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METALLOGENESIS OF THE WORLD'S OCEAN AGAINST THE BACKGROUND OF OCEANIC CRUST EVOLUTION

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In honour of Arvid Pardo of Malta

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Abstract. This paper presents results of the studies on the metallogenesis of the deep-sea mineral resources and their sedimentary environment. Connections between the structure and evolution of the oceanic crust, with regard to the rules of occurrence and distribution of the ores, have been established. Main sources of the material delivered to the ores' forming places and dominating types of processes and environmental factors determining the character of components' concentration in the ores have been recognised. Basing on the obtained results, the present author's own concept of metallogenic systematic of the world's ocean, distinguishing morphotectonic megaprovinces, metallogenic provinces and ore formations has been presented. All these units have their own specificity resulting from differential intensity of tectonic-magmatic and sedimentary processes controlled by groups of factors differing regionally and locally. The key differentiating factors include sources, and more precisely mutual relations between the kind and amount of allogenic and authigenic components delivered to different oceans, distance away from endogenic sources, depth, and morphotectonics of the sea floor, physical and chemical properties of the near-bottom and pore waters, as well as the specific structure and dynamics of the sea water masses. It is demonstrated, against the background of oceanic crust evolution which began about 170 million years ago and proceeded in 4 stages which were different in the Indo-Pacific and Indo-Atlantic areas, that generation of ore deposits was mostly affected by processes operating during the last stage of crust evolution. The manganese metallogenic period is related to the youngest, Alpine geotectonic period in the history of the Earth. Of key importance were here sub-volcanic and volcanic processes taking place at the fracture tectonic phase, during the terminal magmatism. Metallogenic provinces were distinguished within two major morphotectonic megaprovinces (Indo-Pacific and Indo-Atlantic). Within each of these metallogenic provinces, the following major ore deposit formations were distinguished:

— manganese nodule formation, controlled by the domination of hydrogenic and hydrogenic-diagenetic processes,
— polymetallic sulphide formation, affected mainly by subsea floor processes in active hydrothermal systems,
— phosphorite nodule formation, produced mainly by biohydrogenic processes,
— heavy minerals formation, resulting from mechanogenic processes.

It is showed, that the ore deposits formations are regionally differentiated. Regions embrace groups of the ore deposits named subformations. Within the subformations fields have been distinguished. In the ore deposits fields the types of ore deposits have been distinguished.

The present paper is a synthesis of the present author's long-term studies on the metallogenic systematic of the world's ocean. Results of the studies on the oceanic deposit ores are included in the monographic papers, such as: "Geology and mineral resources of seas and oceans" ("Gieołogija i mineralnyje resursy moriej i okieanow" — in Russian — 1990), "Mineral resources of seas and oceans" ("Surowce mineralne mórz i oceanów" — in Polish — 1998), "Explanatory Note — Metallogenic Map of the World Ocean" — 1998, and numerous Polish and foreign publications quoted in this paper.

Key words: metallogenic systematic, morphotectonic megaprovinces, metallogenic provinces, ore deposit formations (regions and fields).

Abstrakt. Na tle ewolucji skorupy oceanicznej przedstawiono wyniki badań metalogenezy głębokowodnych złóż kopalin oraz środowiska ich sedymentacji. Ustalono związki pomiędzy budową i ewolucją skorupy oceanicznej z uwzględnieniem prawidłowości występowania i rozmieszczenia tych złóż. Rozpoznano także główne źródła materiału doprowadzanego do miejsc formowania kopaliny oraz dominujące grupy procesów i czynników środowiskowych determinujące charakter koncentracji składników w złożach. W oparciu o uzyskane wyniki badań przedstawiono autorską koncepcję systematyki metalogenicznej wszechoceanu, wyróżniając megaprowincje morfotektoniczne, prowincje metalogeniczne i formacje złożowe. Odznaczają się one swoistą odrębnością, będącą efektem zróżnicowanej intensywności przebiegu procesów tektoniczno-magmatycznych i sedymentacyjnych, kształtowanych na poziomie regionalnym i lokalnym, przez odmienne grupy czynników. Decydującym czynnikiem wyróżniającym są źródła, a ściślej wzajemne relacje pomiędzy rodzajem i ilością materiału allochtonicznego i autochtonicznego doprowadzonego do poszczególnych oceanów, odległość od źródeł endogenicznych, głębokość oraz charakter morfotektoniczny dna oceanicznego, właściwości fizyczno-chemiczne wód przydennych i porowych, a także swoista struktura i dynamika wód oceanicznych. Na tle ewolucji skorupy oceanicznej, której formowanie rozpoczęło się około 170 mln lat temu i przebiegało w czterech etapach — odmiennie w obszarze Indo-Pacyficznym i Indo-Atlantyckim — wykazano, że decydujący wpływ na formowanie złóż miały procesy zachodzące w ostatnim etapie przeobrażeń skorupy. Manganowy okres metalogeniczny związany jest z najmłodszym, alpejskim cyklem geotektonicznym Ziemi. Decydujące znaczenie miały przy tym procesy subwulkaniczne i wulkaniczne przebiegające w stadium tektoniki załomowej, w okresie magmatyzmu końcowego. W obrębie dwóch głównych megaprowincji morfotektonicznych (Indo-Pacyficznej i Indo-Atlantyckiej) wydzielono prowincje metalogeniczne. W każdej z nich rozpoznano następujące główne formacje złożowe:

— manganową formację konkrecyjną, odznaczającą się dominacją procesów hydrogenicznych i hydrogeniczno-diagenetycznych;

— polimetaliczną formację siarczkową, z dominacją przypowierzchniowych procesów w aktywnych systemach hydrotermalnych;

— fosforytową formację konkrecyjną, z dominacją procesów biohydrogenicznych;

— formację minerałów ciężkich, z dominacją procesów mechanogenicznych.

Wykazano, że formacje złożowe są regionalnie zróżnicowane. Regiony obejmują grupy złóż nazwane subformacjami. W ich obrębie wydzielono pola złożowe. W polach rozpoznano typy złóż.

Niniejsza praca stanowi syntezę wyników wieloletnich badań autora w zakresie systematyki metalogenicznej złóż wszechoceanu. Wyniki badań złóż oceanicznych zawarte są w opracowaniach monograficznych, w tym: „Gieołogija i mineralnyje resursy moriej i okieanow” — 1990, „ Surowce mineralne mórz i oceanów”— 1998, „Explanatory Note — Metallogenic Map of the World Ocean” — 1998 oraz w licznych publikacjach krajowych i zagranicznych cytowanych w niniejszej pracy.

Słowa kluczowe: systematyka metalogeniczna, megaprowincje morfotektoniczne, prowincje metalogeniczne, formacje złożowe (regiony i pola złożowe).

INTRODUCTION

Sea floor sediments are a vast and not fully tapped source of a variety of raw materials of commercial value. As terrestrial resources are bound to be ultimately exhausted, those occurring on the sea floor constitute an ample and convenient alternative. It has been predicted (Lenoble, 1993) that the 21st century will bear witness to a large-scale incorporation of those resources into the world's economy. At present, the most important raw materials derived from sea floor deposits include oil and gas, heavy minerals, construction and chemical materials, and drinking water. Those resources occur, as a rule, in shallow water, whereas polymetallic deposits are formed in the deep-sea (Depowski *et al*., 1998; Kotliński, 1997b, 1998d, e,1999).

In the present paper, a metallogenic systematic of the world's ocean deposits has been presented. Mutual relations between material's sources, and processes and factors determining rules of the origination of a given type of ore deposit, have been accepted as a basis of the proposed metallogenic system. Relations between sources of deposit's components and character of metals' concentration on the one side and geological processes on the other side, have been ascertained. Processes and factors which contribute, under certain sedimentary conditions, to the formation of genetically different ore deposits (for example deep-sea manganese nodules or polymetallic sulphide ore deposits in the rift valleys), have been recognised. The revealed connections between origination and distribution of the deep-sea ore deposits are of a considerable practical importance, because one can use that knowledge to ascertain regional circumstances and criteria for conducting geological prospecting of new ore deposits. Obtained results are also of a great importance for the application of effective methods and recognition of the deep-sea oceanic ore deposits within a reasonable scope.

Detailed studies on the deep-sea manganese deposits have been applied in the case of eastern part of the Clarion-Clipperton Ore Field in the Pacific (Kotliński, 1992, 1993, 1996, 1998b; Kotliński *et al.*, 1997). Besides direct results of studies performed during high sea cruises and sample analyses, results of regional studies published with the present author's contribution in monographic papers (Dimov *et al*., Eds., 1990; Andreev *et al*., Eds., 1998; Depowski *et al*., 1998) have been used in this paper.

The present author's intention has been to present a rational approach to the systematic proposed, i.e., to define connections between the concentrations of ore components in the commercially most promising fields. Here the detailed quantitative data were used. Results of the studies, varying in the extent of insights into different groups of the ore deposits, served as a basis for a comparative analysis of the deposit formations identified.

I would like specially to express my warmest thanks to prof. Marian Banaś and prof. Stanisław Speczik for their encouragement to undertake a synthesis of my works covering the metallogenesis of the oceans' deposits, and for continuous interest in progress of my studies. I would like to thank dr. G.P. Glasby and dr. A. Usui for discussions and sending me results of their most recent studies. I also thank academicians: prof. I.S. Gramberg, prof. L.I. Krasny, prof. E.F. Szniukov, and dr. S.J. Andreev, dr. G.G. Tkatchenko as well as prof. I.F. Glumov, prof. Yuwei Li, prof. C.L. Morgan, dr. J.P. Lenoble, dr. B. Winterhalter from the Legal-Technical Commission of the International Seabed Authority (ISBA) for discussions during working out of the materials. Its final shape the present paper owes to critical remarks of prof. Marian Banaś, prof. Krzysztof Jaworowski, prof. Alina Kabata-Pendias, prof. Stanisław Musielak, prof. Stanisław Speczik and dr. Krzysztof Szamałek.

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AIM AND METHODS OF THE STUDIES

Synthesis of the regional studies, leading to the establishment of systematics and characteristics of the ore deposits identified, as well as to the definition of their relations and genetical distinctness of their origination, was a main object of the present paper. It involves recognition and evaluation of the processes of forming of the ore deposits dominating in a given area, as well as their dependence on the sources of the components and local factors determining sedimentary conditions of their deposition. Classification criteria applied generally to the land ore deposits (Rukhin, 1969; Szatskij, 1954; Roy, 1986; Paulo, 1981; Strakhov, 1986) provided a starting-point for the present studies.

It was accepted, that recognition of the rules of forming and origin distinctness of deep-sea polymetallic deposits is of a paramount importance for the systematics of these deposits.

The following key, discriminating factors have to be taken into account:

— morphotectonic characteristics of oceanic basins, such as its size, shape and bathymetric parameters, age and structure of basement and sedimentary cover — all those shaped by tectonic activity of the oceans' bottom, activity of magmatic processes (including hydrothermal and volcanic ventic ones), as well as by a quantity of material delivered from the surrounding continents;

— main sources of origin of both authigenic and allogenic material, including mutual relations between kind and quantity of the components and mechanisms of transport and sedimentation;

— main factors controlling environmental conditions, including physical and chemical parameters of the near-bottom and pore waters, such as thermodynamics, oxygenation, pH and redox potential (Eh), microbial activity, as well as structure and dynamics of the oceanic waters, such as depth of the level of minimum oxygen content, interval of depth of a calcium carbonate compensation level (CCD) and silica compensation level (SCD), sedimentation rate, waters' biological productivity, current velocity, presence of oceanic divergence or convergence;

— spatial and morphometric characteristics of deposits, such as location and depth of the deposits' occurrence on the sea bottom, surface area covered and lithostratigraphical position of the ore deposits in relation to the surrounding sediments;

— metal concentration as well as mineral and geochemical variability of components in the given ore deposits.

During working out of the systematic of the ore deposits, special attention was paid to the recognition of the main processes leading to the concentration of metals in the ore deposits. Relations between the variability of mineral and geochemical content, and texture and structure from the one side, and conditions of the ore deposits occurrence from the other side, has been studied. Relations between distribution of the ore deposits in the oceans, as well as within the certain bottom's morphostructural units, has been investigated. The ore deposits formations have been distinguished. They embrace the regionally differentiated groups of deposits of a given ore deposit.

SCOPE OF THE STUDIES AND BASIC SOURCE DATA

The present author commenced the regional geological-prospecting studies of the deep-sea nodule deposits in 1988. In the first period they were aimed at the distinguishing of most perspective prospecting areas in the Pacific and Indian Ocean, basing on the accessible results of the regional studies. Basing on the comparative studies, an area located in the eastern part of the Clarion-Clipperton Field in the Pacific was selected. Detailed results of the geological-prospecting studies performed in this area of 540,000 km^2, served to evaluate of geological-mining conditions of the minable areas of nodule deposits (Kotliński, 1992, 1993) and allowed selection of the most commercially promising nodule-bearing area as well as elaboration of effective methods and technology and scope of the geological-documentary works (Kotliński *et al*., 1991). Geological documentation of the nodule distribution, abundance and chemical composition in the area as large as 300,000 km^2 has been worked out. This documentation was a basis for registration of the pioneer area 150,000 km^2 surface area by the Interoceanmetal (IOM) in 1991, according to the United Nations Convention on the Law of the Sea. Scope and obtained results of the studies are included in classified documentation of the ore deposits, as well as in the mentioned publications (particularly in the monograph "Mineral resources of seas and oceans" — Kotliński, Szamałek, Eds., 1998).

Simultaneously, regional studies commenced in the Branch of the Marine Geology of the Polish Geological Institute and aimed at the recognition of the occurrence and distribution of the deep-sea resources have been continued. Complex analysis of source materials, such as the data obtained during cruises and in the laboratories, as well as the published materials, particularly maps, has been performed. Results of the studies are included, among others, in the mentioned above monographs (Dimov *et al*., Eds., 1990; Andreev *et al*., Eds., 1998). Direct contribution of the present author to the mentioned works allowed collection and analysis of many new data. Geophysical data, as well as drilling data and results of the regional studies have been accepted as the basis for the presented metallogenic systematic of the ore deposits.

Bathymetry and bottom relief data, obtained from the world's ocean map 1:10,000,000 (in Mercator's projection, 45^o, 1983), served as a starting point for the present studies. Besides, the following map have been used as the basic ones:

— map of the nodule distribution in the world's ocean 1:23,230,000 (Rawson, Ryan, 1978);

— map of the mineral resources of the world's ocean 1:10,000,000 (Piper *et al*., 1984);

— map of the heat flow and hydrothermal ore deposits of the world's ocean 1:20,000,000 (Gramberg, Smyslov, Eds., 1986);

— map of the mineral resources and geomorphology of the world's ocean 1:25,000,000 (Gramberg, Ed., 1991);

— metallogenic map of the world's ocean 1:20,000,000 (Yegyazarov, Ed., 1989);

— map of the polymetallic mineral resources in the Japanese islands region, North-Western Pacific, 1:7,000,000: 1 — distribution and occurrence; 2 — chemical composition (Usui *et al*., 1994);

— scheme of the metallogenic zonation of the world's ocean 1:25,000,000, compiled against the background of bathymetric map 1:15,000,000 (Andreev *et al*., 1996).

Data included in the mentioned maps were used in the construction of the metallogenic map of the world's ocean 1:60,000,000, compiled against the background of the bathymetric data. Data regarding: distribution of bottom deposits (Horn, 1972; Rawson, Ryan, 1978); bathymetry with data about tectonics and heat flow parameters (Gramberg, Smyslov, Eds., 1986); tectonics with elements of geomorphology and metallogenesis (Yegyazarov, Ed., 1989; Andreev, 1994, 1995, 1997; Andreev *et al*., 1990, 1995, 1996, 1997); distribution of belts of magnetic anomalies (Berger, Winterer (*In*:) Seibold, Berger, 1993; Szlufik *et al.,* according Roeser, Rilat, 1995; Andreev, Gramberg, Eds., 1997; Andreev *et al*., Eds., 1998); thickness of sedimentary cover in the oceans (including results of the Deep Sea Drilling Project, Fisher *et al*., 1971; Gramberg, Ed., 1989); and data about the structure and dynamics of the oceanic waters (Druet, 1994; Humphris *et al*., Eds., 1995; Andreev, Gramberg, Eds., 1997; Zieliński, 1998), were taken into account. The data were useful for recognition of location of linear magnetic anomalies, their symmetry and age differentiation reflected, among others, by "ageing" of the ocean bottom outwards off the spreading centres, identification of the sequence of morphotectonic elements of the ocean bottom and their geomorphological changes. Classification of magmatic rocks of the crystalline complex and their chemical differentiation in relation to the geochemical processes in their source vents, as well as thickness, range and characteristics of occurrence of the recent deposit complexes, were considered (Morgan, 1972; Tanimoto, Anderson, 1985; Wylie, 1988; Busse, 1989).

Accessible results of geological-geochemical investigations of the deep-sea nodules (some 50,000 from 450 sources), polymetallic sulphide ore deposits (about 700 samples from 50 regions of their occurrence), metalliferous sediments (2000 samples), phosphorites (3000 samples), included in the papers of Frazer, Fisk, 1981; Menard, 1976; Cronan, 1977, 1982, 1997; McKelvey *et al*., 1979; Andreev, 1994; Andreev *et al*., Eds., 1998, were used as a basis for analysis of rules of the ore deposits formation and ascertaining of relations between concentration of the components. Results of the laboratory investigations of the sediment samples (1469 samples + 134 cores) and nodules, taken from the eastern part of the Clarion-Clipperton Field, embraced more than 25000 measurements and indications, as well as geophysical, photo-teleprofiling and other investigations. These results were described in earlier publications (Kotliński *et al*., 1991, 1997; Kotliński, 1992, 1993, 1996, 1998 b, c, d, e, 1999). Scope and methodology of the studies of marine deposits were presented by Depowski and Kotliński (*In*:) Kotliński, Szamałek, Eds., 1998).

The comparative method applied by the present author, enabled realisation of regional studies, leading to the recognition of rules of forming of the deep-sea polymetallic deposits from the structural-formation point of view. All the obtained data were used as a basis for elaboration and development of original concept of metallogenic division of the world's ocean. According to this division, the units of the following categories have been distinguished in the present paper:

— **morphotectonic megaprovinces**,

— **metallogenic provinces**,

— **ore deposit formations**, embracing groups of deposits (subformations) and ore deposit fields.

INTERNATIONAL LEGAL REGULATIONS OF CARRYING OUT PROSPECTING, EXPLORATION AND EXPLOITATION OF MINERAL RESOURCES

The universal rule of free access to the seas, commonly accepted from the XVII century onwards and restricting rights of the seaside states to the narrow zones of sea along the shores, had been changed in the first half of this century. One can point to both economical and political reasons of such a change in the legal status of the seas. They resulted from the seek of a rational exploitation of live resources and from the threat of uncontrolled pollution of the nearshore areas, as well as from the political-military reasons. Awareness of the occurrence of rich natural resources on the continental shelf areas, with their exploitation expanding further and further from the shore, became one of the crucial reasons of the new legal order. Number and diversity of the mineral resources exploited from the sea bottom increased from the sixties, due to the results of geological exploration. Expanding of the geological exploration into the deep-sea oceanic bottom areas meant transition to the qualitatively new stage of recognition of the mineral resources. This stage brought introduction of new methods and technology of exploration, which were characterised by unprecedented complexity and effectiveness. The most perspective kind of polymetallic resources among deep-sea deposits are represented by deep-sea manganese nodules, polymetallic sulphide ore deposits, cobalt-rich manganese crusts and metalliferous sediments (Kotliński, 1997a). This is the reason why the possibility of commercial exploitation of marine mineral resources constitutes important issue in securing by the seaside states their respective national interests (Kotliński, 1995a, b, 1997b).

New international legal order regarding the seas and oceans results from the outcome of the United Nations Conference I and II on the Law of the Sea, which was convened in Geneva in 1958 and 1960. In the result of these regulations, the legal rules securing interests of the seaside states, as well as the rules of delimiting of the 12 miles territorial sea have been established. In 1972, facing the incoherence of rules and inaccurate, often conflicting rules introduced to secure particular interests of seaside states, the United Nations adopted the initiative of Malta's UN Ambassador, Arvid Pardo, regarding adoption of an effective international legal regime over the seas and oceans, beyond a clearly defined national jurisdiction. The Commission of International Law has been established, which undertook the task of codifying of the sea law, leading to a complex and rational management of the marine resources. In 1973, the General Assembly of the United Nations took a decision to convene the Third United Nations Conference on the Law of the Sea. It ended nine years later with the adoption of the United Nation Convention on the Law of the Sea. The final act of the Third UN Conference on the Law of the Sea was signed by 119 states on 10th December 1982, in Montego Bay (Jamaica). Apart from reiterating the description of the territorial sea, the Convention defined also the continuous zone, the exclusive economic zone, and the high seas. The Convention states that the territorial sea may reach up to 12 nautical miles, while the continuous zone may extend up to 24 nautical miles away from the baselines. The coastal state enjoys full sovereignety over the sea bed underneath the internal waters and the territorial sea, whereas the exclusive economic zone gives to the coastal state the right to carry out surveying, prospecting, exploration, exploitation, and management of the resources within the zone.

According to Gadkowski (1998) who analysed the legal status of marine areas in the light of the international law doctrine and provisions of the Convention, those areas belong to one of the following three categories:

a) marine areas included into a state's territory, i.e., the territorial sea extending up to 12 nautical miles from the baseline;

b) marine areas subject to limited jurisdicion of a coastal state, i.e., the continuous zone and the exclusive economic zone, extending up to 24 and 200 nautical miles from the baseline, respectively;

c) marine areas beyond the coastal state's jurisdiction (the high seas) to which the principle of the "common heritage of Mankind" can be applied, particularly with respect to mineral resources on and beneath the sea bed.

The high seas, that is the so-called Area, begin 200 nautical miles off shore (the exclusive economic zone limit) or on the seaward shelf board, found up to 350 nautical miles away from the baseline from which the territorial sea breadth is measured.

Geological exploration of the deep-sea mineral resources in the Area is governed by appropriate regulations of the international law. The organization through which States Parties to the Convention shall organize and control activities in the Area, in accordance with the regime for the seabed and ocean floor and subsoil there of beyond the limits of national jurisdiction (the Area) particularly with a view to administering the resources of the Area is the International Sea Bed Authority (ISBA). The Authority is an autonomous international organization established under the 1982 United Nations Convention on the Law of the Sea and the 1994 Agreement relating to the Implementation of Part XI of the Convention (Sowiński, 1998). According to the state of 1st June 1997, the UN Convention of the Law of the Sea has been ratified by 134 States Parties (ISBA, 1997). According to the Resolution II of this Convention, the "pioneer investors" have the exclusive rights to carry out research in the registered pioneer areas. A status of the "pioneer investor" was given to France, Russia, Japan, India, China, South Korea and Interoceanmetal (IOM) (Kotliński, Wilczyński, 1994).

Significance of exploration of deep water mineral resources as an alternative to the many metallic deposits on land which are in short supply, has been confirmed in the practice. Many countries like France, Russia, Japan, South Korea, China and international companies, including IOM (Bulgaria, Czech Republic, Cuba, Poland, Russia and Slovakia), and OMA — Ocean Minning Association, OMI — Ocean Minning Incorporated, LMS — Lockheed Martin System Co. Inc. (combining capitals from USA, United Kingdom, Germany, Netherlands, Belgium, Australia, Canada) have already received explored and registered areas with nodules in the Clarion-Clipperton Fracture Zone in the Pacific Ocean. The government of India has got a registered pioneer area in the Indian Ocean, within the

Central Indian Field. Some of the states performed advanced studies on the polymetallic sulphide deposits and cobalt-rich manganese crusts (Japan, Russia, USA) or on the metalliferous muds (Germany). Taking into account actual possibilities of applying effective, automated exploitation systems (being intensively developed in some most developed countries), and possibilities of acquiring additional metals, such as molybdenum, zinc, titanium and Rare Earth Elements, or using the nodules as sorbents, the perspective of continuation of geological prospecting and other investigations of polymetallic deposits can be extended as an important task to the year 2020 (Pearson, 1975; Lenoble, 1993, 1996; Kotliński *et al*., 1997; Kotliński, Szamałek, Eds., 1998; Kunzendorf, 1998; Kotliński, 1998e).

The year 1998 has been proclaimed by the UN General Assembly as an “International Year of Oceans”, under a slogan “Oceans — common heritage for the future”. No doubt, on the verge of XXI Century, that the oceans will provide a vast source of many minerals, which as terrestrial resources are bound to be exhausted. The near future will show, to which extend these resources will be used. Protecting of the natural conditions of the oceanic environment is one of the conditions of rational management of marine resources (Tkatchenko *et al*., 1996, 1997; Kotliński, Tkatchenko, 1997; Kotliński, Stoyanova, 1998; Musielak *et al*., 1998; Jung Ho-Hyun *et al*., 1998).

ORIGIN AND GEOLOGICAL STRUCTURE OF THE OCEANS

The modern world’s oceans and geological evolution of ocean crust are closely related to the evolution of the entire globe. The present world’s oceans are most often referred to as consisting of the Pacific, Indian and Atlantic Oceans. Palaeogeographic reconstructions demonstrated changes in the spatial coverage and depth of the oceans which underwent multiple evolution throughout the geological history of the Earth. The origins of the present oceans date back to a time much later than it has been thought so far. The prevalent view at present has it that the formation began past Mid-Jurassic, in places (Middle Atlantic) possibly in the late Early Jurassic, past Pliensbachian (Steiner *et al*., 1998). Data obtained during DSDP in the western Pacific, in the Magellan Seamounts area, as well as the linear magnetic anomalies AM 28 allowed to date the ocean crust formation at about 170 million years ago (Andreev *et al*., Eds., 1998). Studies aimed at the explanation of mechanisms and causes of Earth’s crust transformations have been carried out for many years and involve attempts to identify causal relationships between the existing sea floor structures, transfer of matter in the Earth’s interior, and changes in location of the poles (Revelle, 1954; Dietz, 1961; Maxwell, 1968; Le Pichon, 1968; Vogt *et al*., 1971; Wilson, 1973; Burke *et al*., 1977; MacDonald, 1982; Tanimoto, Anderson, 1985; Oberc, 1986; Hager, Gurnis, 1987; Carey, 1988; Dimov *et al*., Eds., 1990; Seibold, Berger, 1993; Koziar, 1993; Dadlez, Jaroszewski, 1994; Tyapkin, 1995a, b, c). Analysis and interpretation of the most recent data collected from the deep-sea floor allows to conclude that the formation of basaltic ocean crust was governed mostly by volcanic-magmatic processes acting in concert with degassing of upper Earth’s mantle. Although still provoking discussion, those relationships — as well as the interaction between the Earth and extraterrestrial physical fields and energy sources — ceased to raise doubts (Czechowski, 1994; Kotliński, 1997a).

The contemporary morphostructural pattern of the Earth is reflected in the ratio between continent and ocean surface areas (29:71), each of the areas having different crust types. The Earth crust accounts for 1.4% of the Earth’s volume and 0.3% of its mass. The continental crust covers about 37% of the Earth surface (about 25% on land and about 12% on the continental shelf). The oceanic crust occupies about 60% of the Earth, the remaining 3% being accounted for by the intermediate crust (Andreev *et al*., Eds., 1998) which occurs in the Asia-Pacific and Australian-Pacific areas on the fringes of oceanic plates, along the so-called active (Pacific) margins like island arcs and marginal seas (i.e. Yamato Massif in the Japanese Sea and continental arcs) (Krasny, 1973, 1998). Intermediate crust is characterised by bigger thickness of the crystalline complexes and volcanism of the andesite-ryolite type. Continental and island arcs are associated with the active subduction zones and oceanic trenches, and represent convergent boundaries of the lithosphere plates. They are characteristic for the coasts of Pacific, their length reaching about 32,000 km. Length of the island arcs in the northern and western part of Pacific can reach about 21,000 km and length of the continental arcs in the eastern part of Pacific may reach 11,000 km. The oceanic plates, like Explorer, Juan de Fuca, Gorda, Rivera, Cocos and Nazca, are being pushed, along the continental arcs, below the continental blocks, the latter representing the lighter parts of plates. Zones of contact between the plates are characterised by intensified seismic and volcanic activity. Different varieties of the intermediate crust occur also along the so-called passive (Atlantic) margins where continental and oceanic plates come into contact, for example Arctic shelf and Northern Canadian shelf (Busby, Ingersoll, Eds., 1995; Pushtcharovsky, Ed., 1995; Dubinin, 1995; Andreev, Gramberg, Eds., 1997; Krasny, 1998). It is worth mentioning, that the blocks with preserved fragments of continental crust can occur within the oceans (i.e. Seychelles in the Indian Ocean or Rokoll Plateau in the Atlantic Ocean — Krasny, 1998).

Most often, the continents directly border the oceans; it is more seldom that a continent is separated from an ocean by marginal seas and island arcs. The oceans, having many common features, differ from each other by specific development of the tectonic movements, which are conditioned by geological structure and specific morphology of the bottom. Isolated from the Earth mantle by the so-called MOHO discontinuity zone, the ocean crust is several times thinner than the continental one. The MOHO is marked by the presence of low viscosity and low plasticity rock layers, whereby a zone of horizontal shifts forms, characterised by intensive magmatic processes. The crystalline complex found in the ocean crust is represented by a relatively homogenous suite of alkaline magmatic rocks (about 3 g/cm^3 mean density) which consists of two layers. The upper layer, the so-called Layer 2, is represented predominantly by toleitic basalts, 0.2–2 km thick. Below lies the so-called Layer 3, most probably consisting of toleitic basalts and ferric basalts. The crystalline complex thickness below the older (Jurassic–Cretaceous) sediments varies from 6.6 to about 8 km, while below the Cenozoic sediments it is below 6.6 km; it decreases markedly towards mid-ocean ridge axes (Andreev *et. al*., Eds., 1998). Locally, one can observe considerable thickness of the ocean crust (up to 20–40 km), for example in the Jurassic-Cretaceous Marcus-Necker volcanic belt in the Pacific. The crystalline complex, composed mainly of trachybasalts, trachyandesites and tephrites, is overlaid by sedimentary complex, composed predominantly of non-consolidated rocks of Upper Jurassic-Cretaceous age (Krasny, 1998). The sedimentary cover thickness, e.g., at abyssal depths, reaches 300, and even 500 m and decreases gradually in a direction perpendicular to mid-ocean ridge axes. Changing thickness of the crystalline complex, shallow occurrence of the upper surface of asthenosphere and presence of large, morphotectonic elements like continental slope, oceanic ridges and trenches, are the features characterising the oceanic bottom. In the oceans, besides zones of active volcanism, fault zones which are more visible than the continental ones, are common. The continental crust is several times thicker than the oceanic one, and is characterised by the occurrence of granitoid-metamorphic rocks of differentiated composition and lower mean density (2.7–2.8 g/cm^3), superimposed on the alkaline magmatic rocks (Kotliński, 1997a).

The scale and extent of oceanic crust transformations have not been fully understood as yet (Ringwood, 1972; Zonenshayn *et al*., 1976; Goran, 1978; Burchfiel, 1983; Bruhn, 1987; Andreev, Gramberg, Eds., 1997; Andreev *et al*., Eds., 1998). The ocean crust, along with its chemical composition, was formed as a result of interactions between complex tectonic and magmatic processes and related processes of upper mantle degassing, which were affected by juvenile waters influx. Hence, in order to understand the evolution of the oceans, it is important to consider the problem of sea water origin and volumetric changes. Palaeooceanographic data allow to adopt a view that the water, as a product of mantle degassing, originated in terrestrial and oceanic basalts, the volume of the oceanic basalt-derived water being 10 times the volume of the terrestrial basalt-derived ones. The major stages of mantle degassing took place between 4.6 and 2.5 billion years ago (Schopf, 1987). These processes are still going on, and their intensity in the individual oceans is regionally differentiated. Despite the chemical composition of the oceanic waters has been in an equilibrium settled already 2 billion years ago, a gradual increase in oxygenation, pH (7.5–7.8) and water column structure can be observed during the last 700 million years of the Earth evolution. Settlement of ionic composition of the oceanic results from the long-term cycles of exchange between atmosphere, lithosphere, biosphere and hydrosphere (Humphris *et al*., Eds., 1995). From the Upper Jurassic onwards, those changes, conditioned by the spreading rate, have been characterised by increased calcite deposition and changing metal contents (Schopf, 1987). Anions content in the oceanic waters has been stabilised mainly due to the endogenic processes, while cation content has been chiefly influenced by amount of products of erosion and weathering supplied to the oceans from the surrounding continents (Andreev *et al*., Eds., 1998). Chemical composition of the oceanic waters, their volume and inner structure, are still shaped by the regional environmental factors (Lebedev *et al*., 1974; Thurman, 1983; Hosino, 1986; Druet, 1994).

Oceans play a crucial role in the processes of energy transmission, including atmospheric ones, on the Earth (Humphris *et al*., Eds., 1995). It is caused, besides other factors, by the fact that the water masses represent enormous heat reservoir, because of its high specific heat. Besides that, vertical and horizontal thermal, salinity and density heterogeneity are factors which form thermohaline circulation, known in oceanology as a global circulation of the water masses of the world's ocean. Setting up of the global circulation is an important factor stimulating energy transmission processes, both in the oceans and in the atmosphere. It should be emphasised, that the amount of energy being transmitted in the oceans can be compared to the amount of energy transmitted in the atmosphere. Interaction between atmosphere and oceans are regulated by the mutual relationships within this system. These relationships determine the circulation of water masses in the oceans and air masses in the atmosphere, and so-created equilibrium shapes the Earth's climate. General circulation in the oceans and atmosphere causes certain climatic zonation on the Earth (Zieliński, 1998).

MORPHOTECTONIC STRUCTURES OF THE OCEAN FLOOR

There are several major morphotectonic units of the ocean floor, each having its own relief. Their formation is related predominantly to different rates of the ocean crust formation and tectonic processes taking place at the boundaries between continental and oceanic plates.

DSDP data as well as results of palaeomagnetic, seismic, acoustic and lithostratigraphic surveys allow to conclude that the basaltic Layer 2 provides the basement of the sedimentary cover. The basement structure indirectly controls the seabed relief and geomorphology. The deep-sea floor, of a ridge-block structure, is slanted downwards away from mid-ocean ridges (Kotliński, 1992).

The following major morphotectonic elements are identified (Shepard, 1963; Burk, Drake, Eds., 1974; Dimov *et al*., Eds., 1990; Seibold, Berger, 1993; Kotliński, Musielak, 1997):

— submerged continental margins, including the continental shelf, slope, and its feet;

— intermediate zones, consisting of marginal (external) sea basins, island arcs, and oceanic trenches;

— oceanic basins, with flat and/or undulated abyssal plains and submarine plateaux;

— mid-ocean ridges.

Marginal parts of the oceans, embracing continental shelf and usually upper parts of the continental slopes, are developed on the continental crust. Shelf extends down usually to 200 m (mean depth 130 m). In areas adjoining some continents, they are narrow (western shore of South America), or very broad (Arctic seas). Arctic shelf and Antarctic shelf are the largest ones. Tilt of the shelves does not usually exceed 0.1°. Further off the shores, the shelves pass into the continental slope, which is characterised by a bigger inclination, up to 6°, in places even 25°. Submarine canyons are characteristic elements of the relief of the continental slope. Continental slope, over 350,000 km long, constitutes a natural geotectonical boundary between the continental and oceanic crust. Within the continental slope, dislocation zones, masked by the sedimentary cover, are common (Chain, 1974; Krasny, 1998). Upper part of the continental slope reaches down to the isobath some 2000 m deep. Below that depth, down to 4000 m deep, one can distinguish the lower part of the continental slope, passing into the continental foot. This zone shows a differentiated characteristics. Within the passive margins (of the Atlantic type), the bottom is usually characterised by a broad shelf of a gentle inclination, passing gradually into the continental foot. Sedimentary complex, composed of lithogenic deposits transported from the shelf by submarine slides and turbidite currents, reach thickness of several kilometres. At the foot of the continental slope, a vast, gently inclined accumulation plains occur. In the case of the active margins (of the Pacific type), shelf is scarcely developed, and the continental slope joins directly the outer (landward) slope of the oceanic trench.

Vast abyssal plains are developed further off the shore, on the oceanic crust. The abyssal plains extent between isobaths 4500 and 6000 m deep, occupying some 42% of the oceanic bottom. Gentle, monotonous, in places undulated relief of the abyssal plains is diversified by the presence of submarine volcanic mounts, isolated or grouped into submarine chains, like in the western and middle part of Pacific. The oceanic bottom rises gradually towards the oceanic ridges, on the average to the isobath 1500–3000 m below the water surface. Below isobath 6000 m, one can distinguish the hadal zone, which occupies only 1.4% of the oceanic bottom.

Oceanic ridges show a mid-ocean location in the Atlantic and Indian oceans, and oceanic-marginal in the Pacific. Usually, the rift valley run along the axis of the oceanic ridges. The ridges are perpendicularly or obliquely cut by the ridge transform faults, which are synchronous to the ridges and rifts. Displacements along these faults may reach even several hundred thousands kilometres. Rift valleys are characterised by occurrence of tectonically active zones of the ocean floor spreading, called the "spreading centres". Transform and downthrow faults divide rift valleys and slopes of the rifts into separate blocks. Partitioned near-rift zones show ridge-and-block relief, with troughs and ridges. The oceanic ridges constitute a unique geological structure on the Earth. Spreading axes coincide with the bulges of asthenosphere, associated with heat sources (magma chambers) of the upper mantle, characterised by lowered viscosity and plasticity. It is confirmed by changing speed of the spreading, increased heat flow, and intensified seismic and volcanic activity along these zones. In the oceans, boundaries of the litosphere plates occur both along the axes of the ocean bottom spreading (so-called divergent boundaries) and along the transform faults, cutting the ridges perpendicularly to the spreading axes (so-called transform boundaries). Divergent and transform boundaries of the plates along the oceanic ridges constitute an interacting system. The third type of the plate boundaries is represented by the asymmetric subduction zones (so-called convergent boundaries). The oceanic trenches, associated with plate margins and occurring along the continental and island arcs, are connected with the last type of the plate boundaries (Le Pichon, 1968; Gramberg, Smyslov, Eds., 1986; Czechowski, 1994). In the north-western Pacific, the arc-shaped oceanic trenches are located some 2000 km away off the shore. In this case, the marginal seas (such as Ochock Sea, Japan Sea, South China Sea, Bering Sea, East China Sea) are separated from the oceans by the island arcs, which are parallel to the trenches.

MAJOR STAGES OF OCEAN FLOOR DEVELOPMENT

According to the theory of plate tectonics, the size of the Earth is constant and lithosphere plates are moving against underlying asthenosphere, which is called the "continental drift" (Dietz, 1961; Hess, 1962; Maxwell, 1968). According to that theory, the accretion of the oceanic crust is compensated by the subduction processes (Condie, 1982; Zonenshayn *et al*., 1976; Hager, Gurnis, 1987; Gurnis, 1988; Czechowski, 1994). Contradicting theory of expanding Earth assumes that the location of the continents is basically stable against the deep basement, but the Earth's volume must have been nearly doubled during Mesozoic and Cenozoic (Carey, 1958, 1976, 1988; Heezen *et al*., 1959). Theory of expanding Earth questions the conception of subduction, adopting an isotropic stretching of the lithosphere's basement, an alternative to the convection mechanism (Koziar, 1985). One can state, that the mechanism of ocean crust accretion and development of oceanic ridges and transform faults can be satisfactory explained by the theory of plate tectonics. Convergent boundaries of the plates (i.e. subduction zones) need further studies (Koziar, Jamrozik, 1991).

It seems now unquestionable that the present oceans were formed as a result of ocean crust spreading (Le Pichon, 1968; Scotese *et al*., 1988; Koziar, 1993; Dadlez, Jaroszewski, 1994). However, ocean floor transformations differed between the oceans and proceeded with different intensities. Also the scope and rate of ocean crust transformations differed between the oceans as well (Condie, 1982; Tanimoto, Anderson, 1985; Wylie, 1988; Gurnis, 1988; Gramberg, Ed., 1997; Andreev, Gramberg, Eds., 1997; Krasny, 1998; Andreev *et al*., Eds., 1998). Assuming succession of the morphotectonic elements of the ocean floor, geomorphologic order, distribution of linear magnetic anomalies, as well as the age and structure of the ocean basement and sedimentary cover, the evolutionary history of the oceans was divided into four major stages:

Stage 1, took place from about 170 until 156 million years ago, it started at the turn of Mid- and Upper Jurassic (Bathonian–Oxfordian), and lasted till Aptian. It is possible that in the central Atlantic area this stage was preceded by even earlier stages, dated back to the Early Jurassic (Steiner *et al*., 1998). In the initial phase of accretion of the oceanic crust, formation of today's peripheral, adjacent to the continents, parts of the sea floor, delineated by anomalies AM28, AM27 and PM29[1]. The oldest parts of the ocean crust are characterised by the normal magnetic field, thickness of the crystalline Layers 2 and 3 exceeding 8 km, and the sedimentary cover thickness exceeding 1000 m. Apart from the absence of spreading, the stage is also characterised by the presence of basalts, picric basalts and andesitic basalts with magnetite, titanomagnetite, ilmenite, and admixture of Fe and Cu sulphides. From 156 million years ago (second period), the accretion of oceanic crust from differently oriented divergent zones took place. The stage of so-called "dissipated spreading" is expressed by the inversion polarity and variable orientation of linear magnetic anomalies from M25 to M0 (Kotliński, 1998a). It is during that stage that ocean crust within abyssal basins, in the western part of the Pacific plate and in the marginal parts of the Indian and Atlantic oceans, began to form. The thickness of the crystalline Layer 2 and 3 is about 6.7–7.2 km, and the sedimentary cover is about 500 m thick. In the basalt of the basement, the presence of Fe and Cu sulphides has been recorded. The slowest sea floor spreading at that stage (about 1 cm/yr.) was observed in the Indian Ocean. The Atlantic sea bed spread at a somewhat faster rate (about 1.2 cm/yr.), the rate varied strongly in Pacific (4–14 cm/yr.). During stages 2 and 3, the oldest fragments of the Pacific and Indian Ocean sea floor plates were undergoing transformations (Andreev *et al*., Eds., 1998).

Stage 2 proceeding from 118 until 85 million years ago (Aptian–Campanian) involved transformations of deep magmatic energy centres and changes in spreading mechanisms which proceeded in conjunction with volcanic processes. They occurred within abyssal plains and were manifested as substantial tectonic and volcanic activity. The stage includes terminal phases of the ocean crust accretion from unevenly distributed divergent centres and forming of the linear spreading zones in the oceans. Therefore, the bottom relief in the areas affected shows the presence of volcanic-tectonic elevations and internal plate volcanism. The crystalline Layers 2 and 3 consist of basalts, andesite basalts and trachybasalts 6.6–7.1 km thick. Results of the magnetic investigations show the normal polarity of the basement rocks. Apart from the presence of titanomagnetite and ilmenite, characteristic is also the occurrence of Fe, Cu, Pb, Zn and Ag sulphides. The sedimentary cover is about 200 m thick (Andreev *et al*., Eds., 1998). This stage marks a transition from old to young ocean crust fragments of the sea floor plates. Typical of the two initial stages of ocean crust development and transformation of the so-called "old ocean crust" is the low heat flow (25–70 mW/m^2), the flow increasing to 70–80 mW/m^2 at the next stages.

Stage 3 began 85 million years ago (Upper Cretaceous–Campanian) and took the longest, more than 60 million years, i.e. until the end of Oligocene. At that stage, the so-called "young ocean crust" began to form from an uniform, linear sea floor spreading centres. The branches of the Indo-Pacific elevations with narrow and poorly developed rift valley as well as the Indo-Atlantic and Indo-Mediterranean Ridges were formed, the latter two with wide, asymmetric rift valley. Transform faults, giving rise to shifts and producing a block sea floor structure, underwent changes. Faults in oceanic fracture zones became activated, volcanism developed, and seismicity increased. The structures formed at that stage are best developed on abyssal plains located on both sides of the spreading centres, that is in areas of "young" oceanic plates. Bimodal linear magnetic anomalies (from 34 to 6-5), forming groups of anomalies of similar orientation, are clearly regular (Kotliński, 1998a). Overlaid by a thin (5–150 m) sedimentary cover, ocean crust consists of toleitic basalts and picrobasalts (sheet and plate-shaped). The Atlantic sea floor spreading rate markedly increased at this stage and reached 1.8–2.6 cm/yr., which testifies to the activation of magmatic energy centres.

Stage 4 began about 24 million years ago (Miocene) and is progressing. It encompasses two periods of mid-oceanic ridge transformations and emergence of recent sedimentary conditions. The basalt-containing ocean crust Layers 2 and 3 are thinner (4.9–6.2 km). They characteristically contain sulphides of a defined specific geochemistry specialisation: Fe; Cu-Fe-Ag; Zn-Cu-Fe-Ag-Au; Cu-Zn-Pb-Fe-Ag (Andreev *et al*., Eds., 1998). The sedimentary cover thickness does not exceed here 100 m. Linear magnetic anomalies of mid-oceanic ridge slopes (from 7-5 to 3) and in rift valleys (from 3 to 0) are strong, with indications of broken linear continuity (Kotliński, 1998a). In this period, the heat flow from the sea floor is clearly increased; the Pacific heat flow is about 200mW/m^2, markedly lower values (about 150 mW/m^2) being recorded in the Atlantic and Indian oceans. The present sea bed relief reflects recent phases of the sea floor transformation and development. A clearly new factor was introduced by the advection, about 12 million years ago, of highly oxygenated Antarctic waters (Glasby, 1998b). Stabilisation of the oceanic water column structure, particularly the near-bottom water oxygenation and circulation, directly resulted in transfer of immense amounts of Mn and Fe, released from the newly formed ocean crust, from poorly to better oxidised sedimentary environments. From the metallogenic point of view, the stage of the ocean crust evolution described constitutes a new **manganese** period (Glasby, 1998b).

Formation of the oceanic crust, along with transformations in the upper mantle and formation of the hydrosphere structure, represent a crucial stage of Earth's evolution. Despite the fact that the Earth's crust represents only 0.3% of the Earth's mass, 60% of which represents the oceanic crust, formation of the oceans is an effect of global transformations of the whole planet. Formation and translocation of huge masses of basalt magma goes on due to the endogenic processes, shaped by the endogenic Earth's energy. Those processes proceed in the upper part of the Earth's mantle, precisely within the MOHO zone. Oceanic volcanism, intensified within the spreading zones, differs from the continental volcanism by the composition of lava, the toleitic lava characterising the former one. Presence of varied magmatic complexes (ultrabasic, alkaline and transitional — according to the TAS classification — Shelley, 1993) reflects differentiated, multi-phase volcanic activity

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[1] Linear magnetic anomaly numbers given after the Kent and Gradstan scale in Kotliński, Szamałek, Eds. (1998).

in the oceans. Within the spreading zones and on the slopes, the toleitic and ferrous basalts dominate, while within the elevations and sea mounts alkaline trachites, trachyandesites and tephrites prevail. The types of eruptive rocks building the crystalline basement originate from different vents and represent products of linear eruptions (plate basalts) or volcanic eruptions (sheet basalts) (Sharkov, Cvetkov, 1986; Saveleva, 1990). According to R.A. Daly, comparison of the mean chemical composition of all basalts with oceanic basalts occurring within "old" and "young" fragments of oceanic crust, shows highly differentiated mean content of Na_2O and K_2O, with similar mean content of other components. Pacific basalts within the "old plates" show the lowest mean content of K_2O (0.15%), with clearly higher mean content of K_2O in the Atlantic Ocean (0.82%) and Indian Ocean (1.50%) — the latter value is close to the general mean content of all basalts — 1.52%. Within the "young" fragments of the Pacific plate, mean content of K_2O is 0.32%, with mean content of Na_2O = 2.49% and SiO_2 = 49.83%. In the basalts of Atlantic and Indian oceans, the mean contents of K_2O are higher (respectively, 0.61% and 1.50%). Tertiary basalts of Atlantic are characterised by the lowest mean content of SiO_2 (44.74%), with highest mean content of Na_2O (2.84%). Besides, they differ from the Pacific basalts by lower value of the ratio MgO/MgO+FeO (up to 0.30), which indicates more advanced proceeding of processes of the basalt magmas differentiation in the Atlantic Ocean. Results of chemical investigations of the recent basalts of the East-Pacific Rise allow to classify the studied rocks (according to TAS classification; Shelley, 1993) to the low-potassium basic basalts (Fig. 1). Mean ratio MgO/MgO+FeO of 0,4, indicating the intermediate stage of basalt magma differentiation and zonal differentiation within the elevation, is their specific feature (Mullen, 1983; Andreev, Gramberg, Eds., 1997).

Recent state of knowledge on different magmatic complexes, including their geochemistry and relation to the shallow intrusive bodies, are not sufficient for recognition of the character of differentiation of basement magmas (Gurevitch, Litvinov, 1992). Because centres of volcanic activity are located below MOHO, one can assume that under the oceans the asthenosphere composition is differentiated. Within the planetary system of mid-oceanic ridges the following three segments can be identified, the segments differing clearly in their spreading rate, activity of volcanic, hydrothermal, and venting processes which control the environmental sedimentary conditions (Andreev *et al*., Eds., 1998):

— Indo-Pacific,
— Indo-Atlantic,
— Indo-Mediterranean.

The three segments come in contact in the so-called Rodriguez triple junction in the Indian Ocean, where the spreading rate reaches 13 cm/yr. Respective lithosphere plates are characterised by differentiated progress of movements and deformations. Changeable character of plate movement and succession of the morphotectonic elements indicate asymmetric development of the oceans during Mesozoic-Cenozoic time. It is reflected by a different evolution of the Indo-Atlantic and Indo-Pacific segments (Krasny, 1998; Andreev *et al*., Eds., 1998). It should be emphasised that in each of these areas, located on the marginal parts of the continents, different morphotectonic units dominate. On the fringes of the Pacific Ocean, Mesozoic-Cenozoic folded belts dominate. At the shores of the Atlantic Ocean and in the western part of the Indian Ocean, Palaeozoic folded belts as well as Precambrian shields, platforms and zones of late Proterozoic tectonic/thermal activity prevail; the latter are also typical for the Mediterranean region. In the Indo-Pacific segment, marginal basins and active, volcanic island arcs and continental arcs associated with oceanic trenches occur.

Contrary to the Indo-Pacific segment, the Indo-Atlantic segment is characterised by intraoceanic contact between continental and oceanic crust along so-called "passive edges". In the Indo-Pacific segment, the contact of oceanic plates runs along the active edges, both divergent and transform ones, while the contact between oceanic and continental or transitional crust runs along the convergent boundaries — i.e. continental arcs and volcanic island arcs. In the same time, dominating rock complexes of the marginal parts of these segments are main alimentary source of the allochtonous components supplied to the oceans.

The ocean crust developed symmetrically in the Indo-Atlantic segment, spreading simultaneously in the Atlantic and Indian Ocean — from a single spreading centre — on both sides of the Indo-Atlantic Ridge. This is manifested by the presence of the "old" (Jurassic–Cretaceous) fragments of the ocean crust on both sides of the ridge, the fragments being delineated by the anomalies M25 (Oxfordian) and M22 (Kimmeridgian). Jurassic and Cretaceous parts of the basement surround "young", Cretaceous-Cenozoic (Campanian–Oligocene and Miocene– Holocene) parts of the plates (Andreev, Gramberg, Eds., 1997; Andreev *et al*., Eds., 1998). Non-consolidated Jurassic and Early Cretaceous sediments are represented by limestones and pelagic sediments. Late Cretaceous and Palaeogene deposits on the vast areas of the sea bottom (apart from the submarine elevations of different origin) are characterised by a high content of terrigenous material derived from the continents. Thickness of Jurassic, Cretaceous and Palaeogene deposits ranges from 400 to 800 m, on the elevations it may be reduced even to 100 m. Non-consolidated sediments, occurring on the bottom of the oceans, were deposited during last 15 or so million years (in Neogene and Quaternary). Their distribution and thickness are differentiated. Lithologically differentiated siliciclastic sediments prevail on continental shelves and upper part of the continental slope, their thickness ranging from 0 to 200 m. At the continental feet, thickness of these deposits can locally reach about 1–1.5 km. The further from the continent and closer to the oceanic ridges, the pelagic sediments become more abundant. Their thickness decreases gradually towards the ridges and on the ridge slopes is only 50 to 100 m. In deep-sea basins, these deposits are represented mainly by brownish pelagic clay, and on the other parts of the bottom by calcareous oozes (foraminiferal, coccolithophoride and pteropode ones), dominating in the Atlantic and Indian Oceans. In the southern parts of these oceans, siliceous oozes (diatom, radiolarian) occur. It should be emphasised, that the area covered with the Jurassic-Cretaceous and Palaeogene sediments in the Atlantic and Indian Oceans is many times smaller in comparison to that in the Pacific. Locally, the

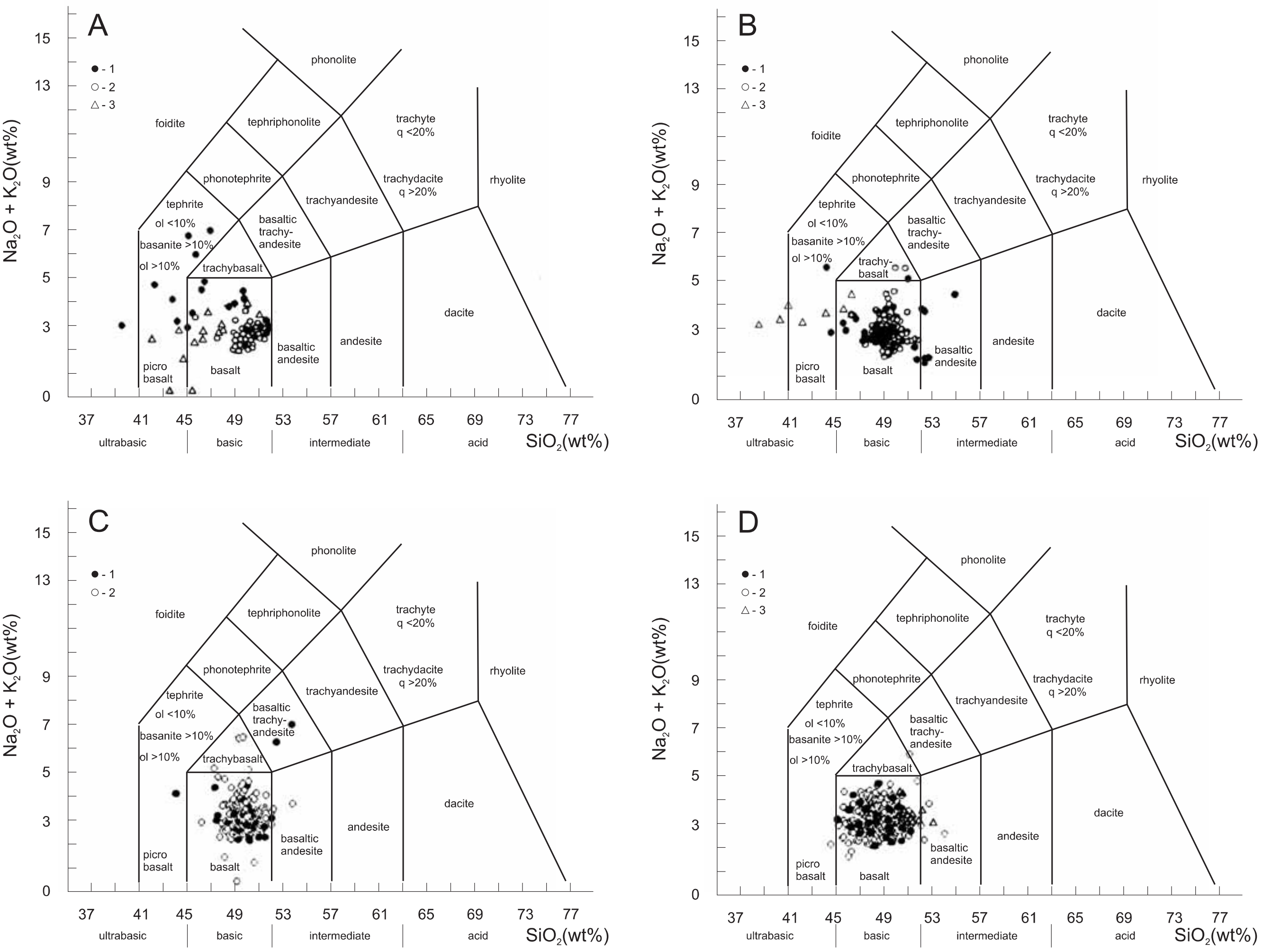


Fig.1. Differentiation of chemical composition of oceanic basalts based on the TAS classification — Shelley, 1993
Based on: Andreev, Gramberg, Eds. (1997)

A — "old" oceanic plates: *1* — Indian Ocean, *2* — Pacific Ocean, *3* — Atlantic Ocean; **B** — "young" oceanic plates: *1* — Indian Ocean, *2* — Pacific Ocean, *3* — Atlantic Ocean; **C**: *1* — southern part of the East Pacific Rise; *2* — northern part of the East Pacific Rise; **D**: *1* — southern part of the Mid Atlantic Ridge; *2* — northern part of the Mid Atlantic Ridge; *3* — Central Indian Ridge

brownish pelagic clay are common in this area; the same clays occupy extensive areas in the northern part of Pacific (Kotliński, 1998a).

Within the Indo-Atlantic Ridge, its rift valleys being devoid of non-consolidated bottom sediments, consolidated basalt sheets are exposed over large areas of the bottom. Locally, intensified activity of volcanic-hydrothermal processes, manifested as the active "black chimneys" with well developed sheets of massive, polymetallic Zn and Cu sulphide ore deposits, is visible. On the slopes of the oceanic ridges no sediments older than Miocene are known.

In the structure of the bottom of Indian Ocean, vast basins as well as ridges and volcanic, block and block-folded massifs can be distinguished (Levtchenko *et al*., 1985). The most characteristic element of the Indian Ocean bottom is the Rodriguez triple junction of RRR type, joining the Middle Indian, West Indian and SE Indian ridges. The SE Indian Ridge passes to the south into the Pacific-Antarctic Ridge and the Afar triple junction of the RRr type, the latter being located at the sound between the Red Sea and the Aden Bay. Forming of these ridges was associated with intensive volcanic activity, which is indicated by a large thickness of pyroclastic material and common presence of basalt rocks in the basement. The oceanic ridges in the Indian Ocean has a shallow water character. Volcanic ridges were formed as an effect of lava eruption from the cracks in the ocean bottom. In one case they formed massive elevations of Mascarene Ridge, in the other case a chain of volcanic cones building the Maldives Ridge and Comoro Islands. Oceanic crust below the basins is composed in its upper part of the sediments several hundred metres thick, which overlie a weakly litified sedimentary complex. In the middle part of the oceans, the basins show a undulated relief, which is related to the numerous disjunctive dislocations (Kotliński, Szamałek, Eds., 1998).

In the Indo-Pacific segment, the old (Jurassic and Cretaceous) parts of the Pacific plate, delineated by the anomalies PM-29 and M-25 to M-0 and 34 to 32, occur west of the present zone of the sea floor spreading. The distribution and varying direction of those anomalies point to the shift — during Cretaceous — of the spreading axis from NW to SE. The "young" ocean crust occurs on both sides of the East-Pacific Rise and is delineated by linear magnetic anomalies — from 32 to 0 (Kotliński, 1998a; Andreev *et al*., Eds., 1998).

Pacific clearly differs from the other oceans by its heterogeneity of the basement structure (with exception of the marginal part of the Antarctic plate, characterised by a low seismicity and weak recent volcanism). Heterogeneity of the basement structure is reflected chiefly by the presence of "old fragments" within western part of the Pacific. These "old" fragments were formed during the initial stages of evolution of the oceanic crust. The "young" oceanic crust was developing from a single spreading centre during the Stage 3 and 4 of the ocean's development. Differentiated structure of the basement is reflected by superimposed and intersecting rift zones and faults of different age. From the morphotectonic point of view, the following regions can be distinguished in the Indo-Pacific area:

— south-western (Australian plate);

— central (Pacific plate and Caroline plate);

— north-western (Philippines plate);

— eastern (Scotia plate, Nazca plate, Cocos plate, Rivera plate, Gorda plate, Juan de Fuca plate, Explorer plate);

— south-eastern, embracing part of the Antarctic plate, which extends also to the southern parts of Atlantic and Indian Oceans.

Within the Pacific one can distinguish microplates of Tonga, Fiji, Solomon, Bismarck, Juan Fernandez, Easter (see map Figure 9). A small shelf area, accounting only for 1.7% of the ocean's area, as well as occurrence of great oceanic trenches (from the north — Aleutian and Kuril-Kamchatka; from the west — Japanese, Izu-Ogasawara, Mariana, Philippines, New Guinea, Witiaz, Tonga, Kermadec; from the east — on the margins of Nazca and Cocos plate, Middle American and Peru-Chilean trenches), are characteristic features of this ocean.

Submarine ridges and elevations in the western and middle part of the Pacific plate run from NW to SE. Volcanic cones and ridges running from the Aleutian Trench along the Imperial Ridge, through Hawaii to the Christmas Ridge and further to the Tuamoto Ridge, are characteristic elements of the middle part of this plate. To the east, a zone of oceanic fractures occurs — generally, the fractures cut the "young" Pacific crust. Main oceanic basins within Pacific: southern, central and north-western, occur on the "old" fragments of the ocean crust, while the north-eastern basin occurs on the: "young" fragments of the ocean crust (Andreev *et al*., Eds., 1998).

Different morphotectonic character of the areas under question was formed under influence of complex mechanisms, associated with a sea floor evolution proceeding at subsequent stages (Krasny, 1973; Sharkov, Cvetkov, 1986; Lustch, 1994). Effects of activity of these mechanisms are manifested as observed sequence, morphometric characteristics and orientation of main forms of ocean bottom relief, as well as bathymetry and specific environmental conditions, determining development of sedimentary processes, which is reflected in spatial distribution and lithology of recent sediments.

EVOLUTION OF ENVIRONMENTAL SEDIMENTARY CONDITIONS

Bottom relief and conditions of forming of the sediments underwent constant changes in the course of oceans evolution. Character and course of the sedimentary processes in the Mesosoic–Cenozoic has not yet been fully recognised in all the oceans. Oceanic sedimentation processes leading to the formation of sedimentary cover reflect global transformations of the Earth crust, affected by processes operating in the upper mantle, the crust itself, and in the oceanic waters. Recently, seismoacousting profiling, employed at a large scale, has made it possible to track the chronology of the deep-sea sediments as several reflectance levels were delineated. They allowed to identify groups of layers consisting of loose, poorly diagenetic, and diagenetic sediments in the sedimentary cover profile. Data of seismo-acoustic profiling, correlated with data yielded by drill holes and outcrops on the ocean bottom, enabled reconstruction of general lithostratigraphical sequence of Mesozoic and Cenozoic sediments (Kotliński, 1998a) (Fig. 2).

Sedimentary cover, of Mesozoic to Cenozoic age, usually overlies basalts. The oldest deposits represent Jurassic sediments; they occur in NW and W part of Pacific and in the margins of Atlantic and Indian Oceans. On the prevailing part of the ocean bottom, on both sides of the oceanic ridges, the sediments younger than Palaeocene dominate. Thickness of sedimentary cover is differentiated, which depends on the varied rate of sedimentation in the oceans (Fig. 3). Vertical and horizontal differentiation of the sediments was caused by two major factors associated with plate tectonics: sinking of particular blocks within the plates as the distance between the blocks and the oceanic ridge axes grew, and their translocation to the NE direction, with simultaneous shift of the zones of high biological productivity. Both the first and the second factor determined the quantity of calcareous bioclasts in the sediments, depending on the relation between the bottom depth and $CaCO_3$ compensation level (CCD), as well as regional biological productivity index. In all the boreholes, a slow rate of sedimentation, ranging from 5 to 13 millimetres/thousand years has been observed. Thus it was adopted that during the calcareous sedimentation the ocean bottom was located approximately at the lysocline level, which led to a partial dissolution of carbonates (Fig. 4). After the Oligocene–Miocene time, siliceous oozes pass gradually into calcareous oozes. Role of the silica-clayey material becomes more pronounced gradually from Miocene, with simultaneous change of hydrodynamic conditions, which activated erosion processes (Kotliński, 1988b).

Evolution of sedimentary conditions (in late Mesozoic and Cenozoic), determining the sediment forming processes, was caused by global changes in vertical and horizontal structure, chemical composition and productivity of the oceanic waters,

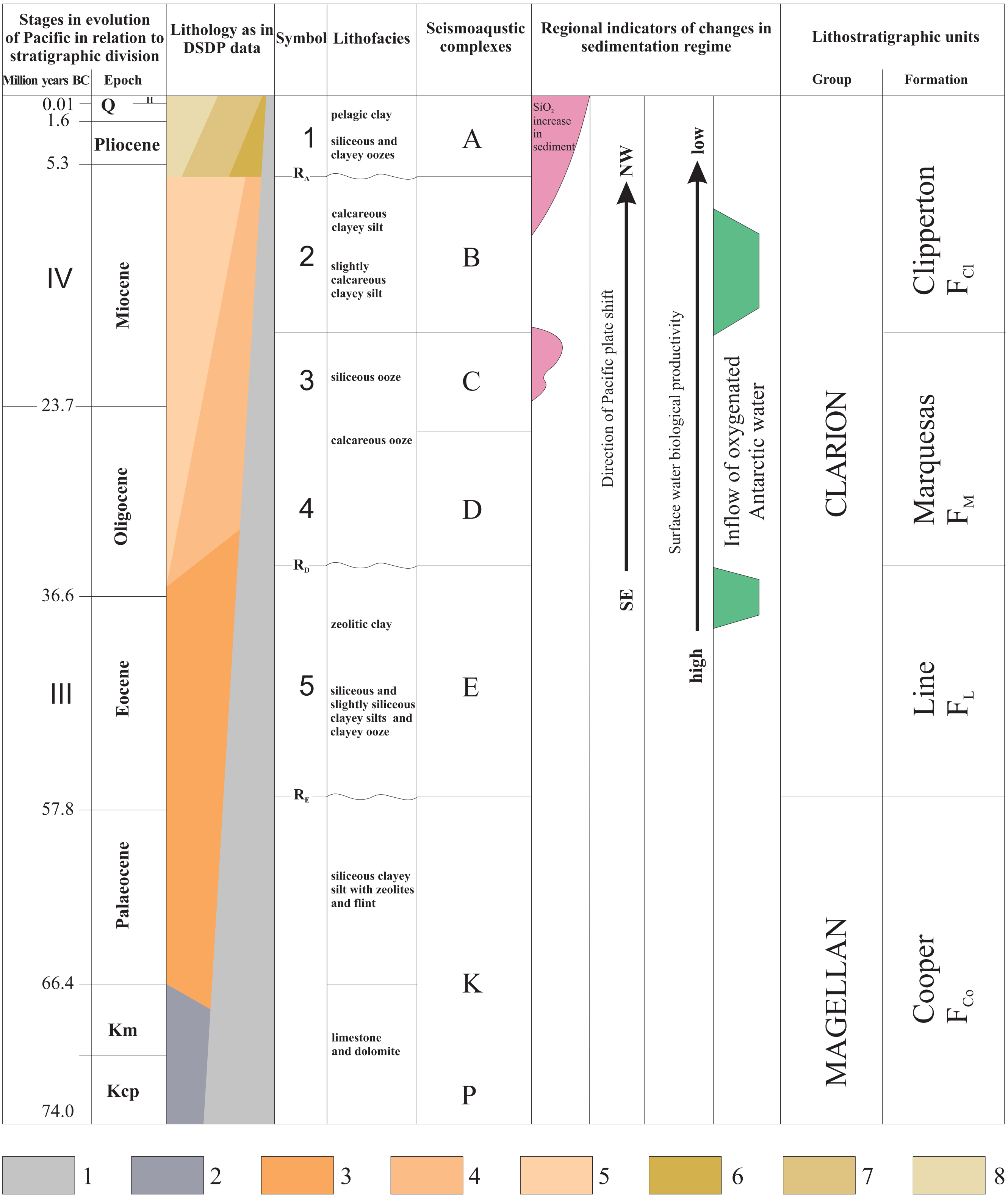


Fig. 2. Lithostratigraphical scheme of the North-East Pacific on the background of oceanic basement evolution. Regional indicators of changes in sedimentation regime

Based on: Riech, Grafenstein (*In*:) Amann, Ed. (1992)

1 — basaltic basement; *2* — limestones, dolomites; *3* — clayey siliceous oozes with zeolites and cherts; *4* — siliceous oozes; *5* — calcareous oozes; *6* — brown pelagic oozes; *7* — zeolite oozes; *8* — clayey-siliceous or clayey-calcareous oozes

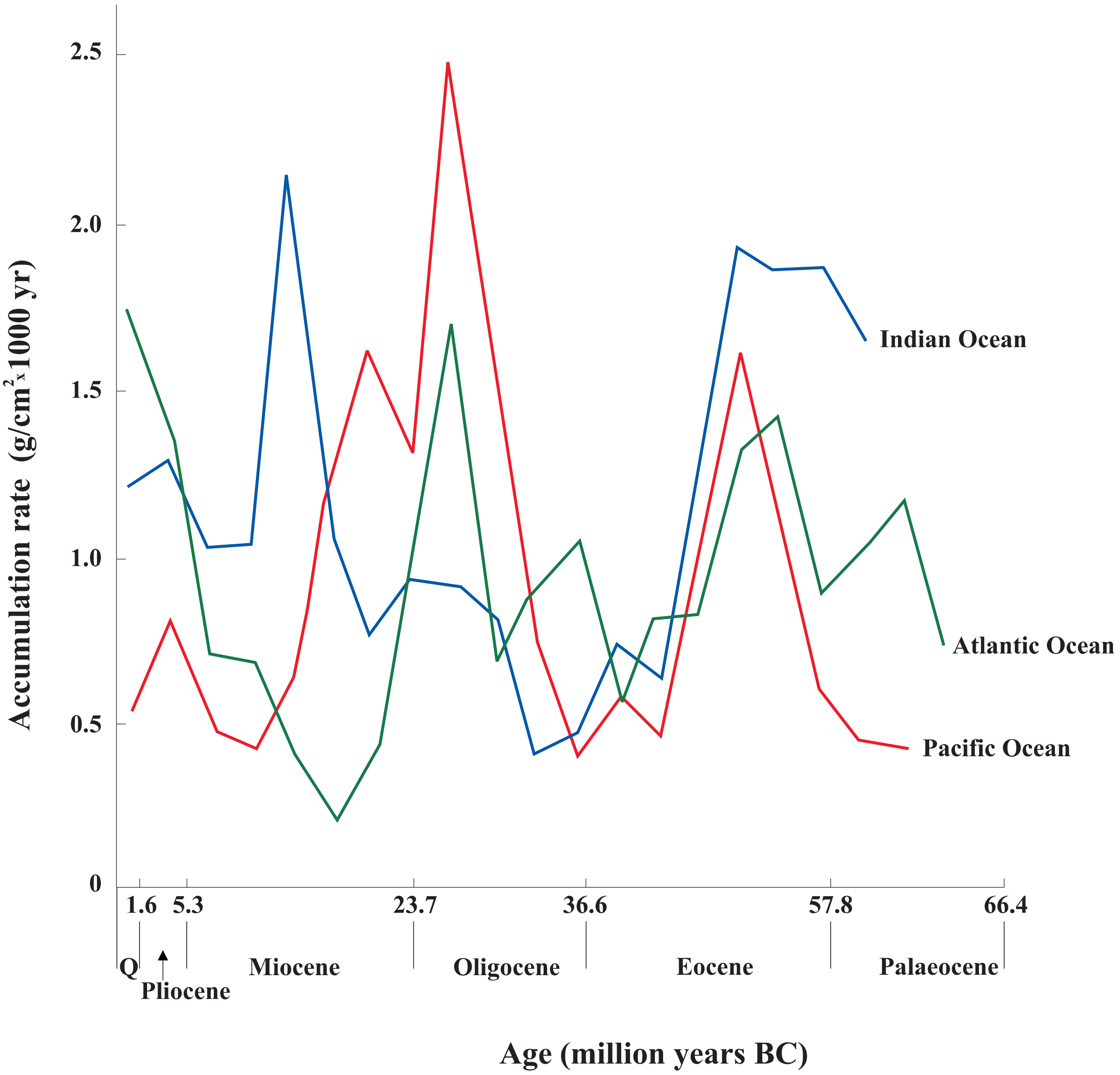


Fig. 3. Changes in accumulation rate of the Cenozoic deposits in main basins of the world's ocean, based on the DSDP data, including lithostratigraphy
Based on: Devis, Worsley (*In*:) Kotliński (1998a)

as well as by amount of material supplied. Climatic factors were of a crucial influence on changes of the sea level and forming of the present-day morphology of the shores (Lisitsyn, 1961, 1978; Kotliński, Musielak, 1997). Those processes were closely associated with volcanic and seismic activity, resulting from tectonic activity in the oceans.

Sedimentary processes in the oceans depend basically on the interrelations between type and amount of authigenic and allogenic material supplied to the oceans. The processes lead to the dominance of lithogenic components on the shelf and continental fringe area, and to the dominance of biogenic and hydrogenic components in the ocean basins, mainly on the abyssal plain areas. Intensity of the processes is reflected by differentiated accumulation rate, lithofacies diversity of the sediments, and size of the area covered with certain sediment types. Therefore, in the oceanic environment one can distinguish regions characterised by higher or lower amount of the lithogenic or oceanic (biogenic, hydrogenic) components supplied. Areas of intensive sedimentation are in contrast with areas of scarce supply of both terrigenous and bioclastic material. The latter areas are dominated by hydrogenic processes. Intensity and range of hydrothermal, venting and infiltration processes, as well as distance from magmatic activity centres, play an important role in development of sedimentary processes. Sedimentation in the regions of occurrence of terrigenous material is connected with intensity of denudation processes on the adjacent continents, while deposition in the areas of occurrence of bioclastic material in influenced by biological productivity of the surface waters. On the other hand, sedimentation of the pelagic sediments is influenced by volcanic activity in the ocean basins.

Spatial lithofacies distribution of the sediments is controlled by vertical stratification of the oceanic waters, including the calcium carbonate compensation depth (CCD) and silica compensation depth (SCD). Development of sedimentation on the given depth level (bathymetric zone), depends, besides the character of sources of material, on the following factors: bottom inclination, distance from the shore, physico/chemical properties and dynamics of the near-bottom waters. Conditions of sedimentation in a given region or zone depend on influence of the mentioned above factors. Consequently, specific features of sedimentation, expressed as typomorphic complexes of properties in groups and types of sediments formed, reflect the set of prevailing conditions (Kotliński, 1998a).

Areas of deep-water sedimentation characteristically show a clearly reduced intensity of diagenetic redox processes. Content of organic carbon (C_{org}) in the pelagic sediments ranges from 10^{-2} to 0.2–0.4%. Mechanisms of accumulation of components in this zone is controlled by the following factors:

— location and thickness of the water column with minimum oxygen content;

— lysocline location, specific for each kind of microorganism;

— calcium carbonate compensation depth (CCD);

— silica compensation depth (SCD);

— near-bottom water oxygenation;

— pH and redox potential (Eh).

Sedimentation in those areas is distinct as it shows a gradual zonal/facies transition from recent deep-sea calcareous oozes at the CCD level to siliceous deposits (see Kotliński, 1997a) at the SCD level. The latter form a clear-cut lithofacies boundary below which the bioclast contribution is markedly reduced. The $CaCO_3$ content in sediments below the CCD level, while $SiO_{2amorph.}$ content contributes up to 10% in the sediments below SCD. Material transported to that area is intercepted by organisms present in the photic zone, i.e. down to 150 m depth, whereby it enters the trophic chain. Polygenic sediments include specific groups of hydrogenic (polymetallic nodules, cobalt-rich manganese crusts) and hydrothermal-vent deposits (metalliferous muds, massive sulphide deposits) (Kotliński, 1997b, 1998b, e).

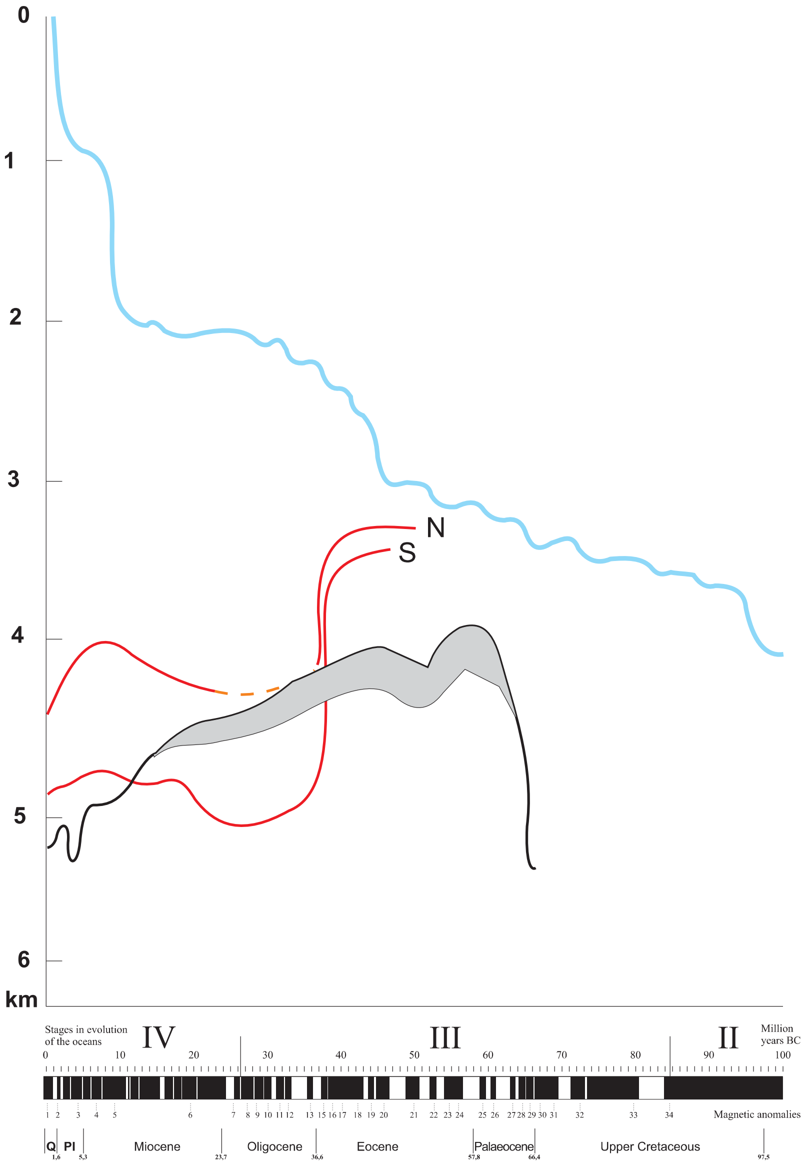


Fig. 4. Ocean water level changes and depth of the CCD level during the last stages of oceans' evolution

Based on: Hosino (1986); Andreev, Gramberg, Eds. (1997)

Blue line = changes of ocean water level; red and black lines = CCD level changes (red lines: S — southern Pacific, N — northern Pacific, black lines — Atlantic Ocean)

METALLOGENIC SYSTEMATIC OF THE WORLD'S OCEAN

Metallogenesis of the world's ocean is one of the most actual problems of the recent marine geology. It particularly concerns recognition of relations between evolution of the oceans (precisely, the stages of forming of ocean crust in the late Mesozoic and Cenozoic) and genesis of the ore deposits (Krasny, 1973; Rona, 1988; Korsakov *et al*., 1988; Shniukov, Ed., 1989; Gramberg *et al*., Eds., 1993). Origin of the oceanic crust and morphostructural forming of the ocean bottom correlate with Alpine orogenic period. Range and intensity of the geological-tectonic processes forming the world's ocean bottom reflect the stage of Earth's evolution, which is unprecedented in the globe's history.

In 1985, S.I. Andreev (Andreev *et al*., Eds., 1985) put foreward conception of metallogenic zonation of the world's ocean. He has been developing his conception since then (Andreev *et al*., 1990; Andreev, 1994, 1995, 1997; Andreev, Gramberg, Eds., 1997; Andreev *et al*., Eds., 1998). Basing on geological and geophysical data, the author attributed metallogenic units to the climatic zones. In this classification, the distinguished metallogenic units corresponding to varied deposits were assigned to the three levels: global, regional and local one. As far as concerns the nodules, the author (Andreev *et al*., Eds., 1998) distinguished megabelt and belt on the planetary level; fields, zones, ore regions and concretion areas on the regional level; deposit nodules, deposits and ore bodies on the local level. For the polymetallic sulphide ore deposits, the following units have been distinguished: megabelt on a planetary level; belts, mettalogenic zones and ore regions on a regional level; ore units, ore fields, ore bodies on a local level. For the phosphorites, megaprovinces have been distinguished on a planetary level; provinces and regions on a regional level; and ore units on a local level. For example, a nodule megabelt covers all the oceans between 35^{o}N and 45^{o}S; zones correspond to the global climatic zones, which means that they run along the parallels. In this division, nodule fields are assigned to the regional structural-metallogenic units. Megabelt and belt of polymetallic sulphide deposits are assigned to the vents, running along the axes of oceanic ridges, for example East-Pacific megabelt; phosphorite megaprovinces correspond to superregions, for example the Central-Pacific megaprovince (Andreev, 1997; Andreev *et al*., Eds., 1998). According to Andreev, morphostructural position and young (Campanian–Oligocene) age of the oceanic crust, play an important role in development of nodule-forming processes (hydrogenic, sedimentary and early diagenetic) in the deep-sea basins. On the "old" fragments of plates, early diagenetic processes causing a high metal concentration in the nodules (mainly Mn, Ni, and Cu), are weekly developed. Higher concentrations of Mn, Ni and Cu towards the "young" fragments of plates, and opposite trend in the case of Fe and Co concentrations results from the geological-tectonic zonation. Early diagenetic processes, along with re-mobilisation of Mn and Ni, play a more pronounced role in the vicinity of oceanic ridges (for example in the Peru Field). The CCD is also an important factor. Above the CCD, hydrogenic nodules and manganese cobalt-rich crusts (of Co and 2Co type) are formed; at the CCD level hydrogenic-sedimentary nodules of Ni-Cu-Co type are formed, while below the CCD level rich nodules of Mn-Ni-Cu-Co type occur (Andreev, 1997). Despite recognition of numerous relations between composition of the deep-sea manganese nodules and their occurrence, the latter author concludes that origin of the nodules can not be fully recognised, because too many factors, acting with different intensity on global, regional and local level, are involved. According to Andreev, this variability reflects the total influence of egzogenic, hydrogenic and endogenic factors, their influence being more pronounced from global, through regional to the local level.

APPLIED ESSENTIALS OF THE METALLOGENIC DIVISION

World's ocean evolution, reflected in the morphostructural relief of the ocean bottom, as well as a scale of magmatic-tectonic processes taking place in the upper mantle during forming of the oceanic crust, represent phenomena which, taking into account both amount of energy and time span of the processes under question, can not be compared to the scale of climatic changes. Global circulation of water masses in the world's ocean stimulates the energy transportation in the oceans and influence the same process in the atmosphere — particularly, the circulation of air masses. It created changeable equilibrium stages, which can also be named as global climatic systems. According to the Andreev's conception, nodule chemical composition should be stable, assuming proportional stability of chemical composition of the sea water. However, even if the nodules are located in the same climatic zone (according to Andreev), one can observe in them considerable differences in metal concentration. Those differences depend on kind, amount and distance from the source of the nodule components. Geochemical differentiation of the deep-sea nodules in the tropical zone of the northern Pacific, north-west and central Pacific can serve as a good example (Piper *et al*., 1985; Usui *et al*., 1987, 1994; Usui, Iizasa, 1995). Besides, there is lack of rich nodule fields in the Atlantic Ocean. Andreev's hypothesis is contradicted also by a differentiated metal concentrations in the nodules, and the age difference between the nodule-forming processes (from 25 to 5 million years ago in the Pacific Ocean and from 55 to 38 million years ago in the Indian Ocean) (Fig. 5). Comparison of age interval of intensified nodule-forming processes in the oceans with fluctuations of the CCD shows that the processes are accompanied with clearly lower CCD levels: down to 3800 m in the Palaeocene–Eocene in the Indian Ocean and down to 4200 m in the Oligocene–Miocene in the Pacific (Andel (*In*:) Gradziński *et al*., 1986). Simultaneously, in those periods one can observe rapid decrease in the accumulation rate to the minimum level, i.e. below 1 g/cm^2/1000 years. Only in the Indian Ocean one can register (in the Miocene) twice as large accumulation rate, at the level above 2g/cm^2/1000 years (Kotliński, 1998a). Dominant role of the authigenic material, including that one derived from the hydrothermal-vent sources, is proved by the data regarding the kind and amount of components supplied to the oceans (Fig. 6). Interrelationships between kind and amount of components supplied to their concentration places are shaped under influence of transport mechanisms and sedimentation conditions, associated with hydrochemical and hydrodynamic factors, as well as distance from the vents. This is a rule at least for the Indo-P acific area. In the Indo-Atlantic area, the amount of terrigenous material dominates over hydrogenic and biogenic material. Indo-Pacific and Indo-Atlantic areas differ from each other by morphotectonic characteristic and intensity of magmatic processes, shaping specific sedimentary conditions.

The alternative metallogenic systematic, proposed by the present author, is based on the known patterns of deep-sea polymetallic deposit formation controlled by geological and tectonic processes in the oceanic environment. The nature and course of those processes as well as the scale and scope of their interactions depend on the distance from the source of components, depth and sea floor relief, as well as physico-chemical structure and dynamics of oceanic water column (Fig. 7). Elevated concentration of certain components in the oceans has been found to depend, in time and space, on the scale, extent, and intensity of magmatic processes and distance from vents as well as on course of sedimentation and intensity of denudation on the continents. The extent and intensity of magmatic processes depend on the varied geodynamic regime and extent of ocean crust transformations and are reflected in the morphotectonic character of the sea bed, i.e. its relief, morphology, and depth, as well as in the differentiated amount of metals derived to the oceanic water. Evolutionary development of magmatic phenomena and certain sequence of ocean crust transformations shaping changes in sedimentation conditions, reveals distinct relationships between forming processes of the deep-sea deposits and the youngest, Alpine geotectonic period. During this metallogenic period, occurrence of subvolcanic and volcanic processes in the active rift valleys is connected with the block tectonics of the final stage of magmatism. It is characterised by forming of tectonic fractures, troughs and blocks, which is an effect of the plates translocations. Changing speed of the ocean floor spreading, proceeding from the linear spreading centres during the last stage of ocean crust evolution, is reflected in complex process of forming of oceanic ridges and associated rift valleys along the divergent boundaries and transform faults. Intensified magmatic processes are expressed as ubiquitous occurrence of toleitic basalts in the "young" ocean crust as well as an intensified activity of hydrothermal venting and infiltration processes in rift valleys and, locally, within deep-sea fracture zones, e.g., the Clarion-Clipperton Fracture Zone. Those processes led to a significant increase in the content of such metals as Mn, Fe, Cu, Ni and Co in the oceanic waters (German, Angel, 1995; Elderfield, Schultz, 1996; Glasby, 1998b). Magmatic processes, on the sub-volcanic and volcanic level, are associated with a relatively shallower location of the asthenosphere along mid-oceanic ridge axes. Vertical translocations and emergent fracture systems provide pathways for migration of the mineral-rich fluids, originating from the so-called magma chambers, associated with the subcrustal lithosphere and oceanic water. Oceanic water penetrates into the emergent fractures, and gets heated in the process by the surrounding rocks. The water, having undergone a change in its chemistry and having leached metals during numerous phases of its circulation, is released together with the juvenile water from the sea floor as plumes leaving hot springs or black smokers. In rift valleys, and also along zones of tectonic weakening, in result of the tectonic deformation, the new fractures are formed and the older ones are renewed and get wider. In such sub-volcanic (i.e. sub-surface) conditions, rapid separation of gases from the magma centres takes place. This process is caused by lowered pressure and temperature. For example, considerable lowering of temperature (from 900 to 100 mW/m^2) is indicated by a high density of geoisotherms outwards from the Galapagos ridge. Sub-volcanic magma forms columns, chimneys and sheets. Large gradients of pressure and temperature changes, caused by periods of intensified tectonic movements, influence the hydrothermal fluids on its way and cause discharge of various amounts of the fluids characterised by differentiated composition. Each phase of cooling of the magma centres is associated with characteristic composition of migrating fluids, which depends on the thermodynamics and physico-chemical conditions occurring in a given zone. Hydrothermal post-magmatic fluids form characteristic zonal Fe, Cu, Zn, Pb and Ag sulphide parageneses, associated with barite, anhydrite and silica, which is connected with periodical recurrences of magmatic activity associated with exhalation of gaseous components. In those zones one can observe manifestations of rejuvenation of mineralisation as a result of joint activity of gases and hot fluids (Humphris *et al.*, Eds., 1995).

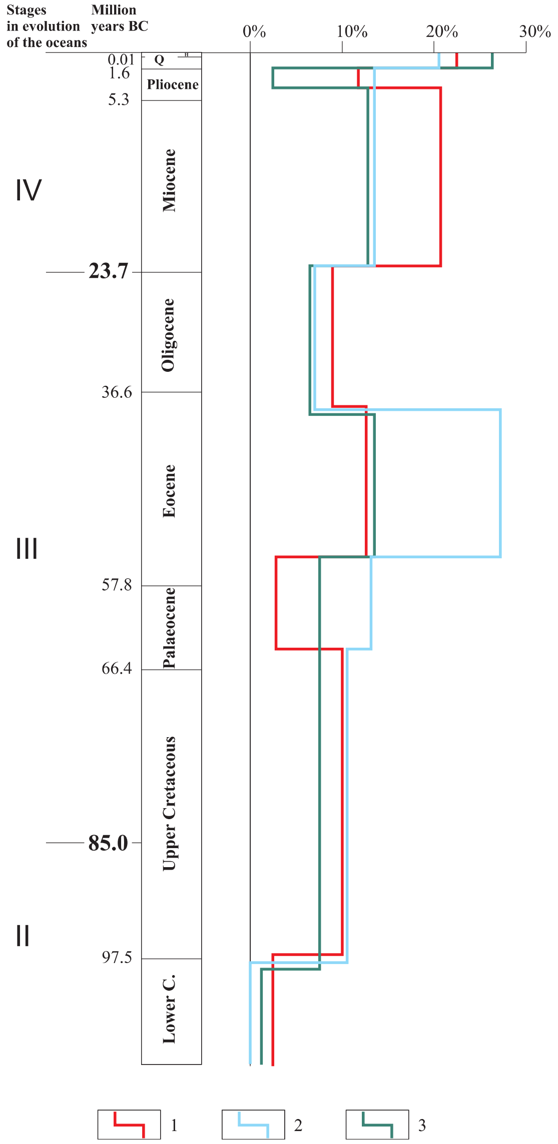


Fig. 5. Frequency of occurrence of nodules and micronodules in the sedimentary cover

Based on: Andreev, Gramberg, Eds. (1997)

1 — Pacific; *2* — Indian Ocean; *3* — Atlantic Ocean

Specific exhalation accumulations and deposits of hot volcanic springs are characteristic for the volcanic level characterised by a lower pressure, rapid changes of temperature and rapid separation of gases. Intensified activity of those processes is particularly well visible within nodal basins, in triple junctions (Humphris *et al.*, Eds., 1995; Andreev *et al.*, Eds., 1998). Metals like Mn, Fe, Cu, Ni, Zn, Cd, Pb and other metals are precipitated in the process, with contribution of the microorganisms (Jannash, 1995) (Table 1).

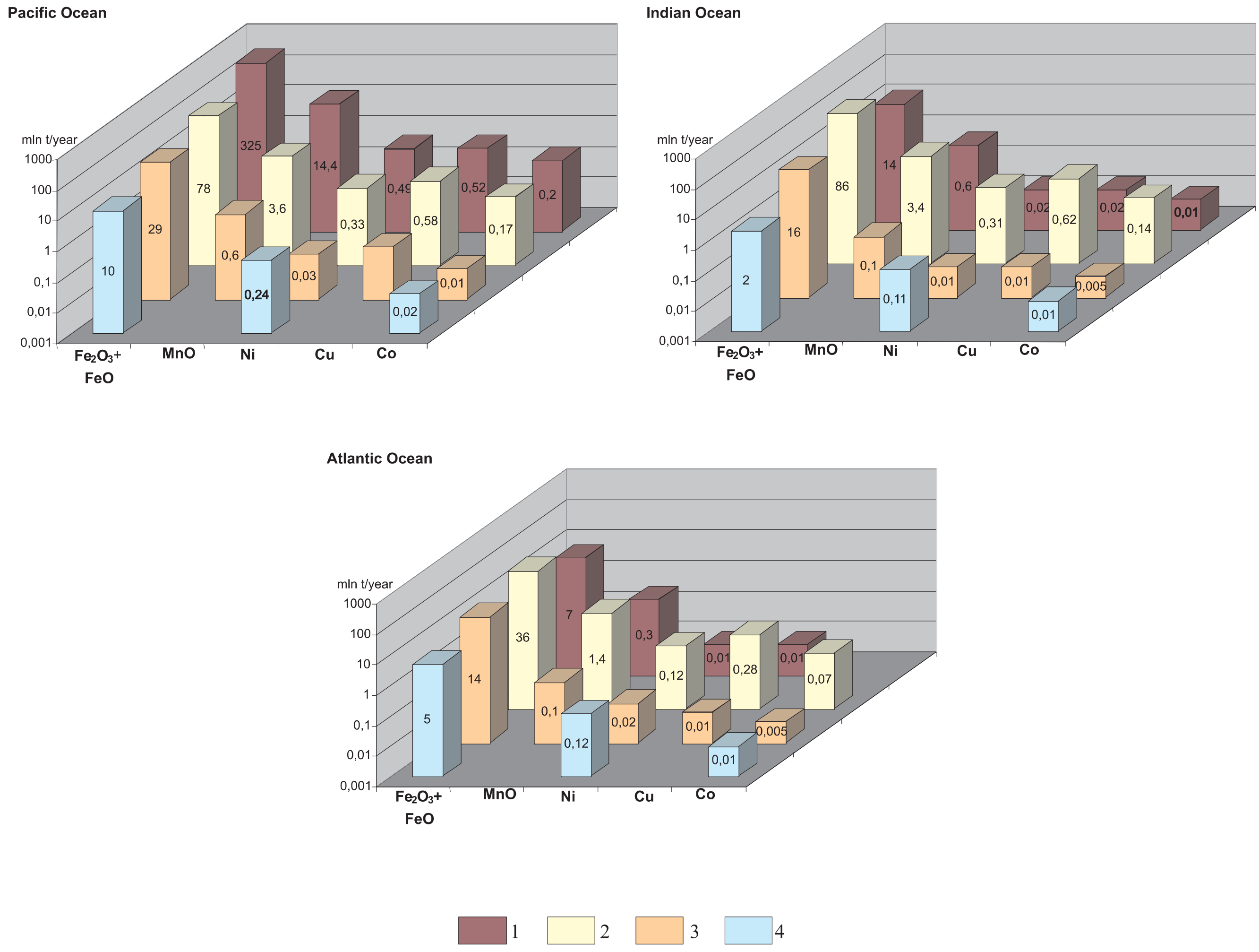


Fig. 6. Contribution of selected chemical components supplied to the oceanic waters from various sources

Based on: Andreev (1994)

1 — hydrothermal components; *2* — terrigenous and biogenic components; *3* — eolian and glacial components; *4* — extraterrestrial components

Table 1

Main types of microbiological processes and interactions with hydrothermal solutions

Processes	Reactions	Free energy, ΔG^0 (kJ/mol)
Photosynthesis	1. CO_2+2H_2S $/CH_2O/+2S^o+H_2O$	+495
	2. CO_2+H_2O $/CH_2O/ + O_2$	+481
Chemosynthesis (under oxic conditions)	3. $H_2S + 2O_2$ H_2SO_4	–706
	4. $CO_2 + 2H_2S + H_2O + O_2$ $CH_2O + H_2SO_4$	–211
Chemosynthesis (under anoxic conditions)	5. $CO_2 + 4H_2$ $CH_4 + H_2O$	–139
	6. $2CO_2 + 6H_2$ $/CH_2O/ +CH_4 + 3H_2O$	–34

Based on: Jannasch (1995)

Presence of silica is a result of reaction between mineralised fluids and host rocks. Forming of sulphides, mainly of Fe, Zn, Cu, Pb and Ag, depends on concentration of the S^{2-} and oxygen ions in the solutions. The S^{2-} ions come from H_2S, which is chemically neutral in the gaseous phase, but in temperatures below 400°C gets soluble and undergoes dissociation with release of H^+, SH^- and S^{2-} ions. In sea water, sulphides of the heavy metals form colloidal solutions. However, presence of H_2S and silica in these zones prevents peptization of metal-sulphide colloidal solutions, which are partly transported further away from the vents. Presence of CO_2 in the sea water oxidise iron and manganese components, leading (in the temperature below 150°C) to the formation of Fe and Mn hydroxides. This in turn leads to the formation of

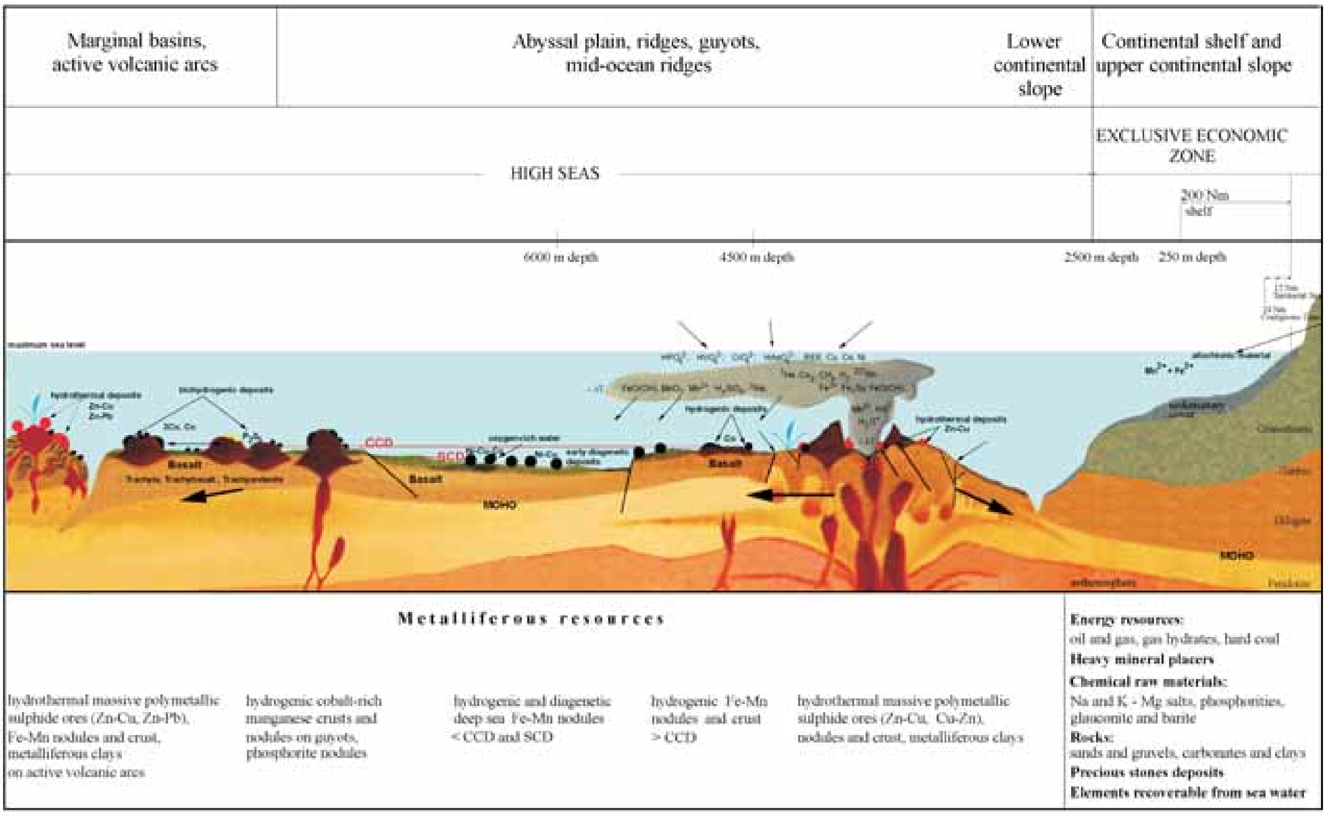


Fig. 7. Zonal-genetical division of oceanic mineral resources

Based on: Kotliński, 1997a, 1998e; Massoth *et al*. (*In*:) Humphris *et al*. (1995)

metalliferous sediments in the vicinity of rifting zones.

Iron separates from manganese in the vicinity of vents. Manganese, more mobile than iron, is transported in the sea water mainly in dissolved form as Mn^{2+} or $MnCl^{+}$, its contents (about 0.2–0.3 nmol/kg) vary across the water column. According to Glasby (1998b), about 90% of manganese in the sea water is of hydrothermal origin, about 80% being precipitated several hundred kilometres away from vents, while about 50% of iron is precipitated closer to them (up to several metres away). The resultant manganese minerals, including todorokite (MnO_2), display well-developed sorption properties and adsorb such cations as Ni^{2+}, Cu^{2+}, or Zn^{2+}. According to the most recent estimates, hydrothermal manganese supply to the sea water amounts to 6.85 x 10^9 kg/yr (German, Angel, 1995), while the river-borne manganese supply amounts to 0.27 x 10^9 kg/yr (Elderfield, Shultz, 1996).

At the ocean crust evolution Stage 4, the water column structure and sedimentation processes were controlled predominantly by the advection of cold, well-oxygenated Antarctic water, which happened about 12 million years ago (Glasby, 1998b).

Analysis of relationship between differentiation of sedimentation conditions, particularly with respect to the distribution of deep-sea deposits and their metallogenic separateness, allows to conclude that the Pacific Ocean represents clearly different characteristic, in comparison to the other oceans (Kotliński, 1998a). The main differences are as follows:

— East-Pacific Rise shows an asymmetric location (moved to the E and SE) in comparison to the central location of oceanic ridges in the Indian and Atlantic Oceans;

— Pacific is distinguished by its intermediate to fast- and superfast spreading rate, twofold of that of the Indian Ocean and threefold of the Atlantic Ocean respectively; it is connected also with wider spreading zones and higher volcanic activity;

— Pacific is distinguished from the other oceans by more pronounced volcanic activity of toleitic composition in the mid-ocean zones (divergent plate boundaries), while in the active zones on the continental plate margins the lavas are of alkaline, calcium-rich composition;

— Pacific is characterised by high tectonic activity taking place along transform faults and blocks located within oceanic fracture zones, as well as by rudimentary development of shelf and presence of deep oceanic trenches;

— Pacific is distinguished from the other oceans by many times higher concentration of manganese, iron, nickel, copper and cobalt, the metals being derived form the hydrothermal springs and vents. In the Indian Ocean, the iron, manganese, nickel, copper and cobalt content of allogenic origin significantly dominate over content of the metals derived from magmatic sources. Relative contents of iron, manganese, nickel and copper from the allogenic sources are similar in the Pacific and Indian Oceans. In the Atlantic Oceans, contribution of the metals derived from the allogenic sources is much higher, and in the same time the total mass of the metals in the Atlantic Ocean is many times lower than that of the Pacific and Indian Oceans;

— In the Pacific, area of which (about 180 million km^2) being nearly equal to that of the Indian and Atlantic Oceans combined (about 181 million km^2), the mobilisation of elements caused by the diagenetic processes in radiolarian and silica-clayey oozes, is taking place on much more expansive areas than in the other oceans (only in the Clarion-Clipperton zone and in the Peru Basin it is an area about million square kilometres).

MORPHOTECTONIC MEGAPROVINCES

Within the planetary system, three morphotectonic megaprovinces can be identified, the megaprovinces characterised by interrelationships in distribution and forming conditions of the deep-sea metalliferous deposits (Kotliński, 1999) (Fig. 8):

— **Indo-Pacific Megaprovince (I)**,

— **Indo-Atlantic Megaprovince (II)**,

— **Indo-Mediterranean Megaprovince (III)**.

The distinguished megaprovinces differ from each other in domination of certain processes (endogenic and exogenic) which shape the regional conditions of forming of ore deposits. Within the Indo-Pacific Megaprovince, amount of the components, including metals derived from the hydrothermal and vent sources to the oceanic waters, is of a premium importance. Amount of the metals derived from these sources is many times bigger than the amount of metals derived from terrigenous sources — opposite to the Atlantic Ocean. Accumulation rate, physico-chemical parametres of the near-bottom waters, as well as structure and dynamics of the ocean water column are also differentiated (Andreev, 1995, 1997; Kotliński, 1998a, 1999). The recent sedimentary-environmental conditions in the distinguished megaprovinces were settled during the last stage of oceans evolution and transformations of oceanic crust, spanning the time from Miocene to Holocene. Different geodynamic regime of development of the Indo-Atlantic Megaprovince in comparison to the Indo-Pacific Megaprovince, along with a lower rate of sedimentation in the latter (particularly during last period), led to the settlement of location, range and relief of the recent ocean bottom and in result to the specific conditions of formation of the sediments.

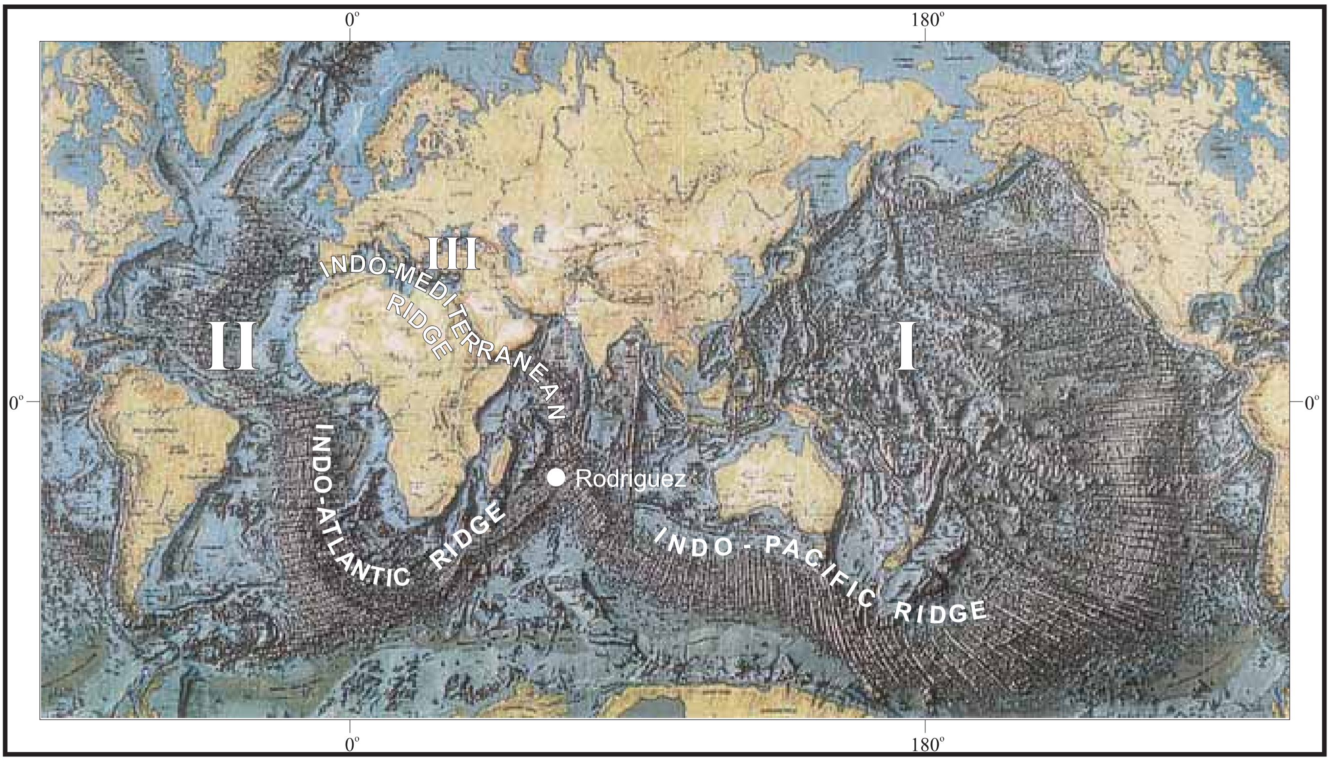
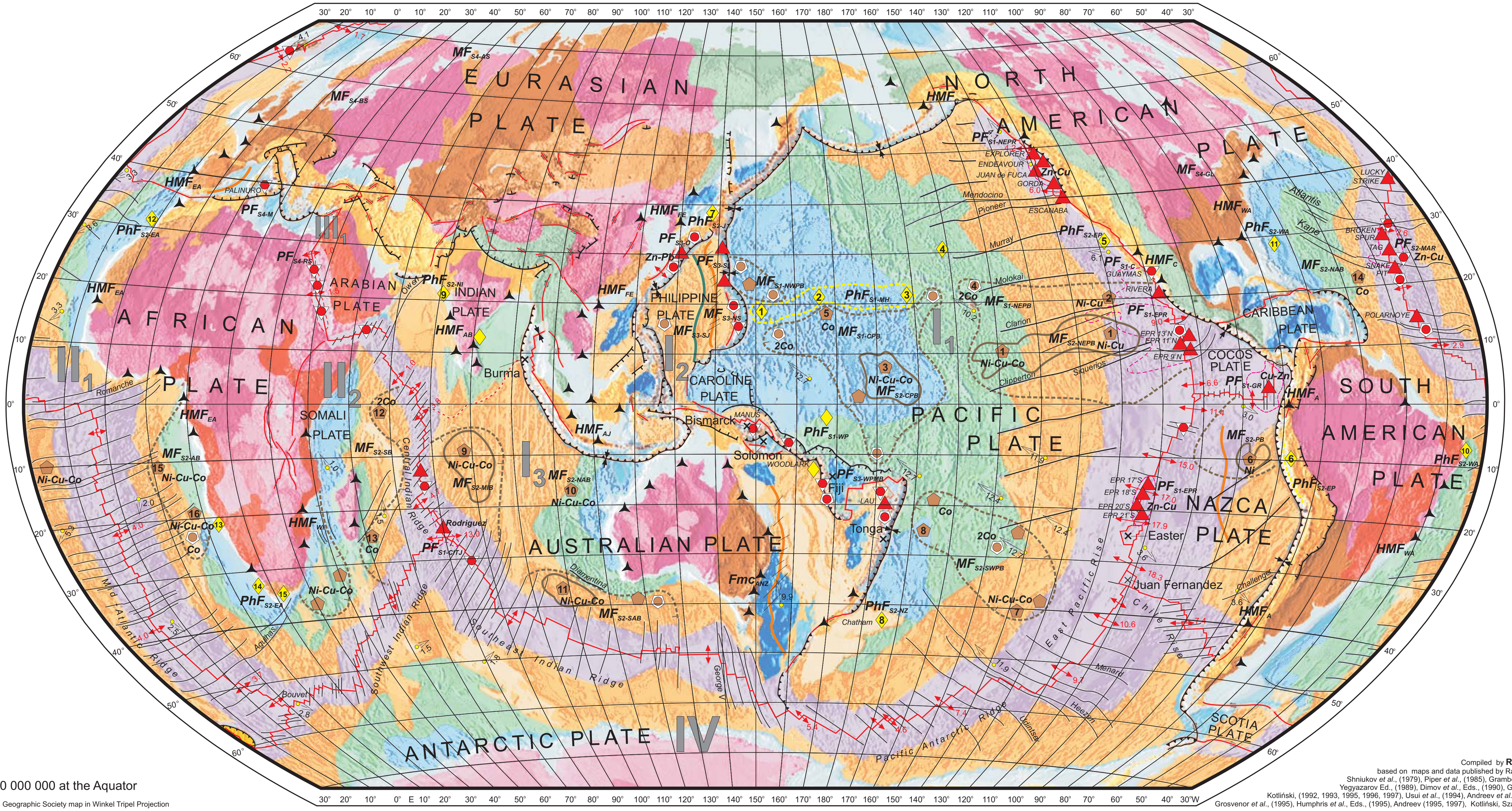


Fig. 8. Geometry and morphostructural character of the morphotectonic megaprovinces of the world's ocean

Based on: Koziar (1993)



Scale 1:120 000 000 at the Aquator

Based on National Geographic Society map in Winkel Tripel Projection

Compiled by **Ryszard Kotliński**
based on maps and data published by Rawson, Ryan, (1978),
Shniukov *et al.*, (1979), Piper *et al.*, (1985), Gramberg, Smyslov, (1986),
Yegyazarov Ed., (1989), Dimov *et al.*, Eds., (1990), Gramberg Ed., (1991),
Kotliński, (1992, 1993, 1995, 1996, 1997), Usui *et al.*, (1994), Andreev *et al.*, (1985, 1996, 1998),
Grosvenor *et al.*, (1995), Humphris *et al.*, Eds., (1995), Andreev (1995, 1997), Kotliński, Szamałek., Eds., (1998)

Fig. 9 METALLOGENIC MAP OF THE WORLD'S OCEAN

MAJOR MORPHOTECTONIC UNITS OF CONTINENTS

▨ Precambrian shield

▨ Areas of Early Proterozoic tectonic and thermal activation

▨ Precambrian platforms

▨ Areas of Palaeozoic foldings

▨ Palaeozoic platforms

▨ Areas of Mesozoic foldings

▨ Areas of Cainozoic foldings

▨ Major intracontinental fractures, rifts and aulacogens

MAJOR MORPHOTECTONIC STRUCTURES OF SEA FLOOR

▨ Continental shelf and slope

▨ Plate divergence boundaries - mid-ocean ridges and rises (spreading axes and transform faults); plate shift direction and rate (cm/yr)

▨ Plate convergence boundaries - subduction zones (deep-sea trenches coupled with volcanic arcs or continental arcs)

▨ Inactive zones:
a) volcanic arcs
b) spreading axes

▨ Deep-sea fracture zones, volcanic seamounts

▨ Marginal sea basins

Burma Microplates

▨ Sea floor rises of different origin

▨ Zones of increased heat flux (above 100 mW/m²)

▨ Hot spots, plate shift direction and rate (cm/yr)

STAGES IN EVOLUTION OF THE OCEANS

▨ stage I (170 - 118 million years BC)

▨ stage II (118-85 million years BC)

▨ stage III (85-24 million years BC)

▨ stage IV (24 million years BC until present)

MORPHOTECTONIC MEGAPROVINCES AND METALLOGENIC PROVINCES

I_1 Indo-Pacific megaprovince (**I**) with major metallogenic provinces (**I_1, I_2, I_3**)
Indo-Atlantic megaprovince (**II**) with major metallogenic provinces (**II_1, II_2**)
Indo-Mediterranean megaprovince (**III**) with metallogenic province (**III_1**)

Deposit formations

1 a) b) Ni-Cu Major regions and deposit fields of manganese nodule formation (***MF***). Dominant geochemical (***Ni-Cu-Co***) and genetic types of nodules in fields (***$MF_{S2-NEPB}$***): a) hydrogenic and diagenetic nodules; b) cobalt-rich manganese crusts and hydrogenic nodules

a) ▲ Zn-Cu b) ▼ c) ⬟ Major regions and deposit fields of polymetallic sulphide formation (***PF***):
a) dominant types of sulphide ores (***Zn-Cu***);
b) metalliferous clays; c) hydrothermal nodules

◆ 8 Major regions and deposit fields of phosphorite nodule formation (***PhF***)

▲ Major regions of heavy minerals formation (***HMF***)

METALLOGENIC PROVINCES AND ORE DEPOSIT FORMATIONS

Metallogenic provinces matches generally the area of recent oceans or their parts. Development of these areas was generally determined by differentiated mechanisms of oceanic basement transformations in the individual plates. Occurrence of the accumulations of mineral assemblages reflects influence of various processes. Conditions of formation of ore deposits within the provinces (Table 2) are shaped in dependence on the intensity of hydrothermal-vent processes, as well as on the bottom relief, depth, distance from the magmatic centres and mechanisms of material transportation. Structure of the oceanic water column (CCD and SCD level, oxygenation degree of the bottom waters, pH and Eh), water circulation and their dynamics, are shaped under influence of outer factors. Sedimentation rate and type of sediments derived to the oceans depend strictly on the geological structure and intensity of weathering and erosion processes on the surrounding continents. Basing on the revealed differences within the megaprovinces, one can distinguish the following major metallogenic provinces (Kotliński, 1999) (Tables 3 and 4):

Indo-Pacific Megaprovince (I) embraces:
— **Pacific Province (I_1)**,
— **Philippines Province (I_2)**,
— **Australian Province (I_3)**.

Indo-Atlantic Megaprovince (II) embraces:
— **Atlantic Province (II_1)**,
— **Somali Province (II_2)**.

It should be emphasised that the **Indo-Mediterranean Megaprovince (III)** matches the metallogenic province embracing the Red Sea and Mediterranean Sea (the so-called **Indo-Mediterranean Ridge — III_1**).

The Antarctic Province (IV), situated on the Antarctic plate, occupies a separate position; no polymetallic deep-sea deposits have been found there as yet (Fig. 9).

Deposit formations were distinguished for the respective types of deposits, formed under influence of certain processes. The formations embrace genetically identical deposit groups.

Table 2

Dominating groups of processes shaping regional and local conditions of forming of polymetallic resources in metallogenic provinces, and main groups of factors determining character of components concentration in deposit fields

GROUPS OF PROCESSES	GROUPS OF FACTORS
1. INTERNAL — shaped by endogenous energy of the Earth. **Diastrophic (tectonic, magmatic, hydrothermal venting).** Mantle degassing, magmatic, and volcanic processes as well as infiltration and hydrothermal venting are a source of metals. The processes lead to transformations of components, sedimentary cover, and oceanic fundament. They also control physical and chemical properties of sea water. Those processes determine age and morphostructure of the deep-sea bottom (fundament and sedimentary cover).	**1. Material sources and transport mechanisms**. Interrelationships between types and quantitites of authigenic components, including metals, and allogenic ones supplied to a deposit formation site.
2. EXTERNAL — shaped by solar radiation energy and chemical bonds. **Denudation- and sedimentation**-related processes, proceeding on continents and within basins, determine amount and type of clastic material, colloidal and true solutions supplied to the oceans. **Oceanic (hydrochemical and hydrodynamic)** processes; the following are of primary importance: — internal sources of water masses and mechanisms of their mixing: they affect, in time and space, the degree of particulate and nutrient concentrations and control transfer and exchange of biomass and nutrients; — processes involved in mass and energy transfer and exchange; they modify, in time and space, physical and chemical properties, including those of near-bottom and pore water. They affect the structure, circulation, and dynamics of oceanic water and affect — depending on basin geometry, including depth and bottom topography as well as distance from shore — physical and chemical properties of oceanic water; accumulation rate; spatial distribution of biogenic, hydrogenic, and lithogenic materials; and early diagenetic processes.	**2. Physical and chemical parameters of near-bottom and pore water** (thermodynamics, oxygenation, carbon oxide content, pH, redox potential (Eh), microbial activity). **3. Structure and dynamics of oceanic water** (depth of minimum oxygen zone, carbonate compensation depth (CCD), silica compensation depth (SCD), near-bottom currents).

Table 3

Metallogenic division of deep-sea polymetallic resources of the world's ocean

Morphotectonic megaprovinces	Metallogenic provinces	Dominant source of material	Major deep-sea deposit formations	Sub-formations	Dominant processes Mineral parageneses Ore types	Major deposit regions and fields	
						Regions	Fields
Indo-Pacific I	**Pacific I_1**	endogenic	**Manganese nodule formation**	Nodules and cobalt-rich manganese crusts on seamounts /MF_{S1}/	Hydrogenic Vernadite, goethite Oxides: **Co, 2Co**	North-East Pacific Basin /$MF_{S1-NEPB}$/ Central-Pacific Basin /MF_{S1-CPB}/ North-West Pacific Basin /$MF_{S1-NWPB}$/	Hawaiian (4), Mid-Pacific Mountains — Magellan, Wake (5), Necker Cook Islands, Kiribati, Tuvalu Ogasawara – Marcus
				Nodules in deep-sea basins /MF_{S2}/	Hydrogenic-diagenetic Todorokite, birnessite, goethite Oxides: **Ni, Ni-Cu, Ni-Cu-Co**	North-East Pacific Basin /$MF_{S2-NEPB}$/ Central-Pacific Basin /MF_{S2-CPB}/ Peru Basin /MF_{S2-PB}/ South-West Pacific Basin /$MF_{S2-SWPB}$/	Clarion-Clipperton (1), Californian (2), Central-Pacific (3), Peru (6), Menard (7), South-Pacific (8)
			Polymetallic sulphide formation	Sulphide deposits in "active" axial zones on intermediate to fast- and superfast spreading rate ridges associated with volcanic activity /PF_{S1}/	High-temperature hydrothermal circulation > 250°C and low- temperature hydrothermal circulation < 250°C > 250°C: chalcopyrite-isocubanite, pyrrhotite, pyrite, wurtzite-sphalerite, anhydrite and $SiO_{2amorph}$ < 250°C: pyrite-marcasite, sphalerite-wurtzite, barite and silica; Massive sulphide ores: **Zn-Cu** Metalliferous clays or muds	North-East Pacific Ridges /$PF_{S1-NEPR}$/ East-Pacific Rise /PF_{S1-EPR}/ Californian /PF_{S1-C}/ Galapagos Rift /PF_{S1-GR}/	Explorer, Endeavour, Juan de Fuca, Gorda, Escanaba Northern (Rivera) Mid (EPR 9°, 11°, 13° N) Southern (EPR 17°, 18°, 20°, 21°S) Guaymas Deep Galapagos
				Sulphide deposits on back arcs and in back-arc basins (slow spreading regime) /PF_{S3}/	Hydrothermal and volcanic activity Sulphides: **Zn-Cu, Ag** and **Au**	Western-Pacific Marginal Basin /$PF_{S3-WPMB}$/	Lau, Fiji, Woodlark, Manus
		biogenic and volcanic	**Phosphorite nodule formation**	Nodules on seamounts /PhF_{S1}/	Biohydrogenic Francolite, colophane Phosphorite	Mariana-Hawaiian /PhF_{S1-MH}/ West-Pacific /PhF_{S1-WP}/	Dutton (1), Scripps (2), Marmokers (3), Musicians (4) Nauru - Banks
	Philippines I_2	endogenic	**Polymetallic sulphide formation**	Sulphide deposits on back arcs and in back-arc basins (slow spreading regime) /PF_{S3}/	Hydrothermal and volcanic activity Chalcopyrite, pyrite, sphalerite, galena, anhydrite, barite, $SiO_{2amorph}$ Sulphides: **Zn-Cu, Ag** and **Au** Oxides: **Co**	Shichito-Iwojima /PF_{S3-SI}/ Okinawa /PF_{S3-O}/	Kita-Bayonnaise, Myojin-sho, Sumisu, Ogasawara Ridge, Suiyo, Kaikata, Mariana Minami-Ensei, Iheya, Izena
			Manganese nodule formation	Nodules on back arcs/MF_{S3}/		Nishi-Shichito /MF_{S3-NS}/	Tempo – Kaikata - Fukutoku
				Nodules and cobalt-rich manganese crusts in back-arc basins/MF_{S3}/	Hydrogenic Vernadite, goethite Oxides: **Co, 2Co, Ni-Cu-Co**	South-Japanese /MF_{S3-SJ}/	Parece Vela, Shikoku, Oki-Daito, Kyushu-Palau

Indo-Pacific I	**Australian I_3**	endogenic-lithogenic	**Manganese nodule formation**	Nodules and cobalt-rich manganese crusts in deep-sea basins/$\boldsymbol{MF_{S2}}$/	Hydrogenic-diagenetic Todorokite, birnessite, goethite Oxides: **Ni-Cu-Co**	Mid-Indian Basin /$\boldsymbol{MF_{S2-MIB}}$/ North-Australian Basin /$\boldsymbol{MF_{S2-NAB}}$/ South-Australian Basin /$\boldsymbol{MF_{S2-SAB}}$/	Central-Indian (9) North-Australian (10) Diamentina (11)
		endogenic	**Polymetallic sulphide formation**	Sulphide deposits in “active” axial zones on fast spreading rate ridge /$\boldsymbol{PF_{S1}}$/	High-temperature hydrothermal circulation >250 ^{o}C Chalcopyrite-isocubanite, pyrrhotite, pyrite, sphalerite, anhydrite, $SiO_{2amorph}$ Sulphides: **Zn-Cu**	Central-Indian Triple Junction /$\boldsymbol{PF_{S1-CITJ}}$/	Rodriguez
Indo-Mediterranean III	**III_1**			Metalliferous sediments in initial rifting zones associated with volcanic activity (slow spreading regime) /$\boldsymbol{PF_{S4}}$/	Hydrothermal and volcanic activity Metalliferous muds with **Fe** and **Mn** hydroxides, **Fe** and **Zn** sulphides	Red Sea /$\boldsymbol{PF_{S4-RS}}$/ Mediterranean /$\boldsymbol{PF_{S4-M}}$/	Atlantis, Albatros, Sudan, Chain, Discovery, Tethys, Valdivia Palinuro, Enaret, Eolo, Santorini
Indo-Atlantic II	**Atlantic II_1**	endogenic-lithogenic	**Manganese nodule formation**	Nodules in deep-sea basins /$\boldsymbol{MF_{S2}}$/	Hydrogenic Vernadite, goethite Hydrogenic-diagenetic Todorokite, birnessite, goethite Oxides: **Ni-Cu-Co, Co, 2Co**	North-American Basin /$\boldsymbol{MF_{S2-NAB}}$/ Angola Basin /$\boldsymbol{MF_{S2-AB}}$/	North-American (14) Damir (15), Cape (16)
		endogenic	**Polymetallic sulphide formation**	Sulphide deposits in “active” axial and “passive” off-axis zones on slow spreading rate ridges associated with volcanic activity /$\boldsymbol{PF_{S2}}$/	High-temperature hydrothermal circulation > 250^{o}C and low- temperature hydrothermal circulation < 250^{o}C > 250^{o}C: chalcopyrite-isocubanite, pyrrhotite, pyrite, wurtzite-sphalerite, anhydrite, $SiO_{2amorph}$ < 250^{o}C: pyrite-marcasite, sphalerite-wurtzite, barite and silica; Massive sulphide ores: **Zn-Cu** Metalliferous clays or muds	Mid-Atlantic Ridge /$\boldsymbol{PF_{S2-MAR}}$/	Northern (Lucky Strike) Central (Broken Spur, TAG, Snake Pit, Polarnoye)
	Somali II_2	endogenic-lithogenic	**Manganese nodule formation**	Nodules in deep-sea basins /$\boldsymbol{MF_{S2}}$/	Hydrogenic Vernadite, goethite Hydrogenic-diagenetic Todorokite, birnessite, goethite Oxides: **Ni-Cu-Co**	Somalian Basin /$\boldsymbol{MF_{S2-SB}}$/	Equatorial (12), Madagascar (13)

NB:

— nodule bearing deposit fields were identified based on mean values of the following parameters: surface area /S/ > 300 thou. km^2; nickel grade X_1> 5; nodule abundance X_2 > 2 kg/m^2, polymetallic sulphide ore deposit fields were identified for areas with resources estimated at > 1.5 million tonnes
phosphorite-bearing deposit fields were identified based on P_2O_5 concentration > 15.0%

— field numbers as shown in Figure 9, e.g. (4)

— formations, subformations, and regions denoted as shown in Figure 9, e.g. /$\boldsymbol{MF_{S1-NEPB}}$/

— North-East Pacific Ridges /$\boldsymbol{PF_{S1-NEPR}}$/, intermediate spreading hydrothermal sites

— East-Pacific Rise /$\boldsymbol{PF_{S1-EPR}}$/, fast- and superfast spreading hydrothermal sites

— Mid-Atlantic Ridge /$\boldsymbol{PF_{S2-MAR}}$/, slow spreading hydrothermal sites

Table 4

Metallogenic division of shallow-water mineral resources of the world's ocean

Morphotectonic megaprovinces	**Metallogenic provinces**	**Dominant source of material**	**Major shallow-water deposit formations**	**Sub-formations**	**Dominant processes** **Mineral parageneses** **Ore types**	**Major deposit regions and fields**	
						Regions	**Fields**
Indo-Pacific I	**Pacific I_1**	biogenic	**Phosphorite nodule formation**	Nodules and sands on continental shelf and continental slope /PhF_{S2}/	Biohydrogenic Francolite, colophane Phosphorite	East-Pacific /PhF_{S2-EP}/ Japanese /PhF_{S2-J}/ New Zealand /PhF_{S2-NZ}/	Californian (5), Peru-Chilean (6) Honsiu (7) Chatham (8)
	Australian I_3					North-Indian /PhF_{S2-NI}/	Cambay (9)
Indo-Atlantic II	**Atlantic II_1**					West-Atlantic /PhF_{S2-WA}/	Brasilian (10), North-American (11)
						East-Atlantic /PhF_{S2-EA}/	Maroccan (12), Namibian (13), St. Helen's Bay (14), Agulhas (15)
		lithogenic	**Manganese nodule formation**	**Fe-Mn** concretions in lakes and shelf seas /MF_{S4}/	Hydrogenic involving micro-organisms Vernadite, goethite Oxides: **Fe-Mn**	Baltic Sea , Black Sea /MF_{S4-BS}/ Arctic Seas (Barents, Kara and White Seas) /MF_{S4-AS}/ Great Lakes /MF_{S4-GL}/	Local accumulations which do not form fields of commercial importance
Indo-Pacific I	**Pacific I_1**	lithogenic	**Heavy minerals formation**	Inshore and offshore heavy minerals placers /HMF_{SX}/	Hydrodynamic (wave action, currents) Ilmenite, rutil, zirconium, monazite, magnetite, titanomagnetite, cassiterite, chromite, gold, platinum	Cordiliera /HMF_C/	Norton Sound, Bristol Bay, Cook Bay, Alexander Archipelago, Good News, Californian
						Andes /HMF_A/	Peru-Chilean
						Far-Eastern /HMF_{FE}/	Tonkin-Taiwanese, Filipino, Japanese
	Australian I_3					Australian-New Zealand /HMF_{ANZ}/	Queensland, New South Wales, Bass, Timor, Carpentaria, Fremantle, Dorset
						Arabian-Bengali /HMF_{AB}/	Kerala, Sri Lanka, Narayanpur-Chatrapur-Gopalpur, Ratnagiri
						Andaman-Java /HMF_{AJ}/	Myanmar-Thai-Malaysian, Sunda
Indo-Atlantic II	**Somali II_2**					West Indian /HMF_{WI}/	Madagascar Mosambique-Somalian
	Atlantic II_1					East-Atlantic /HMF_{EA}/	Cornwall, Iberian, Guinean, Namibian, South-African
						West-Atlantic /HMF_{WA}/	New Scotian, Floridian, Brasilan, Falkland

NB:

— phosphorite deposit fields were identified based on P_2O_5 concentration > 15.0%

— field numbers as shown in Figure 9, e.g. (6)

— formations, sub-formations, and regions denoted as shown in Figure 9, e.g. /PhF_{S2-EP}/

They are characterised by similar relations of occurrence, mineral-chemical composition and texture-structural forms, which are shaped depending on environmental factors dominating in a given area. Within formations, the regional differences are connected mainly with fluctuations of intensity and proceeding of certain processes — for example, tectonic-magmatic, including hydrothermal, volcanic-vent and infiltration processes. Regional differentiation reflects also differences in range of proceeding of mega-scale processes, for example hydrogenic-diagenetic nodule forming processes on the abyssal plains, or specific hydrogenic sedimentation of the nodules and cobalt-rich manganese crusts on the volcanic seamounts another submarine elevations. However, each of the distinguished formation is characterised by obvious domination of certain mineral assemblages, which were formed under influence of certain hydrogenic, hydrogenic-diagenetic, hydrothermal-vent, bio-hydrogenic or mechanogenic processes. For example, in the manganese nodule formation of the North-East Pacific Basin (**MF_{NEPB}**), one can find one group of deposits, where the nodules, in their chemical composition, show a dominance of vernandite and goethite formed by the hydrogenic processes, and the other group characterised by dominance of todorokite and birnessite, formed by the hydrogenic-diagenetic processes. In such case, two deposit subformations were distinguished: nodule and cobalt-rich manganese crusts occurring on the seamounts (**$MF_{S1\text{-}NEPB}$**), and deep-sea nodules (**$MF_{S2\text{-}NEPB}$**). On the other hand, polymetallic sulphide formation in the volcanic island arcs of the Shichito-Iwojima Region, Okinawa Region, and in the fast spreading centres of the East-Pacific Rise or slow spreading centres of the Mid-Atlantic Ridge, is characterised by occurrence of mineral parageneses formed in the temperatures below 250°C and above 250°C. Besides, in the immediate vicinity from the rift valleys, the metalliferous deposits occur. In such cases, the following subformations were distinguished: high-temperature hydrothermal circulation sulphide ores in "active" axial zones on intermediate to fast- and superfast spreading rate oceanic ridges (**PF_{S1}**); and in "active" axial and "passive" off-axis zones on slow-spreading rate oceanic ridges (**PF_{S2}**); a sulphide deposit subformation in island arcs (**PF_{S3}**); and metalliferous sediment subformation in low-temperature hydrothermal circulation and in initial rifting zones, locally associated with volcanic activity (**PF_{S4}**).

Basing on the ascertained differences, the following ore deposit formations were distinguished within metallogenic provinces (Kotliński, 1999):

— **manganese nodule formation**,
— **polymetallic sulphide formation**,
— **phosphorite nodule formation**,
— **heavy minerals formation**.

Table 5

Geochemical types and sub-types of nodules

Types and sub-types		Major characteristics						Auxiliary characteristics						
		Ni+Cu %			Co %			Mn %%	Fe %%	Mn/Fe	Ni %%	Cu %	Ni/Cu	Co/Cu
		mean	min.	max.	mean	min.	max.	mean	mean		mean	mean		
Nickel-copper (Ni-Cu) (2030)[1]	I	2.13	1.70	2.40	0.18	0.15	0.34	26.46	6.69	3.95	1.13	1.00	1.13	0.18
	II	2.70	2.40	2.88	0.21	0.15	0.35	29.30	6.50	4.50	1.47	1.23	1.20	0.17
Nickel (Ni) (220)	I (76)	1.07	0.66	1.70	0.02	0.01	0.15	42.81	2.55	16.78	0.72	0.35	2.06	0.06
	II (144)	2.08	1.70	2.49	0.07	0.01	0.15	33.11	5.70	5.80	1.35	0.73	1.85	0.10
Nickel-copper-cobalt (Ni-Cu-Co) (235)		1.33	0.70	1.70	0.25	0.15	0.40	19.85	10.98	1.80	0.74	0.59	1.25	0.43
Cobalt (Co) (399)		0.58	0.15	0.70	0.31	0.15	0.40	15.14	15.72	0.96	0.39	0.19	2.05	1.63
Cobalt-rich (2Co) (443)	I (352)	0.53	0.14	0.70	0.51	0.40	0.80	17.02	17.17	0.99	0.37	0.16	2.30	3.19
	II (91)	0.51	0.33	0.70	1.24	0.80	2.23	17.76	14.20	1.25	0.43	0.08	5.38	15.50
Hydrothermal manganese crust (G) (72)		–	–	0.30	–	–	0.07	9.47	19.42	0.49	–	–	–	–

Based on: Andreev (1994)

[1] number of assays

Table 6

Nomograph of geochemical types and sub-types of nodules

Co (wt%)	**0.3**	**0.7**	**1.7**	**2.4 Ni+Cu (wt%)**
0.07	G* **Non-determined**	**Nickel** **Ni (I)**	**Nickel** **Ni (II)**	
0.15	**Cobalt** **Co**	**Nickel-copper-cobalt** **Ni-Cu-Co**	**Nickel-copper** **Ni-Cu (I)**	**Nickel-copper** **Ni-Cu (II)**
0.40	**Cobalt** **2Co (I)**	IDENTIFYING CHARACTERISTICS **Ni-Cu (Mn/Fe 2.5<; Mn=20-30%; Ni/Cu=1.0-1.5)** **Ni (Mn/Fe>5; Mn=30-40%; Ni/Cu=1.5-2.0)** **Ni-Cu-Co (Mn/Fe=1.00-2.50; Mn<20.00%; Ni/Cu=1.0-1.5)** **Co (Mn/Fe<1.5; Co>0.15%))** **G^* — hydrothermal manganese crust (Mn/Fe<1.0; Co<0.07%)**		
0.80	**Cobalt** **2Co (II)**			
>2.0				

Based on: Andreev (1994)

Detailed subdivision of the formations into individual regions and fields is presented in the Table 3 and Table 4.

Regional differentiation within a given formation is reflected, besides others, by the degree of deposit abundance on the floor and content of certain components. It should be emphasised that the regions distinguished within formations and occurring in the Indo-Pacific Megaprovince, clearly differs from the regions within the Indo-Atlantic Megaprovince. For example, differences in deep-sea nodule regions are reflected by abundance and the metal content in the nodules; in turn, this is connected with the distance from the components' source to the place of their concentration and with the local sedimentary conditions. In the region of the Central-Pacific Basin, within the Magellan–Wake-Necker Fields, the manganese nodule/cobalt-rich manganese crust shows high cobalt grades.

On the other hand, the deep-sea nodule subformation in the North-East Pacific Basin, occurring within regional sea bed morphostructures, e.g. the Clarion-Clipperton Field and in the Peru Basin (Peru Field — see Table 3), is distinct by its high concentrations of manganese, nickel and copper. Metal concentrations at the ore field level depend mainly on sedimentation-related factors which determine accumulation of components derived mainly from hydrothermal sources. Within nodule fields, the metalliferous accumulations are distinguished by specific geochemistry (Ni, Ni-Cu, Ni-Cu-Co, and Co; Tables 5 and 6). Co-existing geochemical types of nodules are characterised by domination of certain manganese mineral phases; Ni — birnessite, Ni-Cu — todorokite; Ni-Cu-Co — birnessite and todorokite; Co, 2 Co — vernadite. Degree of metal concentrations in the nodules is also differentiated, depending on the depth of their occurrence in relation to the CCD and SCD levels. The Ni, Ni-Cu and Ni-Cu-Co-type nodules, with high concentrations of those metals and manganese occur, as a rule, at the depth interval between CCD and SCD, on sediments whose $CaCO_3$ content does not exceed 10% (radiolarian--diatomaceous oozes), while Co-enriched nodules occur above the CCD calcareous oozes. Nodules occurring on the different depths show also specific morphological features. Basing on the shown variability, fields and areas were distinguished within the formations. The fields marked on the metallogenic map of the world's ocean represent, according to the present author, those ones which bear a potential economic importance. The other fields marked on the map show no numbers and metal content (Tab. 3). The map have been constructed regarding degree of knowledge of geological structure of the oceans. Detailed characteristics of the nodule-bearing fields is included in the monography of Andreev *et al*., Eds. (1998) and Glasby (1998b), Kotliński (1998b).

MANGANESE NODULE FORMATION

The manganese nodule formation (***MF***) encompasses deep-sea manganese nodules, cobalt-rich manganese crusts and ferromanganese concretions (Kotliński, 1998e, 1999). The formation is identified based on the presence of nodule-forming processes at the sediment-water interphase, affected by specific environmental factors (Menard, 1976; Frazer, Fisk, 1981; Piper, Blueford, 1982; McKelvey *et al*., 1983; Piper *et al*., 1984; Korsakov *et al*., 1988; Andreev, 1994; Cronan, 1997; Glasby, 1998b).

Conditions determining forming of the nodules are shaped depending on the following factors:

— dominant processes delivering material (including metals, i.e. Mn, Ni, Cu, Fe, Co), such as hydrothermal, volcanic-vent and infiltration ones;

— distance from the active magmatic centres;

— depth of occurrence, i.e. location in relation to the CCD and SCD levels;

— physico-chemical properties of near-bottom waters and pore waters.

Within a given formation, domination of certain hydrogenic or hydrogenic-diagenetic processes manifests in dependence on the interaction of groups of these factors. Regional differentiation of these processes allowed differentiation of the following regions within the manganese nodule formation (Table 3):

- North-East Pacific Basin (MF_{NEPB}): Clarion-Clipperton and Californian Fields ($MF_{S2-NEPB}$), Hawaiian Field ($MF_{S1-NEPB}$);
- North-West Pacific Basin ($MF_{S1-NWPB}$): Ogasawara and Marcus Fields;

- Peru Basin (*MF*$_{S2\text{-}PB}$): Peru Field;
- Central-Pacific Basin (*MF*$_{CPB}$): Central-Pacific Field (*MF*$_{S2\text{-}CPB}$), Mid-Pacific Mountains — Magellan, Wake and Necker Fields (*MF*$_{S1\text{-}CPB}$);
- South-West Pacific Basin (*MF*$_{S2\text{-}SWPB}$): Menard and South-Pacific Fields;
- Mid-Indian Basin (*MF*$_{S2\text{-}MIB}$): Central-Indian Field;
- North-Australian Basin (*MF*$_{S2\text{-}NAB}$): North-Australian Field;
- South-Australian Basin (*MF*$_{S2\text{-}SAB}$): Diamentina Field;
- North-American Basin (*MF*$_{S2\text{-}NAB}$): North-American Field;
- Angola Basin (*MF*$_{S2\text{-}AB}$): Damir and Cape Fields;
- Somalian Basin (*MF*$_{S2\text{-}SB}$): Equatorial and Madagascar Fields;
- Nishi-Shichito (*MF*$_{S3\text{-}NS}$);
- South-Japanese (*MF*$_{S3\text{-}SJ}$).

The natural deep-sea concentrations of hydrated manganese and iron oxides occur in the form of coatings, crusts, nodules and micronodules. Coatings cover the surface of fine rock particles with thin (several millimetres) layer, while plate-shaped crusts cover the basement rock outcrops with a thicker (several to 15–20 cm) layer. Crusts occur usually at the depth range of 750–1000 m to 2500–3000 m. The cores of nodules are represented by intraclasts coated with alternating lamina of Mn and Fe oxides. The nodules show quite differentiated shapes and sizes (usually exceeding 1 cm). Nodule forms, particularly in the earlier stages of their formation, depend on the size and shape of the core. Micronodules are not bigger than 1 mm. Oceanic nodules and cobalt-rich manganese crusts are of perspective economic importance.

It should be pointed out, that local accumulations of the shallow-water **ferromanganese concretions** occur within the Indo-Atlantic Megaprovince, but they do not form any fields of economic significance. The fields are characterised by a sparse distribution of the concretions and much lower (in comparison to the deep-sea nodules) content of metals — Ni, Cu, Co, Mn, Mo. Accumulations of such nodules occur both in marine and lacustrine basins. Distinguished shallow-water subformation (Fe-Mn$_{S4}$) embraces Fe-Mn concretions from the arctic seas, Baltic Sea, Black Sea, as well as the Punus-Jarvi Lake and Great American Lakes (Kotliński, 1998b). Shallow-water concretions form accumulations of a hydrogenic type and are formed with contribution of the early diagenetic processes. The concretions are distinguished by high variability of the Mn/Fe ratio — from 0.14 to 1.11. Sedimentary environment of recent lakes and semi-closed, epicontinental seas is characterised by a dominance of the terrigenous sediments derived from the surrounding continents. The concretions distinguish in their high growth rate and they are formed in areas of much higher sedimentation rate that the ocean basins. Certain physico-chemical factors, characterising the sedimentary environment conditions, like oxygenation of the near-bottom waters, pH and high Eh, favour, with contribution of the microorganisms (mainly ferrous aerobic, autotrophic bacteria), precipitation of the ferromanganese hydroxides. The precipitation takes place on the residual clasts, with simultaneous and selective accumulation of metals due to the sorption, ionic exchange and join precipitation processes, followed by dehydration of the ferromanganese hydroxides (Winterhalter (*In*:) Kotliński, 1998b; Glasby *et al*., 1996; Trokowicz, 1998).

Deep-sea manganese nodules

Oceanic deep-sea nodules form natural, polymineral aggregations of ferromanganese hydroxides and clay minerals, containing in their chemical composition more than 50 elements. Concentration of these elements in sedimentary rocks usually many times exceeds their geochemical density index, so-called weight clarks. Detailed characteristics of the oceanic deep-sea nodules and cobalt-rich manganese crusts were presented in the previous papers (McKelvey *et al*., 1983; Thissen *et al*., 1985; Andreev, Anikeeva, 1984; Andreev, 1994, 1997; Barriga, 1996; Halbach *et al*., 1982; Halbach *et al*., Eds., 1988; Ilin *et al*., 1997; Kotliński *et al*., 1997; Kotliński 1998b; Andreev *et al*., Eds., 1998; Glasby, 1998b).

Oceanic nodules represent three genetic types: hydrogenic "H", hydrogenic-diagenetic "HD" and diagenetic "D" (Kotliński, 1996). The nodules lie on a bottom surface sediments of the oceanic bottom, on variable depth. They show increased content of certain metals, depending on the depth of their occurrence:

— within a depth interval below minimum oxygen concentration (500–1000 m) to about 3500 m, on the calcareous oozes containing >30% $CaCO_3$, type "H" nodules and cobalt-rich manganese crusts with risen content of Co, Mn, Pt and Fe dominate;

— within a depth interval of occurrence of clayey-calcareous oozes, containing 30–10% $CaCO_3$, down to the CCD level, usually type "H" and "HD" nodules occur, with risen content of Ni-Cu-Co;

— within a depth interval of occurrence of siliceous oozes, between CCD and SCD levels, and below SCD where clayey-siliceous and polygenic clays occur, type "D" and "HD" nodules dominate — they are characterised by risen content of Ni, Cu and Mn, as well as Ni and Mn.

The present author has also concluded, that depending on the depth of nodule occurrence, i.e. their location in relation to the CCD and SCD, one can observe significant differences in morphology of the nodules. Type "H" nodules occurring above CCD are smaller than the type "D" nodules occurring below CCD and SCD levels. Differences in nodules' sizes also reflect their structural and textural features, which is connected with their different rate of growth. Growth of the type "H" nodules is slower than the growth of the type "D" nodules. They also occur in different lithofacies realm, characterised by presence or absence of strongly hydrated, so-called boundary layer of sediment of specific physico-chemical features, in which the nodules are submerged.

Analyses of chemical composition of nodules from recent lacustrine, marine and oceanic environments show that the nodules are generally of bi-metallic (Fe-Mn) character, with

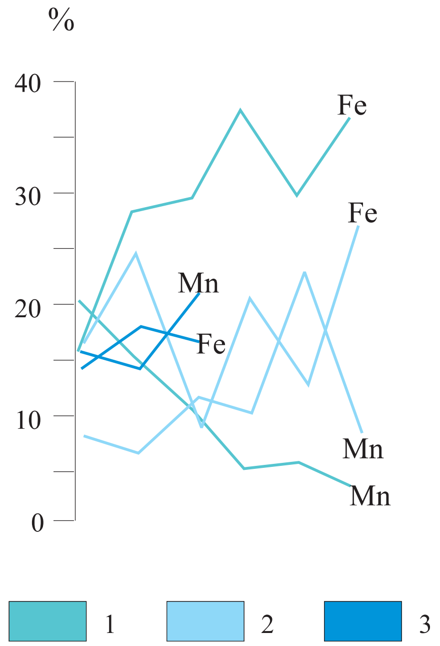


Fig. 10. Comparison between mean iron and manganese contents in nodules of lakes, seas and oceans

1 — lake nodules; *2* — sea nodules; *3* — oceanic nodules

dominance of iron over manganese. In some basins, the content of manganese is higher that the content of iron (Punus-Jarvi Lake, Barents Sea, Gulf of Finland, Pacific Ocean and Indian Ocean). Mean Mn/Fe ratio in the lacustrine nodules is 1.3, in marine nodules is about 1.0, and in the Pacific is 2.0; in the Clarion-Clipperton Field the ratio is frequently higher than 3, but on the other hand in the South-Pacific Field is about 1,0. As far as concerns trace elements, the content of V, Cr, Co, Ni, Mo, Cu, W, Zn, Pb, Ga is much higher in the seas and oceans than in the lakes — in the lakes concentrations of the above mentioned metals are approximately equal in the nodules and the surrounding sediments and can reach few tens of ppm; in the marine nodules the same concentrations are clearly higher than in the surrounding sediments and are as high as tens to hundreds ppm. In the marine nodules the ratio Mn/Fe is often higher than 1.0 (Fig. 10). Oceanic deep-sea polymetallic nodules reveal metal content of hundreds to thousands ppm and much higher metal concentration indexes in the nodules — from 2 to 80 (of such metals as Cu, Ni, Co, Fe, Mn) (Kotliński, 1993, 1998b). Clear rise of Co, Ni, Cu, Mo, W, Zn and Pb content has been observed when comparing lacustrine and oceanic nodules. According to Strakhov (Strakhov, 1986) Ni, Cu, Zn show an affinity to Mn, while Co, Pb, Sr and Ti show affinity to Fe. Deep-sea nodules, in comparison to the lacustrine and marine nodules (which composition was accepted as a so-called geochemical spectrum), contain highest amounts of Mn, Co, Cu, Ni, V and Zn, while Cr, Pb and Ga contents are similar in all groups. In the marine nodules contents of Ni, V, Mo and Zn are the highest, while contents of Cr, Cu, Pb and Ga are the lowest (Fig. 11). In the oceanic nodules, pronounced negative correlation between Fe and Mn (–0.57) can be observed, while in the sediments the same correlation is positive (+0.42 to +0.52). According to the value of concentration index, the elements form for the example the following sequence in the Pacific Ocean: Ni-Mn-Mo-Co-Cu-Pb-Zn-Ti-V-Fe-Sr-Ba- La-Ga-Sc-Cr. More than 20 elements show many times higher concentration in the nodules than in the pelagic sediments. According to the sequence of concentration indexes, the following elements show a high degree of concentration: Ni, Mn, Co, Pb, Mo, Sr, V, Zr, Zn. For example, Ti, Y, Ba reveal similar concentrations in nodules and sediments, while Sc, Cr, Ga show lower concentrations in the nodules than in sediments (Kotliński, 1993). Positive correlations between Mn-Ni-Cu-Zn and Mo, as well as Fe-Co-Pb, ascertained basing on chemical analyses of the nodules, are shown in the Figure 12 (Gromoll, 1996). It was also proved, that concentrations of La, Ce, Nd and Sm are highest in the nodules of the Atlantic Ocean, medium in the nodules of the Indian Ocean and lowest in the nodules of the Pacific Ocean. Concentration of Y in the nodules of the Pacific is the highest, being twice as high as the medium concentration of this element in the world's ocean. Besides that, correlations between concentrations of Mn and the Rare Earth Elements are negative, while the correlations between Fe and Co and the Rare Earth Elements are positive (Kotliński *et al*., 1997). Described geochemical associations of the elements in the nodules are of an universal character.

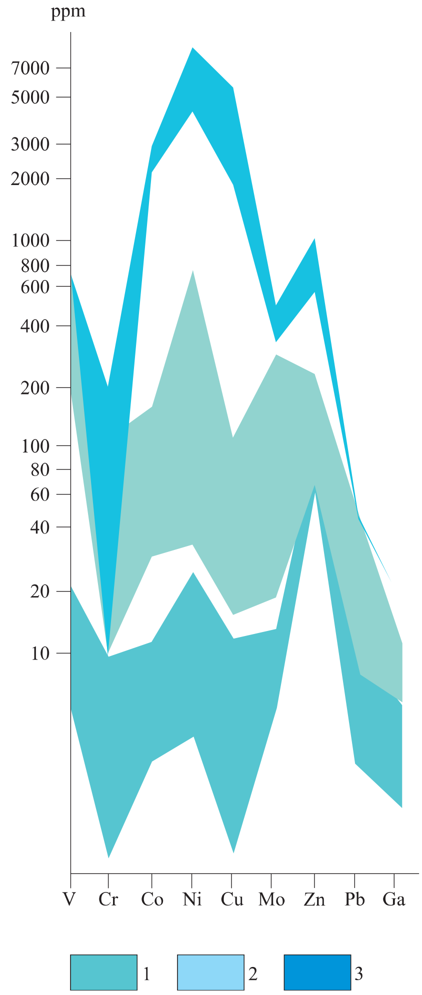


Fig. 11. Geochemical spectrum of selected metals in nodules of different basins

1 — lakes; *2* — seas; *3* — oceans

Birnessite micronodules and oxides (goethite+todorokite+birnessite) nodules, showing massive concentric-laminated structure and occurring in the flysch sediments of Cenomanian and Turonian in the Polish Carpathians, show similarities to the oceanic nodules. Maximum accumulations of the nodules are observed in the reddish-brownish radiolarite claystones of Eocene age, which were deposited near CCD level (Wieser, 1982). It should be emphasised, that birnessite occurring in the nodules belongs to the forms characterised by diminished parameter of unit cell C, which is typical for the marine forms. According to Wieser (1985), it is connected with contraction of the structure, which results from distribution of the Mg, K, Ba and Sr ions within the interlayer spaces. In the nodules studied, no risen content of the trace elements was found, and no clear correlation between main, subordinate and trace elements (with exception of correlations between Al with Cr and Fe with Cu) was observed. Significant distance from the volcanic activity centres was a direct reason of the low concentration of the trace elements (Gucwa, Wieser, 1978).

Performed studies of metals occurrence in the nodule forming processes in different oceans show that the concentration of metals in the nodules is directly connected with amount of Mn, Ni, Cu and Co delivered to the oceanic waters chiefly from the hydrothermal sources (Glasby, 1998b). Proceeding of these processes is stimulated depending on the hydrochemical structure of water masses and their dynamics, physico-chemical properties of the near-bottom and pore waters, depth and bottom relief, accumulation rate, biological productivity, and diagenetical diffusion of Mn^{2+} and Fe^{2+} ions from the oxidised, weakly alkaline, so-called boundary sediment layer. In this layer, released Ca^{2+} ions stimulate pH conditions, which enables precipitation of ferromanganese hydroxides (Trokowicz, 1998). Periodical delivery of Mn, Fe, Cu, Zn, Ni and other elements to the highly oxygenated near-bottom waters is of a premium importance.

Sources of oceanic manganese and other metals are regionally differentiated, while amount of lithogenic components of allogenic and authigenic (hydrogenic and biogenic) origin and elements mobilised in the diagenetic processes is changing in respective oceans. For example, amount of Mn in the near-bottom waters of North Atlantic is 0.15 nmol/kg, while in the Central Pacific is 0.05 nmol/kg, which is connected with higher content of eolian material in the Atlantic Ocean. Within the depth interval 500–4000 m, 80% of Mn occurs in the soluble form, while in the near-surface waters concentration of soluble Mn reaches 99% (Glasby, 1998b). It should be emphasised that concentrations of such trace elements as Cu, Ni, Co, Zn are fluctuating, depending on the depth and regional conditions (Kabata-Pendias, Pendias, 1993). Authigenic components, including those derived from the hydrothermal solutions, volcanic products, infiltration activity of the oceanic waters and halmyrolysis of the basalts, represent the main source of basic metals in the Pacific and Indian Oceans nodules. Distance from the main sources of metals is an important factor, high biological productivity of equatorial waters being additional factor of enriching the sediments in metals.

One of the distinguishing factors of oceanic nodules is higher content of Mn than Fe, and moreover significantly higher content of these metals in the nodules than their mean concentration in the Earth crust. Separation of these elements in the oceanic waters is a function of the oxygenation degree, acidity (pH) and Eh of the near-bottom waters. Those processes are stimulated by the presence of organic complexes, changing stability field of amorphous colloids of Fe and Mn. However, if the water acidity does not rise and Eh does not reach the sufficient value (about +0,4V), the oxidation of ions Fe^{2+} to Fe^{3+} and Mn^{2+} to Mn^{4+} will not proceed. In result of the diffusion of oxygen, Fe^{2+} ions are oxygenated on the water-sediment phase boundary. In the oxygenated near-bottom waters, ion Fe^{3+} easy undergoes hydrolysis, forming weakly soluble iron hydroxide $Fe(OH)_3$, precipitating in the form of gel, under certain thermodynamic equilibrium. On the other hand, manganese should theoretically occur in the Mn^{4+} form, i.e. mainly in the form of almost insoluble MnO_2. However, it was ascertained that manganese occur mostly in the form of Mn^{2+} ion, which undergoes hydrolysis forming soluble $Mn(OH)_2$.

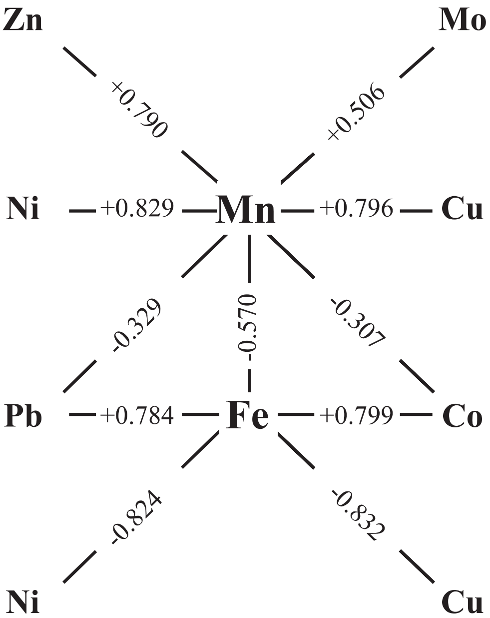


Fig. 12. Metal correlations in Pacific nodules

Based on: Gromoll (1996)

Forming of amorphous $Fe(OH)_3$, usually of a positive surficial charge, and amorphous $Mn(OH)_2$ of a negative charge, conditions the way of ferromanganese hydroxides adsorption and forming of complexes of soluble ions and organic components. Irrespectively of origin of those metals, certain mechanisms of transport of amorphous colloidal particles to the place of reaction (i.e. forming place of the nodules) exist. Amorphous ferromanganese hydroxides and joint-occurring metals undergo migration in the processes of oceanic circulation and mixing of the near-bottom waters. Colloidal particles remain in suspension until they form colloidal complexes. Oxidation and coagulation of amorphous colloids $Mn(OH)_2$ and $Fe(OH)_3$ is the main mechanism of passing of the metals into the sediments. Hydroxide gels, forming in the sediments, undergo complex chemical reactions with the organic substance. Surficial charges of the ferromanganese hydroxides determine the way of adsorption and forming of the complexes with soluble ions. These complexes form hydrophobic colloids, easily undergoing aggregation. Spatial segregation of ferromanganese hydroxides results from the different conditions of their coagulation. These hydroxides show dipole properties and thanks to the binding forces form, with contribution of the microorganisms, colloidal agglomerates on the intraclasts. This process is associated with selective accumulation of elements on the way of sorption, ionic exchange and joint-precipitation. Presence of biogenic $CaCO_3$ in the sediment, which undergoes slow hydrolysis, causes that Ca^{2+} ions keep pH above the isoelectrical point for the amorphous $Fe(OH)_3$ and $Mn(OH)_2$, on the suitable levels necessary for their precipitation (Trokowicz, 1998). After their precipitation, crystallisation of MnO_2 as well as forming of goethite from $Fe(OH)_3$ on the way of dehydration follow.

Processes of concentration of metals in the nodules are also polyphase and proceed depending on if the vernadite (with higher content of Co, Pb and Ti) or todorokite (with higher content of Cu, Ni, Mo and Zn) is formed (Halbach *et al*., 1982; Halbach *et al*., Eds., 1988). Intensity of early diagenetic or diagenetic processes depends on the environmental conditions and is regionally diversified. In environment characterised by a high biological productivity, considerable rate of sedimentation and simultaneous accumulation of organic matter, sub-oxidising (dysaerobic and anaerobic) diagenetic processes show complex proceeding of the redox reactions. They lead to reduction and translocation of the Fe, Mn and Rare Earth Elements to the solution (Halbach *et al*., 1982; Dymond *et al*., 1984; Müller *et al*., 1988). The elements are being precipitated on the bottom or in immediate vicinity of the bottom, where the Eh is higher. Because of higher mobility of Mn, the oceanic nodules show Mn/Fe index, which is above 5–7. The nodules from the Peru Field provide a good example of sub-oxidising, diagenetic forming of the nodules. On the other hand, the oxidising conditions of forming of the nodules are typical for the basins characterised by average biological productivity, relatively small to medium accumulation rate and low organic content in the sediments. Such basins are characterised also by relatively high Eh on the whole surface of bottom sediments. Studies of the pore waters show, that slight diminishing of Eh within the surface layer of sediments, resulting from oxidising of the amorphous organic matter, lead to preferential dissolution of Mn^{2+}, at the cost of poorly soluble Fe^{3+}. Increase of the Mn/Fe index, upward migration of reactive components and forming of todorokite follow these processes (Müller *et al*., 1988; Halbach *et al*., 1982; Halbach *et al.*, Eds., 1988). Oxidising diagenetical processes proceed in the so-called boundary layer, composed of hydrated, strongly oxidised sediments, which constitutes a specific geochemical zone, enabling hydrogenic migration of the elements. Geochemistry of Mn and Fe in the nodule forming processes has been precisely studied by Glasby (1998b).

As it was mentioned above, the equally important role in delivery of trace elements to the sediments is played by biogenic migration and accumulation processes. Water provide the crucial medium for functioning of any biocenose. Physiological, as well as chemical and phisico-chemical processes proceed with contribution of water solutions of organic and inorganic substances. Water dissolves chemical components, which due to oxidisation and hydrolyse get more assimilable for living organisms. Water is also a medium for migration of elements and transport of mineral material and organic substance, which occur in suspension. Some bacteria, having enzymatic system which enables them to perform various oxidising reactions, produce organic matter from mineral components in chemosynthesis processes, the energy being derived from oxidising reactions of certain inorganic components. Chemosynthesis processes play an important role in migration of some elements. Role of microorganisms in the forming and growing processes of the nodules is significant (Trokowicz, 1998).

Energetically, endothermal processes such as biogenic accumulation of mineral components from actual solutions, character of colloidal solutions, dehydration and dissolving, play a crucial role in circulation of elements. Among exothermal processes, the important role is played by oxidation, precipitation from the solutions, mineralisation and hydration. Solubility, Eh and pH govern intensity of migration either of dissolved chemical components (in ionic form) or colloidal particles. Chemical and mineralogical composition of the waters is also an important factor. Considerable amounts of colloidal substances occurring in organic, mineral, or mineral/organic form show specific sorption abilities and mobility in the water masses. Important role is played also by migration of elements, liberated in result of submarine volcanic eruptions. However, they are the living organisms which play a crucial role in migration of the elements — they act not only as accumulators and transmitters of energy, rising atomic energetic stage, but represent also the factors responsible for selection and distribution of the elements. For example, skeletons of radiolarians of *Acantaria* genus, enriched in trace elements in the surface waters, are deposited on the bottom and undergo total dissolution in sediments, constitute an additional source of metals in the near-bottom and pore waters. Besides that, radiolarian oozes are characterised by high porosity and higher than other sediments content of organic matter, which conduct diffusion processes and hydrogenic migration of such metals as Mn, Cu, Ni, Co and others. Comparison of contents of some metals or groups of metals indicate that the metals are absorbed by amorphous Fe and Mn colloids. Trace elements adsorption ability of the Fe and Mn minerals depends on physico-chemical parameters of sedimentary environment. In the oceans, the nodules has not yet been found in poorly-oxygenated environment. In such sediments, rather manganese carbonates than oxides are precipitated. Even if the environmental conditions are favourable, the forming of the nodules can not proceed without crystallisation nuclei, on which the oxides could precipitate. Because of lack of intraclasts, which could serve as potential nodules' nuclei, rather micronodules are formed. Most of the nuclei are of allogenic origin (biogenic — such as bone fragments), hydrogenic (disintegrated fragments of older nodules), or lithogenic (volcanic debris). Presence of disintegrated fragments of older nodules, which provide nuclei for new nodules, testifies to the long-lasting and stable nodule-forming processes. In such conditions, high nodules' accumulations occur (Cronan, 1977).

Sedimentation rate is also an important factor. The slow sedimentation rate is conductive for forming of the nodules. In the case of high sedimentation rate, the intraclasts which might provide potential nuclei for the nodules, are quicker covered by sediments, what prevents the precipitation of oxides on them. The higher sedimentation rate is also connected with bigger amount of organic matter which is delivered to the sediments. Presence of organic matter may lead to decreasing of oxygen content in the water-sediment boundary layer.

The morphological character of the nodules depends directly on the following factors: minerals composition; character, shape, size and age of the nuclei; crystallisation conditions; and diagenetic processes. Important role is also played by the mechanisms of delivery of the elements, which are concentrated in the nodules — if they are derived directly from the near-bottom sea water, or additionally from the pore waters.

Mineral substance, which covers the nuclei of the nodules, shows different structure. Different texture forms within the nodules, which are frequently as large as fraction of millimetre, constitute groups of rectangular or elongated forms, generally accordingly oriented with the direction of nodules' growth. Generally, one may distinguish the following forms: concentric-laminated (Plate I, Phot. 1), massive, radial-dendritic (Plate I, Phot. 2), radial (Plate I, Phot. 3) or collomorphic ones.

Cracks represent another characteristic feature of the nodules. They can be radial or tangential (Plate I, Phot. 4 and 5). They are usually filled by barren clayey material or secondary manganese minerals (Plate I, Phot. 6). In those cracks, clayey, mostly zeolite (phillipsite, clinoptilolite) secondary pseudomorphoses after volcanic glass are formed (Plate II, Phot. 1, 2, and 3).

Cracks in the nodules are formed during their growth in result of inner tension occurring in the processes of dehydration and recrystallisation. Forming of the cracks in the nodules is a direct function of their rate of growth. Differences in rate of nodules' growth are significant, which is reflected by different thickness of the altered lamina of Fe and Mn minerals and varied nodules' sizes. In the case of nodules from the Peru Field, the rate of nodules' growth reaches 160 millimetres per 1 million years, in the case of Clarion-Clipperton Field is about 1 mm per 1 million years. Such a rate of growth limits the nodules' sizes. Broken fragments of older nodules provide nuclei for the new ones.

Cracks observed in the nodules can be also connected with diagenetic mobilisation and migration of components inside the nodules, what is confirmed by presence of re-crystallised organic fragments (Plate II, Phot. 4). Intensity of diagenetic processes, which govern the processes of forming of cracks and joints, limits the nodules' growth, frequently leading to their disintegration. Disintegration processes of the nodules can be locally intensified in effect of multiple translocations of the nodules by the near-bottom currents. Secondary processes, such as migration and recrystallization of Mn and Fe minerals and arrangement of their structure during dehydration and contraction, proceed after precipitation of the Mn and Fe minerals (Plate II, Phot. 5 and 6).

Usually the nodules cover the sediment surface or are slightly submerged in the strongly hydrated, semi-liquid layer of sediment. According to terminology proposed by R.G. Burns, V.M. Burns (1977), Burns *et al*. (1982), Usui *et al*. (1987), Halbach *et al.* (1982), the main manganese minerals occurring in the nodules are: todorokite (= manganite=busserite), birnessite (=manganite), and vernandite (= birnessite with chaotic structure). Pirolusite, ramsdellite, psylomelanite and kryptomelanite occur in subordinate amounts. Manganese minerals are usually cryptocrystalline, with exception of vernandite, which is amorphous. Main iron minerals are represented by polymorphous varieties of FeOOH, identified as goethite, akageneite, lepidocrokite, hematite and maghemite.

Besides that, subordinate amounts of phillipsite, quartz, feldspars and plagioclase were found in the nodules. Aragonite, apathite, amorphous silica (opal), pyroxenes, amphiboles, barite, spinels, rutile, anatase, clay minerals (chlorites, illite and montmorillonite) occur as accessory minerals (Cronan, 1977; Piper, Blueford, 1982; Halbach *et al*., 1982; Andreev, 1994; Kotliński, 1992, 1993, 1998b). Authigenic sulphide minerals such as pyrite, troillite, chalcopyrite, as well as gold and gases, such as helium, occur in the nodules (Amann, Ed., 1992). Spoil components, represented by clay minerals and zeolites, occur usually in the nodules' nuclei. Usually, the SiO_2 and Al_2O_3 content in the nodules reaches 25% (Kotliński, 1993).

Specific thermodynamic equilibrium, which dominates in the environment of forming of main minerals, depends on the physico-chemical parameters. They shape chemical and morphological features of forming minerals. The minerals can adsorb admixtures of other elements, which represent "masked components", admixed due to the crystallographic affinity (diadochy). Main minerals of Mn and Fe in the nodules represent authigenic forms, being generally components precipitated from the solution, in the form of amorphous hydroxide gels of those metals. Hydroxide gels represent a type of surficially active particles, which in the sediment undergo decomposition and ageing, followed by crystallisation (Kotliński, 1998b).

Concentration of trace elements in the nodules depends on ratio of content of main mineral phases, which the elements are associated with. Nodules, in which todorokite prevails, are usually enriched in Mn, Ni, Cu, Zn, while those where vernandite prevails, are enriched in Fe, Co and Pb. Reasons, why the concentrations of trace elements within those main geochemical types of pelagic nodules are not fully explained yet, because the structure of todorokite is not fully recognised. This mineral contains Mn^{2+} ions, which can be replaced by bi-valent Zn^{2+}, Ni^{2+} and Cu^{2+} ions. Deep-sea manganese nodules contain todorokite, which can contain up to 8% Ni and Cu, which can partly explain higher content of those metals in the nodules containing todorokite, that in those ones which contain vernandite (Burns, Burns, 1977; Burns *et al*., 1982). Nodules enriched in todorokite contain in manganese phases more Ni, Cu and Zn. Vernandite contain mainly Mn^{4+}, which can be probably substituted by Pb^{4+} (Cronan, 1982). However, because of differences in the ionic diameters (Pb 0.775 and Mn 0.540), adsorption of Pb on the vernandite is more probable (Kotliński, 1998b). Adsorption of Cu, Ni, Zn, and Pb on the Mn and Fe oxides was confirmed experimentally — Ni and Cu, to lesser extent Co, do not generally enter the crystalline structure of todorokite, being adsorbed on its surface instead (Cronan, 1982). Some data show, that significant enrichment in Ni and Cu of the nodules containing todorokite, and same enrichment in Co in the case of nodules dominated by vernandite, can be associated with possibility of diadochian substitutions within the crystalline structures of those minerals (Glasby, Ed., 1977; Glasby, 1998a, b; Dymond *et al*., 1984; Skorniakova, 1989).

The latest studies indicate that manganese minerals in the nodules give two kinds of EPR spectrum:

a — spectrums originating from the clusters of "specific aggregates" of ions characterised by a big width of line;

b — spectrums of isolated, interacting ions.

In case of manganese one can observe superfine structure, which results from the electro-nuclear interactions. Further studies will allow recognition and definition of parameters of the spectra, definition of share of different phases and identification of the local structure around paramagnetic centres (Podgórska *et al*., 1998).

Accepting as a basis the division of the nodules into genetical types (Halbach *et al*., 1982; Amann, Ed., 1992), type "H" and "D", as well as type "HD" (intermediate type between "H" and "D", assuming the form, size and composition) were distinguished — Table 7 (Kotliński 1996, 1997b, 1998b). Forming of the type "H" nodules is dominated by the hydrogenic processes, while the near-bottom waters provide a source of metals. The type "D" nodules are formed by hydrogenic-diagenetic processes, and the pore waters in the "boundary layer" provide additional source of components. Type "H" nodules (Plate III) are characterised, comparing to the type "HD" (Plate IV), and type "D" (Plate V), by lower average manganese, nickel and copper contents and higher contents of iron and cobalt. Type "H" nodules show also, in comparison to the types "HD" and "D", higher content of the Rare Earth Elements (Kotliński *et al*., 1997). Chemical analyses of nodules' growth zones, performed by the EDX method (either point or linear analyses) on certain genetic types, confirm big scale of chemical changes in the particular zones (Pawlikowski, 1998).

Type "H" nodules are generally spheroidal or irregularly spheroidal and are characterised by smooth or finely rough surface and small modal sizes (3–6 cm and below). Nuclei of the nodules are usually represented by transformed volcanic glass, of the size up to 0.5 millimetre. Volcanic glass is often secondary transformed into clay minerals (usually zeolites) by halmyrolise processes. Around the core, lamina of Mn and Fe minerals are altered with clay minerals lamina. The nodules are porous, and fragments of bioclasts are also present in their cores. Microcrystalls of vernandite and goethite constitute the main mineral components. The nodules are frequently cracked, and are characterised by presence of secondary veins filled by clay or manganese minerals, and thin (up to 3 microns) concentric lamina. The growth rate is about 1 mm/million years. The mean specific weight is 1.94 g/cm^3, and humidity is 31.2%. Type "H" nodules occur usually on the calcareous oozes, above the CCD.

Type "D" nodules are usually discoidal or ellipsoidal, with modal size 6 to 12 or more cm, and are characterised by strongly differentiated or asymmetrical surface structure "Ds/r". These nodules have characteristic rims around, which forms at the water-sediment contact. These nodules show higher contents of Mn, Ni, Cu and Zn, and lower content of Rare Earth Elements. Nodules' nuclei are usually represented by fragments of older nodules or bioclasts. The nodules show massive, radial, dendritic or collomorphic texture and are characterised by presence of radial cracks. One can observe clearly visible alteration of Mn minerals (black lamina) and Fe (red-brown ones), as well as differentiated growth rate — in case of the manganese minerals it is twice as high as in case of the iron minerals. Ni and Cu concentrations are associated with the main manganese minerals (todorokite, birnessite). Lamina of Mn and Fe minerals are often separated by lamina of volcanic silt (Fig. 13). Lamina of Mn and Fe minerals are thicker than lamina observed in the type "H" nodules, they reach 1.5–2.0 mm. Rate of growth of these nodules are estimated at about 5–15 mm/million years (Amann, Ed., 1992). Their mean specific weight is 1.91 g/cm^3, humidity is 33%. Density of bottom's coverage often exceeds 10 kg/m^2. These types of nodules occur on the bottom surface, in the zones characterised by even, slightly undulated relief, below the CCD. They usually rest on the radiolarian-diatomaceous oozes, less frequently on the polygenic clays.

The present author proved, that the following factors directly influence the forming of the nodules in oceans: distance from the metals sources, certain physico-chemical conditions of the near-bottom and pore waters, oxidation degree, pH, Eh, depth of CCD and SCD, water dynamics, low accumulation rate and occurrence of the intraclasts, providing potential nuclei for the nodules. Complex interaction of either regional or local factors occur in the nodule fields and areas (Kotliński, 1993, 1996, 1998b). Mutual interaction of the above mentioned factors is reflected by variability in joint occurrence of individual genetic types of nodules. Such variability is particularly evident in the fields with strongly varied bottom relief, or near the fault zones. Generally, the lower abundance of the nodules are observed along the valleys axes and on the tops of elevations, while the higher abundance are met on the slopes of valleys and submarine elevations. It should be emphasised, that not only amount but also morphology of the nodules is clearly determined by the depth factor. Multi-core, smaller nodules occur generally on the steep slopes, but bigger, single-core ones occur in the fields characterised by even relief. Big nodules are generally located *in situ*, while the smaller ones are often redeposited (Kotliński, Modlitba, 1994). Redeposition of the nodules causes, that at the bottom of slopes one can find different morphological types of the nodules. It should be emphasised, that the typical nodules' features frequent in one area are rare in the others.

In the pelagic zones characterised by good oxidising conditions and very slow accumulation rate, often on the consoli-

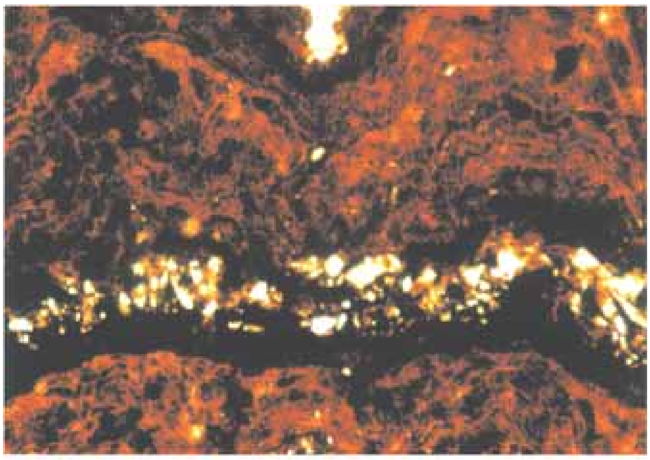


Fig. 13. Volcanic ash laminae between Mn/Fe minerals lamina
(100x, nicols crossed). *Photo. M. Pawlikowski*

Table 7

Genetical types of polymetallic nodules in the Clarion-Clipperton Ore Field

Lithofacies	Calcareous oozes and calcareous clayey silt down to the CCD level	Clayey silt (slightly calcareous and slightly siliceous) between CCD and SCD	Siliceous oozes and brown pelagic clays below SCD
Genetic type	**H**	**HD**	**D**
Mean nodule abundance:			
no. nodules /m^2	548	268	72
kg/m^2	8	7	9
Co-occurrence on the genetic types	**H+HD**	**H+HD-HD+D**	**HD-D**
Size (cm)	<3.0	3.0–6.0	6.0–12
Average size (cm)	3.4	4.4	6.5
Mean per cent contribution to fractions:			
>3 cm	75	50	5
3–6 cm	20	45	60
6–12 cm	>5	5	35
Average weight (g) **of modal fraction**	about 20	about 45	about 170
Graphic granulometric characteristics after Trask (Amann, Ed., 1992):			
skewness	2	4	5
sorting	1.09	1.15	1.50
Surface structure*)	r/b; r; s/r; s; m	s; m; s/r; r; b	r; s/r; b; r/s, s
Dominant morphotype*)	**Sr/b, SP** **IPr, IEs/r** **Ds, EDs/r**	**I(D,T)s, IT s/r** **Ps, Pr** **Dr,b., Es**	**Dr,s/r,b, EDs/r** **ITr/s ,ISr** **Br,s, V**
Nucleus type	clayey-zeolitic, more seldom volcanoclastic or bioclasts	clayey-zeolitic, bioclasts, more seldom nodule fragments	fragments of older nodules
Fractures	radial	irregular	clearly radial
Lamination:	thin (<0.5)	medium (0.5–1.0)	coarse (>1.0)
no. laminae/cm	15–75	7–15	1–7
prevailing lamina thickness (mm)	<0.4	0.4–1.5	>1.5
Textures	radial-dendritic	radial-dendritic, concentric-laminated	massive, radial-dendritic, colomorphic
Dominant Mn and Fe minerals	vernadite, goethite	birnessite, vernadite, todorokite, goethite	todorokite, birnessite, vernadite, goethite
Average contents (%) **of major metals:**			
Mn	23.63	27.39	30.50
Fe	10.09	7.41	5.46
Cu	0.70	0.97	1.22
Ni	1.05	1.23	1.27
Co	0.23	0.20	0.19
Zn	0.085	–	0.145
Mn/Fe	2.4	4.6	6.5
Physical properties:			
— density of mineral part (g/cm^3)	3.35	3.35	3.34
— density (g/cm^3)	1.94	1.92	1.91
— volumetric weight (g/cm^3)	1.33	1.29	1.28
— moisture content (%)	31.2	32.1	33.0
— porosity (%)	58.3		

*) Explanations in Kotliński (1996, 1998b)

Table 8

Main regions and fields of manganese nodule formation of the world's ocean

Regions and fields	Nodule geochemical type a) Depth interval /km/	Mean metal content b)																					X_1	X_2 a) (kg/m^2) X_3
		Mn %	Fe %	Ni %	Cu %	Co %	Mo %	Ti %	Zn %	Pb %	Zr %	V %	Au ppm	Pt –	Y ppm	La ppm	Ce ppm	S+P+As %	SiO_2 %	Al_2O_3 %	CaO %	MgO %		
North-East Pacific Basin /*MF_{NEPB}* /																								
Clarion-Clipperton /1/* 2186 thou. km^2	**Ni-Cu Ni-Cu-Co 3.9-5.1**	27.24	6.29	1.216	1.022	0.214	0.057	0.374	0.152	0.053	0.054	0.042	0.0204	0.104	264.16	152.99	303.26	0.2971	15.15	5.04	2.66	3.20	6.3	$\frac{6.4}{12–13}$
Californian /2/ 396 thou. km^2	**Ni-Cu**	25.00	9.89	1.046	0.653	0.136	0.040	0.434	0.178	0.055	0.059	0.038	0.0015	0.085	–	153.20	435.00	0.3548	13.26	3.58	2.05	3.90	5.3	2.8
Hawaiian /4/ 396 thou. km^2	**2Co**	20.37	15.89	0.370	0.039	0.557	–	1.151	0.104	–	–	–	–	–	–	–	–	0.170	13.31	5.28	2.50	–	6.4	4.2
Peru Basin /*MF_{PB}* /																								
Peru /6/ 1018 thou. km^2	**Ni 3.8-4.4**	33.43	5.76	1.249	0.659	0.082	0.067	0.259	0.147	0.042	0.064	0.051	0.0025	–	3.07	35.33	72.18	0.3502	11.95	4.80	2.72	2.70	5.79	$\frac{9.8}{3.6}$
Central-Pacific Basin /*MF_{CPB}* /																								
Central-Pacific /3/ 1960 thou. km^2	**Ni-Cu-Co 4.6–5.4**	21.49	9.63	0.763	0.696	0.237	0.042	0.695	0.092	0.050	0.086	0.042	0.0083	0.085	135.00	119.00	552.50	0.4635	13.62	4.58	2.75	3.10	5.2	$\frac{9.0}{7.9}$
Wake /5/ 188 thou. km^2	**2Co**	19.24	14.45	0.529	0.276	0.419	0.044	1.069	0.064	0.085	0.077	0.040	0.0097	0.066	351.94	280.80	1530.77	1.5204	15.29	5.77	5.40	2.56	5.9	14.8
South-West Pacific Basin /*MF_{SWPB}* /																								
South-Pacific /8/ 1150 thou. km^2	**Co**	14.04	16.88	0.335	0.212	0.330	0.027	1.159	0.062	0.060	0.094	0.056	0.0152	0.120	–	185.00	–	–	14.77	7.28	2.11	2.88	2.18	12.4
Menard /7/ 1244 thou. km^2	**Ni-Cu-Co**	19.95	12.50	0.835	0.357	0.344	0.043	0.759	0.064	0.112	0.056	0.045	0.0022	–	138.33	100.00	–	0.072	16.09	6.03	2.18	2.46	5.1	2.5
Mid-Indian Basin /*MF_{MIB}* /																								
Central-Indian /9/ 1470 thou. km^2	**Ni-Cu 5.0–5.4**	22.68	9.00	0.931	0.798	0.141	0.030	0.266	0.112	0.052	0.036	0.034	0.0070	0.120	–	–	–	0.2085	17.36	4.14	2.80	2.68	5.7	$\frac{5.1}{1.6}$
South-Australian Basin /*MF_{SAB}* /																								
Diamentina /11/ 867 thou. km^2	**Ni-Cu 4.2-5.1**	22.73	12.02	0.829	0.407	0.190	–	0.518	0.149	0.100	–	–	0.0300	0.047	–	–	–	0.468	17.12	5.41	2.62	2.79	4.96	$\frac{14.9}{3.0}$
North-Australian Basin /*MF_{NAB}* /																								
North-Australian /10/ 622 thou. km^2	**Ni-Cu-Co**	17.72	10.69	0.544	0.411	0.201	0.039	–	0.060	0.092	–	–	0.0200	–	–	136.50	926.50	0.4425	–	7.86	1.45	–	4.3	8.0
Somalian Basin /*MF_{SB}* /																								
Equatorial /12/ 151 thou. km^2	**2Co**	14.90	18.98	0.301	0.116	0.491	0.032	1.335	0.045	0.168	–	0.059	–	–	–	–	–	–	–	–	—	–	0.56	–
Madagascar /13/ 302 thou. km^2	**Co**	12.43	17.88	0.170	0.105	0.302	0.016	0.910	0.039	0.105	–	0.050	–	–	–	–		0.284	18.65	6.02	2.60	–	0.44	2.8
Angola Basin /*MF_{AB}*/																								
Damir /15/ 151 thou. km^2	**Ni-Cu-Co**	19.74	9.67	0.721	0.505	0.118	0.032	0.214	0.088	0.030	0.080	0.088	0.0106	0.067	116.65	–	–	0.397	16.25	7.23	2.26	3.80	4.8	–
Cape /16/ 188 thou. km^2	**Ni-Cu-Co**	18.34	7.38	0.693	0.310	0.160	0.021	0.484	0.072	0.080	–	0.032	0.0028	0.095	–	–	–	0.174	26.50	5.33	1.68	1.77	–	–
North-American Basin /*MF_{NAB}*/																								
North-American /14/ 603 thou. km^2	**Co**	14.38	18.84	0.324	0.162	0.261	–	0.610	–	–	0.061	0.054	–	–	–	–	–	–	–	–	–	–	0.4	–

Based on: a) Yegyazarov, Ed. (1989); b) Andreev *et al.*, Eds. (1998)
X_1 — nickel index, calculated as in Kulyndyshev (1993): Ni_E=1.0Ni+0.13Mn+0.25Cu+5.0Co; X_2 — mean nodule abundance; X_3 — estimated nodule resources (billion tonnes dry weight) in nodule fields;
*/1/ — number of nodule bearing deposit fields (see metallogenic map — Figure 9 and Table 3)

dated bedrock, manganese crusts are formed. Metals occurring in the crusts come directly from the near-bottom waters, pore waters do not provide any metals. Nodules occurring in the zones of occurrence of near-bottom currents get majority of the metals directly from the sea water and are characterised by flattened shapes (discoid nodules). The shape of a nodule core determine shape of earliest lamina of the nodule's growth, the irregularities being gradually smoothed by later lamina. Thus, the small nodules show generally the most irregular forms. For example, ellipsoid nodules are characterised by presence of a core of the same shape, while nodules built on fragments of older nodules are often multi-nuclei of irregular. Multi-nuclei nodules occur frequently in the regions with strong currents, where rate of sedimentation is minimal. In the areas of lack of sedimentation, so-called sheet crusts are formed. Diagenetic processes leading to differentiation of the components within the nodules, also influence the morphological features of nodules.

Deposit fields are usually connected with the regional morphostructural elements of the sea floor. Groups of deposits coexist within a field, forming deposit areas. Those groups of deposits are represented by genetically identical nodules, which are characterised by specific morphological features (shape, size and character of the surface). Their location parameters (such as depth, relief and lithology of the sediments) are also similar, same concerns hydrodynamic, hydrochemical and hydrobiological conditions — all these factors determine the nodules' forming processes (Kotliński, 1998b).

Distinguishing of the nodule fields and deposit areas by the present author is based on the following criteria: mean index of nodules' occurrence, content of base metals, and geochemical type of nodules. When characterising the fields, the way of the nodules placement (i.e. their location in relation to the bottom forms and to the CCD and SCD level), as well as lithology of the sediments and morphostructural position of the accumulations, were taken under consideration. Performed analysis of distribution and conditions of the nodules' origin confirm that distinguished oceanic fields and nodule areas show specific regional separateness, which reflects specific sedimentary conditions, determined by the local factors (Kotliński, 1995a, 1998b).

The Clarion-Clipperton and Californian Fields occur in the North-East Pacific Basin themselves (within the Pacific plate), while the Peru Field in the Peru Basin (within the Nazca plate). The regions distinguish by specific structural-tectonic position. They are located in the immediate vicinity to the East-Pacific Rise, which is characterised by its fast- and superfast spreading rate, and between irregularly distributed oceanic dislocation zones. Spreading rate in this part of the ocean ranges from 6.6 to 15 cm per year. Dominance of Ni, Ni-Cu and Ni-Cu-Co geochemical types of nodules is distinguishing feature of this region. Nodules in the Peru Field show high contents of Mn and Ni, while the Co content is low.

Accumulations of the nodules in the Central-Pacific Basin (Magellan, Wake-Necker Fields in Mid-Pacific Mountains and Central-Pacific Field — see Table 3) as well as in the South-West Pacific Basin (Menard Field and South Pacific Field) are characterised by high nodule's occurrence index, reaching in places even 50 kg/m^2, while the total content of Ni, Cu and Co is only half of this reported from the eastern part of the Pacific Ocean. Nodules of the Central-Pacific Field are characterised, in comparison with nodules of the Clarion-Clipperton Field, by higher negative Mn-Fe correlation (–0.81) and high Mn/Fe index (above 3), which indicates the more advanced separation processes of separation of Mn from Fe. Nodules of the Menard Field show, in comparison with the Central-Indian Field, relatively higher Ni content. The Ni-Cu-Co, Co and 2Co geochemical types dominate in this field.

In the eastern part of the Pacific Province, the Ni and Ni-Cu geochemical types show the widest extension, while in the western part Ni-Cu-Co or Ni-Cu-Co, Co or 2Co types dominate (Table 8). Distribution of the geochemical types of nodules in this province reflects, by the present author's opinion, a geochemical asymmetry of the Pacific Ocean. This asymmetry is connected with intensity of hydrothermal and venting processes in the spreading zones and considerable influx of metals from these sources, as well as with general geodynamic regime of this ocean. In comparison, in the nodules from the Central-Indian Field Mn/Fe correlation is clearly lower and ranges at about –0.32. Correlations between Mn and Ni, Cu and Zn are also lower, which by the present author's opinion is connected with relatively lower amount of those metals delivered from the hydrothermal sources. Results of performed studies confirm the unique position of the Clarion-Clipperton Field. Within the field, in the area about 2 million km^2 large, a high concentration of nodules on the bottom surface, the nodule abundance index exceeding 10kg/m^2 and the highest metal contents in the nodules were observed (Glasby, Ed., 1977; Skorniakova, 1989; Lenoble, 1996; Kotliński, 1992, 1993, 1996, 1998b). Detailed characteristics of the deposit fields was presented in the previous studies (Andreev, 1994; Kotliński, 1998b; Andreev *et al*., Eds., 1998).

Cobalt-rich manganese crusts

Cobalt-rich manganese crusts represent natural, consolidated aggregates of hydrated oxides of iron and manganese, developed as coatings, incrustations, or aggregates. They usually occur on basaltic outcrops; less frequently they can be found as solid covers on consolidated sediments. Forming of the crusts is influenced by hydrogenic or hydrothermal processes (Usui *et al*., 1986; Yamazaki *et al*., 1995; Usui, Terashima, 1997; Glasby, 1998b). Presence of cobalt-rich manganese crusts of hydrothermal origin was observed also in the upper part of the basalt layer II, which was confirmed by numerous DSDP cores. Mineral composition and metal content are main genetical criteria for distinguishing of the crusts. Hydrothermal crusts are characterised by a high Mn/Fe ratio and domination of vernandite.

In the Pacific Province, cobalt-rich manganese crusts of hydrogenic origin show high cobalt contents, even up to 1.6%, and markedly lower (about 1.0) Mn/Fe ratio, which is associated with higher contents of Mo and Pt. The crusts occur on the slopes of seamounts (guyots) or on subhorizontal terrace-like surfaces, at the depth range of 500–1000 m to 2000–3000 m (Fig. 14).

The crusts occur on the Tricorn Rise (Central Pacific) at the depth range of 1100 to 2800 m, their thickness reaching 8 cm. The age of these crusts is estimated at about 22–24 million years, while the growth rate is changing from 1 to 5 millimetres per 1 million years (Koshinsky *et al*., 1995). Cobalt-rich man-

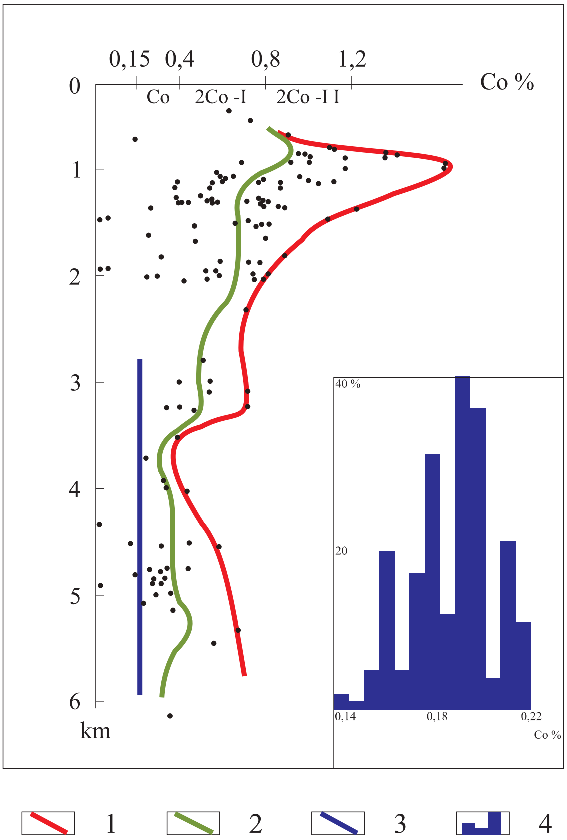


Fig. 14. Depth-dependent variability in Pacific cobalt-rich manganese crusts

Based on: Andreev (*In*:) Yegyazarov, Ed. (1989)

1 — maximum Co contents in crusts; *2* — mean Co contents in crusts; 3 — mean Co contents in Pacific nodules; *4* — frequency of nodules with different Co contents in Clarion-Clipperton Field

ganese crusts occur also in the northern part of the Lain Ridge, in the Ogasawara-Marcus, Magellan, Wake, Necker and Cartographers' heights areas, at the depth range of 1400–3000 m (Dimov *et al*., Eds., 1990; Andreev *et al*., Eds., 1998). Thickness of the crusts ranges there from several millimetres to 20 cm. They show changing contents of: cobalt from 0.5 to 1.29%; manganese from 20.3 to 28.6%; nickel from 0.36 to 0.45%, and low copper content from 0.04 to 0.10%. Low copper content, associated with higher than in the nodules Mo (0.05 to 0.10%) and Pt (0.5 to 5 ppm) contents, is a specific feature of the crusts from the seamounts. Nodules coexisting with crusts show chemical composition similar to the crusts and are characterised by dark-brown colour. The nodules are usually ellipsoidal or spheroidal and are often fused. Cobalt-rich crusts, which occur in the Tuamotu area, differ from the others by more pronounced positive correlation between Mn and Co (0.50), while the mean content of cobalt is 0.82%, and mean content of manganese is 19.7%. With positive Mn/Co correlation, they show negative Co/Ni (–0.15) and Co/Cu (–0.38) correlations, which indicates that in the hydrogenic processes Co is sternly associated also with Mn. Weakening of the correlations between these metals is characteristic for early-diagenetic processes, specific for the "D" and "HD" genetic types.

It should be emphasised that the cobalt-rich manganese crusts show, similarly to the hydrogenic nodules, higher La, Ce, Nd, Sm, Mo and Pt content. In the Manihiki Plateau region, the crusts show higher uranium content (in average 13.7 ppm), as well as Cr, As and Br contents, while the nodules show higher mean thorium content (29 ppm) and Hf content (10.8 ppm) (Kunzendorf, Glasby, 1994). In some regions, for example in the Hawaiian area (Haleakala and Puna Ridges), manganese crusts occur at the depth range of 1500–2200 m, are thin (up to 3 mm) and are formed under influence of hydrogenic-hydrothermal processes (Hein, 1996; Usui, Tarashima, 1997). Mineralogically, they are characterised by presence of vernandite and show higher contents of Zn, Co, Ba, Mo, Sr and V. Metals were derived from the alkaline and ultramafic rocks infiltrated by oceanic waters and from sandstones with clayey matrix enriched in manganese, which came from the mixed near-bottom and juvenile waters. In this area the manganese oxides often build the matrix of the breccia. The sediments differ from the manganese crusts by presence of todorokite and birnessite, i.e. minerals characteristic for diagenetic nodules. Manganese crusts of the Hawaii area show many common features with the crusts occurring in other areas of Pacific. They are characterised by twice as high mean Co content (4133 ppm) that the Ni+Cu mean content (2120 ppm). Equally high Co content is shown by the crusts occurring in the West-Pacific (Co — 7800 ppm), with Ni+Cu content of 6100 ppm. One should note the higher mean content of Sr (884–1133 ppm) and Pb (1300–1700 ppm) in the crusts, with Mn/Fe ratio at about 1.0. Rate of crusts' growth in this part of the ocean ranges from 0.07 to 4 millimetres per million years (Hein, 1996).

Cobalt-rich manganese crusts of hydrogenic origin in the Atlantic Province have been discovered between Portuguese coast and Madeira, to the North of the Lion Elevation, at the depth 1500 m (Koshinsky *et al*., 1995). Both crusts (up to 7 cm thick) and nodules occur in this setting. Average nickel content ranges from 0.34% to maximum 1.11%, while average cobalt content is 0.55%, with maximum content up to 0.85%. Second area of their occurrence is located on the Tropic Rise, about 260 nautical miles from Cap Blanca. The crusts occur here in the depth interval 1000–2500 m, Mn content in them reaches 24%, cobalt content reaches 0.85% and Ni content reaches 0.6%. As far as concerns the mineral composition, vernandite (s-MnO_2) and amorphous goethite (FeOOH) dominate. The richest in Mn and Co are crusts several cm thick, registered at the depth range of 1200–1600 m, directly below minimum oxygen layer, which lays between 300 and 1200 m. Manganese in the crusts shows strong positive correlation with Co and Pb (above 0.7) and Ni (0.3) and Ti (0.5). It should be emphasised, that mean contents of Co and Ni, Zn, Cu and Ti in the cobalt-rich manganese crusts in the Atlantic Province are lower in comparison to those from the Pacific. Both iron-manganese nodules and crusts of the Atlantic Province show, in comparison to those ones from the Pacific Province, prevalence of Fe over Mn and higher contents of Al and Si, which is connected with substantial supply of the terrigenous material from the African continent (Table 9).

In the Australian Province, cobalt-rich crusts occur in the North-Australian Basin Region, on the slopes of seamounts, cobalt content reaching even 10% (Yamazaki *et al*., 1995). On the other hand, cobalt-rich manganese crusts of the Philippines

Table 9

Metals content in the cobalt-rich manganese crusts

Oceans		**Mn**	**Fe**	**Co**	**Ni**	**Zn**	**Cu**	**Pb**	**Ti**	**Al**	**Si**
		%									
North-East Atlantic[1]	min.	12.9	12.7	0.35	0.20	0.05	0.02	0.12	0.4	1.11	1.87
n = 20	max.	24.6	28.2	0.85	1.11	0.12	0.10	0.25	1.7	2.80	7.33
	mean	17.7	21.3	0.55	0.34	0.07	0.07	0.20	0.9	1.65	3.38
Central Pacific[2]	min.	20.4	10.4	0.50	0.36	0.07	0.04	0.13	0.7	0.31	1.21
n = 272	max.	28.8	18.8	1.38	0.74	0.10	0.19	0.23	1.4	1.86	8.08
	mean	23.0	13.4	0.87	0.51	0.09	0.08	0.15	1.2	0.74	2.12

Based on:

[1] SONNE SO'83

[2] Pateanus, Halbach (*In*:) Koschinsky *et al*. (1995)

Province in the South-Japanese Region (in the back-arc marginal basins and on the volcanic island arcs) occur at the depth down to 2500 m and are up to 100 mm thick. The crusts were formed in result of the hydrogenic processes and are connected with Cretaceous and Tertiary sediments (Usui, Iizasa, 1995). On the other hand, the crusts occurring in the Ogasawara Ridge are formed in result of the hydrothermal processes (Usui, Terashima, 1997). On the shelf and continental slope the crusts have not been found. Vernandite is the main mineral of the crusts. The crusts are characterised by a high mean content of cobaltium (0.64%). Risen contents of platinum and the Rare Earth Elements are connected with higher content of Fe in the crusts (Andreev *et al*., Eds., 1998). The results obtained hitherto from the oceanic cobalt-rich manganese crusts of hydrogenic origin, indicate to the high economic perspectives of these deposits because of possibility of acquiring cobalt, platinum and Rare Earth Elements. Economical viability of exploitation of these deposits remain as a problem (Manheim, 1986; Kotliński, 1998e; Andreev *et al*., Eds., 1998).

POLYMETALLIC SULPHIDE FORMATION

Within the distinguished formation (***PF***) one can find polymetallic sulphide ores and metalliferous sediments of hydrothermal origin. New data about occurrence of recently active hydrothermal zones with accumulations of so-called massive polymetallic sulphide ores on the East-Pacific Rise and on the Central-Indian Triple Junction, in "active" axial hydrothermal zones (intermediate to fast- and superfast spreading ridges) and on the Mid-Atlantic Ridge, in "active" axial and "passive" off-axis hydrothermal zones (slow-spreading ridges) have been presented in numerous papers during the last years (Haymon, 1983; Rona, 1983, 1984, 1988; Gramberg, Smyslov, Eds., 1986; Rona *et al*., 1993; Hannington *et al*., 1991, 1995; Humphris *et al*., Eds., 1995; Andreev, 1997; Kotliński, Szamałek, Eds., 1998; Andreev *et al*., Eds., 1998). The intrusive and extrusive igneous activity as well as spreading rate at mid-ocean ridges controll the tectonism, while the physical properties of young crust and near-surface permeability of different lava morphologies play an important role in controlling hydrothermal discharge (Humphris *et al*., 1995).

Hydrothermal sites of occurrence of massive polymetallic sulphide ores are connected with the zone of water-rock interaction "reaction zone" in "active" axial zone at oceanic ridges and active island arcs of the Shichito-Iwojima Region and back-arc basins of Okinawa, and Fiji, Bismarck, Solomon, Tonga microplates. Fields of massive sulphide ores are formed as a result of interaction between oceanic water with subsurface high-temperature hydrothermal fluids, oceanic basalts, and upper gabbros near active magma chambers (Humphris *et al*., Eds., 1995). Oceanic ridges are distinguished by presence of asymmetric rift valleys delimited by rift valley faults. Neovolcanic zones occur in the valleys' axes, they are characterised by intensive hydrothermal and volcanic/vent processes concentrated both in the axis and on the valleys' slopes. Large sulphide deposits as TAG Field at slow-spreading ridges is associated with pillow volcanoes near transfer faults in rift valley (large scale tectonic features), while intermediate to fast- and superfast spreading rate ridge crests as Juan de Fuca Ridge have a greater proportion of lobate, shell and ponded lava flows along eruptive fissures in the floor of rift valley (Humphris *et al*., Eds., 1995). It should be emphasised, that locally, in the neighbourhood of massive polymetallic sulphide ores occurring on the volcanic island arcs and back-arc basins, hydrothermal cobalt-rich manganese crusts occur (Usui, Iizasa, 1995).

Regions of occurrence of sulphide ores with high metal concentrations are connected with presence of magmatic centres situated below recent axes of magma chambers expansion. Expansion axes are characterised by presence of open cracks (up to several metres), with manifestations of high-temperature hydrothermal activity, which is differentiated depending on the reaction of oceanic waters with different magma classes (Andreev, 1997; Andreev *et al*., Eds., 1998). Faults and cracks associated with conditions of intensive tectonic activity enable oceanic water infiltration into the expansion axes, the oceanic water being heated in the process and forming compound with juvenile vapour, which causes selective leaching of different elements from the basalt magma. Oceanic waters of temperature 2–3°C and pH about 7.8 contain about 2678 ppm of SO_4^{2-} and 1272 ppm of Mg, with low Fe (<0,06 ppb), Mn (<0,06 ppb), Zn (0,65 ppb) and Cu (0.45 ppb) content (Seibold, Berger, 1993). During migration, at the depth 3–4 km, on the contact with basalts of temperature 1200°C, oceanic water looses Mg^{2+} , SO_4^{2-} , and Na^+, and is enriched in Ca^{2+} , Fe^{2+} , SiO_2^{2-} , Mn^{2+} , Cu^{2+} , Pb^{2+} , Zn^{2+} , Ge^{2+} , Be^{2+} , Al^{3+} , Ba^{2+} , Li^+ , Pb^+ (Andreev *et al*., Eds., 1998). Formed hydrothermal fluids, 350–400°C hot, constitute compound of juvenile water vapour and gases with admixture of oceanic waters. During exhalation, they are characterised by high temperature and pH of about 3.5, with considerably higher contents of iron, manganese, zinc and copper (Fe — 80 ppm, Mn — 49 ppm, Zn — 6 ppm, Cu — 2 ppm). Solutions contain Mn^{2+} , FeO(OH), Fe^{2+} , Fe_xS_y and ^3He, CO_2 , $(CH_4)H_3O^+$, HS^- , with total elimination of Mg; FeS and Mn^{2+} , in presence of oxygen, form $Fe(OH)_2$, MnO_2 and $S_2O_3^{2-}$ in the post-exhalation solutions (Jannash, 1995).

In the neovolcanic zones, high-temperature fluids >250° contain admixtures of H_2S, HS^-, CH_4, CO_2 and HF, while low-temperature <250°C contain mainly H_3O^+ with admixture of H_2S and CO_2 (Fig. 15). Gases content in the oceanic waters depends mainly on exhalation place and time, which passed since the exhalation. Studies on changes of temperature anomalies fields and salinity above the so-called "black smoker chimneys" in the North-East Pacific Ridges (Juan de Fuca) or Guaymas Deep in the Californian Region, show that the water column 200–300 m above the bottom is characterised by risen temperatures (from 0.1 to 0.35°C) and higher salinity (from 0.01 to 0.02%). These anomaly zones have an extent from 5 to 10 km. Horizontal water flow from the hydrothermal exhalation centres can reach current velocity of 170–270 cm/s, even at the distance of several hundreds metres from the source (Edmond *et al*., 1982; Ainemer *et al*., 1988; Gramberg, Smyslov, Eds., 1986). In the oceanic waters, FeO(OH), MnO_2 , Mn^{2+} , H_4SO_4 and ^3He, migrate depending on the temperature gradient and are mixed with oxidised anions, heavy metals and Rare Earth Elements (REE), and then undergo selective deposition. Water analyses in the zones of these anomalies show risen Mn, Fe, ^3He and CH_4 contents. Total content of soluble Mn — TDM (total dissolvable manganese, i.e. amount of Mn dissolved in the water, passing from suspension to solution in pH = 2) is an universally accepted index of the water characteristics. Mn — TRM (total reactive manganese) and Fe — TRM are equally important indexes. Difference between TD and TR for Mn and Fe points to the differences in content of these metals in the colloid solutions and suspension. Risen contents of TRMn and TRFe are observed in the vicinity of active hydrothermal sources. The waters in these zones show also risen contents of ^{210}Pb, ^{210}Po, ^{222}Rh, Hg, Cd, Cr, Cu, Pb, Ni, Al (Ainemer *et al*., 1988; Andreev *et al*., Eds., 1998). Zone of hydrogeochemical anomallies of the Guaymas Deep differs from the oceanic ones by thickness of the water column affected by the anormal changes (to 900 m when the sea depth is 2000 m), while in the oceans thickness of this water column is 200–600 m from the bottom. Areas of intensified water turbidity can reach extent up to 100 km.

Volcanic-thermal belts, characterised by risen heat flow in the oceanic bottom (usually above 100mW/m^2, 100mW = 0,024 cal/s) and active volcanism, represent characteristic features of zones of the hydrothermal activity (Gramberg, Smyslov, Eds., 1986; Kotliński, 1997b). It should be emphasised, that one can locally observe manifestations of hydrothermal solution exhalations in the zones characterised by heat flow as low as 60–80 mW/m^2. The most perspective places for exploration of the massive sulphide ores are nodal basins, frequently forming triple junctions on the intersection between transform faults and rifts. They are characterised by presence of disjunctive structures of extension character as well as cracks and downthrow/transform faults (Gramberg, Smyslov, Eds., 1986; Andreev, 1997; Andreev, Gramberg, Eds., 1997; Krasny, 1998). In this context, one can mention the following examples: Rivera Triple Junction and Mendocino Triple Junction on the Gorda, Explorer and Juan de Fuca Ridges (Sclater, 1978; Law *et al*., 1981; Rona, 1984, 1988; Rona, Claque, 1989; Tunnicliffe *et al*., 1984). Another example of occurrence of rich accumulations of sulphide ores is represented by deposits associated with transform faults joining two spreading centres of the RR type. These zones are located in the Pacific Ocean, between 8°20' and 14°N (Siqueiros and Clipperton) and on the Mid-Atlantic Ridge between Kane and Atlantis faults (Rona *et al*., 1993; Okamoto, Matsuura, 1995; Humphris *et al*., Eds., 1995). In each of the recognised cases, accumulations of hydrothermal sediments are associated with spreading axes and occurrence of neovolcanic zones. In these zones, active ridges or dispersed volcanic cones occur (Francheteau *et al*., 1979; Francheteau, Ballard, 1983; Hannington *et al*., 1988, 1995; Hein, 1996).

Accumulations of sulphide ores in the NW Pacific, which are associated with active volcanic island arcs (Shichito-Iwojima Region) and marginal basins (Okinawa, Fiji, Solomon Islands), confirm that the mineralisation degree of the hydrothermal solutions and in consequence the particular metal's contents in the deposit ores are differentiated. Island arcs are distinguished by occurrence of magmas of the basalt–andesite sequence, while in the marginal basins calcium-alkaline magmatic sequence (dacites–ryolites) dominate (Okamoto, Matsuura, 1995). In comparison to the rift valleys, accumulations of sulphide ores in the volcanic arcs (Mariana Islands) show lower contents of Cu and Zn, while the Pb and Ag contents are high. In the ores from Suiyo relatively high mean content of Cu (34.5%) can be observed (Watanabe, Kajimura, 1993). On the other hand, hydrothermal sulphide sediments in the back-arc basin of Okinawa show higher contents of Ag, Pb and Au, with relatively high concentrations of Cu and Zn.

In the present author's opinion, gradient of pressure and temperature, pH and chemical composition of the waters associated with penetration of a local magmatic centre, are of a paramount influence on the processes of metal's sulphide precipitation.

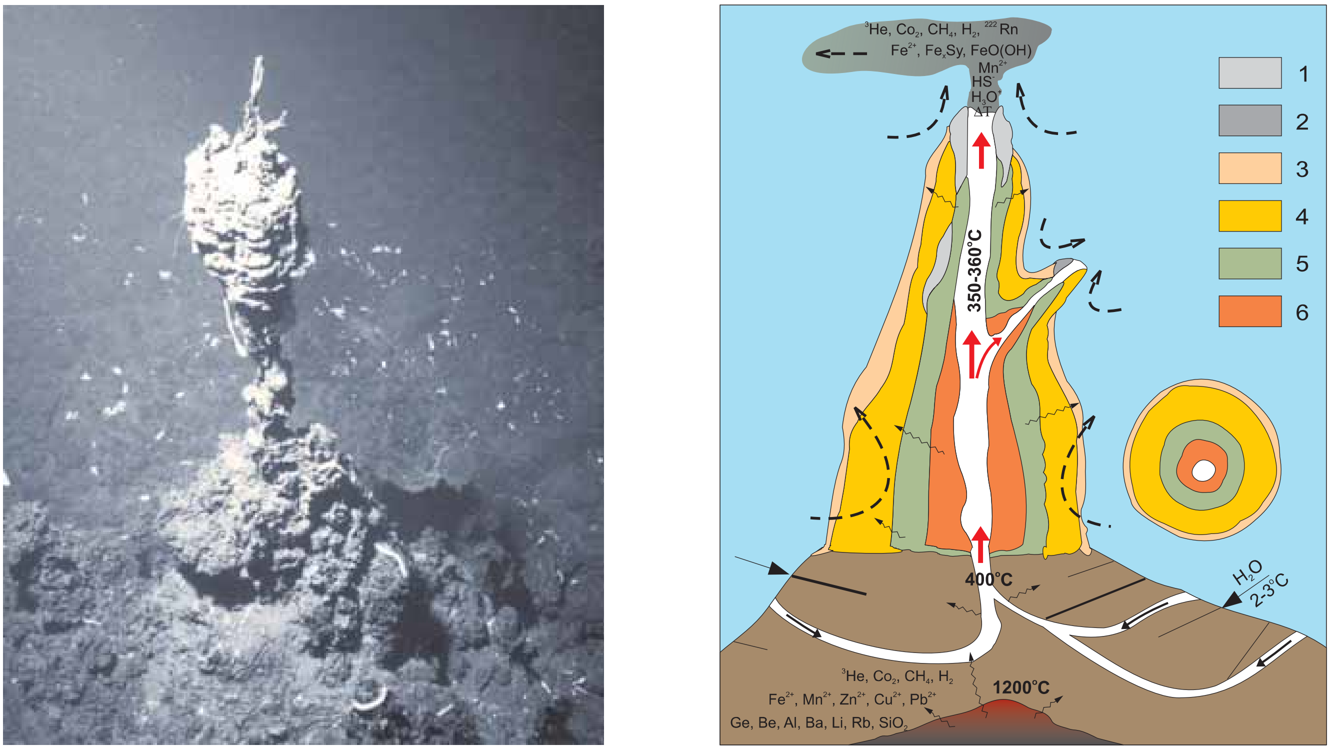


Fig. 15. Sketch of accretion of a "black chimney" forming above the hydrothermal venting spot, with zonal occurrence of mineral parageneses

Based on: Haymon (1983)

1 — anhydrite; *2* — $SiO_{2amorph.}$ and barite; *3* — marcasite; *4* — pyrite and sphalerite; *5* — pyrrhotite, pyrite and sphalerite; *6* — chalcopyrite

Polymetallic sulphide ores

Polymetallic sulphide ores on the oceanic ridges embrace three main groups of deposits: (Zn and Cu), (Cu and Zn) and (Zn and Pb). Depending on the dominating processes, petrographical character, degree of magma's differentiation (or local magmatic centres) and microbial activity, they differ by the mineralogical composition of the ores, expressed by the changing base metal contents and accessory elements (Table 10). Main minerals which were found in sulphide ores are represented by sphalerite, chalcopyrite, pyrite, marcasite, pyrotine, wurtzite, galene, isocubanite and sulphates: anhydrite, barite, as well as opal and sulphur (Hannington *et al*., 1995). It should be emphasised, that depending on the pressure and temperature gradient, chemical composition and pH of hydrothermal solutions, the mineral associations of metal's sulphides occur in a certain succession (Fig. 15). For hydrothermal sites of temperature 260–300°C, from so-called "white smoker chimneys": pyrite–marcasite, sphalerite–wurtzite, silica and barite, paragenesis is specific, while in the case of solutions of temperature 350–360°C from "black smoker chimneys": chalcopyrite–isocubanite, pyrite, pyrrhotite, wurtzite–sphalerite, anhydrite and silica, paragenesis is typical (Haymon, 1983; Hannington *et al*., 1991, 1995; Humphris *et al*., Eds., 1995). In the regions and fields certain mineral assemblages, forming specific sequences of metal concentration, are formed. Thermodynamics, chemical composition of the hydrothermal fluids, type of microbial processes, interaction with hydrothermal solutions, all of that is directly reflected by differentiation of metal's concentrations. "Black smoker chimneys" typically contain a high proportion of Cu and Fe-sulphides with the most typical minerals: chalcopyrite, sphalerite, isocubanite and pyrrhotite, the later never being present in low-temperature "white smokers". Concentrations of metals in the main minerals of selected groups of deposits is presented in Table 11. Highest concentrations of Ag, Au, Cd and Mn are observed in sphalerite, pyrite and marcasite. Marcasite–sphalerite assemblage is characterised by relatively high Sr concentrations. On the other hand, relatively high cobalt concentration is characteristic for chalcopyrite–pyrite assemblage (Hannington *et al*., 1991, 1995).

Copper and zinc deposit group occurs on the volcanic cones, located on both sides of the Galapagos ridge spreading axis and in the marginal basins of Fiji and Solomon Islands (Okamoto, Matsuura, 1995).

Copper and zinc deposit group occurs commonly in the Mid-Atlantic Ridge and East-Pacific Ridge spreading zones. These deposits are characterised by differentiated metal concentrations in individual fields. Zinc concentration, which is many times higher than copper concentration, with low concentrations of Pb and changing concentration of Ag, is a characteristic feature of these deposits. Good examples are provided by the deposits in the TAG and Snake Pit Fields on the Mid-Atlantic Ridge, and by the fields occurring in the East-Pacific Rise Region. The highest zinc contents were reported

Table 10

Main regions and fields of polymetallic sulphide formation of the world's ocean

Selected regions and fields	**Number of assays**	**Depth** (m)	**Deposits** (m) **surface area**	**Cu** (wt.%)	**Zn** (wt.%)	**Pb** (wt.%)	**Ag** (ppm)	**Au** (wt.%)
Mid-Atlantic Ridge /PF_{S2-MAR} /								
TAG (26°08'N) ***Zn*** and ***Cu***	40	3600	250 x 200	6.2	11.9	< 0.1	78	2.2
Snake Pit (23°30'N) ***Zn*** and ***Cu***	16	3400	up to 100	2.0	6.3	< 0.1	119	2.2
North-East Pacific Ridges /$PF_{S1-NEPR}$ /								
Explorer (49°45'N) ***Zn*** and ***Cu***	66	1800	250 x 200	3.6	6.1	0.1	132	1.0
Endeavour (48°N) ***Zn*** and ***Cu***	31	2100	up to 200	3.0	4.3	< 0.1	188	< 0.1
Juan de Fuca (S Ridge– 44°40'N) ***Zn*** and ***Cu***	11	2200	localised	1.4	34.3	0.2	169	0.1
Escanaba (40°30'N) ***Zn*** and ***Pb***	7	3200	up to 250	1.0	11.9	2.0	187	< 10
East-Pacific Rise /PF_{S1-EPR} /								
Rivera (21°N) ***Zn*** and ***Cu***	14	2600	localised	1.3	19.5	0.1	157	0.1
EPR (14°N) ***Zn*** and ***Cu***	5	2500	small deposit	2.8	4.7	< 0.1	48	0.5
EPR (13°N) ***Zn*** and ***Cu***	33	2600	localised	7.8	8.2	< 0.1	49	0.4
EPR (11°N) ***Zn*** and ***Cu***	11	2600	localised	1.9	28.0	< 0.1	38	0.2
EPR (17°S - 21°S) ***Zn*** and ***Cu***	61	2600-2900	localised	6.8	11.4	< 0.1	121	0.5
Galapagos Rift /PF_{S1-GR} /								
Galapagos (86°W) ***Zn*** and ***Cu***	73	2700	100 x 100	4.1	2.1	< 0.1	35	0.2
Shichito-Iwojima /PF_{S3-S1} /								
Mariana (18°N) ***Zn*** and ***Pb***	11	3600	localised	1.2	10.0	7.4	184	0.8
Myojin-sho (Bonin – 33°N)$^{*)}$ ***Zn*** and ***Pb***	–	–	–	2.1	36.6	6.08	260	1.62 (ppm)
Suiyo (Bonin – 29°N) $^{*)}$ ***Zn*** and ***Cu***	–	–	–	12.6	28.8	0.8	202.9	28.9 (ppm)
Okinawa /PF_{S3-O} /								
Minami-Ensei (27°30'N) ***Zn*** and ***Pb***	9	1400	300 x 100	3.7	20.1	9.3	1900	4.8
Izena (27°N) $^{*)}$ ***Zn*** and ***Pb***	–	–	–	4.7	26.4	15.3	1645	4.9 (ppm)
Californian /PF_{S1-C} /								
Guaymas Deep (27°N)	14	2000	localised	0.2	0.9	0.4	78	< 0.2
Red Sea /PF_{S4-RS} /								
Atlantis II Deep	–	2000	–	0.5	2.0	< 0.1	39	0.5

Based on: Hannington *et al*. (*In*:) Humphris *et al*., Eds. (1995)
$^{*)}$ Usui, Iizasa (1995)

from the deposits of Juan de Fuca Ridge (in average 34.3%), Gorda Ridge (in average 23.3%) and Central Field (EPR 11°N — in average 28.0%) (Rona, Claque, 1989; Usui, Iizasa, 1995).

Deposits connected with the recent volcanism on the back-arcs, in comparison to the ones formed in the spreading zones, are characterised by relatively high contents of Pb, Ag and Au and high Zn contents (in average 36.6%), antimonium (11200 ppm) and cadmium (up to 3950 ppm) (Usui, Iizasa, 1995). On the other hand, ores occurring in the marginal basins are characterised by highest Pb content (in average 15.3%) and Ag (in average 1645–1900 ppm) (Usui, Iizasa, 1995), as well as arsenic (up to 93100 ppm) (Usui *et al*., 1994). Groups of deposits occur within depth interval from 1800 to 3200 m on the East-Pacific Rise, connected directly with spreading axes and volcanoes located on rift valley slopes, while in the rift valley of Mid-Atlantic Ridge they occur much deeper, in the interval from 3400 to 3700 m. Size of deposit accumulations, which build different forms, is differentiated. In the East-Pacific Rise Regions, along the fast- and superfast spreading ridges (12 cm/year) and intermediate spreading rate (6–12 cm/year), the forms get shapes of cut cone, 5 m, sometimes even 25–35 m high, with base diameter reaching 30 m. Locally, deposit accumulations form belts 0.5–1 km wide, in which, every 100–200 m, individual forms resembling links of a chain occur. Frequently, these forms are fused and form ridges 10x200x250 m (Explorer) or 40x100x100 m (Galapagos). Locally, on the volcanic cones dispersed on the slopes of valleys along the spreading axes, the ore deposits form covers as large as 9x500x800 m (Ainemer *et al*., 1988). On the other hand, in the Central Fields of the Mid-Atlantic Ridge characterised by a slow spreading rate (below 3 cm/year), the dome forms, which are 70 m high and have bases up to several hundred metres in diameter, are more frequent (in the TAG and Snake Pit Fields) (Andreev *et al*., Eds., 1998).

Polymetalic sulphide ores within the Northern part of the Mid-Atlantic Ridge Region occur in the Lucky Strike Field (37^{o}N), while within the Central Field in the Broken Spur (28^{o}N), TAG (26^{o}N), Snake Pit (23–24^{o}N) and Polarnoye Fields (14^{o}45'N). Central part occurs between node zones of the RR type (Fig. 9). Slow spreading rate between Kane and Atlantis fracture zone is several times slower (2.3–2.5 cm/year) than that one in the Pacific Ocean. Snake Pit hydrothermal field extends over a distance of about 300 km. On the other hand, hydrothermal Mn and Fe crusts occur in the TAG Field, in the vicinity of sulphide deposits. Mn, Fe and trace elements contents in these crusts are relatively high (Rona, 1983, 1984). Comparison between base metals (Zn, Cu, Pb) contents of the deposits from the East-Pacific Rise Region with Zn, Cu and Pb contents in the deposits of the TAG Field shows that the former ones contain many times more Zn, Cu and Ag (Table 10) and Cd, Co and Pb. It is worth mentioning, that metalliferous calcareous ooze occurring in the rift valley (about 45^{o}N, the Lucky Strike Field), are enriched in iron, arsenic and mercury.

In the Australian Province, manifestations of hydrothermal sulphide mineralisation occur in form of inclusions and veins within crystalline rocks, lying in the rift valley (Gramberg, Smyslov, Eds., 1986). Oxide and sulphide concentrations of Fe and Mn of hydrothermal origin in the metalliferous muds and in the form of crusts occur locally in a node basin of the Central-Indian Triple Junction (Rodriguez), on the cross-section of Central-Indian Ridge with South-East Indian Ridge and South-West Indian Ridge (5^{o}N region) as well as in the zone of Vernatsky Fracture Zone (Yegyazarov, Ed., 1989). Area of occurrence of metalliferous sediments is limited by the geo-isotherms of heat flow above 100 mW/m^{2}, between zones of active transform faults, joining the spreading centres (of RR type). Metalliferous sediments occur also within the Aden Bay rift.

Polymetallic sulphide ores in the Pacific Province occur generally within spreading axes and associated with them volcanic zones of the East-Pacific Rise and North-East Pacific Ridges: Explorer, Juan de Fuca, Gorda and Galapagos Rift. East-Pacific Rise is characterised by the highest mean value of heat flow (82.3 mW/m^{2}), which in the Atlantic Ocean is 67.6 mW/m^{2}, while in the Indian Ridge is 62.1 mW/m^{2}. In comparison, mean value of heat flow for the continents is clearly lower (59.9 mW/m^{2}) (Gramberg, Smyslov, Eds., 1986).

The North-East Pacific Ridges Region embrace the following Fields: Explorer, Endeavour, Juan de Fuca, Gorda, Escanaba. In the intermediate spreading rate of the Juan de Fuca Ridge, the most intensive processes associated with hydrothermal activity occur in the RF type node, on the cross-section of spreading

Table 11

Chemical composition of selected mineral assemblages from sulphide deposits

Selected regions and fields	Selected mineral assemblages	No. of assays	Cu %	Fe %	Zn %	Pb %	S %	SiO_2 %	Ba %	Ca %	Au ppm	Ag ppm	As ppm	Sb ppm	Co ppm	Se ppm	Ni ppm	Cd ppm	Mo ppm	Mn ppm	Sr ppm
Mid-Atlantic Ridge /*PF* $_{S2\text{-}MAR}$/																					
TAG ***Zn*** and ***Cu***	**pyrite–chalcopyrite**	2	12.8	37.3	1.4	0.02	38.9	2.2	<0.01	<0.1	1.43	38	67	6	75	8	–	38	144	77	–
	marcasite–sphalerite	4	3.6	32.4	3.6	0.05	39.6	3.6	<0.01	7.7	2.29	35	122	10	14	<2	42	73	82	220	2277
	sphalerite–marcasite	10	1.5	21.6	21.3	0.06	33.1	7.4	<0.01	5.3	3.28	151	98	33	19	<2	76	650	35	1255	1451
North-East Pacific Ridges /*PF* $_{S1\text{-}NEPR}$/																					
Juan de Fuca ***Zn*** and ***Cu***	**sphalerite–pyrite**	3	0.2	19.7	36.7	0.26	39.3	5.1	0.06	<0.1	0.11	178	359	18	11	13	8	519	13	970	53
East-Pacific Rise /*PF* $_{S1\text{-}EPR}$/																					
Rivera ***Zn*** and ***Cu***	**sphalerite–pyrite**	2	1.1	21.5	31.1	0.18	38.8	–	0.05	1.9	<0.20	118	493	33	4	91	4	840	45	296	14
EPR (13^{O}N) ***Zn*** and ***Cu***	**pyrite–chalcopyrite**	2	6.0	35.7	0.4	0.02	39.9	–	–	<0.1	0.05	19	86	–	3500	186	–	19	–	—	<10
	sphalerite–pyrite	5	0.9	20.1	31.4	0.18	35.5	4.7	<0.01	0.6	0.45	163	412	–	38	8	–	835	72	310	32
Galapagos Rift /*PF* $_{S1\text{-}GR}$/																					
Galapagos ***Zn*** and ***Cu***	**pyrite–marcasite**	22	5.1	36.1	1.4	0.04	35.4	16.9	0.03	0.1	0.21	25	152	8	360	78	17	50	141	413	26
	pyrite–sphalerite	6	2.2	19.7	13.8	0.06	24.5	33.8	0.06	0.8	0.85	122	94	24	24	18	13	323	87	1015	33

Based on: Hannington *et al*. (*In*:) Humphris *et al*., Eds. (1995)

Table 12

Estimated metal resources in selected regions and fields of polymetallic sulphide formation

Selected regions and fields	Types of ores	Estimated resources (10^6 t)	Metal resources				
			10^3 t			t	
			Cu	**Zn**	**Pb**	**Ag**	**Au**
Mid-Atlantic Ridge /*PF*$_{S2-MAR}$/							
TAG	***Zn*** and ***Cu***	14.5	1141.2	488.7	–	1029.0	33.5
Snake Pit	***Zn*** and ***Cu***	2.4	430.0	96.0	–	108.0	24.0
North-East Pacific Ridges /*PF*$_{S1-NEPR}$/							
Explorer	***Zn*** and ***Cu***	3.0	153.3	272.2	–	6120.0	6.42
Juan de Fuca	***Zn*** and ***Cu***	4.8	32.8	190.2	–	208.7	0.59
East-Pacific Rise /*PF*$_{S1-EPR}$ /							
EPR (13°N)	***Zn*** and ***Cu***	5.8	166.0	504.2	0.7	466.5	0.5
Galapagos Rift /*PF*$_{S1-GR}$ /							
Galapagos	***Cu*** and ***Zn***	10.0	380.0	88.0	–	280.0	1.1
Californian /*PF*$_{S1-C}$ /							
Guaymas Deep (27°N)	–	23.0	13.7	29.8	–	37.5	0.2
Red Sea /*PF*$_{S4-RS}$/							
Atlantis II Deep	–	90.0	–	–	–	–	–

Based on: Dacenko (*In*:) Andreev *et al*., Eds. (1998)

axis and the Blanco transform fault, where so-called black and white chimneys are common. Hydrothermal exhalations on the "white chimneys" of temperature 200–293°C are characterised by high zinc concentration. Juan de Fuca Ridge has been intensively investigated with bathyspheres "Alvin" and "Cianu". In this area, ore deposit accumulations build dome or chimney forms up to 80 m high. The deposit resources are estimated at about 5 million tonnes (Table 12). Polymetallic ores of this field show high mean contents of Zn (34.3%), with lower mean copper content (1.4%) and high Ag content (169 ppm) (Hannington *et al*., 1995).

In the Gorda intermediate spreading rate ridge (in the Escanaba Field), Zn and Pb deposit groups occur. They show mean zinc content of 11.9%, while Pb content is 2%, copper content is 1% and silver content is 187 ppm (Hannington *et al*., 1995).

In the East-Pacific Rise Region between 9° and 21°N embraces the Rivera Field and EPR Fields (9°, 11°, 13°). This hydrothermal sites are characterised by relatively high values of the heat flow, registered in the spreading axis (above 200mW/m^2) and fast- and superfast spreading rate (9–11.4 cm/year).

Hydrothermal solutions above the "black chimneys", 380°C hot, are ejected with velocity of 3m/s. In the zones of active volcanism, on the slopes of volcanoes dispersed along a rift valley at various distances from a spreading axis, the covers of different sizes (up to several hundred m^2), containing Zn, Cu and Pb sulphides, are formed. They are superimposed on the basalt rocks. In the mineral composition of the polymetallic sulphide deposits, the following minerals have been found: sphalerite, pyrite, marcasite and chalcopyrite (Renard *et al*., 1985; Okamoto, Matsuura, 1995). In the central part of the EPR, between 9° and 13°N, the covers of sulphide deposits on the volcanoes slopes reach thickness of 3 m. Hydrothermal site shows various width (5.9 to 29.6 km from the spreading axis) and occur at the depth range of 2090 to 2625 m. The covers usually form dome structures with the base size from 300 to 950 and height from 20 to 80 m. Zn and Cu resources in the deposits are estimated at about several thousands tonnes per one structure. Mean Cu content in these deposits ranges from 1.9 to 7.8%, with mean Zn content ranging from 4.7 to 28.0% (Usui, Iizasa, 1995; Okamoto, Matsuura, 1995).

Deposits in the EPR 13°N Field near the Ogorman fault show lower mean Zn content (8.2%), with relatively higher mean Cu content (7.8%) (Usui, Iizasa, 1995). Higher copper contents in this field are associated with deposits occurring on the slopes of volcanoes. Mean silver content in these deposits is 49 ppm, while mean gold content is 0.4%. Locally, in the ores located on the volcanoes' slopes, deposits with mean Cu content of 9.94%, mean zinc content of 7.87% and silver content of 409 ppm (mean) and 1771 ppm (maximum) occur (Okamoto, Matsuura, 1995).

In the intermediate spreading rate centers of the Galapagos Rift, along the boundary between Nazca and Cocos plates, several zones with exhalation of hot solutions occur (Malahoff *et al*., 1983). Around them sulphide ore deposits are formed (Law *et al.*, 1981; Sclater, 1978). The richest zones are located between 89^o and 84^{o}N, 100^o and 101^{o}W and 1^{o}S and 2^{o}N. Low-temperature hydrothermal fluids above 200^{o}C hot are ejected under pressure of about 300 atmospheres. These exhalations resemble rhythmic geysers. Occurrence of specific "plumes" of hot water, which can reach height of even 2 km from the bottom has been recorded. The plumes are usually colder (about 20^{o}C) and enriched in iron, manganese and copper components. Investigations performed with the American bathysphere "Alvin" in the end of the seventies, showed that the domes and chimneys occurring at the base of plumes, directly above outlets of hot water, reach height of several to about 30 m. In the spreading axis, the ridge 1 km long, 200 m wide and 40 m high occur. It is built of sulphide ore deposit. The ore deposit resources are estimated at about 25 million tonnes (Malahoff *et al.*, 1983). Bottom surface area, on which the domes and chimneys occur, is extended over several square kilometres and the deposit resources accumulated in these forms are about 20 million tonnes. The main component of the deposits is pyrite. The deposits contain in average 4.5% of Cu and 4.0% of Zn, the mean content of Ag is 46 ppm (Usui, Iizasa, 1995). Similar contents of Cu and Zn have been also observed in deposits of the North-East Pacific Ridges (Tunnicliffe *et al.*, 1984).

It should be emphasised, that in the vicinity of outlets of hot, mineralised waters, very abundant life forms, particularly microorganisms, have been found (Humphris *et al.*, Eds., 1995; Kotliński, Szamałek, Eds., 1998).

In comparison to the hydrothermal deposits of the East-Pacific Rise, the massive sulphide deposits occurring in the active volcanic arcs and in the marginal basins of the Philippines plate (Shichito-Iwojima Region and Okinawa Region) show most of all relatively higher Pb content (in average from 6.08 to 15.3%), with mean Zn content 10–36.6%, Cu content 1.2–12.6% and the highest registered in the ocean deposits Ag concentration (184–1900 ppm) (Usui, Iizasa, 1995; Hannington *et al.*, 1995) (Table 10).

Hydrothermal manganese crusts occurring in the active volcanic arcs and in the marginal basins are characterised most of all by high Mn/Fe ratio, with many times lower, in comparison to the nodules, Cu, Ni, Co, Pb, Zn, V, Y, U, Th and REE (Rare Earth Elements) contents (Usui, Iizasa, 1995). In the active volcanoes of the Ogasawara (Bonin) and Mariana arcs the crusts form widespread covers, up to several km^2 large, or they cement accumulations of nodules. Pace of growth of hydrothermal manganese crusts is more than three times higher than in the case of nodules and hydrogenic abyssal crusts (Usui *et al.*, 1986, 1994; Usui, Iizasa, 1995).

It should be emphasised, that no hydrothermal metalliferous sediments have been found in the inactive ridges. Either, no fossil sulphide deposits have been found in the DSDP/ODP (Deep Sea Drilling Project/Ocean Drilling Programme). Only in DSDP drilling no. 471, in the vicinity of Californian Penninsula, in the Middle-Miocene siliceous shales, the intercalations of pyrite, chalcopyrite and sphalerite have been found. In DSDP drillings, in the uppermost basalt beds of the second oceanic layer, manifestations of hydrothermal sulphide mineralisation represented by magnetite and copper dendrite aggregations have been observed (Gramberg, Ed., 1989). These data indicate that only recent hydrothermal and hydrothermal venting processes in the spreading zones led to the forming of polymetallic sulphide ore deposits of economic value.

Metalliferous sediments

Metalliferous deposits are defined as muddy-clayey sediments distinguished by presence of Mn oxides or Fe hydroxides and sulphides, while the total content of Fe and Mn exceeds 10%. The sediments are characterised by high Fe+Mn+Al index (above 2.5), changes in physico-chemical properties expresses by its early lithification and differentiated composition. The highest values of the Fe+Mn+Al index are observed in sediments covering slopes of the mid part of the East-Pacific Rise. Sediments occurring in the Guaymas Deep are characterised by higher Fe and Mn contents (up to 19.5% and 5.8% respectively), while the mean contents of Fe and Mn in the brown pelagic oozes are 5.4% and 0.44% respectively. The metalliferous sediments are also distinguished by higher concentrations of $SiO_{2amorph.}$, $C_{org.}$, Ba, Cu, Zn, Pb, Hg, V, Mo, Ag, Au, As, Sb, Cd, U and Se. Metalliferous clays or muds occur on the bottom surface, close (some tens of kilometres) to the sources of hydrothermal activity (Ainemer *et al.*, 1988; Andreev *et al.*, Eds., 1998). The metalliferous sediments are associated with hot exhalations occur also in the northern part and central part of the Mid-Atlantic Ridge (see Table 3).

Red Sea Region represents a typical initial rift zone, which is characterised by a presence of the "hot spots" located along the rift axis. For example, in the sulphide facies of Atlantis II Deep, the contents of base metals are as follows: Fe — 15.74%, Zn — 10.93%, Mn — 1.11%, Cu — 2.22%, Cd — 430 ppm, Co — 185 ppm, Ni — 130 ppm, Mo — 330 ppm, Pb — 1850 ppm, Ti — 460 ppm (Cronan, 1982). The muddy-clayey, up to several hundreds metres thick, metal-enriched sediments are underlain by calcareous sediments lying directly on basalts. The column of hot, 200 m thick, concentrated salt solution lies directly above the sediments. The brine passes upwards into the sea water. The metal resources, only in the Atlantis II Deep (of an area of 90 km^2) are estimated at about 24 million tonnes of Fe, 3.2 million tonnes of Zn, 0.8 million tonnes of Cu, 80 thousand tonnes of Pb, 4500 tonnes of Ag and 45 tonnes of Au (Seibold, Berger, 1993). The above mentioned data regard only the surficial, 10 m thick layer of sediments. Sedimentation rate of metalliferous sediments is very high and reach 7 to 60 cm/1000 years. The rift zone of the Red Sea is still active which causes that the African plate drifts apart from the Arabian plate with a speed of 1 cm/year.

The metal-bearing sediments occur also in the Mediterranean Region (see Table 3). Recently, their occurrence is known from the submarine volcanoes of Tyrrhenian and Aegean Sea (drowned caldera of the Santorini Island) (Humphris *et al.*, Eds., 1995). Diversity of hydrothermal sediments in the mentioned localities is high, from massive sulphide ore deposits in the crater of submarine Palinuro volcano, to the metal-bearing sediments enriched in Fe oxides and sulphides, occurring in the Enaret and Eolo seamount area (Kotliński, Szamałek, Eds., 1998).

Table 13

Main regions and fields of phosphorite nodule formation in the world's ocean

Selected regions and fields	Number of P_2O_5 assays	Mean concentration										
		P_2O_5 %	SiO_2 %	TiO_2 %	Al_2O_3 %	MgO %	CaO %	CO_2 %	$C_{org.}$ %	F+S+Fe+Sr %	U+Th ppm	Y+La+Ce ppm
Mariana-Hawaiian /*PhF*$_{S1-MH}$/												
Dutton /1/	28	28.28	7.17	0.05	1.64	1.74	37.79	3.74	0.67	4.250	32.80	62.14
Scripps /2/, Marmokers /3/, Musicians /4/	51	22.05	12.72	0.61	1.92	1.20	61.71	6.37	0.21	5.440	7.77	683.30
East-Pacific /*PhF*$_{S2-EP}$/												
Californian /5/	14	27.21	15.03	0.23	2.39	2.02	42.06	4.86	1.09	6.045	84.12	48.00
Peru-Chilean /6/	85	21.40	19.32	–	4.45	1.27	35.03	3.98	1.24	3.980	113.57	41.37
New Zealand /*PhF*$_{S2-NZ}$/												
Chatham /8/	62	20.63	6.37	0.02	0.91	0.61	45.29	–	0.40	2.785	219.57	35.40
West-Atlantic /*PhF*$_{S2-WA}$/												
Brasilian /10/	2	21.89	15.37	0.10	7.29	1.06	42.73	10.97	0.41	7.280	–	–
East-Atlantic /*PhF*$_{S2-EA}$/												
Maroccan /12/	38	17.56	3.83	0.15	0.74	2.51	43.75	15.70	0.48	7.887	–	–
Namibian /13/	25	21.83	5.36	0.10	1.17	1.33	39.07	6.26	0.94	3.620	166.40	–
Agulhas /15/	59	16.23	15.02	0.12	2.15	1.50	36.70	11.07	0.55	7.23	–	–

Based on: Andreev *et al*., Eds. (1998)

PHOSPHORITE NODULE FORMATION

The following regions and fields were distinguished within the phosphorite nodule formation (***PhF***): Mariana-Hawaiian, East-Pacific, New Zealand, West-Atlantic and East-Atlantic (Table 13). In the Pacific Province, the seamount and shelf/continental slope subformations were distinguished.

The major types of phosphorite deposits on the deep-sea floor include phosphorite nodules, phosphorite sands, and phosphorite oozes. In addition, laminae of consolidated phosphatised deposits can be found in Tertiary or older rocks which often form outcrops on the sea floor (for example Agulhas Field).

Phosphorite deposit accumulations occur usually on shelves and in the upper part of the continental slope, most often within the 35–400 m depth range and deeper, and — under different geomorphological and facial-genetic conditions — also on slopes of seamounts (guyuots) and rises, usually in mid-latitudes, under diverse facies and environmental conditions. Phosphorite nodules are formed within the depth interval from 35 to 3000–4000 m in areas of biogenic (diatomacean and carbonate) particle sedimentation accompanied by a large input of terrigenous components. Phosphorite nodules occur in Cretaceous to Holocene sediments: these usually are Neogene sediments on the shelves and Upper Cretaceous and Palaeogene sediments on Pacific seamounts and rises (Andreev *et al*., Eds., 1998).

The main mineral components of the phosphorite deposits are following: varieties of carbonate-fluoric apatite (francolite and collophane), quartz, plagioclases, feldspars, glauconite, Fe oxides, pyrite and volcanic glass. Depending on the P_2O_5 content, one can distinguish the following phosphate sediments: poor (P_2O_5 <15%); medium (15% < P_2O_5 <30%), and rich (P_2O_5 >30%).

Conditions for phosphorite deposit formation differ between regions. Analysis of data regarding distribution, composition, geochemistry and facies settling of the sediments on the oceanic shelves allow a new rethinking of their origin. Neogene and Quaternary, possibly also older phosphorite sediments were formed on shelves in result of complex biohydrogenic processes, proceeding in a certain order. Assimilation degree of phosphorus by the organisms depends on phosphorus concentration in sea water. In the regions of intense upwelling, the organisms are rapidly transported to the shallow zones, where they quickly die. In the case of high biological productivity of the waters, the intense biogenic sedimentation follows, which means intensified accumulation of phosphorus-rich bioclasts in the sediments. In those sediments, the diagenetic mobilisation of phosphorus follows. Its concentration in pore waters is also high, which lead to supersaturation and precipitation of phosphorus. Phosphorus saturation degree of the pore waters plays an important role. Enriching of the sediments in phosphorus results from continuous supply of bioclasts by intensive currents.

Phosphorite deposits of the Mariana-Hawaiian Region (Table 3) occur on the seamounts and rises, forming a long zone. The deposits are distinguished by their much lower content of C_{org} and U+Th, while Y+Ce+La content is many times higher. The origin of phosphorite sediments occurring on seamounts and rises is still discussed. Partly, those sediments were formed in the shallow water upwelling zones, which is proved by presence of numerous bioclasts in the sediments. Some authors connect the phosphatisation processes (for example in the Marmokers Field) with periods of increased volcanic activity (Safonov, 1982). Safonov believes that sediments on the seamount slopes are prone to the phosphorus-enriched water infiltration coming from the hydrothermal sources, what led to the forming of rich accumulation of these deposits. Important role is played also by bacterial decomposition of organic matter coming from plankton (Andreev *et al*., Eds., 1998).

The phosphorite accumulations (Table 4), in the East-Pacific Region, Peru-Chilean Field, and Californian Field are associated with such a genesis of forming of phosphorite sediments. Phosphorite sediments of the Japanese Region (Honsiu Field) and New Zealand Region (Chatham Field) are probably of similar origin, although they represent different hydrological conditions (Andreev *et al*., Eds., 1998).

Chatham Field occupies an area of 86.5 thousand square kilometres, and the phosphorite sediments occur at the depth range between 366 and 1280 m. Phosphorite nodules above 15 cm large, show concentric structure, where altered lamina reflect pyritisation, phosphoritisation, glauconitisation and repeated glauconitisation, phosphatisation and pyritisation. The main minerals are represented by francolite and collophane, with high (even up to 50%) content of glauconite. High concentration of uranium and thorium, with mean P_2O_5 content = 20%, is a characteristic feature of the sediments.

Phosphorite sediments of the Japanese Region are represented by massive phosphorites and phosphorite sands characterised by a high P_2O_5 content (10– 90%, in average 28%), while CaO content is about 40%, SiO_2 content = 8%, and F content is up to 3%.

Phosphorite nodules of the Californian shelf (East-Pacific Region) were formed in the Miocene–Pliocene period. They occur within a zone up to 80 km wide, at average depth about 100 m. The nodules are characterised by a high mean P_2O_5 content — 27%. Phosphorite deposits of this region are distinct in containing relatively more SiO_2 and C_{org}. The association with diatomaceous and foraminiferal oozes is a distinguishing feature of phosphorite deposits in the Peru-Chilean Field.

Phosphorite deposits of the Atlantic Province occur in sediments dating from Upper Cretaceous to Miocene. The main mineral is fluoric collophane. The association with zones of occurrence of calcareous sediments at the depth range from 100 to 1240 m and high uranium, thorium and strontium contents, is characteristic feature distinguishing phosphorite nodules and sands of the East-Atlantic Region.

Detailed characteristics of phosphorite deposits was presented by Safonov (1982), Rühle (*In*:) Kotliński, Szamałek, Eds. (1998) and Andreev *et al*., Eds. (1988).

HEAVY MINERALS FORMATION

It should be emphasised that the heavy minerals formation (***HMF***) occupies different position and encompasses mechanogenic deposits formed by hydrodynamic processes in shallow sea zones (Table 4). Differences in concentrations of certain placer heavy minerals in various deposits are closely related to the geological structure of a region as well as to intensity of denudation, erosion, and accumulation in the inshore and offshore zones. The fact that the deposition of those deposits is preceded by a long-time wave- and wind-driven transport, selecting the mineral grains depending on their size, shape and specific weight, is a distinguishing feature characterising forming processes of these deposits.

Primary ore deposits, fossil mineral sands, as well as accessory minerals occurring in the rocks, are primary sources for economically important components of recent placer heavy minerals. Erosion of primary ore deposits supply components for the detrital deposits of gold, platinum, cassiterite, sphalerite, volframite, schorl, columbite and cinnabar. On the other hand, concentrations of accessory minerals in such rocks as basalts, andesites or metamorphic rocks (basites, norites, anorthosites) provide main source of monazite, ilmenite, rutile, zirconium and magnetite. Supply of big amounts of heavy minerals from the continents to the sea and sustained reworking of the sediment in the near-shore environment are crucial factors in forming of the detrital deposits. For example, forming of ilmenite, rutile and monazite detrital deposits (mineral sands) is connected with debris of eroded Precambrian and Palaeozoic rocks, delivered to the seas by rivers (Indian deposits, East Australian deposits, North American deposits in Florida). On the other hand, placer heavy minerals of the Baltic Sea and Alaska are products of denudation of glacial deposits. In New Zealand and Japan the components of mineral sands were derived from volcanic rocks. The veins and intrusions of volcanic rocks occurring within Mesozoic-Cenozoic sedimentary rocks, as well as alluvial sediments of the drown valleys on the shelves (Indonesia, Thailand, Alaska) can provide detrital gold, platinum or cassiterite (Dimov *et al*., Eds., 1990; Kotliński, Szamałek, Eds., 1998; Andreev *et al*., Eds., 1998).

The most important regions of occurrence of detrital deposits (placer heavy minerals) are: in the Pacific Province — Cordillera, Andes, Far-Eastern Regions with concentrations of gold, cassiterite, platinum, chromite; in the Somali Province — West-Indian Region with concentrations of titanium, zirconium, iron, Rare Earth Elements and diamonds; in the Australian Province — Australian-New Zealand, Arabian-Bengali, Andaman-Java Regions with concentrations of ilmenite, zirconium, rutile, magnetite, monazite; in the Atlantic Province — East-Atlantic and West-Atlantic Regions, with concentrations of gold, chromium, platinum, diamonds, titanium, zirconium, ilmenite and Rare Earth Elements. In view of different sources of components and environmental conditions of deposit formation, determined by the course and intensity of denudation processes, regions, fields, and areas of heavy mineral accumulations are clearly region- and area-specific. In the present paper, the characteristics of fields and areas of heavy mineral occurrence has not been presented (Table 14). Those aspects have been presented in detail in the previous publications (Kotliński, Szamałek, Eds., 1998; Andreev *et al*., Eds., 1998).

Table 14

Heavy minerals and main regions of their exploration

Minerals and major metals	Major mineral components, major use	Regions
Ilmenite, rutile, zirconium, monazite (Fe, Ti, Zr, Th, RRE)	**$FeTiO_3$, TiO_2, $ZrSiO_4$, $CePO_4$**	Australia, India, Sri Lanka, USA, Republic of South Africa, Sierra Leone, Mozambique, Brazil
Magnetite, titanomagnetite (Fe, TiO_2 i V)	**Fe_3O_4**	Japan, New Zealand, Philippines, Indonesia
Gold	**Au**	USA (Alaska), Canada
Platinum	**Pt**	USA (Alaska)
Cassiterite (Sn)	**SnO_2**	Indonesia, Malaysia, Thailand, Great Britain
Chromite (Cr)	**$FeCr_2O_4$**	USA (Oregon, Washington)
Diamonds	jewellery and industrial raw material	Namibia, Republic of South Africa
Garnets	jewellery and industrial raw material	India, Sri Lanka
Syllimanite	fire-resistant raw material	India

Based on: Dimov *et al*., Eds. (1990)

CLOSING REMARKS

The formation, within the Mesosoic–Cenozoic, of ocean crust has been, along with transformations in the upper Earth mantle and development of hydrosphere, an extremely important stage in evolution and development of the Earth. Formation and transport of gigantic amounts of basalt masses, associated with degassing of the upper mantle, result from mega-scale endogenic processes driven — on the planete's scale — by endogenic energy of the Earth. A gradual increase in sea water carbonate content, led to the development, in the Jurassic, of the ionic composition, pH (7.5–7.8), and the structure of the water masses, at a certain oxygen content level. The supply of anions was basically controlled by endogenic processes, the supply of cations being dependent on the amount of terrigenous input to the oceans. The sea water chemical composition as well as the internal structure of water masses are still undergoing changes depending on the regional environmental conditions. The studies performed confirm that the scale and pace of oceanic crust transformations are regionally differentiated. Lithosphere plates are differentiated in terms of their movements and deformation processes proceeding in each of them. The differentiation is reflected in different geometry of, i.a., oceanic plates, i.e. their size, present bathymetry as well as morphometry and succession of morphotectonic elements of the oceanic bottom. The temporally differentiated intensity of magmatic processes and the morphotectonic characteristics of the recent oceans directly determine conditions of the sedimentary environment at the regional level.

The present author identified four major stages in transformations of the oceanic crust:

I. 170–118 million years ago,
II. 118–85 million years ago,
III. 85–24 million years ago,
IV. from 24 million years ago till recent.

The interactions, recently revealed, between distribution of polymetallic deposits and factors determining metal concentrations in the ore deposits, are typical of the last, fourth stage of the world's ocean evolution. At stage, branches of the Indo-Pacific Rise, with its narrow, inconspicuously sculptured rift valley, emerged, as did the Indo-Atlantic and Indo-Mediterranean Ridges, with asymmetric, wide rift valleys. Transform faults, along which shifts occurred and the block structure of the seabed formed, were transformed. Faults in oceanic rift zones were activated, volcanism developed, and seismicity of those areas increased, giving way to the recent phase of transformations and development of the deep-sea floor, including its present relief. The advection, about 12 million years ago, of strongly oxidised Antarctic water was clearly a new factor. Stabilisation of the water column structure, particularly with respect to oxygenation and circulation of near bottom masses, was the direct cause of transport of great amounts of manganese and iron, released from the newly forming ocean crust, from poorly to better oxygenated sedimentary environments. This new phase of crust transformations and development is, metallogenetically, a new **manganese** period.

However, the connection between patterns in the polymetallic ore deposits and the last (IV) stage of the world's ocean evolution, albeit justified at the present state of knowledge, seems to be disputable.

The concept of a stage-wise evolution and transformation of the oceanic crust in the Mesozoic–Cenozoic period, assuming the plate tectonics mechanism, only partly explains of the existing geological patterns (Andreev *et al*., Eds., 1998). In view of the differential rate of those processes at the successive stages of the world's ocean evolution, it is obviously purposeful to continue the studies. They should be particularly aimed at:

— explanation with reference to the plate tectonics concept, of the spatial closeness of "old" plate fragments in the Western Pacific and "young" ones along the American coastline as well as the origin of "older" system of the submarine volcanic arc within the Pacific; for example, the pattern of accretion of the Pacific crust can be explained also by radial spreading of the plate (Earth expansion hypothesis) (Koziar, 1993) in a direction opposite to that assumed from the plate tectonics theory;

— explanation of the poor differentiation of basaltic magmas during the entire period of ocean crust spreading; this differentiation is unexplainable if one accepts the scale and range of subduction processes and possible considerable magma differentiation in those processes;

— clarification of basalt magmatism as well as elucidation of differentiation and geochemical characteristics of the ocean crust crystalline complex, with a particular reference to transition zones;

— elucidation of the sedimentary cover structure and its lithostratigraphic variability, along with explanation of metallogenesis in the sediments in order to develop and clarify genetic concepts of deposit formation.

Structural-formation studies on metallogenesis in the world's ocean, in connection with differential evolution of individual oceans and mineralogenesis on the continents, represent one of the key problems in marine geology.

The origin of the recently identified oceanic deposits points to:

— direct connections between the near-shore detrital deposits and geological structure of the adjacent continents, as far as their occurrence, distribution patterns and content of economically important minerals are concerned;

— similarities between hydrothermal Cu-Zn mineralisation in the oceans and on the continents;

— manganese oxide deep-sea ore deposit formation, typical of oceans only.

The currently known patterns of the deep-sea polymetallic ore deposit and the demonstrated effects of processes and factors determining metal concentration in the ore deposits indicate the dominant, albeit ocean specific role of endogenic processes, which affect, both qualitatively and quantitatively, metal supply to the oceanic water.

The regions and fields identified within the manganese nodule formation include accumulations of ferromanganese oxide ore deposits, the deposits being estimated at about 86.6 billion tonnes, including 18.2 billion tonnes of manganese, 569 million tonnes of nickel, 349 million tonnes of copper and 339 million tonnes of cobalt (Andreev *et al*., Eds., 1998). On the other hand, the prognostic metal resources in the hydrothermal sulphide ore deposits known so far are estimated at about several million tonnes, including copper, zinc and lead as well as several tonnes of gold and silver. The metal resources in the heavy mineral detrital deposits known to date (118 areas) still play an important role in supplying the world's demand for zirconium, titanium, tin, chromium as well as gold, platinum, and diamonds.

Taking into account the existing resources of metal deposits on the continents, distribution and accessibility of the ores, current trends of supply and demand as well as current the low metal prices, it can be predicted that the potential producers will not be interested in non-conventional methods of deep-sea metal mining in the nearest future. Although political risk and social hazards, in comparison to the land-based deposits, are not so much involved in the potential deep-sea deposits, mining and despite the fact that the deep-sea resources can simultaneously supply several metals, thus giving the potential investors chance for more stable income, the wariness of the potential investors hardly provide a stimulus for oceanic studies. The current state of knowledge on the ore deposits as well as the use of oceanic mineral resources is presented in Table 15 (Kotliński, 1998e). The geological-economical analyses, which take into account the continuously increasing costs of land-based exploitation, including those of habitat remediation, and which assume also the continuously low metal prices, predict that the exploitation of deep-sea polymetallic deposits will not start earlier than in 20–30 years (Lenoble, 1993; Kunzendorf, 1998).

The metallogenic map of the world's ocean (Fig. 9) is based on, i.a., available results of geological studies. The synthesis of those results, both at a regional and local scales, along with a comparative analysis, allowed the author to work out a new concept of metallogenic division of the world's ocean, the concept being placed within the structural-formation framework. The known patterns of the deep-sea, polymetallic deposit formation connected with processes dominating at individual stages of the world's ocean evolution, served as a basis for the systematics presented here. A particular attention has been paid to couplings between the stages of oceanic crust transformations and morphostructural characters of the see floor on the one hand, and sources of components and conditions of their sedimentation on the other. The concept of metallogenesis in the world's ocean presented here involves both geotectonic and morphometric aspects affecting interactions between amounts and types of components supplied to the oceanic waters and certain effects of sedimentary factors leading to concentration of the components in the deposits. The course and scope of the mechanisms and processes dominating deposit formation differ from region to region. The units identified (morphotectonic megaprovinces, metallogenic provinces, deposit formations and subformations) reflect a hierarchy of the dominant groups of processes and factors which lead to the formation of certain mineral deposits, from the planetary scale through regional to the local scale.

Table 15

Mineral resources of the world's ocean and major producers

Sources of non-renewable resources	Mineral (metallic and non-metallic) resources	Inshore zone and continental shelf within coastal states' jurisdiction	Continental slope and slope feet	Deep seafloor		Major producers
				Abyssal plains	Mid-ocean ridges and guyots	
			(open sea)			
Sea water	Salts of different composition	🟨				Russia, USA, Great Britain, Japan, France
	Magnesium (Mg)	🟨				Russia, USA, Great Britain, Japan
	Bromine (Br), iodine (J)	🟨				USA, Great Britain, Japan, India, Argentina
	Sodium (Na), potassium (K)	🟨				USA, China, Italy, Japan
	Other metals [uranium (U) etc.]	🟩				Great Britain
	Fresh water distilled from sea water	🟨				USA, Saudi Arabia, Kuwait, Japan, China (Hong Kong)
Deep-sea sediments	Metalliferous muds				🟩	Saudi Arabia, FRG, USA
	Rocks resources: sands, gravels, lime, gypsum, etc.	🟨	🟦			USA, Russia, Great Britain, Iceland, Ireland
	Heavy mineral placers: gold (Au), platinum (Pt), cassiterite (SnO_2), ilmenite ($FeTiO_3$), zirconium [$Zn(SiO_4)$], monazite ($CePO_4$), rutile (TiO_2)	🟨				Philippines, USA, Indonesia, India, Australia, Brazil, Republic of South Africa, Malaysia
	Diamonds, amber, corals, pearls	🟨				Republic of South Africa, Japan, Poland, Russia, Indonesia
	Barite ($BaSO_4$)	🟨				USA
	Phosphorite (P_2O_5)	🟩	🟥			USA, Australia, Mexico, Japan
	Glauconite	🟩	🟦			USA
	Polymetallic nodules (Mn, Ni, Co, Cu)			🟥	🟩	Russia, India, USA, China, FRG, Cook Islands, Japan, France, Republic of Korea, IOM
	Cobalt-rich manganese crusts (Co, Ni, Pt)		🟦	🟥		USA, Japan, Russia, FRG
	Massive polymetallic sulphide ores (Zn, Cu, Ag, Au, Ni, Co, Cd)				🟥	Russia, Japan, FRG, France, Republic of Korea
Substrate	Oil and gas	🟨	🟦			USA, Middle East, Mexico, Venezuela, Great Britain, Norway, Russia
	Iron ores	🟥				Canada, Sweden, Finland, France, Japan
	Coal	🟨				Japan, Great Britain
	Sulphur	🟨				USA, Russia, Persian Gulf
	Salt	🟨				USA (Gulf of Mexico)
	Non-ferrous metals	🟥				Great Britain, Canada

Based on: Dimov *et al.*, Eds. (1990), supplemented Kotliński (1997a)

🟦 Prospecting
🟩 Pilot mining
🟥 Exploration
🟨 Commercial mining

CONCLUSIONS

The comparative analysis used by the author throughout this work proven its utility in the regional analysis. It allowed identification of patterns in the occurrence and distribution of the deep-sea polymetallic deposits as well as processes and factors leading to their formation. Based on the analysis of a vast material, an original metallogenic systematics of the world's ocean has been developed. Within the morphotectonic megaprovinces and metallogenic provinces, identified deposit formations and subformations were distinguished. They encompass groups of deposits which show specific features reflecting differential intensity of tectonic-magmatic and sedimentary processes. The dominant processes and factors were shown to affect sedimentation regimes at regional and local levels. The sedimentary conditions determine metal concentrations in various deposits. The source of metals and interactions between such features as: the type and amount of the components supplied to the oceans; depth, structure and dynamics of the sea water; and the bottom relief are crucial for metal concentration.

1. It was demonstrated that certain endogenic and exogenic processes clearly dominated in the morphotectonic megaprovinces (Indo-Pacific, Indo-Atlantic and Indo-Mediterranean). Previous studies showed, that the processes occurring at the last (IV) stage of the oceanic crust transformation exerted a decisive effect on formation of the deposits. The manganese metallogenic stage is connected with formation and specific transformation of recent oceanic ridges, associated with differential intensity of magmatic processes and the resulting amount of metals supplied to the sea water from the hydrothermal/vent sources. That stage is characterised by the specific differences between Indo-Pacific and Indo-Atlantic Megaprovinces, namely, in that the metals derived from the endogenic sources prevail in the former both quantitatively and qualitatively. The structure and dynamics of oceanic waters were shaped by tectonic processes, which determined the specific development of the sea floor relief and the influx of highly oxygenated Antarctic waters about 12 million years ago. The differential development of geodynamic regime in the megaprovinces, with differing sedimentation rate, led to the formation of their recent geometry. In the Indo-Atlantic Megaprovince, the development of oceanic crust was symmetrical, i.e. proceeding from a single spreading centre to the two opposite sides of the Indo-Atlantic Ridge, simultaneously in the Atlantic and Indian Oceans, in the Indo-Pacific Megaprovince, the ocean crust accretion was asymmetrical. The "old" Jurassic and Cretaceous parts of the oceanic crust occur NW from the recent zone of oceanic bottom spreading zone. The "young" oceanic crust occur in the southern and eastern parts, on both sides of the East-Pacific Rise.

2. The metallogenic provinces correspond to the boundaries of the present-day oceans or their parts. Development of those areas was determined by different mechanisms of transformation of the oceanic basement within each plate. Within the provinces, the conditions of ore deposit formation depended on the bottom relief, depth, and distance from the magmatic centres as well as on the intensity of hydrothermal/vent processes, transport mechanisms and sedimentation of the components. The structure of the sea water (CCD level, SCD level, near-bottom water oxygenation, pH and Eh), its circulation and dynamics, affected the sedimentation processes, as well as depending on the exogenic factors. Sedimentation rate and type of material supplied to the oceans are closely related to the intensity of weathering and denudation processes on the adjacent lands.

3. Within the metallogenic provinces, the manganese nodule, polymetallic sulphide, phosphorite nodule and heavy minerals formations have been identified. The formations listed involve genetically identical groups of deposits. They are differentiated regionally. In a given region, deposits form under the influence of certain processes depending on specific environmental factors. Within a given formation, individual groups of deposits are characterised by similar distribution patterns, mineralogical-chemical composition, and texture, all of these being shaped by hydrogenic, hydrogenic-diagenetic, hydrothermal-venting, biochemogenic and mechanogenic processes dominant in the region. The intensity of those processes is strictly related to certain factors determining conditions of the sedimentary environment. Within a formation, considerable differences in component' concentrations, including metals, occur. Deposit fields show geochemical differentiation manifested in domination of certain metals which form specific concentration sequences. The known patterns in deposit formation distribution and conditions of occurrence are the criteria for prospecting for new deposits.

4. The known patterns of the occurrence, distribution, and conditions of formation of the oceanic nodules and cobalt-rich manganese crusts indicate that, within the manganese nodule formation, the following factors are of crucial significance for metal concentration: amount of metals supplied to the oceanic waters from hydrothermal sources; structure and dynamics of the waters; low accumulation rate; depth and bottom relief. They determine hydrogenic and hydrogenic-diagenetic processes, proceeding within the hydrated and strongly oxidised boundary layer, in which the nodules are submerged. Depending on the depth of occurrence (in relation to the CCD and SCD levels), the nodules are classified by their concentrations of certain metals.

Analysis of the nodule morphology shows variation in nodule shape occurring in fields of strongly differentiated bottom relief, while areas of a smooth bottom relief have nodules of a similar shapes. Morphology of the nodules is also affected by the depth. Smaller, multi-nuclei nodules usually occur on steep slopes, while larger, single-nucleus ones occur in the areas with smooth relief. Large nodules usually occur *in situ*, while smaller ones are often redeposited. Mineral composition and nucleus type (bioclasts or debris of older nodules as well as nucleus shape, size and age) as well as degree of mineral crystallisation, directly influence the nodule morphology. Nodule creaching is a function of the nodule growth rate.

The studies show that the formation of type "H" nodules is controlled by hydrogenic processes, near-bottom waters being the source of metals. On the other hand, type "D" nodules are formed as a result of hydrogenic-diagenetic processes, the near-bottom water in the so-called "boundary layer" of bottom sediments being on additional metal source. Analysis of the mineralogical composition of the nodules confirm that the major manganese minerals include: todorokite (=manganite = busserite), birnessite (= manganite) and vernandite (= birnessite with chaotic structure). Processes of metal concentration in the nodules proceed in a number of phases, their course depending on whether vernandite or todorokite dominates. Metal concentration in the nodules depends on the content ratio of major mineral phases associated with the metals. Those nodules characterised by the todorokite domination are enriched in Mn, Ni, Cu, Zn, while those in which vernandite dominats are enriched in Fe, Co, and Pb.

5. In the manganese nodule formation of the North-East Pacific Basin Region the Ni-Cu geochemical type of nodules occupy the larger areas of the bottom while in the western part of the region Ni-Cu-Co type or Co type dominate. The geochemical asymmetry of the Pacific is mainly related to the distance from hydrothermal sources. Ore components are supplied to the sea water as a result of tectonic-magmatic processes. The occurrence of Ni and Ni-Cu geochemical nodule types, characterised by high metal contents, in the vicinity of the East-Pacific Rise, can serve as an index of the intensity of the tectonic-magmatic processes. The studies carried out to data confirm unequivocally the unique position of the Clarion-Clipperton Field. Within at field, on the surface of about 2.0 million km^2, a high nodule concentration on the see floor (nodule abundance exceeding 10 kg/m^2) and highest concentrations of such metals as manganese, nickel, and copper in the nodules, were observed. In the Mid-Indian Basin Region nodules, correlations between Mn and Fe and between Mn and Ni, Cu and Zn are clearly lower, which is related to relatively lower amounts of those metals supplied by the endogenic sources.

6. Cobalt-rich manganese crusts are natural, consolidated accumulations of hydrated iron and manganese oxides. The crusts take form of coatings, incrustations or aggregates. They usually occur on the basalt outcrops, and less frequently form covers on the consolidated sediments or occur in the regions where massive sulphide ores are abundant. The deposits are formed by hydrogenic or hydrothermal processes, depending on the place of a deposit' occurrence. The cobalt-rich manganese crusts of hydrogenic origin are characterised by increased concentration of cobalt, even up to 1.6%. The crusts occur on seamount (guyuot) slopes or on slightly inclined terraces, at depths ranging from 500–1000 to 2000–3000 m. Manganese in the hydrogenic crusts shows high positive correlations both with Cu and Pb. Correlation coefficients with Ni and Ti are lower. It should be emphasised that the mean contents of Co, Ni, Zn, Cu, Pb, and Ti are clearly lower in the cobalt-rich manganese crusts from the Atlantic Ocean. Ferromanganese deposits in the Atlantic Ocean are distinguished, compared to those in the Pacific, by predominance of iron over manganese, while at the same time contents of aluminium and silica, supplied by the African continent, are higher. Those deposits (in the form of crusts) are associated with nodules which show similar chemical composition and dark-brown colour. The hydrogenic nodules usually are ellipsoidal or spheroidal in shapes and are often fused. The positive Mn-Co correlation is associated with the negative Co-Ni/Cu correlation, which indicates that in the hydrogenic processes cobalt is strongly associated with manganese. Vernandite is the major mineral of the crusts, which also show high mean contents of cobalt, lead, and platinum, a higher iron content is associated with increased concentrations of platinum and Rare Earth Elements.

7. Regions of occurrence of the so-called massive polymetallic sulphide deposits are associated with active spreading axes along the oceanic ridges and the island arcs. Fields of the sulphide ores are formed mainly in "active" axial and "passive" off axis zones along the rift valleys, as a result of interaction between heated oceanic water and basalts. Accumulations of sulphide ores, characterised by high metal' concentrations, are associated with the presence of the so-called "magma chambers", situated below the spreading axes. The "magma chambers", or magmatic centres, constitute specific energy source, which enabling migration of heated (above 100^{o}C) oceanic waters along cracks.

Polymetallic sulphide ores are represented by the three geochemical types: zinc and copper (Zn and Cu), copper and zinc (Cu and Zn) and zinc and lead (Zn and Pb). Depending on the place of their formation, they differ in both the major metals contents and those of accessory elements. Depending on the pressure gradient and temperature, chemical composition and pH of the hydrothermal solutions of metal sulphides are precipitated in a certain succession. The pyrite–marcasite, sphalerite–wurtzite, barite and $SiO_{2amorph.}$ paragenesis is characteristic of the hydrothermal solutions having the temperature of <250^{o}C, while the chalcopyrite–isocubanite, pyrrhotite, pyrite, wurtzite–sphalerite, anhydrite and $SiO_{2amorph.}$ paragenesis is characteristic of the hydrothermal solutions of >250^{o}C. Thermodynamics and chemical composition of the hydrothermal solutions as well as microbial processes, including interactions with hydrothermal solutions, are directly reflected in the differentiation of metal contents in the ore deposits. Zinc and copper group of deposits usually occur on the volcanic cones. On the other hand, copper and zinc group commonly occurs in the active spreading axes slow spreading rate of the Mid-Atlantic Ridge and intermediate to superfast spreading rate East-Pacific Rise. Deposits associated with the present-day volcanism in the back-arcs and back-arc basins are characterised, in comparison to those formed in the active spreading axes, by relatively high contents of lead, silver and gold, as well as high zinc contents.

Metalliferous mudes or clays are distinguished by the presence of manganese oxides or hydroxides and sulphides of iron, of total Fe and Mn content above 10%. They occur in zones of intensive hydrothermal activity and are characterised by different chemical composition.

8. The major types of phosphorite deposits on the deep-sea floor include phosphorite nodules, phosphorite sands, and phosphorite oozes. In addition, beds of consolidated phosphatised deposits can be found in Tertiary of older rocks which often form outcrops on the sea floor.

Phosphorite deposits occur usually on shelves and in the upper part of the continental slope, most often within the 35–400 m depth range and deeper, and — under different geomorphological and facies-genetic conditions — also on slopes of seamounts (guyots), usually in mid-latitudes. Phosphorite nodules are formed within the depth interval from 35 to 3000–4000 m in areas of biogenic (diatomacean and carbonate) particle sedimentation, accompanied by a large input of terrigenous components and a contribution of volcanic material. Phosphorite nodules occur in Cretaceous to Holocene sediments: these usually are Neogene sediments on the shelves and Upper Cretaceous and Palaeogene sediments on Pacific seamounts and rises. Conditions for phosphorite deposit formation differ between regions.

9. The coastal heavy minerals formation encompasses mechanogenic deposits formed by hydrodynamic processes in shallow water areas. Differences in concentrations of certain heavy minerals in various deposits are closely related to the geological structure of a region as well as to intensity of denudation, erosion, and accumulation in the inshore and offshore areas. In view of different sources of components and changing hydrodynamic conditions of deposit formation, regions and fields of heavy mineral accumulations are clearly region- and area-specific.

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PLATE I

Textures and cracks in nodules

Phot. 1. Concentric-laminated texture of a nodule (16 x, nicols parallel). *Photo*: *P. Markiewicz*.

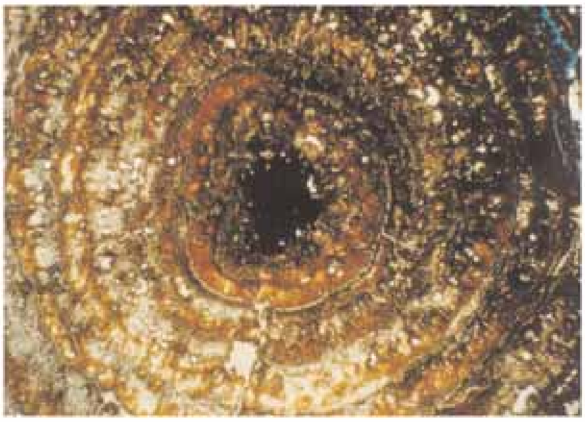
Phot. 2. Radial-dendritic texture of a nodule (16 x, nicols parallel). *Photo*: *P. Markiewicz*.

Phot. 3. Radial arrangement of needle-shaped manganese minerals (200 x, nicols parallel). *Photo*: *M. Pawlikowski*.

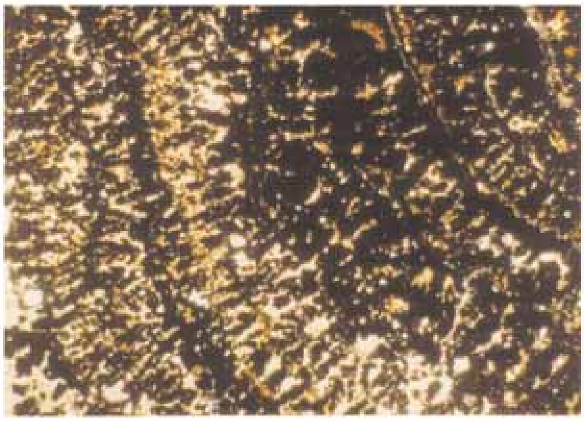
Phot. 4. Cracks in the nodules with disturbed arrangement of accretion lamina (100 x, nicols parallel). *Photo*: *M. Pawlikowski*.

Phot. 5. Fracture zone in hydrated manganese minerals (200 x, nicols parallel). *Photo*: *M. Pawlikowski*.

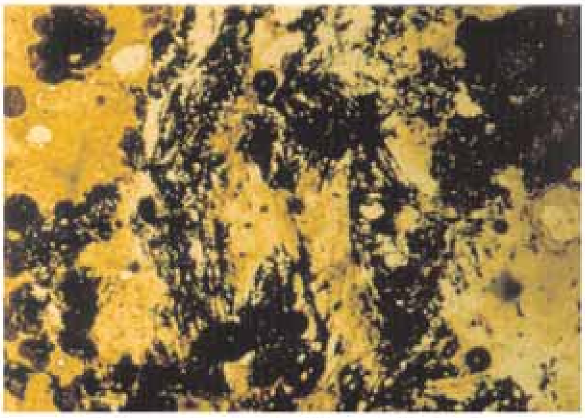
Phot. 6. Cracks filled in with manganese minerals and manganese dendrites within clay pseudomorphosis after volcanic glass (100 x, nicols parallel). *Photo*: *P. Markiewicz*.



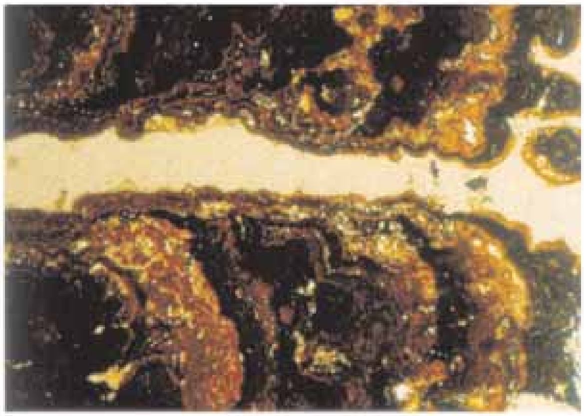
Phot. 1



Phot. 2



Phot. 3



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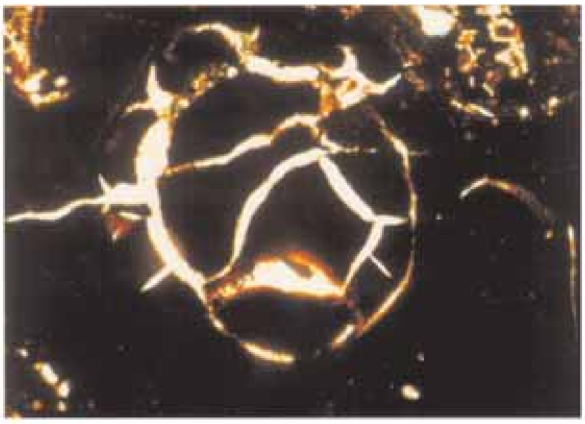
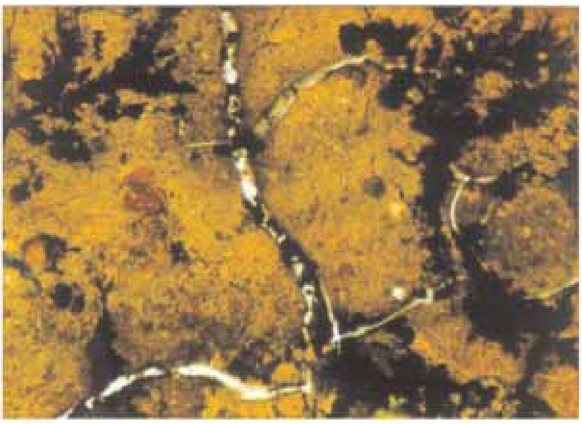


Phot. 5



Phot. 6

PLATE II

Minerals in the nodules

Phot. 1. Clay pseudomorphoses after volcanic glass (200 x, nicols parallel). *Photo*: *M. Pawlikowski*.

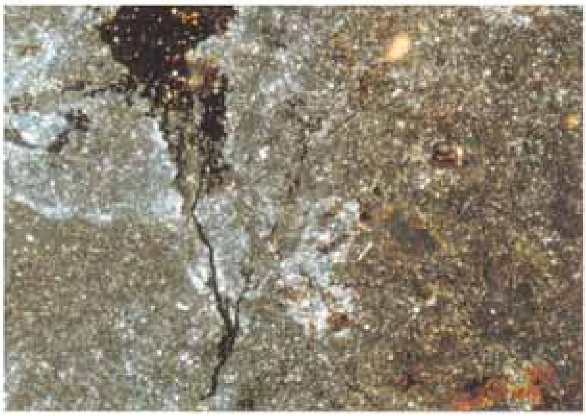
Phot. 2. Clay pseudomorphoses after volcanic glass with manganese inclusions (16 x, nicols parallel). *Photo*: *P. Markiewicz*.

Phot. 3. Volcanic glass of vitroclastic type (40 x, nicols crossed). *Photo*: *M. Pawlikowski*.

Phot. 4. Feldspars with visible radiolarian shell and fish bones fragments (100 x, nicols parallel). *Photo*: *P. Markiewicz*.

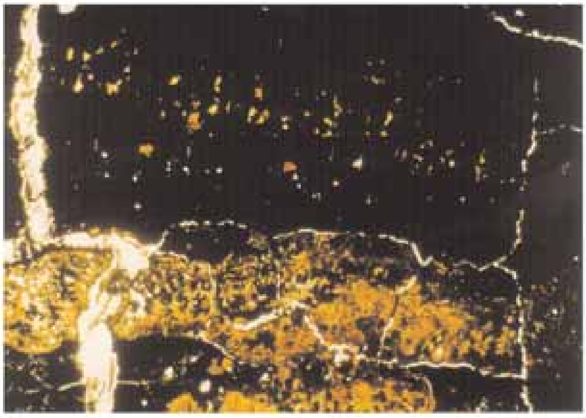
Phot. 5. Arrangement of minerals structure in nodules (100 x, nicols parallel). *Photo*: *P. Markiewicz.*

Phot. 6. Micronodules in a nodule’s nuclei, initial phases of crystallisation and arrangement of minerals structure (100 x, nicols parallel). *Photo*: *P. Markiewicz*.

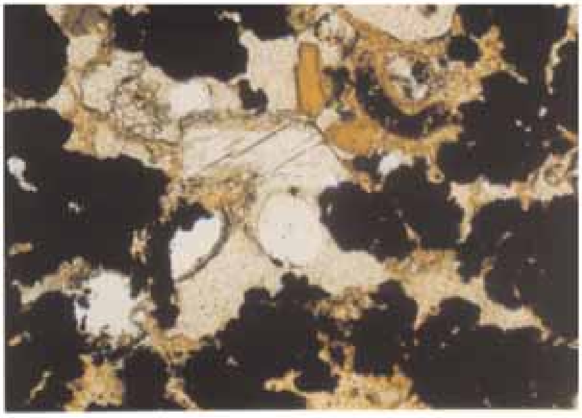


Phot. 1

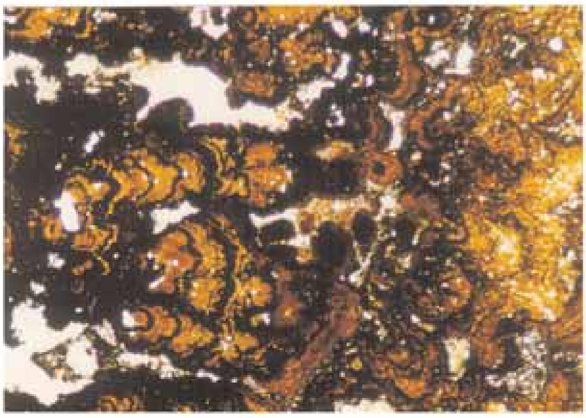
Phot. 2



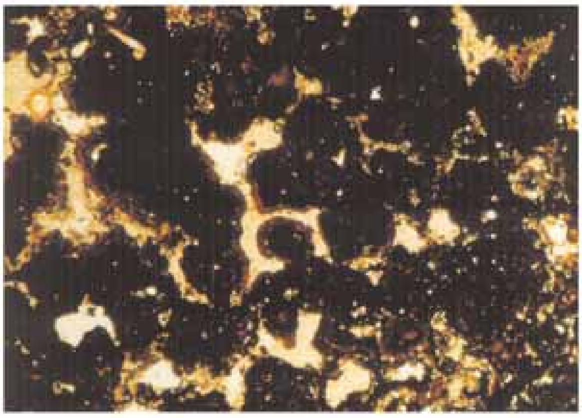
Phot. 3



Phot. 4



Phot. 5



Phot. 6

PLATE III

Energy spectrum (EDX) and base metals distribution in a genetic type “H” spheroidal nodule

a — central part; b — outer part

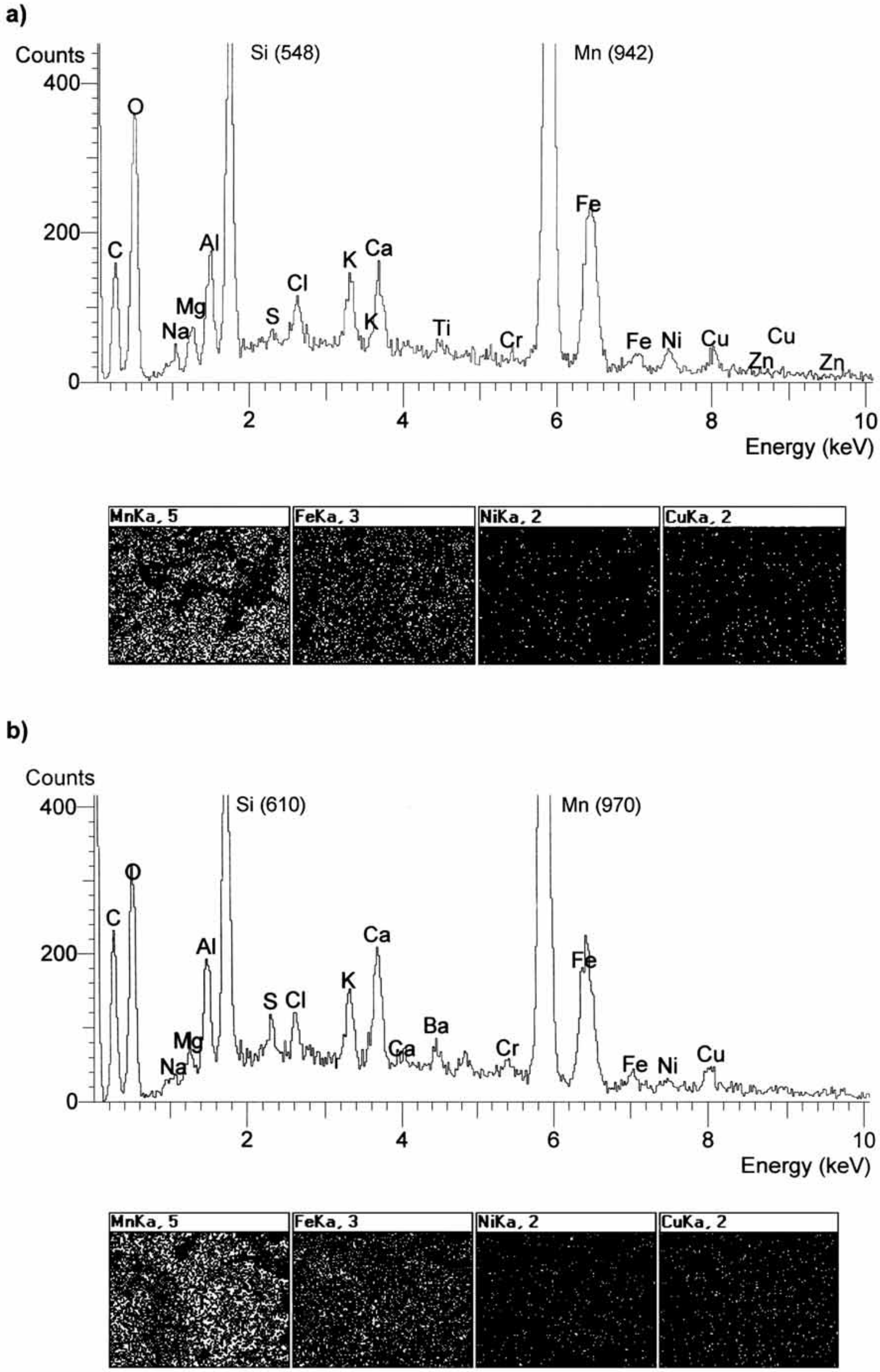
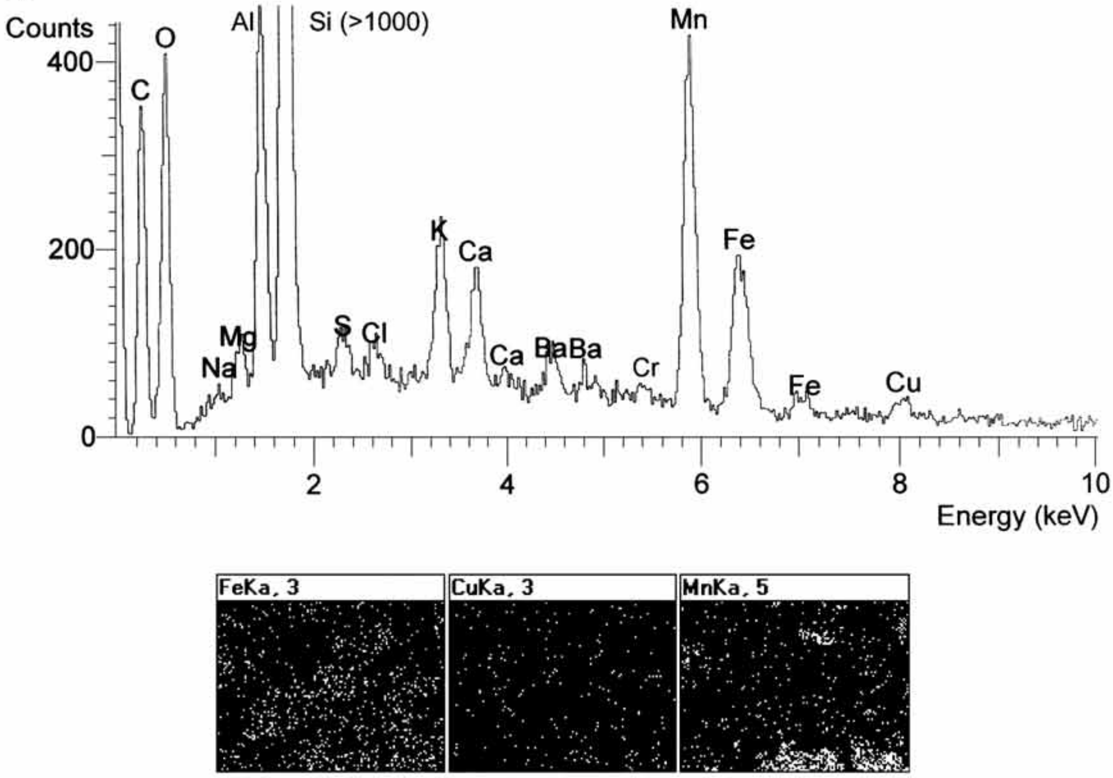

a)
Counts
400
200
0
Si (548)
Mn (942)
O
C
Al
Mg
Na
S
Cl
K
Ca
K
Ti
Cr
Fe
Fe
Ni
Cu
Cu
Zn
Zn
2
4
6
8
10
Energy (keV)
MnKa, 5
FeKa, 3
NiKa, 2
CuKa, 2
b)
Counts
400
200
0
Si (610)
Mn (970)
O
C
Al
Mg
Na
S
Cl
K
Ca
Ca
Ba
Cr
Fe
Fe
Ni
Cu
2
4
6
8
10
Energy (keV)
MnKa, 5
FeKa, 3
NiKa, 2
CuKa, 2

PLATE IV

Energy spectrum (EDX) and base metals distribution in a genetic type “HD” ellipsoidal nodule

a — central part; b — outer part

a)


Counts
400
200
0
C
O
Al
Si (>1000)
Na
Mg
S
Cl
K
Ca
Ca
Ba
Ba
Ba
Cr
Mn
Fe
Fe
Cu
2
4
6
8
10
Energy (keV)
FeKa, 3
CuKa, 3
MnKa, 5

b)

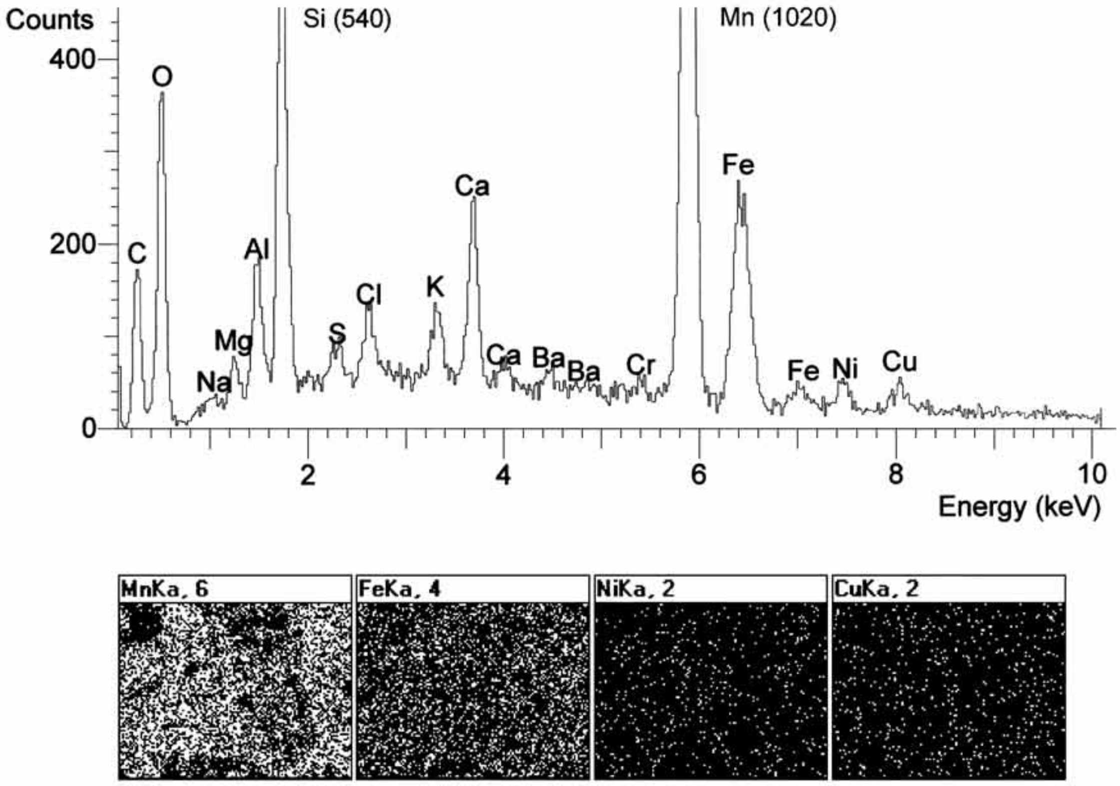
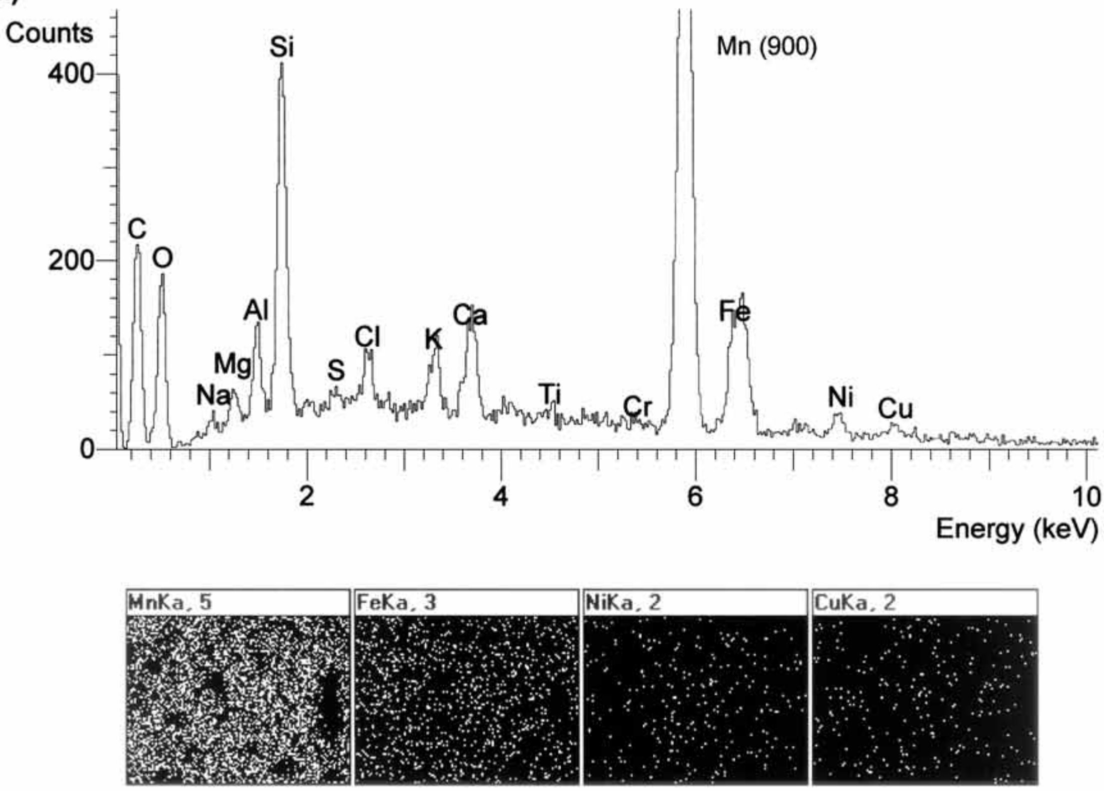

Counts
400
200
0
C
O
Na
Mg
Al
Si (540)
S
Cl
K
Ca
Ca
Ba
Ba
Cr
Mn (1020)
Fe
Fe
Ni
Cu
2
4
6
8
10
Energy (keV)
MnKa, 6
FeKa, 4
NiKa, 2
CuKa, 2

PLATE V

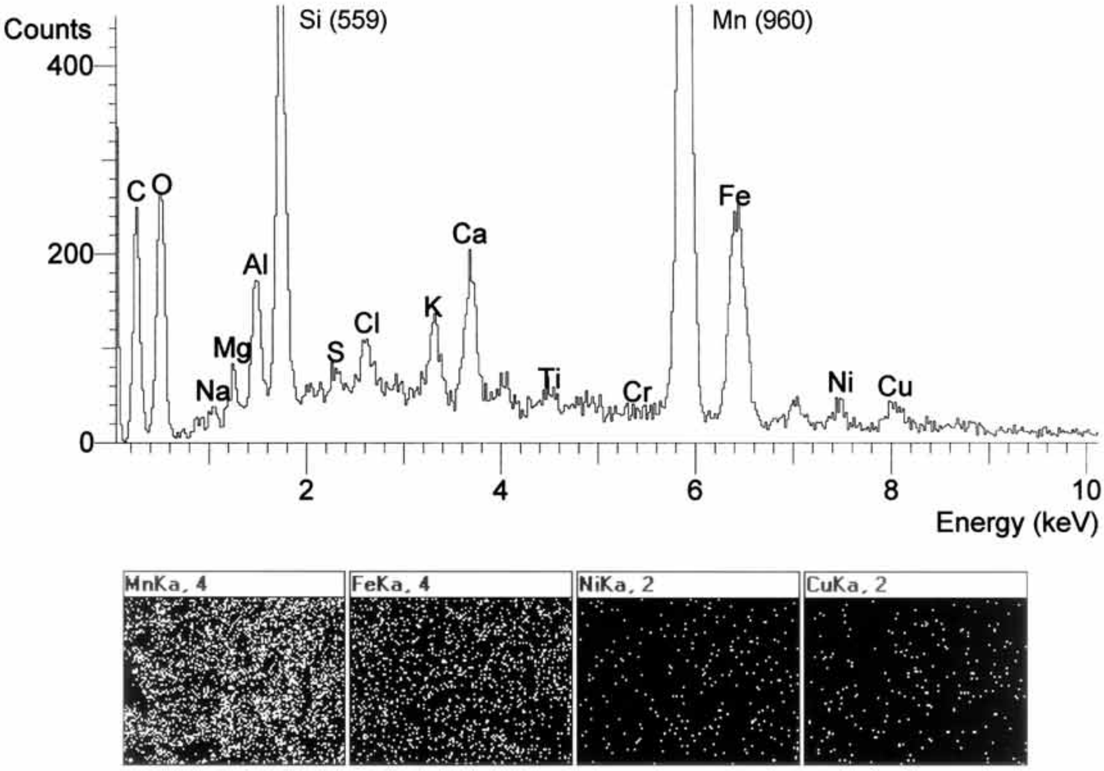
Energy spectrum (EDX) and base metals distribution in a genetic type “D” discoidal nodule

a — central part; b — outer part

a)


Counts
400
200
0
C
O
Na
Mg
Al
Si
S
Cl
K
Ca
Ti
Cr
Mn (900)
Fe
Ni
Cu
2
4
6
8
10
Energy (keV)
MnKa, 5
FeKa, 3
NiKa, 2
CuKa, 2

b)


Counts
400
200
0
C
O
Na
Mg
Al
Si (559)
S
Cl
K
Ca
Ti
Cr
Mn (960)
Fe
Ni
Cu
2
4
6
8
10
Energy (keV)
MnKa, 4
FeKa, 4
NiKa, 2
CuKa, 2