Deep sea exploration for metal reserves – objectives, methods
and look into the future

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Abstract. Polymetallic nodules, as one type of deep sea mineral resources, are composed mainly of manganese and iron hydroxides. But they are economically attractive especially due to their high concentrations of trace metals such as Ni, Cu, Co and Mo and, lately also rare earth elements. The enrichment of metals in nodule is either hydrogenetically by the precipitation of metals from the seawater or through release from the interstitial spaces in the underlying sediments, or by a combination of both. Nodule fields can be explored by remote and contact methods. Interpretation of echosoundings helps to watch how looks the topography of the seabed and what is hidden beneath it. Photo-profiling discovers the level of nodule coverage of the sea bottom as well as reveals obstacles for nodule collector. Box corer sampling, as a contact method, provides full scale geological and geotechnical information about the site with nodule abundance. The IOM has prepared 5 preferential exploitation blocks for detailed exploration. Detailed exploration will include swath mapping, hydro-acoustic and photo-profiling, bottom sampling and *in situ* carried out geotechnical soundings.

Introduction

For Interoceanmetal Joint Organization (IOM) and its predecessor the history of prospecting of polymetallic nodule fields on the seabed of the eastern part of the Clarion-Clipperton zone started at the beginning of 80's last century at the area of more than 500 000 km^2. In 1987, the year when the IOM was established, the prospecting and exploration was conducted at 300 000 km^2. In 1991 the IOM became so-called pioneer investor with the area for exploration 150 000 km^2, one half of which it relinquished for the benefit of International Seabed Authority (ISA). In 2001 the IOM signed 15 years contract for exploration with ISA for the area of 75 000 km^2 (Fig.1).

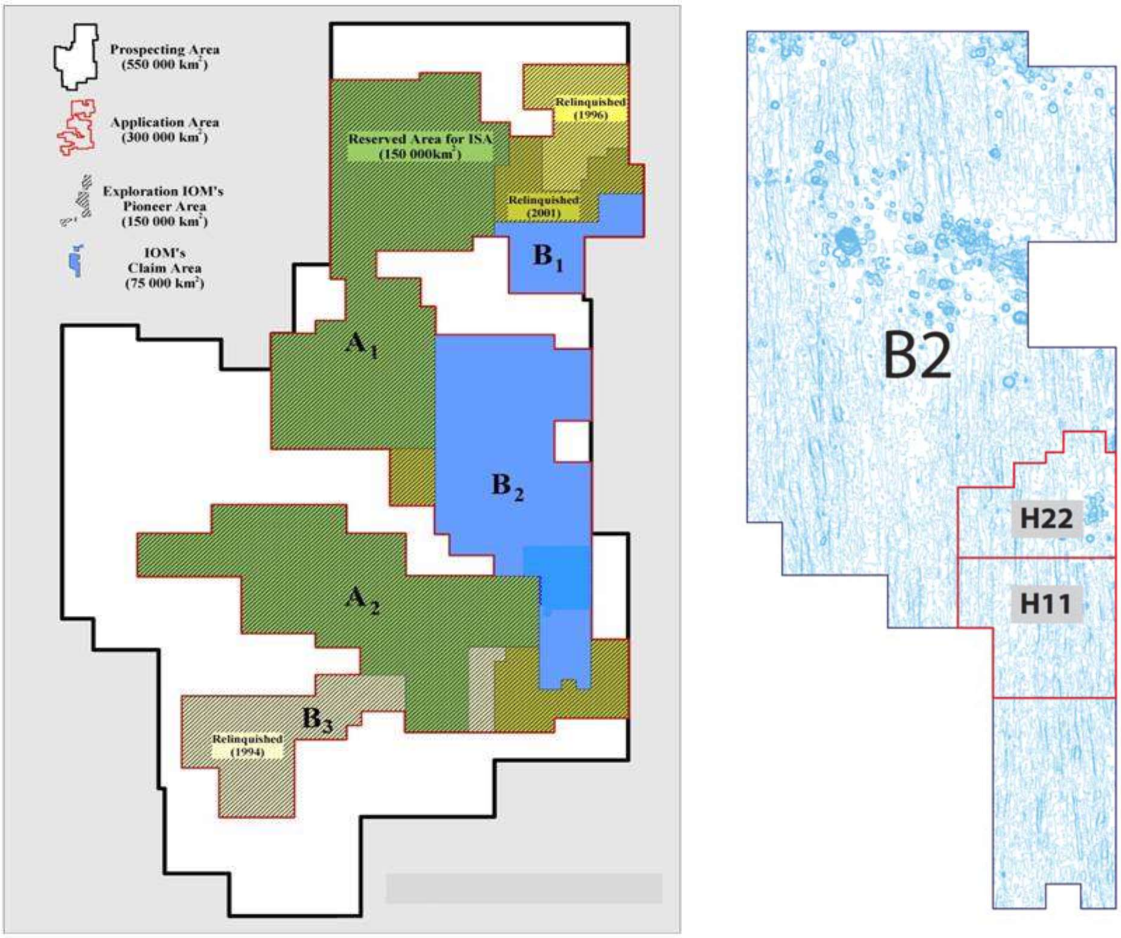


Fig.1. The prospecting and exploration areas of the IOM.

In a nutshell, polymetallic nodule looks much like a small potato except for being black, it is composed mainly of oxides and hydroxides of Mn, Fe, however, there are trace metal contents such as Ni, Cu, Co and Rare Earth Elements (REE) that attract to mine these deposits to meet the growing demand for these metals. The nodules vary in size from micro-nodules to about 20 cm, the common size being two to eight centimeters. They occur abundantly as 2 D deposits at the unconsolidated sediment-water interface, and sometime buried in sediments at different layers. They occur in areas of extremely low sedimentation rate. As a rule nodules require a nucleus to start forming. This nucleus could be old nodule piece, basalt debris or shark tooth. The enrichment of metals around the nucleus is either hydrogenetically by the precipitation of metals from the seawater or through release from the interstitial spaces between the underlying sediments, by early digenetic process or by a combination of both.

1. Methods applied for deep sea exploration and examples of interpretations

For the exploration remote and contact methods are recognized. Sonars, using sound waves, belong to remote methods. There are two main types of sonars; multibeam sonars for mapping bathymetry, and sidescan sonars for mapping seafloor imagery. Multibeam sonar, attached directly onto the vessel, measures the time it takes for a pulse (120 kHz) to be reflected back and it is useful in determining the depths of the seafloor while sidescan sonar, mounted on a towfish device, measures the strength of pulse that is returned. The side scansonar works at 34 kHz frequency. It is usually coupled with a 3.5 kHz frequency profiler. Such frequency is less attenuated when passing through the sediment.

With acoustic imagery swaths up to 16 km wide and a survey speed of 8.5 knots, multibeam sonar can image up to 250 km^2 per hour. From multibeam echosounding a bathymetric image and a backscaterred signal image can be derived. As for the IOM exploration area the topography of the sea bed is represented by raised and immersed blocks, deep troughs, horsts and grabens, strictly north-south oriented (Fig.2).

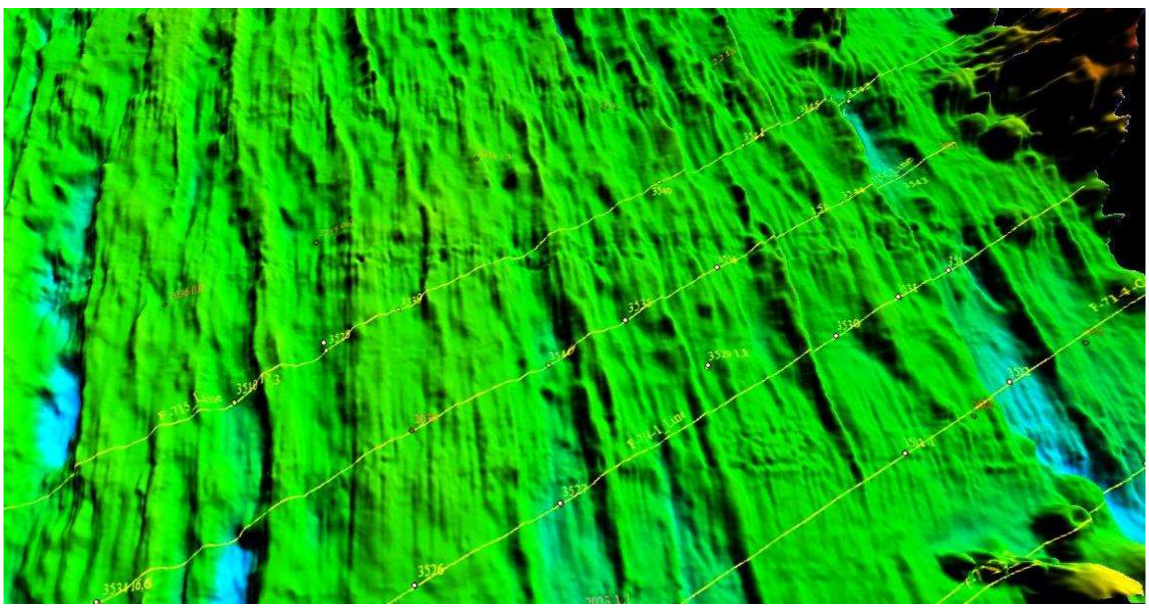


Fig.2. Topography of the fragment of the IOM exploration area.

Backscaterred signal helps to determine basement outcrops, volcanoes, soft nodule free areas and nodule rich fields (fig.3).

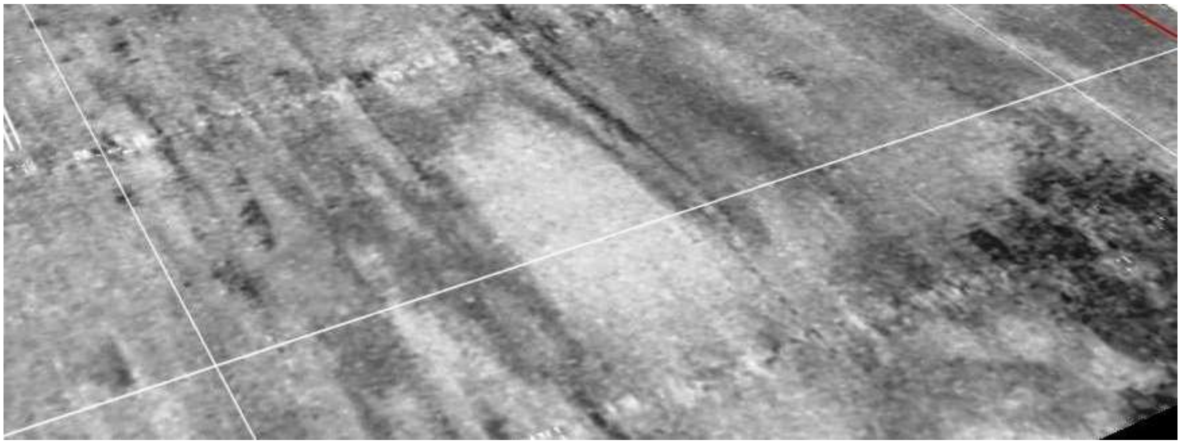


Fig.3. Basement outcrops (dark color at right) and a nodule free area (light in the centre).

The hydro-acoustic system employed by the IOM is capable of covering an about 1000 m seafloor area on either side of the towfish, while the profiler has a capacity to penetrate the sedimentary cover down to 150 m which is sufficient for the IOM area where it no more than 100 m thickness of the sediments is expected. There are subsurface interfaces reflecting a part of the acoustic waves penetrating beneath the seafloor. Interpretation of hydro-acoustic profiles helps to watch how looks the topography of the seabed and what is hidden beneath it. It can be distinguished 4 hydro-acoustic facies: transparent A and C, stratified B and massive basement F. The A facie can somewhere further be divided in A1 and A2 with a border constituted probably by zeolitic or argillaceous crust (fig.4).

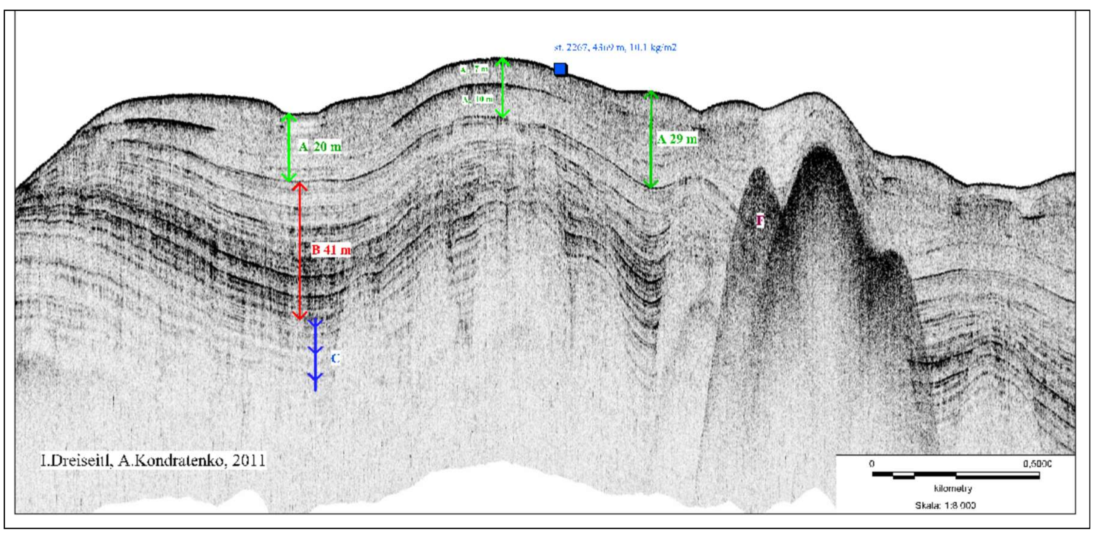


Fig.4. Interpretation of standard hydro-acoustic profile.

The knowledge of the sea bed surface (topography and nodule occurrence) is enriched with results of photo- video profiling. The device (Neptun C-M1, Russia) is towed on a coaxial cable 8 km long. The speed of the vessel during operation is 1-1.2 knots. The intervals between snapshots are 30-40 seconds. The particular photo is taken only when the device is 4 m above the seafloor what ensures uniform picture area 5 m^2. Parameter “nodule coverage” for any photo is calculated using a special software. For comparison two examples of nodule coverage are brought (fig.5).

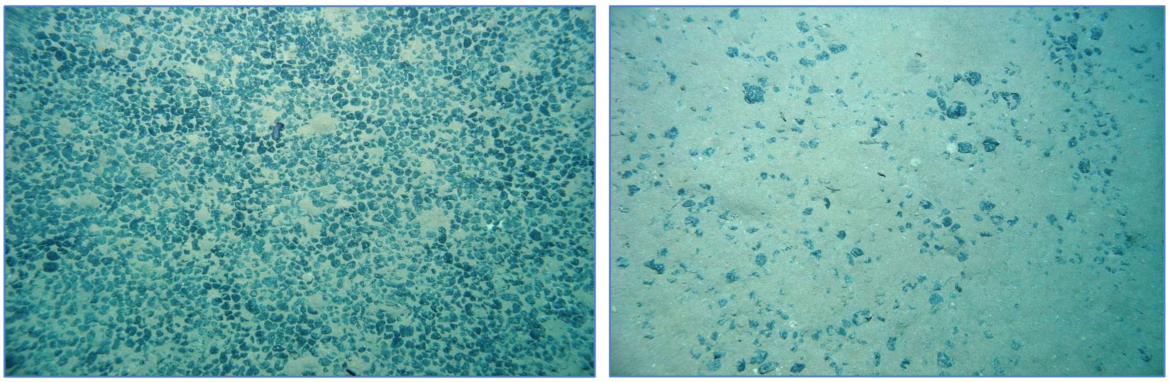
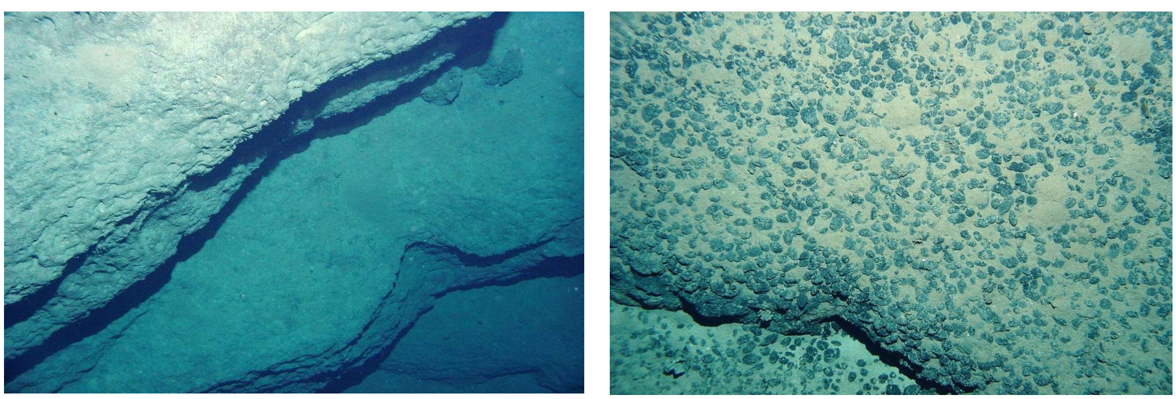


Fig.5. Calculated nodule coverage: left – 68 %, right – 13 %.

Photo-video profiling reveals also non favorable areas for mining. They are formed by solid rock (nanofossil carbonates or basalts) with multi steps in meters (fig.6a). Another example of non favorable area is following: although abundant of nodules, lava outcrops make it complicated (fig.6b). Lava outcrops are poorly recognized in sonograms and method of photo-video profiling is the only way to detect them.



a b

Fig.6. Examples of non favorable areas for mining.

The combination of sidescan sonar surveys and photo-video profiling data and their simultaneous analysis makes it possible to reveal the true appearance of the seafloor and its underlying structure (fig.7). At the point 1 (left) the light-shaded elongated patch on the sonogram represents a soft sediment and a nodule-free area. Seabed photo left proves the area to be nodule-free. The acoustic profile crossing point 1 indicates the occurrence of an erosion canal 256 m wide and about 15 m deep. The absence of nodules can be explained by the fact that near-bottom currents that possibly eroded the canal prevent nodule formation.

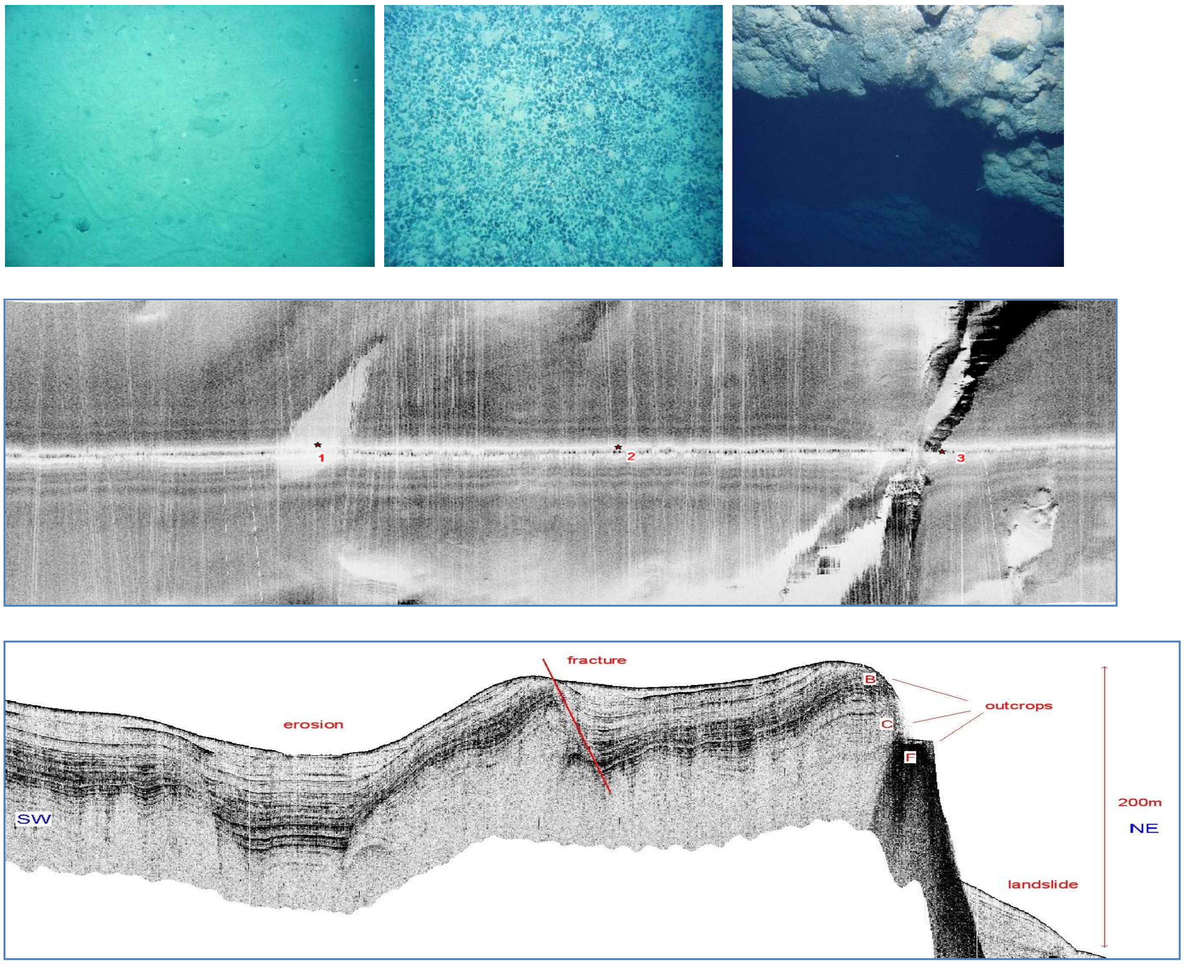


Fig.7. Simultaneous analysis of the seafloor photo, sonogram and profiler.

Point 2 (centre) indicates an undulating plain with rich nodule occurrence, i.e. the area favourable for mining. Point nr 3 reliably reveals dangerous zone of solid rock outcrop forming steep cliff (about 200 m high) in all three images.

The most important <u>contact method</u> is box corer sampling with which the huge knowledge both on nodules and sediments can be obtained. In the IOM exploration area all three genetic types of nodules occur. Hydrogenetic type (fig.8) is characterized by its small size and smooth surface. These properties are seen in at-spot seabed photo, inside the box corer and also on the grid. But the main indicator for hydrogenetic nodule is its chemical composition: low manganese x high iron, low ratio Mn/Fe. On the grid different morphological types are seen: ellipsoidal E, discoidal D, accreted (multi-nuclear) P and the fragments f of all.

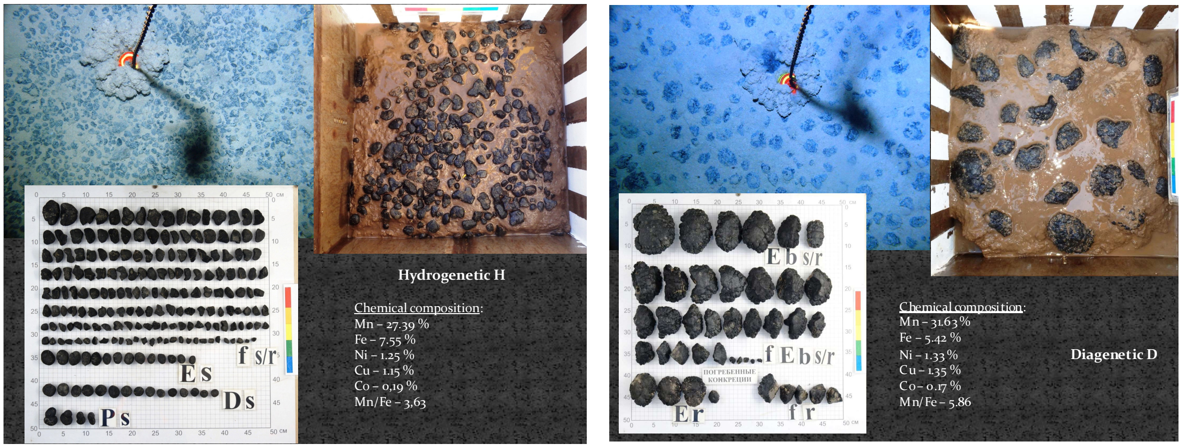
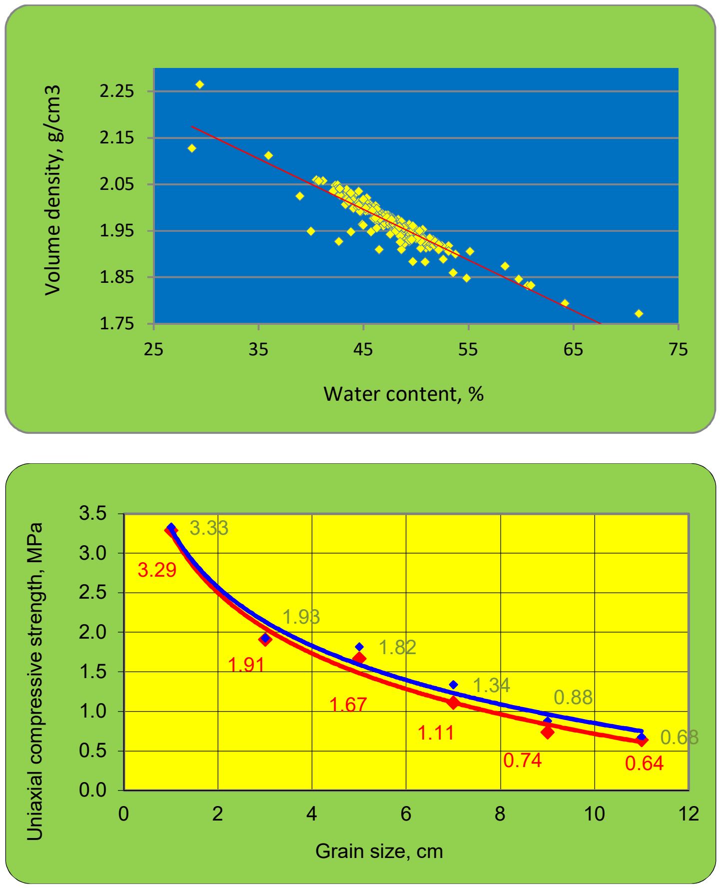


Fig.8. Box corer sampling with hydrogenetic (left) and diagenetic (right) nodules.

Diagenetic nodules (fig.8) are bigger in size, often more than 10 cm in diameter, smooth on upper side, rough on the contact with sediment. They have different chemical composition, high manganese x low iron and high ratio Mn/Fe. If occur, buried nodules (fig.9) are deployed on the grid with a label of morphological type and character of surface (fig.8). Nodules can be buried in a result of e.g. landslides. At a couple of box corer stations in the IOM area up to 3 depth levels with buried nodules were found.

Fig.9. Buried nodules in box corer found at the depths 20-25 cm.

Box corer sampling provides also geotechnical data of nodules and sediments. Volume density and water content of nodules are the main physical properties (fig.10) which can be determined straight in a vessel laboratory. There exists a relationship between these two parameters: the more the density, the less the water content. For nodules the density varies from 1.85 to 2.05 g/cm^3 and water content from 40 to 55 %.



Kondratenko, 2011

Fig.10. Geotechnical properties of nodules, physical (up), mechanical (below).

Uniaxial compressive strength, expressed in MPa, is a single mechanical (strength) property that is routinely determined in a vessel laboratory. The property expresses the amount of stress that needs to be applied to break a nodule. The property is not dependent on nodule genetic type or nodule morphotype. There is the grain size what plays the main role. There are some generalities observed: the smaller the nodule, the higher the compressive strength value (fig.10)and, the spheroidal nodules are harder than the discoidal and/or the ellipsoidal ones.

IOM also conducts gravity corer sampling. This technique enables to obtain a geological knowledge about sediment layers below the sea bottom, including physical and strength properties of the sediment, down to 3-4 m. Based on the results of 8 gravity corer analysis the cross section was built (fig.11).

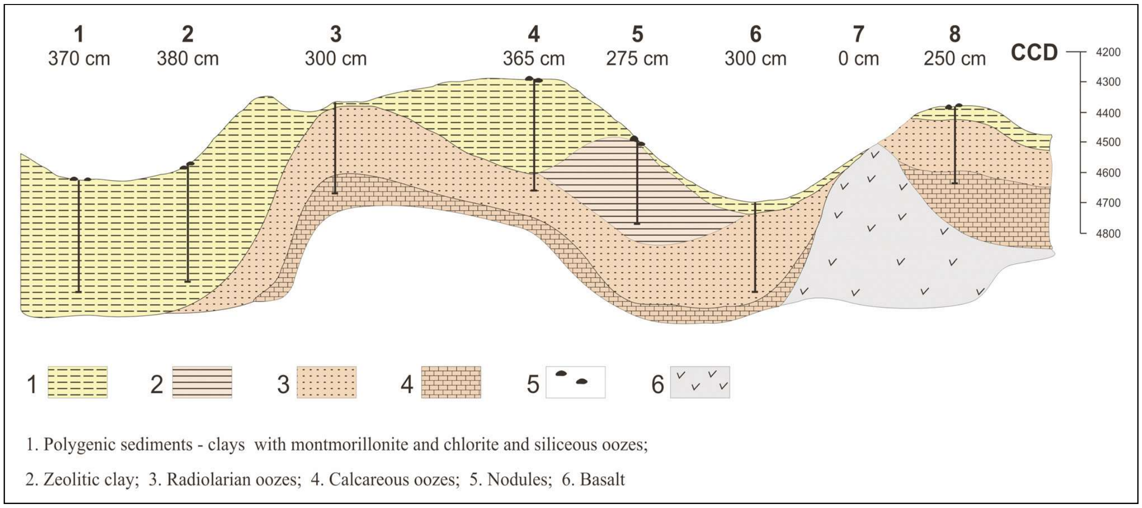


Fig.11. The cross-section through the uppermost part of the sedimentary cover, compiled on the base of gravity corer data (Zadornov, 2001).

Up to 7 stations provided full scale information about sediments near the sea bottom from depths of 0-380 cm except of station No 7 where the corer badly hit the lava outcrop (fig.11).

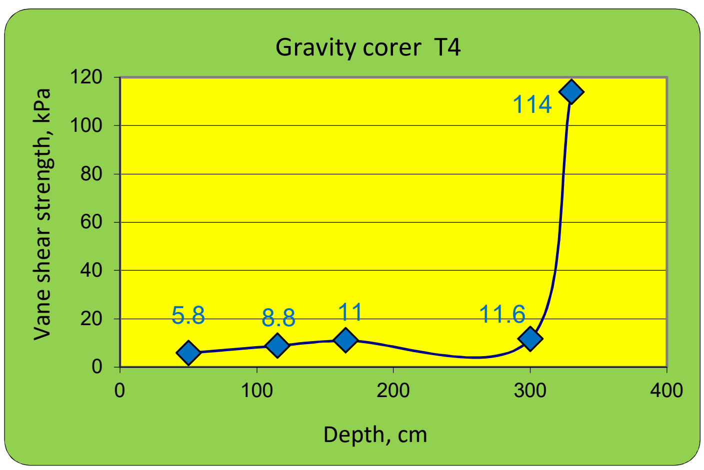


Fig.12. Development of vane shear strength in station T2.

The replacement of siliceous clays with substantially solid radiolarian oozes at the depth 330 cm at station T4 represents the curve at fig.12 where the values of vane shear strength increased more than 10x. The effect of the change of sediment type is documented in the cross-section at the point 4 (fig.11).

Another contact method, the trawling (dredging) is applied to obtain the large scale sample of nodules for metallurgical experiment. During the cruise IOM-2014 more than 2300 kg of wet nodules from 4 trawling operations were extracted.

2. Delineation of preferential exploitation blocks and ore bodies

Having used above mentioned methods and having processed all the data obtained during 15 years and more the IOM drew up the map of preferential exploitation blocks (PEB), fig. 13. (red hatched areas).

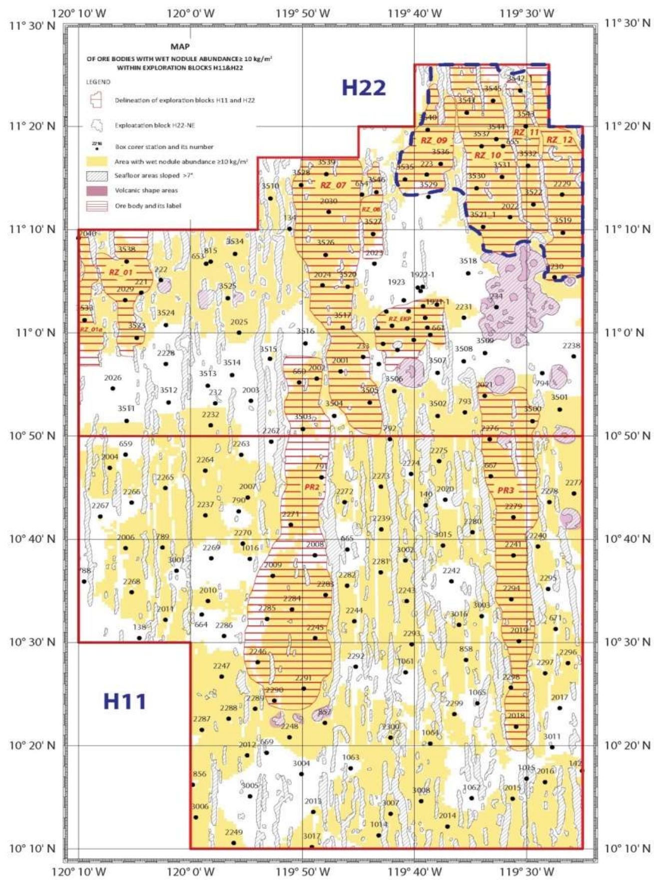


Fig.13. Map of preferential exploitation blocks.

The characteristics of the particular exploitation blocks show table 1. The main column in the table is that with the resources. The resources were estimated using geostatistics, the Kriging method.

Table 1. The main characteristics of PEB's

	Area, km^2	Number of stations	1 station per __ km^2	Wet nodule abundance, kg/m^2	Resources wet, mil. ton	St. error ε_R, %
H22_NE	627.6	20	31	15.7	9.9	10
H22_MID	537.3	23	23	15.5	5.7	11-28
H11_PR2	564.9	12	47	13.0	6.2	13
H11_ PR3	358.8	9	40	15.5	4.2	12
H22_NW	179.2	5	35	14.2	2.4	20-28
∑PEB	**2267.8**	**69**	**35.2**	**14.8**	**28.4**	

In accordance with CRIRSCO classification an about 28 mil. metric tons of indicated wet nodules is prepared for detailed exploration and, afterwards, for commencing of mining operations.

The most promising PEB is believed to be the H22-NE (fig.14). That block consists of 4 ore bodies: RZ_09, 10, 11 and 12. Its total area of 628 km^2 was fully covered by swath mapping (bathymetry), 100 km of photo-profiling in 5 profiles (bold lines) was carried out on which 20 box corer stations at depths from 4249 to 4501 meters were deployed. From RZ_10 and RZ_12 more than 2 metric tons of nodules were extracted. In the block diagenetic type of nodules prevails.

Ore body RZ_10 itself (fig.14) represents an undulating area complicated by north-south oriented mini-ridge in its central part which in the southernmost part disappears. It has an area 255 km^2, it is further crossed by 4 photo-profiles with total length 32 km. 9 box corer stations have been deployed within the ore body since 2001 with depths ranging from 4272-4386 m. Mean nodule abundance: 16.5 kg/m^2, wet resources: 3.9 mil. ton of mostly diagenetic type. In the northernmost part of ore body a hydrogenetic-diagenetic type occurs. Coefficient of blanketing varies from 1.0 (no blanketing) to 1.6.

As an example the profile 714 crossing askew RZ_10 is brought (fig.15). The green outline confirmed undulating plain feature complicated by mini-ridge in the central part. Red curve above at fig.15 displays nodule coverage obtained from photo-profiling. It is evident that the surface of mini-ridge is practically nodule free. On the other hand, the flat passages of the profile are nodule abundant with nodule coverage 50-70%. Two box corer stations on this profile are located with promising nodule abundance 16 and 17 kg/m^2 which corresponds to 50-60 % of nodule coverage from images of photo-profile. Taking into account the skewness of the profile the width of strips rich of nodules at this profile extends to 2-3 km (and 20 and more km in length) which is suitable for effective exploitation of nodule fields.

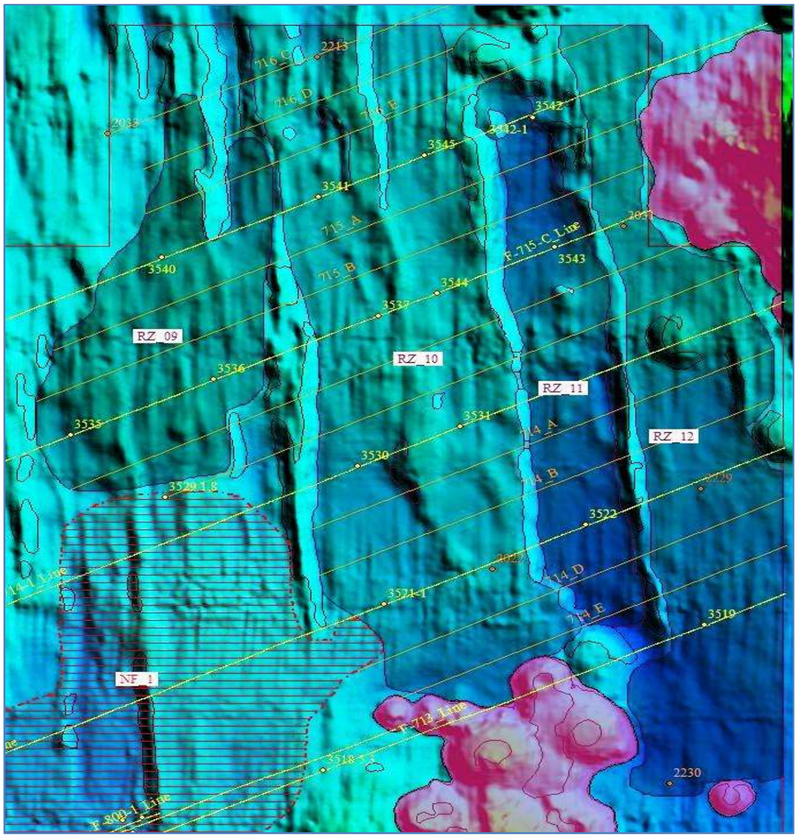


Fig.14. Four ore bodies of H22_NE.

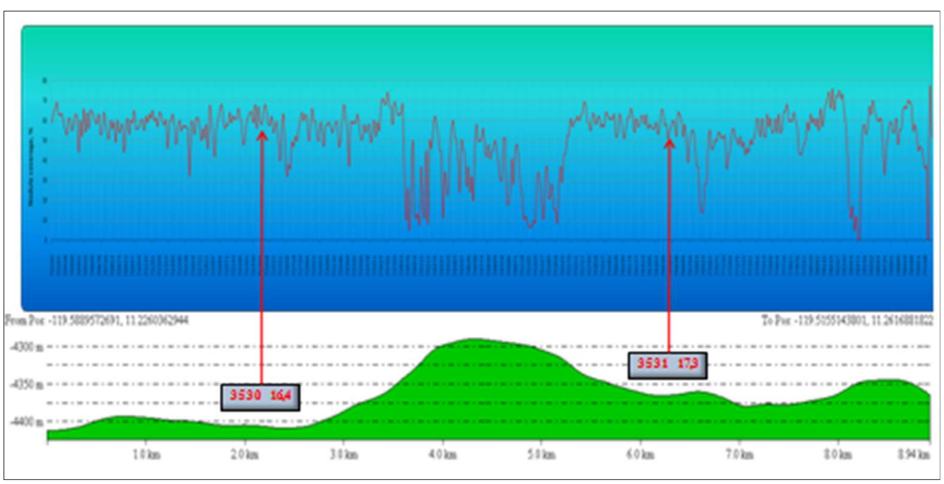


Fig.15. Topography (green) of profile 714 crossing the RZ_10 with nodule coverage (red curve).

Conclusions

1. The remote and contact methods for prospecting and exploration of polymetallic nodule fields used in the IOM are presented.

2. Only simultaneous interpretation of both can give satisfactory results.
3. The proper graphic software should be applied to display all the results in the set of well arranged maps (e.g. MapInfo and Global Mapper in the IOM).
4. To complete the phase of exploration in the IOM exploration area there have already been drafted new additional hydro-acoustic and photo-profiles (thin lines at fig.14). Afterwards new box corer stations will confirm the assumptions come from hydro and photo-profiling. Gravity corer sampling enables to build geological cross-section crossing at least two ore bodies of H22_NE. Geotechnical sounding *in situ* will test the bearing capacity of the sediments essential for perfect work of nodule collector.

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