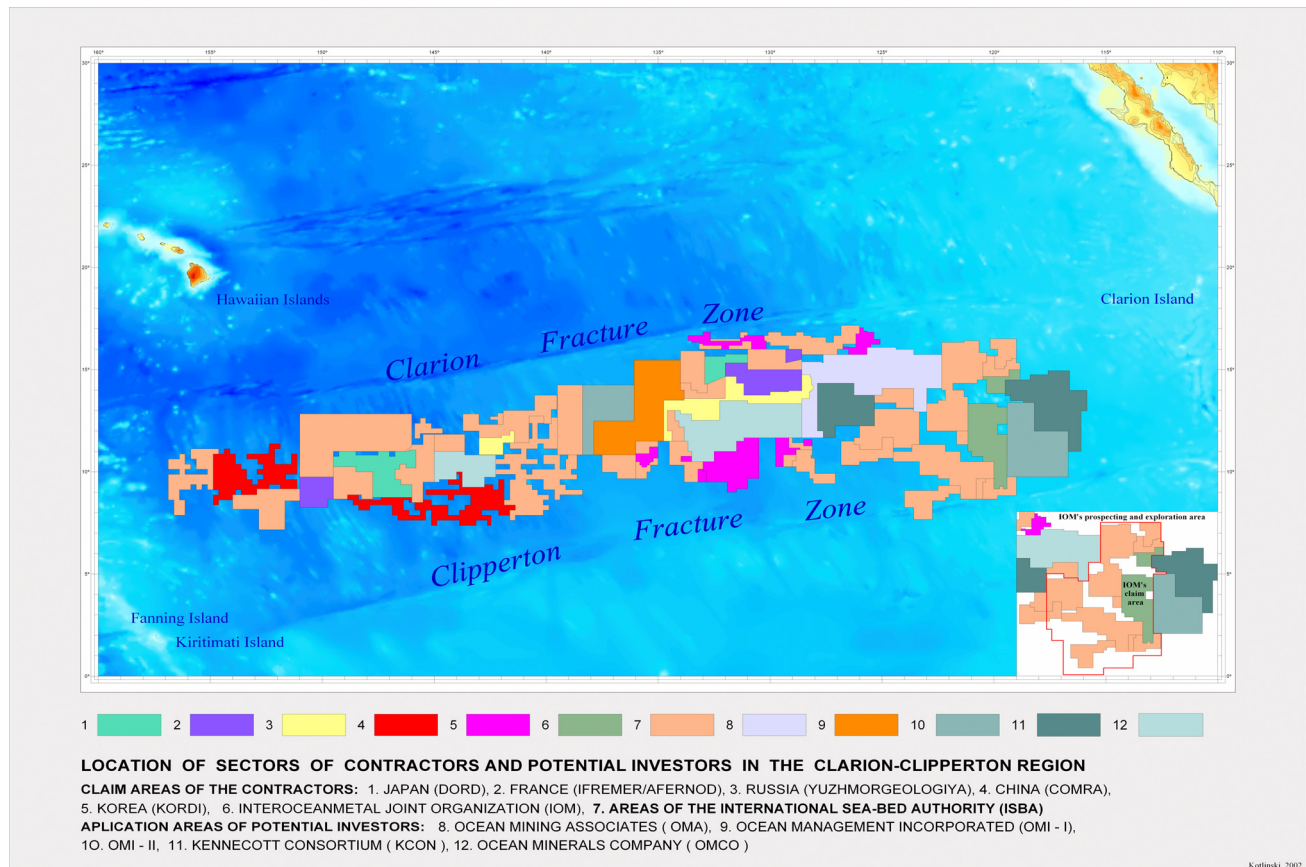
The ISA Secretariat Report and the results presented during the first seminar (January 2003) demonstrate the diversity, within the areas selected in the Clarion-Clipperton nodule region, of conditions enhancing nodule distribution, patterns in the distribution, and the nodule metal contents. The patterns of nodule distribution and of conditions enhancing their presence in the eastern, central, and western areas of the Clarion-Clipperton region show certain differences, expressed through certain area-specific features (Kazmin, Stackelberg, Beiersdorf, Lu Wenzheng, Hoffert, Kotliński).

Identification of the most characteristic parameters is of critical importance for the geological model to be developed. This paper is aimed at highlighting the most important, in the author's opinion, parameters and patterns typical of the eastern area of the Clarion-Clipperton region. The results obtained demonstrate certain specificity of the area, expressed, i.a., in the basement age and structure and in the sedimentary cover development, in seafloor depth and topography, activity of the East Pacific Rise, level of the carbonate compensation depth (CCD), a high productivity and a relatively high sedimentation rate, distribution of nodules and conditions controlling their formation, and base metal contents. The nodule patterns identified show a high variability of properties, manifested both at the local level and in comparison with other areas of the region in question (Kotliński, Zadornov, 2002; Kotliński, 2003).

IOM AS A CONTRACTOR

The Interoceanmental Joint Organization (IOM), an intergovernmental consortium, was set up in April 1987 to survey and explore polymetallic nodule deposits in the eastern part of the Clarion-Clipperton nodule region (Fig.1) and to prepare their commercial development.

Fig. 1. Location of sectors of Contractors and potential investors in the C-C region.



Using the results of its comprehensive research and analysis of regional geological and geophysical data, IOM selected, within 1987-1990, a prospecting area of about 553 thou. km² within which to conduct multi-faceted geological and geophysical studies. The studies carried out in the eastern part of the Clarion-Clipperton nodule region were aimed at narrowing an application area down to 300,000 km² and to collect data necessary for IOM to apply to the Preparatory Commission of the International Seabed Authority (ISA) and International Tribunal for the Law of the Sea for registration and allocation of a 150,000 km² *pioneer area*.

Based on the data submitted, in accordance with regulations of the United Nations Conventions on the Law of the Sea and Resolution II, IOM was granted, in June 1992, *the pioneer investor status and the certificate of registration*. Having fulfilled its obligations as a pioneer investor, IOM focused, within 1994-2001, on comprehensive geological and environmental research and exploration, aimed at relinquishing to ISA parts of the registered pioneer area (1994, 1996, 2001)

and at collecting environmental data. In 1995, IOM carried out its Benthic Impact Experiment (IOM BIE) at an abyssal site located within the IOM claim area (Kotlinski et al, 1996, Kotlinski and Stoyanova, 1998; Radziejewska and Kotlinski 2002).

The long-term studies and regional analyses based on data collected during research cruises have made it possible to establish general patterns of nodule distribution and relationships between conditions controlling nodule formation processes in the eastern area of the C-C nodule region.

As stipulated by the “ Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area” adopted by ISA in 2000, any activity within the pioneer area should be preceded by ISA’s approval of a 15-year Plan of Work for Exploration and by conclusion, with ISA, of a contract for implementation of the Plan.

ISA approved IOM’s Plan of Work for 2001-2015 in 1997. Subsequently, in March 2001, a contract between ISA and IOM for the implementation of the Plan was concluded. According to the contract’s provisions, the area intended for IOM’s exploratory activities covers 75 thou. km². The contracted work has been conceived as an investigation of geological and mining conditions of the future mining area.

As a preliminary to the actual exploration, the IOM pioneer area was – in 1999 - surveyed by means of a SIMRAD multibeam echo sounder. The survey resulted in compilation of 1:200 000 maps of bottom relief, slope angles, and bathymetry; side-scan sonar images of the bottom were collated as well.

In May 2001, IOM embarked upon implementation of the first stage of its “Plan of Work for Exploration” by launching a cruise to its pioneer area on board RV Yuzhmorgeologiya. During the cruise, a B-2 area was surveyed. The cruise was intended to acquire data with which to identify areas most suitable for more detailed geological exploration aimed at mapping potentially valuable nodule deposits as well as at assessing spatial variability in nodule coverage and base metal contents in the deposits (Kotlinski, Zadornov 2002).

BASEMENT AND SEAFLOOR TOPOGRAPHY

The area of IOM’s exploration is situated on the western slope of the East Pacific Rise and extends longitudinally over 510 km between the Clarion and the Clipperton fractures, the mean width of the area being 150 km.

Based on data collected during that and the preceding cruises, the seafloor of the area may be visualised as a series of longitudinal blocks of volcanic and tectonic origin, separated by sub-latitudinal and longitudinal fractures (including transform ones; Jubko et al., 1990; Kotlinski, 1992; Kotlinski, Zadornov 2002).

Judging by the age of the seafloor basalts, the morphology and structure of the bottom dates back to early Miocene/late Oligocene. As volcanic and tectonic activity intensified in late Miocene-Pliocene, sub-latitudinal volcanic massifs emerged, adding to the structural complexity of the area.

The seafloor within the boundaries of the IOM exploration area was found to be inclined N-S towards the centre; a slight inclination is observed in the E-W direction as well. The seafloor is a part of an undulating (4300-4400 m below sea level) plain, its morphology being rendered more complex by a system of longitudinal horsts (4100-4300 m) and grabens (4400-4750m). The presence of volcanic massifs results in modification of the basic structural plan of the seafloor. The horsts and grabens have emerged as a product of the seafloor fracturing.

The 4300 m depth contour seems to be the reference depth for the undulating horst-graben relief of the seafloor. The horsts vary in width from 1.0 to 15 km and extend for 5 to 70 km in length. The broadest and longest horsts are encountered in the central and southern part of the area surveyed. The horsts can be either symmetrical or asymmetrical on the cross-section. Slopes of the asymmetrical horsts are steeper (the slope angle exceeding 10°). The horsts are 200 m high at most (in the north), the minimum height (recorded in the central-western part) being 75 m.

The 4400 m depth contour appears to be the reference level for the rifts (grabens). Along the 4500 m isobaths, the rifts vary in width from 0.8 to 25 km and extend for 4.5 to 150 km in length. On the cross-section, the grabens are predominantly trough-like. The grabens may contain depressions up to 210 m deep, their size varying from 0.8 x 1.4 km to 3.0 x 18 km. The depression axes are curved in outline; certain wide grabens have several axes. The graben walls are steep, occasionally almost vertical. Most often, the grabens are symmetrical on the cross-section. Their depth varies from 225 m (from the reference level) in the south to 310 m in the central-western part. The axes of both the horsts and the grabens show a characteristic undulation.

The seabed over 30% of the area slopes down at more than 7° . Slopes of this kind are typical of volcanic structures, of the feet of the horsts and of the graben walls.

SEDIMENTS

In the eastern area, three sedimentary units were identified above the basement. They were termed 3.5 kHz seismoacoustic facies: the upper transparent layer A (Unit A); the upper stratified layer B (Unit B); and the lower transparent layer C (Unit C); they correlate with the DSDP results (Drilling Hole No. 159; Kotlinski 1992).

The basement composed of toleitic basalt is Miocene in age, as concluded from the analysis of linear magnetic anomalies.

Unit A is an acoustically transparent layer, Quaternary to late Miocene in age.

Unit B is an acoustically semi-transparent layer, late Miocene to early Miocene in age.

Unit C is an acoustically transparent layer, early Miocene in age.

Unit A is never thicker than 20 m, its thickness averaging 10 m. The unit's thickness is not only dependent on topographic variations of the seabed, but also on such factors as the deep-sea currents which can affect erosion processes. The seafloor sediments within the area surveyed consist of the Marquesas (early Miocene -Pliocene) and Clipperton (Pliocene-Holocene) formations within which 4 major layers can be identified (Table 1).

Table 1. Characteristics of bottom sediments within the IOM exploration area (Kotlinski, Zadornov 2002).

Layer symbol	Sediment type	Sediment origin	Layer sampled (cm)	pH range	Eh range	SiO ₂ ^{amorph} (%) range	Moisture content range	Bulk density (g/cm ³) range
IV_{CL}	Clay and siliceous ooze; geochemically active layer	Elluvial-deluvial	0-12	7.26-7.46	546-588	1.22-32.25	337-431	1.16-1.19
	Siliceous ooze (ethmodiscoid oozes)	Deluvial-solifluction produced	10-30	7.36-7.48	510-592	13.78-28.6	319-383	1.18-1.21
	Clay and siliceous ooze	Elluvial-deluvial	10-30	7.32-7.58	269-598	1.73-17.85	245-399	1.17-1.25
			35-350				231-310	1.21-1.25
III_M	Zeolitic clay	Elluvial	10-20	7.39-7.46	488-556	1.22-17.85	218-226	1.26-1.28
			35-135				198-240	1.26-1.29
	Zeolitic crusts		0-40	7.38-8.02	502-625	0.9-27.73	370-533	1.14-1.21
II_M	Radiolarian ooze	Elluvial	50-330	7.32-8.02	502-625	0.9-27.73	370-533	1.14-1.21
I_M	Calcareous ooze	Biogenic	215-300	7.57-8.09	543-573	1.36-7.75	152-208	1.22-1.37

The lowest layer (I), represented by calcareous, nanofossil-containing oozes, is characterised by an elevated bulk density as well as by reduced moisture and amorphous silica contents. The sediments are believed to be a product of the primordial biogenic sedimentation.

That layer is overlain by another (II), represented by siliceous ooze or a mixed sediment, a product of halmirolysis of the underlying deposits. The sediment is an elluvial formation characterised by a reduced bulk density, increased moisture content, and a high content of amorphous silica. The thickness of that deposit does not exceed 2.5 m.

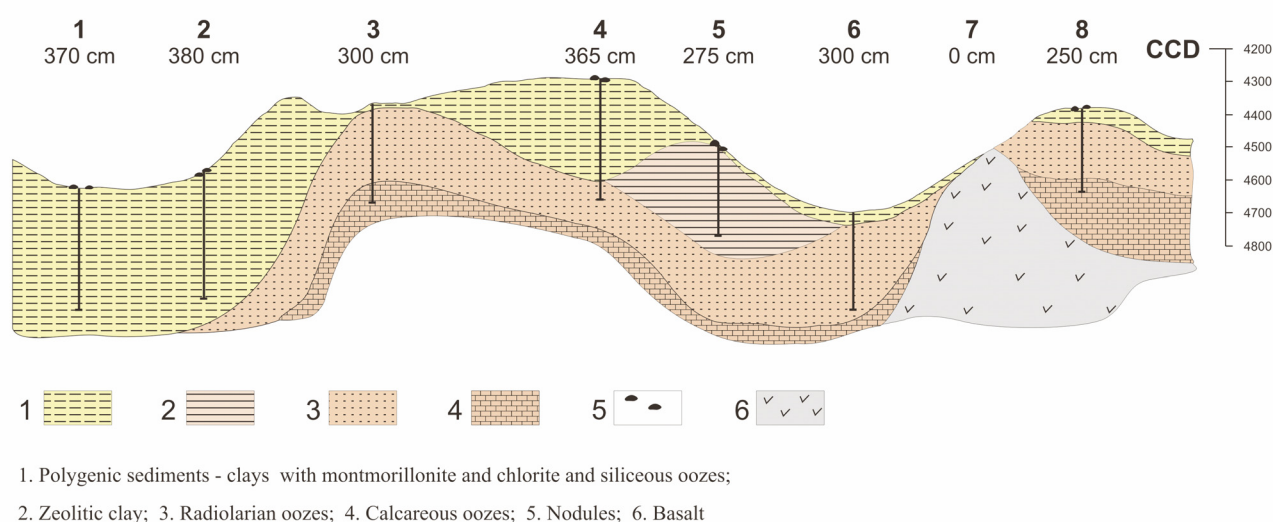
The overlying deposit (layer III) consists of the zeolitic red deep-sea clay and thicker zeolitic crusts characterised by a high bulk density, a reduced moisture content, and the amorphous silica content reaching up to 18%. This elluvial deposit is probably up to 3 m thick.

The sediments making up the three layers described above belong probably to the Marquesas formation.

The uppermost layer (IV) belongs to the Clipperton formation. This sediment consists of elluvial-deluvial clays and oozes with montmorillonite and chlorite, and is mottled, patchy or smudgy in appearance. The amorphous silica content varies from 1 to 20%. The layer may be up to 3.5 m thick.

Some sites revealed a specific sediment completely devoid of nodules. Such sediment is formed by reduced bulk density clays and aleuritic siliceous oozes the amorphous silica content of which reaches up to 30%. That sediments is deluvial-solifluction in origin, a product of transportation and resedimentation in local, confined depressions (Fig. 2).

Fig.2. Distribution of sediments (according Zadornov, 2001).



The seafloor sediment vertical profile is topped by clays and siliceous oozes of the geochemically active (2-12 cm thick) layer on which nodules are formed and in which they are partly embedded. Those sediments are characteristic in their reduced bulk density and increased moisture content. The layer discussed is known as the sediment–water interface boundary (SWIB layer sensu Sharma, Kodagali, 1992). The nodules are partially or fully buried, which results in nodule abundance estimates from bottom photographs being lower than those based on grab contents (Fot.1) The degree of embedding depends on the thickness of the (SWIB) layer. If it is thin, coefficient R assumes low values (< 1.5) because more nodules are exposed; whereas a thick layer and even larger nodules produce higher R values (> 1.5).

Fot.1. Typically sediment blanketed nodules.



Generally speaking, the sediments of the area belong to the polygenic type. Their granulometry places them on the boundary between clayey-aleuritic and aleuritic-clayey oozes, the <0.001 mm fraction making up 89-92%; the median grain size is close to 4 μ m.

The base metal contents in the sediments can be arranged in the following order:

Fe > Mg > Mn to form a series of 5.97-6.61 > 3.0 – 3.1 > 0.13 – 0.67%.

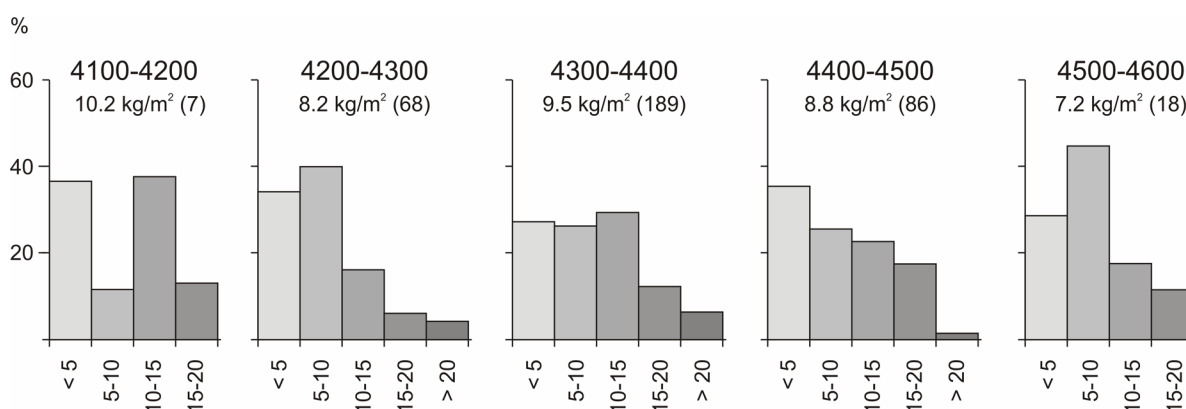
The low manganese content may be explained by diagenetic “scavenging” of manganese by nodules. The base metal contents are higher in nodule-bearing areas of the seafloor than in nodule-free patches. The metal contents decrease with increasing depth in the sediment, with a characteristic maximum within 3-6 cm in the sediment. The pore water shows a reverse relationship of metal content vs. depth in the sediment.

DISTRIBUTION AND CHARACTERISTICS OF NODULE IN RELATION TO GEOLOGICAL SETTINGS

The complexity of the seafloor morphology is reflected in the nature of nodule coverage of the bottom. Although the IOM area may be generally regarded as a nodulised one, it contains, in fact, both nodule-bearing and completely nodule-free patches.

Notwithstanding the relatively constant base metal contents in the nodule deposits, nodule coverage varies widely (Fig.3).

Fig.3. Distributions of the nodule abundance.



Within the IOM exploration area, sediment samples were collected (with a 0.25 m² box corer equipped with a photo-camera) from a total of 371 sites; nodules were present at 324 (87.3%) of them, while at 154 (47.5%) of them the nodule abundance (wet weight-based) exceeded 10 kg /m² (Fot.2).

Fot.2. Discoidal (Dr) nodules in boxcorer.



No regular pattern could be observed in the distribution of polymetallic nodules in the area surveyed; in other words, no single morphological element of the seafloor relief tended to be more amenable to nodule aggregations than the remaining ones. Both nodule-rich and nodule-depleted patches of the seafloor could be found on the undulating abyssal plain, on tops and slopes of ridges (horsts), and on the walls of grabens.

Bulk mineralogy and chemistry

Although the crystallographic description and mineralogy of manganese nodules are still controversial, they are important because they reflect the origin of the nodule and to some degree determine their chemical composition (Usui, Someya, 1997; Kotlinski, 1999).

Minerals in the nodules are commonly identified by powder X-ray diffraction (XRD). Due to low crystallinity and hydrous nature, the XRD diagrams are usually insufficient for more detailed analysis of nodule structure. In terms of mineralogical criteria and results of the analyses, the following three minerals can be assumed to be the major components:

1. 10 Å manganite (Cu-Ni rich busserite) the main mineral busserite forms probably from dissolved manganese in poor waters during early diagenesis.
2. birnessite; its diagnostic reflection is 7 Å.
3. vernadite, a hydrogenetic Fe-Mn oxide; it is poorly crystallized; while Fe- and Co-enriched, it contains negligible amounts of Cu and Ni.

The nodules contain also microscopic detrital silicates, feldspar, plagioclases, and quartz.

The mineral and chemical composition of nodules, particularly relationships between contents of hydrogenetic minerals (iron and manganese hydroxide, i.e., vernadite) and diagenetic-manganite-busserite, as well as the Mn/Fe ratio and concentrations of Ni, Cu, and Co reflects the major processes responsible for nodule formation, i.e., hydrogenetic or diagenetic processes (Usui, Terashima, 1997).

As a rule, larger nodules with rough surfaces are Mn-, Ni-, Cu-, and Mo-enriched, busserite being the major mineral component. On the other hand, smaller, smooth nodules are relatively rich in Co, Fe, and Pb and show a higher vernadite content.

Distribution and origin of the nodules

The area surveyed was observed to harbour all the known nodule genetic types: Hs, HD, and Dr (Kotlinski, 1996; 1999; 2001; 2003). In terms of nickel content, a sub-type Dr₁ may be separated within the nodule type Dr, the Dr₁ nodules containing more copper than nickel (Table 2).

Table 2. Basic characteristics (mean values) of the diagenetic nodule types in the IOM exploration area (Kotlinski, Zadornov 2002).

Parameter	Type		Entire exploration area (324)
	Dr (148)	Dr ₁ (96)	
<i>Wet weight-based abundance (kg/m²)</i>	12.9	7.3	10.2
<i>Dry weight-based abundance (kg/m²)</i>	8.8	5.0	7.0
Ni (%)	1.37	1.25	1.31
Cu (%)	1.26	1.34	1.23
Co (%)	0.18	0.16	0.18
Mn (%)	31.90	31.48	30.80
<i>Moisture content (%)</i>	31.6	32.0	31.7

*Number of sampling sites from which the data were acquired is given in parentheses

Distribution of the genetic types of nodules is controlled by the position of CCD in relation to the seafloor, the CCD in the eastern region being located at the depth of about 4200m. The hydrogenetic, smaller and smooth nodules occur above and within the CCD depth interval, whereas the diagenetic - larger and rough nodules occur, as a rule, below the CCD. (Table 3). Differences in nodules sizes reflect their structural and textural features, which is related to their different growth rate (Kotlinski, 1999).

Table 3. Distribution of sediment sampling sites by nodule genetic types (Kotlinski, Zadornov 2002).

Location within the area surveyed	Nodule type				
	Nodule-free sites*	Hs	HD	Dr	Dr ₁
northern part	17.7'	6.2	21.5	46.2	8.4
central part	9.6	4.2	13.3	39.4	33.5
southern part	11.3	1.9	18.9	26.4	41.5
total in the area surveyed	12.7	4.5	17.0	39.9	25.9

*; % of the total number of stations in the location;

northern part: 13°20'-12°00'N;

central part: 12°00'-10°30'N;

southern part: 10°30'-9°10'N.

The richest deposits are formed by large (6-12 cm) type Dr nodules (weighing up to 2.6 kg), their abundance reaching 28.4 kg/m². Nodules of this type are encountered throughout the area surveyed and occur under various conditions in terms of seafloor morphology and depth.

The large type Dr nodules, up to 10 cm in size, have nucleus made of fragments of older nodules. Although the nodules are irregular in shape, they reveal some features of the primarily discoidal form. In a number of cases, large nodules are mushroom-shaped, with a “stalk” embedded in the sediment and a loose, easily chipping, rough surface. The upper surface of some large specimens is bothroidal and smooth. The equatorial belt is usually well-developed, visible as large bothroids. On the cross-section, those nodules show thick layers that, in certain largest specimens, are up to 10 mm thick each. They usually show a radial, dendritic or colomorphic texture and are cracked.

The nodules of this type are typically sediment-blanketed. On numerous photographs of the seafloor, taken at the moment of sampling, the nodules appear to occupy as little as a few per cent of the frame. A significant number of nodules remain buried in the SWIB layer and are revealed only when the sediment sample is being processed. The coefficient R (a ratio between the area of the bottom actually covered by nodules and the nodule-covered area as seen on the photographs) may be as high as 15 and averages 1-3 (Table 4)

Table 4. Distribution of ratio „R”.

Index „R”	% of the stations
1.0	29.1
1-3	56.4
3-10	11.6
>10	2.9

Small (up to 6 cm in size) type Dr nodules are, as a rule, coreless (cross-sections show a single generation of concentric layers about 1 mm thick each; even a microscopic examination fails to reveal the presence of a core). The nodules are discoidal or ellipsoidal in shape, the smallest being spheroidal. They usually have rough surfaces.

Type Hs nodules are particularly abundant in the northern part of the area; they usually lie on the seafloor surface at water depths shallower than 4200 m (CCD level) and are well-visible on photographs of the bottom. A characteristic feature of their distribution, useful in interpretation of images, is their chain-like arrangement on the bottom.

Those nodules are usually small and spheroidal (not larger than 6 cm, most of them attaining 2-4 cm in size). They usually show smooth surface; occasionally the surface shows large monocrystals and zeolitic accretions. Those nodules are porous and frequently cracked. Their nuclei are, as a rule,

formed by concentrations of zeolites; more seldom are they made up by fragments of older nodules. The nodule cross-sections show the layers to be a fraction of a millimetre thick each. Those nodules occur in conjunction with calcareous oozes or calcium carbonate–poor siliceous clayey oozes.

Some sites located at depths shallower than 4200 m show the presence of crusts up to 3 cm thick on more consolidated zeolitic clays.

Moisture content of those nodules varies within 28-40% and averages 32%; their density ranges from 1.75 to 2.06 g/cm³, averaging 1.95 g/cm³.

Most numerous in aggregations of those nodules are discoidal (morphotype D) ones and their regenerated fragments (fD); the summary contribution of other morphological types (ellipsoidal, spheroidal, accreted, and plate-like) does not exceed 13%. The aggregations described extend both latitudinally and at various water depth ranges. The contribution of morphotypes D and fD increases from type Hs towards type Dr nodules, the share of other morphotypes decreasing.

In 95% of the cases, the nodules have been formed around a nucleus of older ones. It is only among nodules of morphotypes S, R, and T that their cores are occasionally formed by sediment (primarily zeolitic clay) agglomerates.

A gradual increase in contribution of larger fractions, up to the maximum at fractions exceeding 8 cm (from 3.2% contributed by 0-2 cm to 40.7% of the >8 cm fraction) is observed. In the N-S direction, the contribution of >8 cm nodules is seen to decrease (from 52.5% in the northern part to 5.6% in the south). The nodules in the southern part of the area are mostly those 4-6 cm in size (38%). As the depth increases, the amount of nodules >8 cm decreases (from 56 to 32.9%), while the respective contributions of nodules 2-4, 4-6, and 6-8 cm in size increase. The most stable size distribution of nodules is observed within the depth range of 4300-4500m (Table 5).



Table 5. Characteristics of polymetallic nodules in the IOM exploration area by depth (Kotlinski, Zadornov 2002).

Depth range (m)	Number of sampling sites	Mean abundance (kg/m ²)		Mean metal content (% by weight)				Mean moisture content (%)
		Wet nodules	Dry nodules	Ni	Cu	Co	Mn	
3400-3500	1	0	0	-	-	-	-	-
4000-4100	2	5.0	3.3	1.05	0.86	0.20	24.02	34.0
4100-4200	7	10.2	7.0	1.22	1.01	0.20	27.45	31.3
4200-4300	68	8.2	5.7	1.3	1.16	0.18	29.77	31.2
4300-4400	189	9.5	6.5	1.32	1.24	0.17	31.08	31.9
4400-4500	86	8.8	6.0	1.32	1.27	0.17	31.31	31.8
4500-4600	18	7.2	4.9	1.24	1.19	0.19	30.47	32.5
Entire area	371*	9.0	6.1	1.31	1.22	0.18	30.79	31.8

*all sampling sites, including nodule-free ones, are included.

The nodule size increases from type **Hs** to **Dr** (the contribution of the >8 cm fraction increases from 37.9 to 43%), while the respective contribution of the 0-2 cm and 2-4 cm fractions sharply decreases (from 17.5 to 2.0% and from 19.0 to 10.3%). The type **Dr** nodules have the most stable size distribution.

The basic characteristics of nodule deposits in the IOM exploration area are summarised in Table 6.

Table 6. Characteristics of the genetic types of nodules in Eastern CC region.

Lithofacies	Calcareous oozes and calcareous clayey silt within 4200m -CCD depth interval	Clayey silt (slightly calcareous and slightly siliceous) 4200-4500m	Siliceous oozes and brown pelagic clays below CCD 4300-4700m
Genetic type	Hs	HD	Dr
Mean nodule abundance: kg/m ²	10.5	8.3	12.9
Co-occurrence on the genetic types	Hs+HD	Hs+HD-HD+Dr	HD-Dr Dr₁
Size (cm)	<3.0	3.0-6.0	6.0-12
Average size (cm)	3.4	4.4	6.5
Mean diameter and percent contribution to fractions:	1-4	2-8	4-12
>6 cm	54.0	49.8	66.9
>8 cm	37.9	39.2	43.0
Index “R”	1.0	1.0-3.0	1.0- >10.0
Surface structure	s/r; s	s/r; r	r; s/r; r/s, s
Dominant morphotype D+fd %	D, fd, S, P, E, T 46.8	D, fd, E 83.4	D, fd, E 93.7
Nucleus type	clayey-zeolitic, more seldom volcanoclastic or bioclasts	clayey-zeolitic, bioclasts,	fragments of older nodules, micronodules
Fractures	radial	irregular	clearly radial
Lamination (mm)	thin (<1.0)	medium (1.0)	coarse (>1.0)
prevailing lamina thickness (mm)	<0.4	0.4-1.0	>1.0
Textures	radial	radial-dendritic, concentric- laminated	massive, radial-dendritic, concentric- laminated
Dominant Mn minerals	vernadite	birnessite, vernadite	buserite, birnessite, vernadite
Average contents (%) of major metals:			
Mn	23.79	28.31	31.90
Fe	5.38	5.88	5.25
Cu	0.89	1.10	1.26
Ni	1.06	1.24	1.37
Co	0.20	0.20	0.18
Zn	0.10	0.12	0.14
Mo	0.044	0.065	0.062
Pb	0.025	0.035	0.032
Mn/Fe	<5.0	3.0-5.0	>5.0
Physical properties:			
- density of mineral part (g/cm ³)	3.35	3.35	3.34
- density (g/cm ³)	1.93-2.00	1.88-2.03	1.75-2.24
- volumetric weight (g/cm ³)	1.33	1.29	1.28
- moisture content (%)	31.0	32.3	31.6

Latitudinal variability in nodule abundance and related parameters is shown in Table 7.

Table 7. Latitudinal variability of nodule abundance and base metal contents (Kotlinski, Zadornov 2002).

Part of the area explored	Nodule abundance parameter						
	Wet weight-based abundance (kg/m ²)	Dry weight-based abundance (kg/m ²)	Ni (%)	Cu (%)	Co (%)	Mn (%)	Moisture content (%)
Northern	11.3	7.6	1.32	1.17	0.19	30.31	32.9
Central	10.0	6.8	1.29	1.27	0.17	30.86	31.8
Southern	9.0	6.2	1.24	1.25	0.165	31.13	31.1
Total area	10.2	7.0	1.31	1.23	0.18	30.80	31.7

From the north to the south of the area, the mean abundance of the nodules and their Ni and Co contents are observed to decrease, the Cu and Mn contents increasing. The maximum contents of Ni and Co are typical of nodules in the northern part of the area, the highest Cu and Mn contents being found in the nodules occurring in the central and southern parts, respectively.

Furthermore, the respective contributions of type Hs and Dr nodules are seen to decrease in the N-S direction (from 7.5 to 2.1% and from 56.1 to 29.8%), while the contribution of type Dr₁ nodules increases (from 10.3 to 46.8%). The abundance of type HD nodules shows a decreasing trend in the same direction, but their minimum abundance is found in the central part.

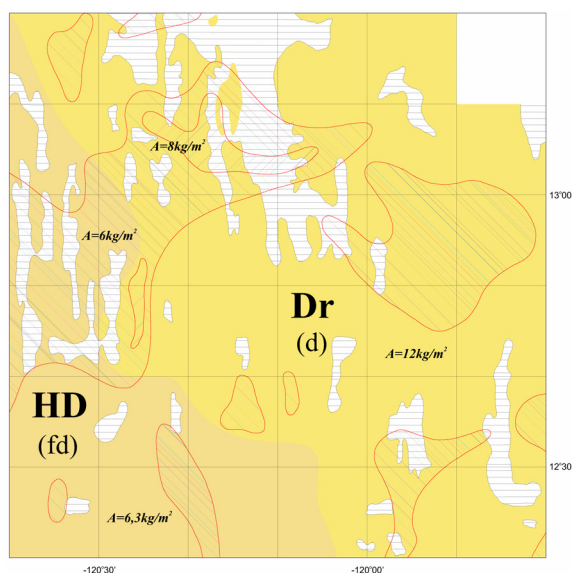
Variability in the nodule attributes increases in the following order: Co – Ni – Cu – Mn – abundance. It is only in type Hs nodules that Ni and Cu change places.

Formation of the deep-sea nodules involves complex, multi-stage processes of biogenic migration and hydro-diagenetic differentiation of Mn and Fe and trace elements, proceeding in the uppermost sediment layer, under specific conditions. Intensity of those processes is directly related to complex reaction between amorphous substances which form active colloidal complexes with Mn and Fe. Metal concentration in the nodules is also a multi-phase process the course of which depends on whether busserite or vernadite is being formed (Kotlinski, 1996; 1999).

In the entire area explored, the depth range of 4300-4500 m appears to be the most productive one, both in terms of nodule abundance and with respect to the base metal contents. This is the depth range that the basic nodule resources are concentrated in.

No clear-cut relationship between the nodule occurrence and the thickness of the seismoacoustic complex A has been found either; the thickness of the complex varying from 0 to about 20 m. Changes in the thickness bear not relationship with nodule abundance on the seafloor. No relationship between domination of a particular genetic nodule types, or increased metal content, and the complex thickness has been found (Fig.4).

Fig.4. Relationship between thickness of the seismoacoustic complex A, nodule abundance and genetic nodule types.



It was for the first time in the area explored that buried nodules, occurring at 8 – 27 cm in the sediment (average depth in sediment: 15-20 cm) were found. They were recorded at 15 sampling sites. At 5 sites, the abundance of buried nodules was comparable to that on the sediment surface. The buried nodules did not differ in morphology or size from those found on the surface. The buried nodules showed, as a rule, slightly lower contents of ore components.

It should be pointed out that increased resolution of surveying and exploration has changed our comprehension of the local nodule-bearing potential of the area. However, the increase in resolution was achieved without sacrificing the reliability and representativeness of nodule sampling, which is of a particular importance at the exploration stage. Results of such finely tuned surveys are extremely valuable in that they broaden the existing knowledge on different spatial scales of natural variability in the potentially exploitable areas.

A characteristic feature in the eastern area of the CC nodule region is a relatively high Mn-Cu content at a lower Co concentration, compared to the central area the nodules of which show lower Mn-Cu contents and higher Ni and Co ones. A trend involving a westward increase in the contents of Co and Ni and a decrease in those of Mn and Cu is observed in the region (Kotlinski, 2003).

CONCLUSIONS

The structure and geology of the eastern area of the Clarion-Clipperton nodule region (*sensu* Kotliński, 2003), is characterised by:

- The shallowest location of the crystalline basement, dated to Late Oligocene/Miocene, toleithic basalts being exposed at numerous sites on the seafloor. In Late Miocene/Pliocene, the eastern area experienced intensified volcanic and tectonic activity, as evidenced by the presence of overlapping volcanic covers.
- Block basement structure, determining the seafloor topography, and a high variability of sedimentary cover thickness which is represented by sediments classified to three seismoacoustic complexes correlated to the Marquesas and Clipperton formations.
- Seafloor depth and topography determining the specific distribution and high variability (both vertical and horizontal) of surface sediment which are represented by various types of polygenic and biogenic sediments. At numerous sites on the seafloor, usually within local rises, older sediments (e.g., zeolite clay and calcareous oozes of the Marquesas formation) are exposed by erosional processes.
- Siliceous-clayey oozes and siliceous oozes cover extensive parts and form a strongly hydrated, geochemically active, sediment-water interface boundary (SWIB) layer 2-12 cm thick. As shown by the results, the small thickness (up to 4 cm) of the layer corresponds to low nodule abundance. The increase in the layer's thickness is usually accompanied by the increasing abundance. No relationship between a specific genetic nodule type or their metal content and the active layer thickness has been found.

- No clear-cut relationship between the nodule occurrence and the thickness of the seismoacoustic complex A has been found either; the thickness of the complex varying from 0 to about 20 m. Changes in the thickness bear not relationship with nodule abundance on the seafloor. No relationship between domination of a particular genetic nodule type, or increased metal content, and the complex thickness has been found.
- The eastern area of the Clarion-Clipperton nodule region carries nodules belonging to the two basic genetic nodule types, Hs and Dr, co-occurring with an intermediate types HD and Dr₁. As a rule, the nodules are embedded in the sediment –water interface layer and partly blanketed by contemporary deposits. The presence of blanketed nodules was revealed at about 70% of the sites. The extent of blanketing (index R) was found to increase with depth from the north to the south, conforming to the change in CCD. At the CCD of 4200 m, dominant are small (2-4 cm) spheroidal, smooth nodules belonging to type Hs. Below that depth, as a rule, discoidal, larger (6-12 cm) nodules with rough surface are found. The general north-south increase in depth is accompanied by a decrease in the proportion of Hs and Dr nodules of 8 cm modal diameter, the contribution of Dr₁ nodules of 4-6 cm modal diameter gradually increasing.
- The highest nodule abundance, at a high frequency of their occurrence, was recorded within the depth range of 4300-4500 m. The north-south depth increase is accompanied by a certain pattern of change in the nodule metal content. The maximum contents of Ni and Co are found in the nodules present in the north part (nodule types Hs and HD); increased Cu contents are observed in nodules present in the central part (nodule type Dr₁), the Mn content increasing clearly in the nodules present in the south part (nodule type Dr). Parameters of nodules present in the eastern area of the Clarion-Clipperton nodule region change in the following order: Co-Ni-Cu-Mn – abundance.
- Nodule distribution on the seafloor and their coverage are extremely diverse. Contours, size, and form of the deposits are determined by the seafloor relief. Borders of streaked deposits, 2 - 10 km wide, and up to several tens km long, coincide with contours of rises and depressions in the seafloor, usually with steep slopes. On the other hand, patchy deposits, about 70 km wide and up to 120 km long, occur on a level bottom. The deposit types are highly variable, both in terms of size and in terms of nodule distribution within them.

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