

The Cyclops Mountains Massif (New Guinea, Indonesia) as the provenance area for metal-bearing shelf sediments from the Carolinian Sea

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In 2009, on the initiative of PT Halmahera Perkasa the “Jayapura” exploration project was carried out in Indonesia. As part of this project, exploration of the sea bottom in the northern coast of New Guinea was carried out over a distance of ~45 km. The suction dredge collected 59 samples of loose sediments from the shelf bottom surface of the Carolinian Sea (to a depth of 60 m below the sea-floor). The extracted samples are usually poorly and moderately sorted sands (5 samples), medium-grained sands (21 samples), and fine-grained sands (33 samples). The sand composition shows, among others, a wide spectrum of heavy minerals of ultra-mafic (Cr-garnet, chromium spinel, Mg-olivine) and metamorphic (epidote, clinocllore, amphibole, titanite) origin. The content of heavy minerals in the sediments is up to 54.77 wt.%. It was found that the source of heavy fraction in the eastern and western parts of the coast is the rock of the ophiolite series building the Cyclops Mountains Massif. The mineral composition of sediments from the central coastal zone corresponds to the types of rocks building the metamorphic core of the Cyclops Mountains (amphibolite, gneisses, andesite). Three mineral-geochemical subprovinces were determined on the basis of analyses of heavy mineral decomposition and chemical analyses of sediments. Shelf sediment from the eastern part of the coast is characterized by an increased content of strategic metals (Ni up to 3560, W up to 3130 and Co up to 142 ppm). In the central zone, the V content increases up to 244 ppm and the Ag content up to 5 ppm. In the shelf sediments there is a strong depletion in the REE.

Key words: continental shelf sediments, Cyclops Mountains, New Guinea, heavy minerals, geological prospection, marine minerals.

INTRODUCTION

Mineral composition of coastal sediments is the result of provenance rock-type and sedimentation cycle factors (Morton and Smale, 1990; Morton and Hallsworth, 1994, 1999; Garzanti and Andò, 2007). Sedimentation processes can lead to concentration of metal-bearing sediments, which may be defined as economically significant in the whole spectrum of texture: gravel, sand, mud, silt and clay deposited offshore (Van Gosen et al., 2014). Mineral composition of the (inner) shelf sediment is closely linked to coastal hydrodynamics, where there is a direct interaction between the marine and littoral environments (Rosa et al., 2013).

Intense weathering processes under tropical conditions combined with a constant uplift of the area can contribute to the supply of large volume of sediments of different geochemical compositions to nearby water reservoirs (Liu et al., 2012). The

rivers of New Guinea transport $1.7 \cdot 10^9 \text{ t}^{-1}$ of sediments to the World Ocean yearly (Milliman, 1995). The amount of mineral masses coming in is spatially distributed within the whole inner shelf surrounding the island. A significant part of the sediments is supplied by rivers draining the areas of northern New Guinea (Milliman and Syvitski, 1992; Milliman, 1995). The existence of underwater canyons directed towards the edge of the New Guinea Trench cause the direct distribution of sediments on the shelf to disperse. Hypothetically, the hypopycnal or homopycnal flows are particularly significant for the process of moving a large volume of material, but there is no research data from this process. Part of the rock material is accumulated within the shelf and continental slope. The rest of the sediment is moved by gravity or hyperpycnal flows to the open sea mostly by a system of submarine channels (Krause, 1965; Hamilton, 1979; Tregoning and Gorbатов, 2004; Miller and Kuehl, 2009). The quantity and quality of the material supplied to the coastal waters of New Guinea depends on the mass movements (land slumps, landslides) and wave processes having a destructive effect on the coastline.

The northern part of New Guinea (Jayapura region) is now a marginal zone of convergence between the Indo-Australian and Pacific plates. The presence of convergent plate boundaries results in the possibility of occurrence of characteristic deposit

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mineralization similar to that associated with the island arcs, such as podiform chromite (Mosier et al., 2012), Besshi-type copper sulphide deposits (Dergatchev et al., 2011), Kuroko-type massive sulphide (Sato, 1977) and porphyry copper ores (Sun et al., 2017). The complex geological history of the Jayapura area (Monnier et al., 1999), results in the presence of numerous base metals of potential economic significance (Baker, 1955, 1956; Ubaghs, 1955; Pieters et al., 1979; Thirnbeck, 2001, 2004; Zglinicki, 2016). Department of Energy and Mineral Resources West Papua Province (Ind.: *Dinas Energi Dan Sumber Daya Mineral Provinsi Papua Barat; Peta...*, 1995) has identified five provinces of significant mineral deposits on the island of New Guinea, which include the Jayapura region with a Cu-Zn-Pb-Fe-Cr-Co-Ni zone, within the Cyclops Mountains Massif. The lithologically diverse formations of the area, resulting from the complex geodynamic genesis, may abound in a number of elements and useful metals (Baker, 1955; Ubaghs, 1955; Pieters et al., 1979). Probably, undescribed types of deposits may exist around the Cyclops Mountains Massif as: **alluvial** Ag-Au, Cr, Ni, Co, PGE; **coastal** Ti, Ni, Co, Cr, Au, Ag, PGE; and **epithermal** Au.

The depletion of onshore mineral deposits makes it necessary to conduct continuous research and exploration in marine areas (Szamalek et al., 2013, 2015, 2018). The high geopotential of seas and oceans implies an increase in the deep sea mining role (Kotliński, 2001; Szamalek and Mizerski, 2011). Nowadays, marine geological and mining activity is focused on the coastal and continental shelf areas under the jurisdiction of the Coastal State (UNCLOS, 1982; Szamalek and Mizerski, 2011; Wolkowicz and Paulo, 2019). The quarry mining of loose minerals is an important and easily accessible source of useful metal raw material. The increasing demand for non-energy raw materials, including metals of strategic importance, creates the need to reach for mineral resources of seas and oceans. Considering geological and mining opportunities of ocean resources, many researches are conducted in this region (offshore tin mining – PT Timah TBK, Indonesia; extraction of diamonds – Namibia, De Beers Group, Solwara Project, Bismarck Sea – Nautilus Minerals, PNG).

As part of the geological operations carried out in the Malay Archipelago (Szamalek et al., 2013, 2015), geological reconnaissance of shelf sediments from the Carolinian Sea was done. The aim of the project was to determine the source area, the type of parent rocks and the spatial variability of mineral sediments. The results may be the basis for the continuation of detailed identification of the deposit from the shelf around the coast of New Guinea. Sea sediments of the Jayapura coast are the subject of detailed geological analyses for the first time. The results may be used for reconstruction of the geological evolution of the northern coast and may contribute to a better understanding of the development of the marginal convergence zone of New Guinea and the deposit formation processes.

GEOLOGICAL SETTING

The northern part of New Guinea has a complex geological history, so far not explained in details (Davies, 2012). The geodynamic evolution of the region has resulted in an isolated coastal massif of the Cyclops Mountains (Fig. 1) and a narrow continental shelf formed in the Melanesian Collision Arc zone (Krause, 1965; Monnier et al., 1999; Cloos et al., 2005). The geological structure of the Carolinian Sea shelf is very poorly

known in this region. Krause (1965) suggests that the stratigraphy and history of seabed formation is closely related to the formation of the northern coast of New Guinea.

Geological exploration carried out in the 1950s (Baker, 1955, 1956; Ubaghs, 1955) and earlier by Zwierzycki (1921) in the Cyclops Mountains contributed significantly to the tectographic and mineralogical recognition of the region.

The Cyclops Mountains can be considered an anticline composed of two floors overlapping an unknown ground (Monnier et al., 1999). The anticline core consists of crystalline schists, gneisses and metamorphosed rocks of the calc-alkaline series (Gisolf, 1921; Zwierzycki, 1921; Baker, 1955; Monnier et al., 1999). The metamorphic rocks contain ore minerals, such as chalcopryrite, ilmenite, hematite, magnetite, rutile, and platinum group metals.

The upper floor of the Cyclops Mountains is composed of an ophiolite sequence obducting on a metamorphic core. The structure of the ophiolite complex is typical for ophiolite series. It consists of residual, mantle peridotites, cumulates of isotropic gabbro, massive dolerites, troctolites and small amounts of pillow and boninite lavas (Baker, 1955; Monnier et al., 1999; Pubellier et al., 2004). Peridotites are represented by harzburgites, dunites, wehrlites and websterites. Chromium spinels, pyrrhotite, chalcopryrites, magnetites and platinum group metals (PGM) appear in ultramafic rocks. The mafic ophiolite complex consists of plutonic and volcanic alkaline rocks represented by gabbro, troctolites, dolerites and pillow lava. Unlike plutonic rocks, the mafic series is almost unchanged by serpentinization processes (Baker, 1955; Monnier et al., 1999). Bornite, chalcopryrite, chalcocite, covellite, cubanite, pyrite, pyrrhotite, chromite, hematite, ilmenite, magnetite and native PGEs are found in the ophiolite rocks. The ophiolite sequence is covered in the SE by volcanic rocks of the Auwewa Formation, and by marine sediments of the Hollandia Group on the SE side of this ophiolite sequence. The entire Cyclops Mountains Massif is covered with Quaternary gravel and sand sediments (Monnier et al., 1999). Geochemical studies of the rocks of the Cyclops Mountains Massif carried out by Monnier et al. (1999) indicate that the ophiolite was formed in a supra-subduction environment. The geodynamic evolution of the Cyclops Mountains lasted from the Eocene to Pliocene.

STUDY AREA

The exploration area included a shallow seabed (Fig. 1) on the northern coast of New Guinea (Jayapura region), ~45 kilometres long and 6,434 hectares in size (located between 140°20'0"E–45°0"E meridian and 2°32'0"S–26°0"S parallel). In 2009, during the research cruise, 58 samples of loose sediments from 24 points, ~2 km apart on average, were collected with a suction dredge (Table 1) from the Carolinian Sea shelf bottom. The bottom sediment was excavated from the shelf during summertime, when there was no upwelling on the coast. The cruise route and the sampling points were defined by the exploration concession issued by the Governor of Papua Province for PT Halmahera Perkasa. The sea depth ranged from 18 to 30 metres. The distance from the collecting points to the land ranged from 100 to 460 metres. The weight of the excavated sediment was ~2 kg/per sample. The loose material was transferred to specially prepared hoppers on the ship. For analytical purposes, the weight of samples was reduced by quartering to ~70 g.

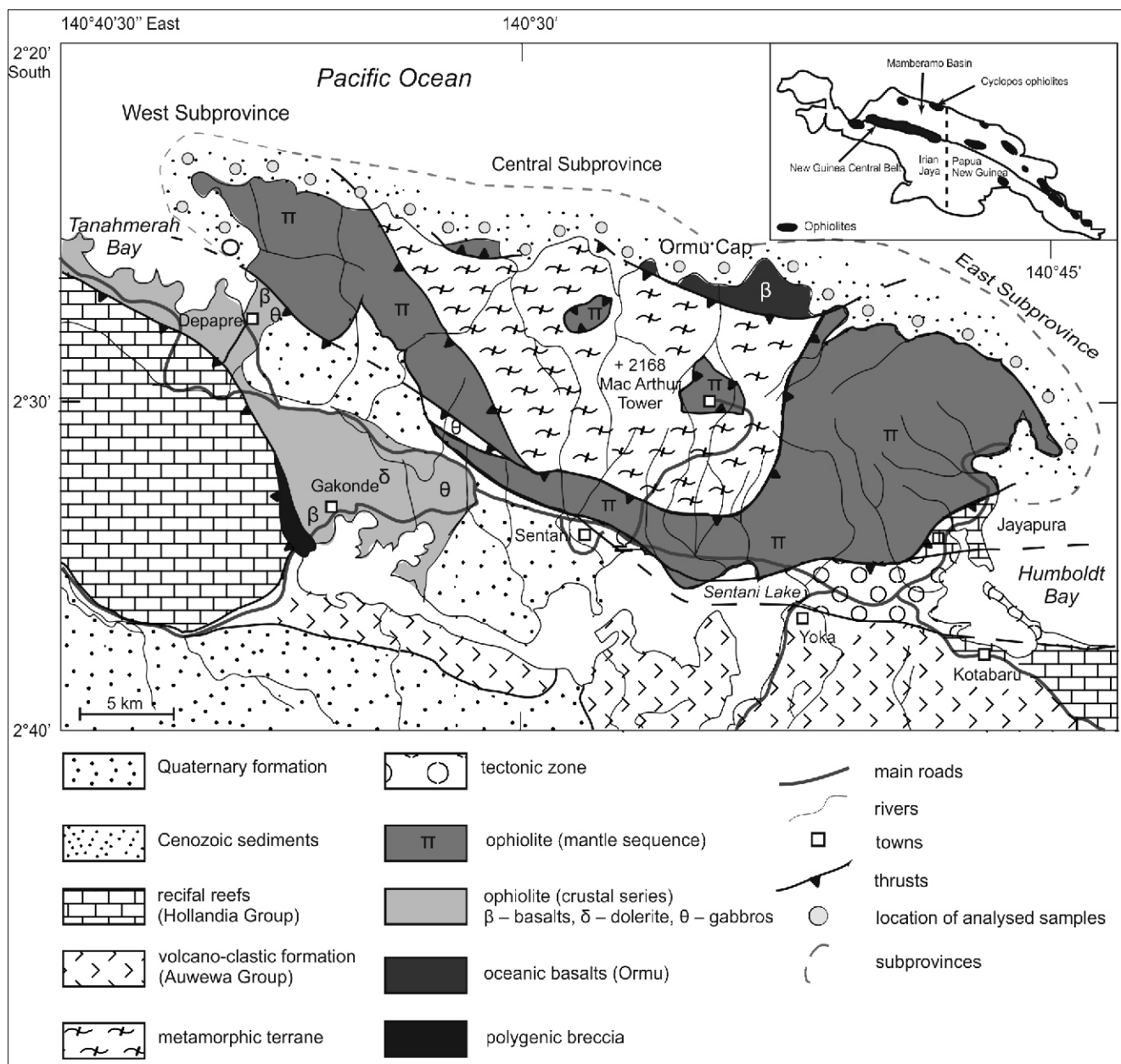


Fig. 1. Geological map of the Cyclops Mountains in Irian Jaya (after Monnier et al., 1999)

MATERIAL AND METHODS

Shelf sediments were washed with deionized water to purify and remove sodium chloride (NaCl). Using 10% acetic acid and 30% hydrogen peroxide, fragments of marine fauna (foraminifers, sponges, bivalves, snails, corals) were dissolved in a water bath at 60°C. The sieve analysis was performed for the samples of sediment extracted with a suction dredge, after removing organic elements from the samples. The sediment was sieved through a set of nylon sieves with a mesh diameter of 2–0.063 mm according to Wentworth classification (1922). For statistical calculations, the open source program GRADISTAT v.5.11 (Blott and Pye, 2001) was used. For the separation of heavy fraction from the samples, sodium polytungstate of density $2.89 \pm 0.02 \text{ g/cm}^3$ was used. Heavy

minerals were immersed in epoxy resin (Araldite 2020). The phase composition was investigated using an AXS D8 Advance Davinci Bruker diffractometer equipped with a copper anode lamp. Diffractograms were recorded in the angle range 3–85° 2θ (Cu Kα), measurement step 0.02°, and measurement time: 2.5 s/step. Crystalline phases were identified using X'Pert HighScore Plus software by comparing the registered diffractograms with the ICDD PDF – 2 and PDF – 4+ standards. SEM-BSE microscopic observations were performed with the use of a IGMMA VP scanning microscope equipped with two EDS detectors (SDD XFlash | 10). The analyses were performed at an accelerating voltage of 25 kV in a high vacuum. Samples for SEM and EPMA tests were covered with coal. Point analyses of chemical composition were performed with the use of a CAMECA SX-100 electron microprobe equipped with wave dispersion spectrometers. The analysis was per-

Table 1

Location data of the marine sediment samples

No.	Sample	Longitude	Latitude	Water depth [m]	Distance from coast [m]
1	NMI 01/25/60	140°38'10.4"E	2°27'58.2"S	22	330
2	NMI 02/17	140°44'36.0"E	2°31'30.1"S	25	130
3	NMI 03/42	140°36'55.0"E	2°26'23.9"S	24	460
4	NMI 05/62/63	140°44'23.6"E	2°30'36.2"S	25	380
5	NMI 06/23	140°28'58.6"E	2°25'46.3"S	22	125
6	NMI 07/14/64	140°40'48.1"E	2°28'41.9"S	23	220
7	NMI 08/04	140°25'50.0"E	2°24'40.2"S	26	340
8	NMI 09/29	140°33'40.7"E	2°26'27.7"S	28	158
9	NMI 10/61	140°34'41.7"E	2°26'42.9"S	28	170
10	NMI 12/20	140°31'54.6"E	2°26'12.8"S	18	250
11	NMI 13/51/68	140°35'43.5"E	2°27'10.6"S	23	260
12	NMI 15/59/66	140°37'44.3"E	2°27'04.5"S	30	240
13	NMI 16/33	140°30'54.7"E	2°25'46.8"S	28	100
14	NMI 18/41/67	140°39'15.5"E	2°28'20.3"S	25	390
15	NMI 19/22	140°29'44.8"E	2°26'30.6"S	27	110
16	NMI 21/39/43	140°40'17.1"E	2°28'27.2"S	15	200
17	NMI 24/55/65	140°41'50.1"E	2°28'45.2"S	28	261
18	NMI 27/53/58	140°42'48.2"E	2°29'08.7"S	27	140
19	NMI 28/34/52	140°31'54.6"E	2°26'12.8"S	18	250
20	NMI 32/11	140°26'56.4"E	2°25'19.7"S	20	220
21	NMI 36/38	140°27'55.0"E	2°25'53.3"S	22	132
22	NMI 35/37	140°23'14.0"E	2°23'55.1"S	18	240
23	NMI 40/54/56	140°43'41.0"E	2°29'45.8"S	24.5	270
24	NMI 57/31	140°20'48.4"E	2°23'40.6"S	20	290

formed at an accelerating voltage of 15 kV and a beam current of 20 nA on individual spectrometers equipped with crystals (TAP, LIF, PET, LPET). The standards included in the equipment of the Inter-Institutional Laboratory of Microanalysis of Minerals and Synthetic Substances of the Faculty of Geology of the University of Warsaw were used for the studies: Mg, Si, Ca-diopside; Al, K-orthoclase; V-vanadinite; Mn-rhodonite, Fe-hematite; Cu-cuprite; Zn-sphalerite; Cr-chromite; Ti-TiO₂; Na-albite; Ni-NiO; P-xenotime; Nb (metallic)-Nb. The limits of detection in ppm were as follows: Al-257; Ca-334; Cr-469; Cu-1648; Fe-1027; K-267; Mg-238; Mn-974; Na-373; Nb-541; Ni-1269; P-192; Si-270; Ti-399; V- 740; Zn-2100.

Preliminary magnetic separation was performed using a magnetic separator *Franz Magnetic Barrier Laboratory Separator Model LB-1*, at 0.3A current intensity, 20° angle of repose, and 15 and 20° elongated angle of inclination.

The chemical composition of marine sediments (bulk samples or bulk analyses) was done in a certified laboratory of Bureau Veritas (BV) in Vancouver (Canada). The analyses were carried out using the *LF200* and *FA330* analytical programs (www.acmelab.com). Samples for the *LF200* program were melted with Na₂B₄O₇/Li₂B₄O and then dissolved in a mixture of aggressive acids. For the analysis of precious metals the Fire Assay methodology adopted in the BV laboratory was used. The analyses were carried out using optical mass and emission spectrometry coupled with inductively induced plasma

(ICP-MS and ICP-OES). The loss of ignition (LOI) was determined by roasting the sample at 1000°C. The contents of organic carbon and elemental sulphur were determined with the LECO analyzer.

Concentrations of rare earth elements were normalized (N) to PAAS; Post-Archean Australian Shale (McLennan, 1989). Eu and Ce anomalies were calculated from $Eu_N/Eu^* = 2Eu_N/(Sm_N + Gd_N)$, $Ce/Ce^* = 3Ce_N/(2La_N + Nd_N)$, and $Ce_{anom} = \log(Ce/Ce^*)$ formulas, which are used to determine the anomaly values for marine sediments (de Baar et al., 1985). The La-Th-Sc, Th-Co-Zr/10 and Th-Sc-Zr/10 diagrams (Bhatia and Crook, 1986) were used to determine the bedrock source.

RESULTS

PETROGRAPHY OF MARINE SEDIMENTS

Sea sediment (Fig. 2) shows local variability related to biological activity on the shelf, geological structure of the Cyclops Mountains Massif, and coastal line shape. The results of the sieve analysis of loose material (Appendix 1*) showed that the shelf sediment is represented by coarse-grained sands (23 samples) and medium-grained sands (20 samples); fine-grained sands (16 samples) are a smaller group. The sam-

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1512

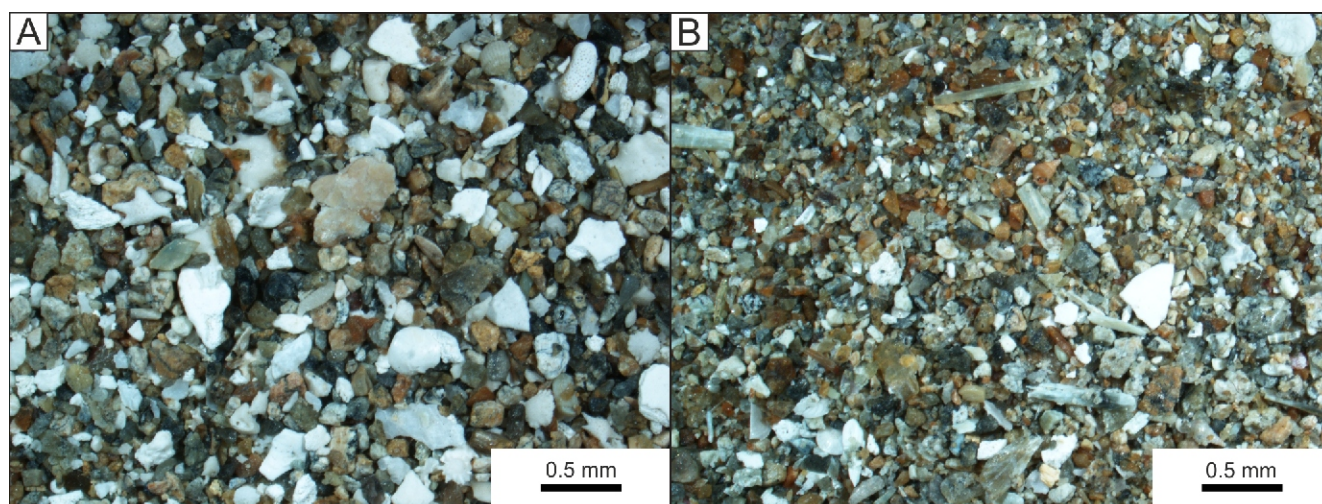


Fig. 2. Shelf sediments: A – sample JP10 and B – sample JP12, stereoscopic microscope

ples contain significant amounts (average 58.88 wt.% of sediment) of carbonate skeletons of marine organisms, such as foraminifers, sponges, bivalves, snails and coral fragments occurring mainly in coarse- and medium-grained fractions. Terrigenous components (on average 41.12 wt.%) are a less numerous group. There are no biogenic silica components.

The average content of carbonate components in coarse-grained samples is 86.69 wt.%. The average carbonate content is 45.13 wt.% for medium-grained and 36.10 wt.% for fine-grained sediments.

Bottom sediments after the removal of marine fauna are composed of fine-grained sands (33 samples) containing 0.77–84.40 wt.% of terrigenous components, on average 35.05 wt.% (Appendix 2). There are no fine-grained sediments (silt and clay) as a consequence of the sampling method using a suction dredge. The content of terrigenous components is from 0.24 to 84.84 wt.% (average 54.87 wt.%). The least numerous group of sediments are coarse-grained sands (5 samples) with an invariable content of detrital components. The content of terrigenous components in the coarse-grained samples varies from 19.36 to 39.60 wt.%.

THE MINERALOGY OF MARINE SEDIMENTS

Mineral composition of the shelf sediments shows spatial diversity within the whole examined seabed along the coast. The presence of light minerals (21.58 wt.%) and heavy minerals (20.37 wt.%) was found in the sediments (Fig. 3). Barren and ore minerals were separated from the heavy mineral fractions. Heavy minerals dominate in the grain class 0.1–0.25 mm. The content of heavy fraction is up to 54.77% of the sediment mass.

Phase analysis of seabed sediments from the northeastern coast revealed the presence of calcite, aragonite, halite, quartz, plagioclases and talc. The group of heavy minerals consists of siderite, garnet, pyroxene, serpentine, olivine, chrome spinels and magnetite. Tungsten minerals have not been observed. The samples contain fragments of limonite clasts. Bottom sediments from the central coastal zone are characterized by a different mineral composition. Within the seabed from the central part of the coast, two zones – eastern and western – have been identified. The bottom sediment in the eastern section is dominated by aragonite, halite, calcite and talc. The heavy components are olivine, pyroxenes, and minerals of the serpentine

group. Useful minerals are represented by chromium spinels, magnetite, copper and iron sulphides, rutile and hematite. In the western section, the mineral complex consists of albite, aragonite, biotite, calcite, quartz, muscovite and plagioclase. The heavy mineral complex consists of amphiboles, epidotes, clinocllore, pyroxene, siderite and titanite. Ore minerals include ilmenite, hematite, magnetite, rutile and copper and iron sulphides. The bottom sediment extracted from the north-western part of the coast is characterized by the presence of aragonite, calcite, halite and talc. The group of heavy and complex minerals comprises amphiboles, olivine, chrome spinels, magnetites, pyroxenes and serpentine group minerals.

GEOCHEMISTRY OF MARINE SEDIMENTS

The chemical composition of shelf sediments shows wide lateral differentiation along the whole coastline (Appendix 3). Marine sediments from the northeastern part of the coast, in contrary to the upper continental crust (Rudnick and Gao, 2003), were enriched in strategic metals (Appendix 4): Ni up to 3561 ppm, W up to 3130 ppm, and Co 47–142 ppm, and significantly impoverished in LILE (Large-Ion Lithophile Elements). Samples JP6 and JP7 show a clear enrichment in Sr up to 3231.5 ppm. Increased contents of MgO 16.25–38.33 (wt.%) and Cr₂O₃ 0.849 (wt.%) are found in the sediments. In contrary to the samples from the eastern part of the coast, the marine sediment from the central and western zones is characterized by increased contents of Cu 7–28 ppm, V 41–244 ppm, Zr 12–55 ppm and TiO₂ up to 0.78 wt.%. The sediment is enriched in LILE. The samples show a heterogeneous distribution of TOT/C values from 0.07 to 8.26%. The TOT/S is homogeneous throughout the coastline. The loss on ignition (LOI) for the sediments ranges from 2.5 to 31.1%.

The contents of precious metals do not exceed normally the lower detection limit of the test method used. The maximum contents in shelf sediments for Au are up to 3.8 ppb, Pt up to 9 ppb, and Pd up to 8 ppb. There are increased contents of Ag up to 5 ppm.

The distribution of REE in shelf sediments was analysed (Fig. 4). There is a strong impoverishment of REE in relation to PAAS in all samples. Two groups of sediments have been identified based on the REE content results. The first group excavated from the central and western coastal zone is character-

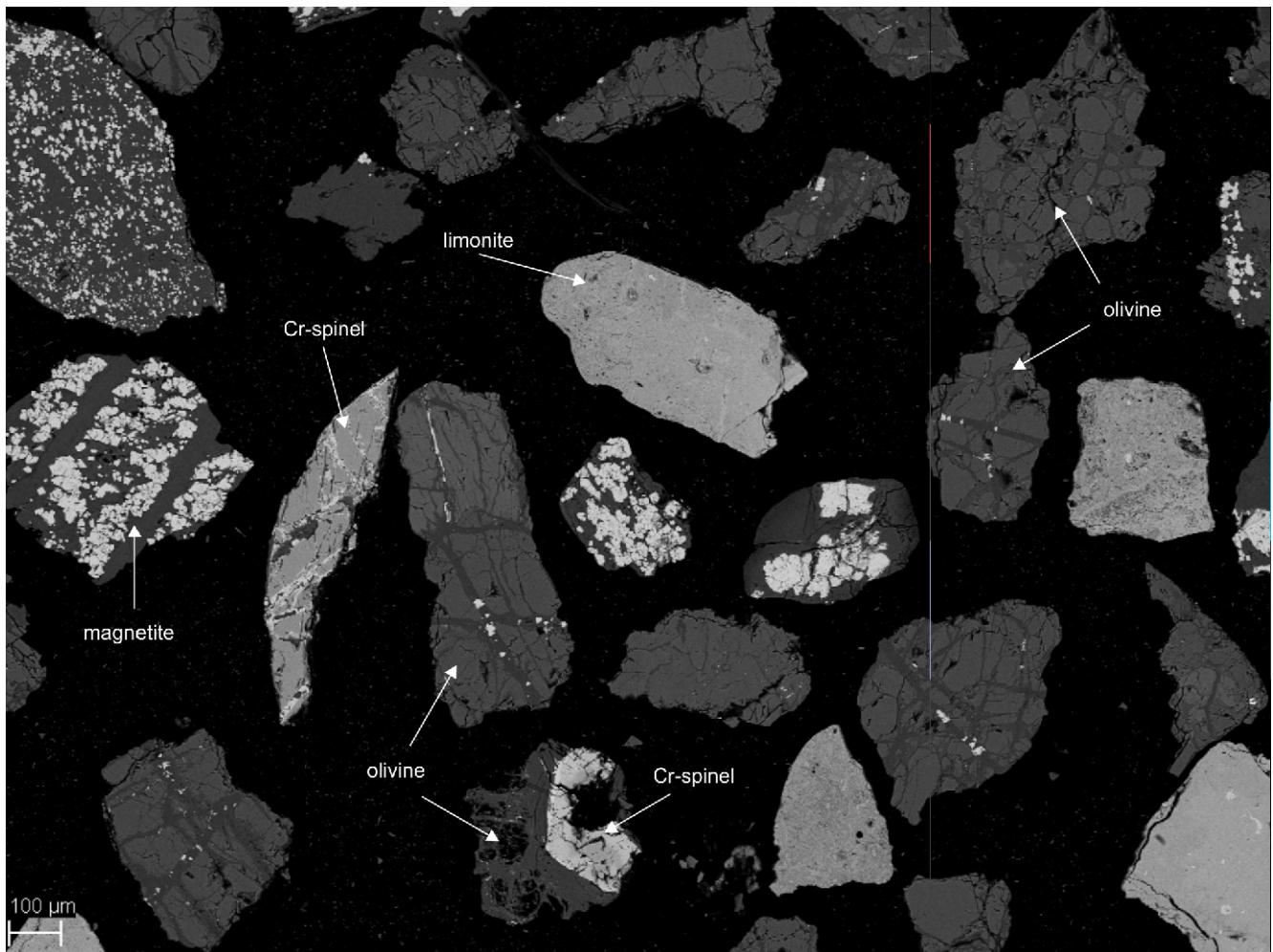


Fig. 3. Mineral composition of the shelf sediments, sample JP12, SEM-BSE image

ized by a regular distribution of REE. The REE content is in the range of 15.12–99.26 ppm, LREE 6.52–50.27 ppm, and HREE 8.60–54.03 ppm. A negative anomaly for Ce and positive for Eu was found. In two samples (JP29, JP49) a positive Ce anomaly appears. MREE and HREE are characterized by a regular distribution of the content with a slight Yb fluctuation.

The second group of samples from the eastern part of the coast indicates the lack of clear homogenization. The REE content is in the range of 1.4–4.53 ppm, LREE 1.10–3.34 ppm, HREE 0.30–1.53 ppm. Positive Eu and negative/positive Ce anomalies, and negative Pr, Sm and Er anomalies are present in the samples. Depletion of HREE is identified in the sediment.

DISCUSSION

THE SOURCE OF CONTEMPORARY MARINE SEDIMENTS

REE distribution in shelf sediments is an important indicator of material source (Table 2) and differentiation processes (Kazuhiro et al., 1990; Terry and Charles, 1998; Pramod and Rajamani, 2001; Yang et al., 2002). Terrigenous sediments deposited in the coastal environment show REE curves similar to their land counterparts of parent rocks (Cullers and Podkovyrov, 2000; Yan et al., 2010; Piper and Bau, 2013) due to poor fractionation during transport (Yang et al., 2003). Stan-

dardization of the extracted samples against PAAS (Fig. 4) indicates two sources of the original material. The group of sediments extracted from the western and eastern parts of the coast has a very low REE content. Low concentrations of MREE and HREE are characteristic for residual peridotites. The calculated values correlate with the results of analyses obtained by Monnier et al. (1999). Positive and negative anomalies of cerium were recorded in the sediments. The presence of the anomalies may indicate redox conditions on the continental shelf. Negative anomaly may indicate a supply of “freshly deposited” sediment that has not yet been oxidized. The second group of sediments shows a homogeneous decomposition of REE with a small Eu anomaly. The homogeneous value correlates with the REE decomposition of the Cyclops Mountains metamorphic core.

The study of the mineral composition of beach sediments allowed separating three subprovinces that differ in the character of parent rocks' source. Shelf sediments from the eastern and western parts of the coast contain minerals typical for rocks of the mafic/ultramafic environment – chromium spinels, Mg-olivine, serpentine group minerals, and limonite fragments. Research on mafic rocks conducted by the Monnier et al. (1999) and on chromium spinels conducted by Zglinicki (2016) reveals that the minerals in seabed sediments in the eastern and western parts of the coast originate from rocks of the ophiolite sequence formed under supra-subduction environment conditions. The occurrence of amphibole, epidote and clinoclhoride

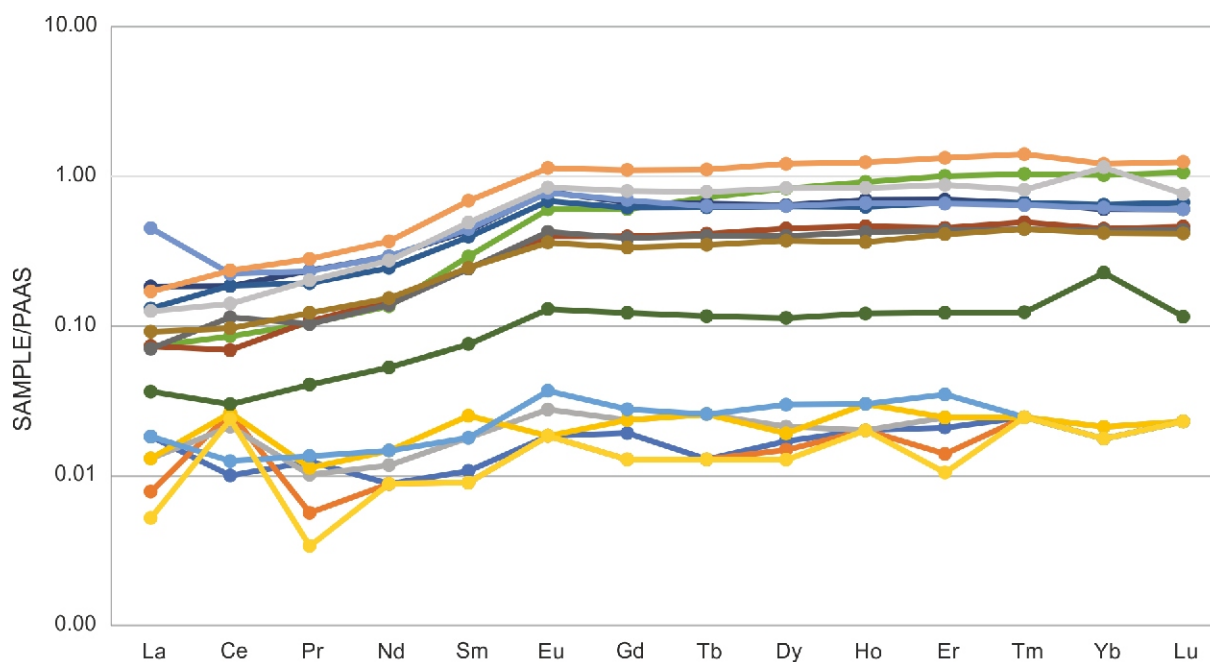


Fig. 4. PAAS-normalized REE diagram for the coastline sediments

Table 2

Comparison of average ratios and total REE contents in coastal sediments from Jayapura-related rocks with average REE contents of modern tectonic environments

Tectonic settings	(La/Yb) _N	(La/Sm) _N	(Gd/Yb) _N	Eu/Eu*	REE
Oceanic Island Arc ¹	2.9 ± 0.9	–	–	1.04 ± 0.11	58
Passive Margin ²	9.80	3.67	1.40	0.74	106.83
Back Arc Basin ²	6.50	2.95	1.30	0.79	83.63
Continental Arc Basin ²	7.18	3.19	1.30	0.76	113.49
Marine Sediments from Jayapura ³	0.33	0.57	0.91	0.21	33.56

¹ average data from [Bhatia \(1983\)](#); ² average data from [McLennan et al. \(1990\)](#); ³ average data from this research

minerals in shelf sediments in the central part of the coast coincides with the results of studies conducted by [Zwierzycycki \(1921\)](#), [Gisolf \(1921\)](#), [Baker \(1955, 1956\)](#), [Monnier et al. \(1999\)](#) and [Zglinicki \(2016\)](#). The presence of the minerals indicates a metamorphic nature of the source area.

Trace elements (Th, Sc, Zr, REE) were used to determine the provenance of shelf sediments. These elements are an excellent tool for determining the source of parent rocks due to their low solubility and mobility during weathering, transport and diagenesis. At the same time, they retain the features of parent rocks in the sedimentological record. The La/Th vs. Hf ratio ([Floyd and Leveridge, 1987](#)) is an indicator used to determine the source of parent rocks. The Hf and Th contents in sediments from the east coast are below the lower detection limit of the used test method (ICP-MS). The values calculated for central coastal sediments indicate that the source is the rocks formed from andesite magma associated with island arcs. The La/Th index for West Coast sediments is typical for the tholeiitic magma sequence of islands arcs. The geochemistry of the

shelf sediments may be related directly to tectonic processes leading to the generation of parent rocks. On the La-Th-Sc, Th-Co-Zr/10 and Th-Sc-Zr/10 diagrams ([Bhatia and Crook, 1986](#); Fig. 5) the geotectonic position of parent rocks has been determined. The obtained values indicate that the parent rocks are associated with the active oceanic island arc.

INFLUENCE OF MARINE CONDITIONS ON HEAVY MINERAL CONCENTRATIONS

The dynamics of deposit-forming processes, leading to the concentration of heavy minerals in the coastal environment, is diversified both between individual basins and within a single basin. There is no single universally accepted depositional model for offshore deposits. Mechanical and chemical weathering processes, hydraulic sorting, abrasion and dissolution may lead to significant concentrations of heavy minerals in marine sediments with characteristic features ([Smirnow, 1986](#); [Depowski et al., 1998](#); [Van Gosen et al., 2014](#)).

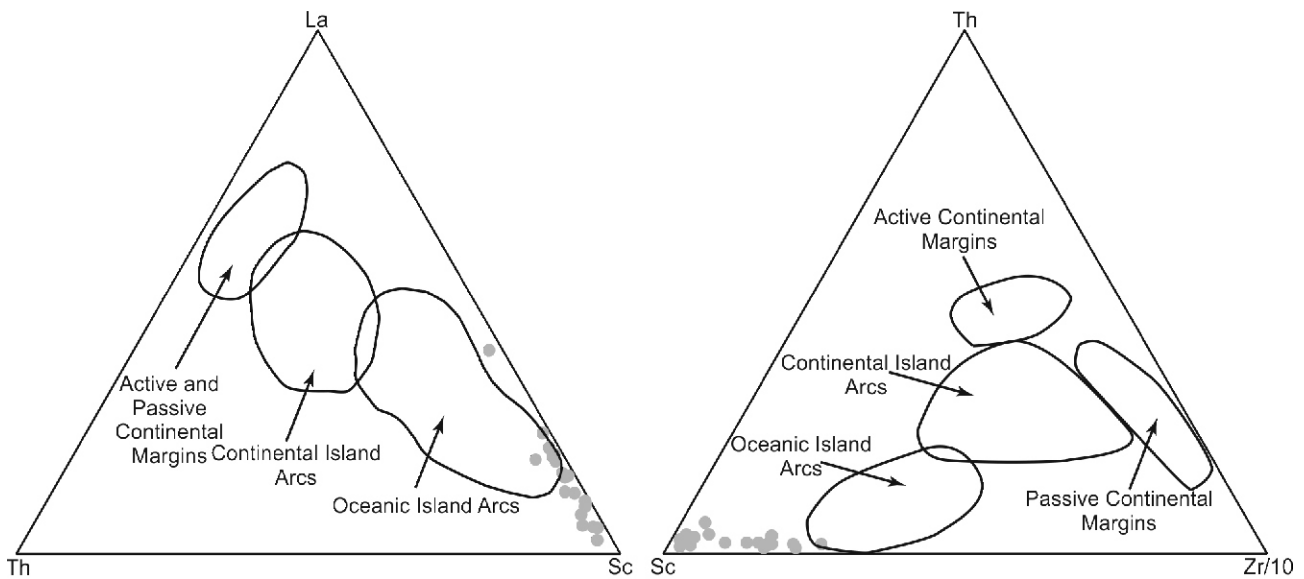


Fig. 5. Discrimination plots La-Th-Sc and Th-Sc-Zr/10 for tectonic settings (after Bathia and Crook, 1986)

Tectono-eustatic changes in the late Pleistocene sea level shaped the contemporary coastline of the Jayapura region (Verstappen, 1975). The sea level rise is usually accompanied by a gradual migration of coastal morphodynamic barriers. The migration of forms enriched in heavy mineral layers can lead to a concentration of economically important useful components. The preservation of structures enriched in heavy minerals is possible when the migratory forms are trapped, e.g., in coastal longitudinal channels (Tixeront, 1978). The landward transport of rich layers of heavy minerals is accompanied by a clear decrease in heavy mineral content as a function of depth and distance. It is confirmed by the Australian shelf model proposed by Kudrass (1987). A similar dependence exists in the coastal sediments of the northern coast of New Guinea. The energy distribution of wave processes along the entire coastline is heterogeneous. This results in a variable wave base surface below which the kinetic energy of the waves does not initiate the movement of the material towards the shore. The uneven influence of wave processes significantly affects the regional differentiation of heavy mineral content as a function of depth and distance from land. Fractional sedimentation is caused by coastal currents from the eastern part of the Jayapura district. In the case of coastal sediments, a linear decrease in heavy mineral content with increasing water depth is evident. The visible degeneration of the heavy fraction is below the isobathic level of 27 metres below the sea-floor (m b.s.f.). The share of heavy minerals in the sediment weight is 45.76%, while at the isobath of 30 m b.s.f. – only 5.73%. The greatest amount of heavy minerals is recorded at a depth of 23 to 27 m b.s.f. The heterogeneity of the sediments is also visible in relation to the distance from land. The linear degeneration of heavy minerals takes place at a distance of ~260 m from the coast. The average heavy mineral content drops from 48.33 to 0.21 wt.% at point 460 m from the land border. The greatest share of the heavy fraction in seabed sediments occurs at distances between 200 and 300 m. The concentration of heavy minerals also depends on the sea-bottom slope angle. This angle has not been studied.

MINERAL DEPOSIT POTENTIAL OF SHELF SEDIMENTS

Poorly consolidated, moderately graded medium to fine sands enriched with heavy minerals can be a useful mineral. The accumulation of the heavy fraction has a polymineral character, laterally differentiated. The dominant grain class of the heavy fraction is grains with a particle size of 0.1–0.25 mm. The spectrum of high-density minerals consists of amphiboles, biotite, chromium spinel, epidote, hematite, clinocllore, Mg-olivines, serpentine group minerals, pyroxenes, rutile, copper and iron sulphides, titanite, and limonite fragments. The grains of heavy minerals form characteristic paragenesis of various features, e.g. from substitution, mixing, in the form of irregular veins. The shape of the textures directly influences the technology and costs of mineral processing. The fraction of heavy minerals underwent magnetic separation (Fig. 6), obtaining a concentrate of magnetic and weakly magnetic minerals. The fraction of strongly magnetic minerals is composed mostly of magnetite. Less magnetic minerals are composed of olivine (with paragenesis of magnetite and chromium spinel), chromium spinel (with paragenesis of magnetite), hematite and amphibole with ilmenite. The non-magnetic group consists of the other components in the sediment (plagioclase, micas, epidotes).

A prospective mineral for the heavy fraction in the seabed sediment is chromium spinel. The percentage of the mineral in the entire coastline is variable. In the eastern part of the coast at the sampling sites, homogeneous chromite grains are on average 7.36% of the heavy fraction, and in paragenesis with olivine and magnetite: 1.44 and 2.70%, respectively. In the central part, which is an extension of the eastern subprovince, the content of homogeneous chromium spinel grains is on average of 4.98%, co-existing with magnetite 1.22% and olivine 0.02%. The western mineral subprovince is characterized by an average chromium spinel grain content of 2.71%, with magnetite 0.93% and olivine 0.79%.

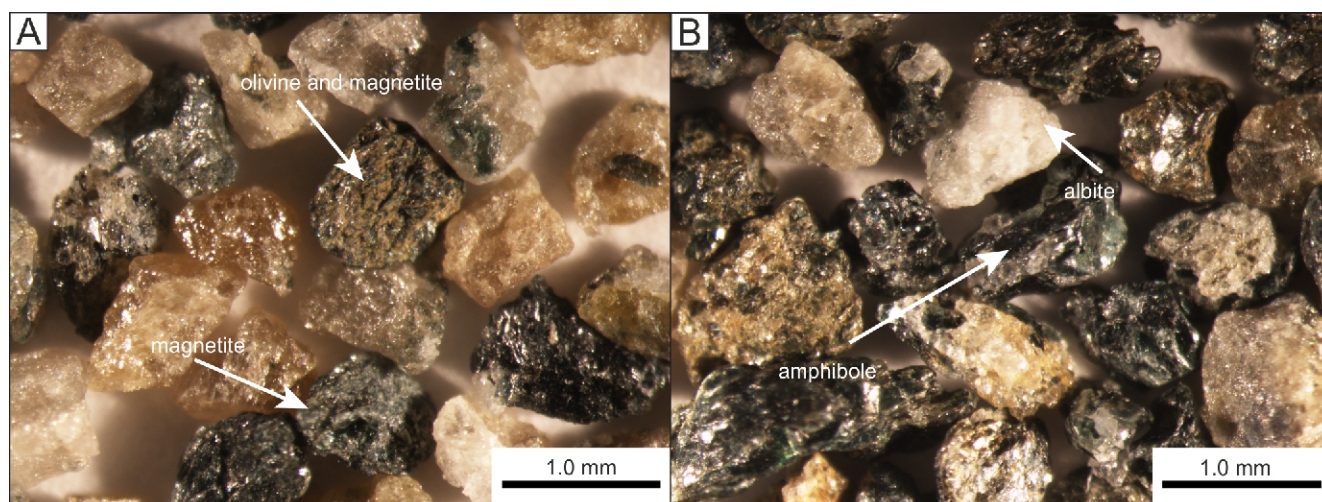


Fig. 6. Grains obtained from magnetic separation

(A) sample JP8 and (B) sample JP41; stereoscopic microscope; magnification 2

MINERALOGICAL-GEOCHEMICAL SUBPROVINCES

The spatial diversity of seabed sediments from the Jayapura coast is the result of the heterogeneous geological structure of the region. The heterogeneous mineral composition of the terrigenous sediments along the whole coastline determines the presence of three mineralogical subprovinces with a variable character of the source area.

The eastern and western subprovinces are characterized by minerals from mafic and ultramafic rocks: Mg-olivines, pyroxenes, serpentine group minerals, and limonite fragments. Ore minerals are represented by chromite, magnetite and small amounts of hematite.

The central subprovince is characterized by the presence of minerals from the metamorphic environment. The phase composition of the flat-bottomed sediments of the northern coast of New Guinea corresponds to the mineralogy of the rocks of the Jayapura region. The group of heavy minerals includes amphiboles, biotite, epidote, clinocllore, pyroxenes and titanite. The useful minerals are represented by magnetite, ilmenite, hematite, rutile, and copper and iron sulphides.

The mineralogy of the seabed surface sediments of the Jayapura coast correlates with the phases described onshore by [Zwierzycki \(1921\)](#), [Gisolf \(1921\)](#), [Baker \(1955, 1956\)](#) and [Monnier et al. \(1999\)](#).

The concentrations of elements in bottom sediments are particularly correlated with the occurrence of mineral subprovinces. The central part of the source area, composed of metamorphic rocks, is a zone of accumulation of elements characteristic for minerals present in these rocks. This zone shows increased values of the local geochemical background for Cu, K, Mn, Sr, Ti, Zr, REE, and V. In the eastern and western parts of the coast, increased contents of Co, Cr, Fe, Ni and Zn were found. The accumulation of elements is characteristic for mafic and ultramafic rocks, which are a source for the sediments of the eastern and western coasts of Jayapura.

PRELIMINARY GEOLOGICAL AND MINERAL DEPOSIT PROSPECTS

The sediments analysed in the study contain chromium and tungsten. At the current preliminary recognition level (58 samples from the seabed surface) it is impossible to determine the criteria of minimum abundances and average contents of useful components. Based on the mineral deposit forecasts ([Fig. 7](#)), it can be assumed that the sediment enriched with chromium and tungsten occurs in two blocks (A and B) covering 29.7 and 15.2 km², respectively. Due to lack of data, the exploratory works should be carried out in two subprovinces (western and extended eastern) excluding the central non-prospective zone. Based on the contemporary exploration results the resources were determined as inferred (based on JORC Code). For more detailed recognition it is necessary to perform sediment probing on the seabed of the designated area in the future. The operations should cover the area of the narrow continental shelf. The probing stage should be preceded by a survey of the basin seabed surface. An irregular seabed surface of the shelf is expected, with numerous narrow channels facing the New Guinea Trench.

CONCLUSIONS

1. The mineralogical-geochemical studies of shelf sediments have shown that the contemporary shallow-water sediments of the Jayapura coast are derived from rocks of the ophiolite sequence and metamorphic core of the Cyclops Mountains. The values of function discrimination indicate that the Cyclops Mountains Massif was formed under the conditions of oceanic islands arc. This is confirmed by research conducted by [Monnier et al. \(1999\)](#) and [Zglinicki \(2016\)](#).

2. Depending on the sampling site, the sediment shows significant differences in colour, grain size and presence of organic components. The variability is the result of regional differentiation

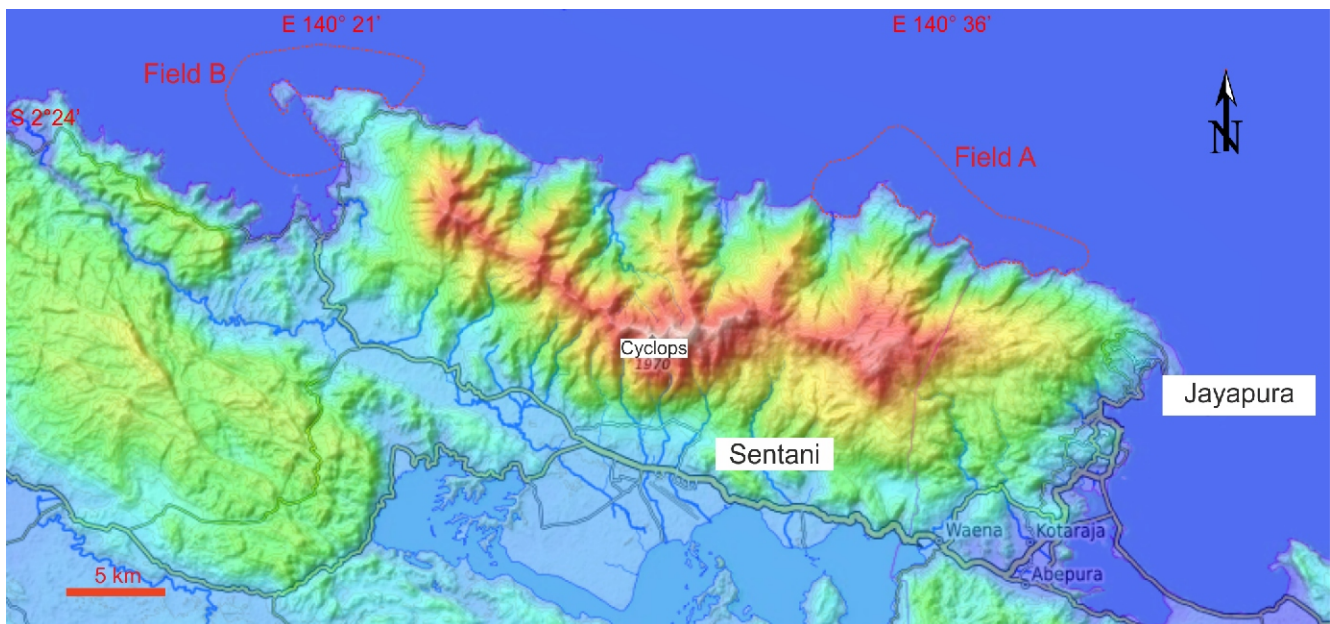


Fig. 7. Prospective fields

Two blocks (A and B) covering 29.7 and 15.2 km², respectively

in the coastline morphology, coastline processes, and the source of the material. The detrital sediment (after carbonate removal) is represented by coarse-, medium- and fine-grained sands.

3. The heavy fraction accumulated in the sediment has a polyminerall character (amphiboles, chromium spinel, epidote, hematite, ilmenite, clinocllore, magnetite, serpentine group minerals, olivine, pyroxenes, rutile, copper and iron sulphides, titanite). Heavy minerals in the seabed sediment show lateral differentiation along the entire coastline.

4. The spatial analysis of the mineral composition of the sediments allowed determining three subprovinces with different source areas. The eastern and western subprovinces are characterized by a mafic and ultramafic source of material origin. The central zone is represented by sediments of metamorphic origin. The geochemical diversity correlates with the mineral composition.

5. The occurrence of individual elements coincides with the mineral subprovinces identified. In the central zone there is enrichment with Ba, Cu, V, Zr, Sr, REE and Ti. The eastern and western zones are characterized by the Cr-Ni-Co-W geochemical association.

6. Poorly consolidated, moderately sorted, medium- and fine-grained sands enriched in heavy minerals (heavy mineral content from 0.10 to 54.77 wt.%) may be a potential useful mineral deposit. Chromium spinels are of significant importance for the deposit. The average content of heavy minerals in the seabed surface sediments is 11.5%.

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