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Methods for Production of Metallogenic-Prognostic Map of Red Karst Bauxite in the Region of Nikšićka Župa, Montenegro (Europe)

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Abstract

Production of Metallogenic-prognostic map (MPM) was preceded by the preparation of instructions that define three phases of work: preparation (with preparation of the Project), realization of field and laboratory research and data processing with production of different maps and, finally, production of the prognostic map with the accompanying instruction book. During the Project realization, the main task was construction of high-quality structural-geologic map at the scales of 1:25,000 and 1:50,000. Particular attention was paid to facial (lithological-stratigraphic) characteristics of geological formations in the hanging wall and footwall of Jurassic bauxites, including a detailed survey of numerous geologic columns. Besides, up to four geologic columns with detailed sampling for chemical, mineralogical and geochemical analyses were measured in each deposit and occurrence of bauxite. Production of special-purpose maps of the bauxite-bearing area was based on the geologic map and geologic cross-sections at the same scale. In order to produce these maps, particular criteria were defined and worked out, including classification and scoring according to the class. The next phase involved the production of the Basic map for MPM, with basic geographical ang geological contents. Isolines and scoring data were transferred to the MPM from the special-purpose maps. After that, points were gathered into six classes. Isolines were constructed by the perspectivity classes with the following scores: I: 4-6; II: 7-11; III: 1214; IV: 15-19; V: 20-22; VI: 23 points. In this way, regional zonation of the bauxite-bearing area was made according to the level of perspectivity, i.e. the Metallogenic-prognostic map of the investigated area was produced.

Keywords: *Metallogenic-prognostic map, Red bauxite, Karst bauxite, Paleorelief, Footwall, Hanging wall.*

1. Introduction

Project of production of metallogenic-prognostic map of red karst bauxite was carried out in order to make regional zonation of a bauxite-bearing area, by the level of prospectiveness, according to scientific and professional principles. The region of Nikšićka Župa (Fig. 1) was chosen for this research, because this is the area in which the most important deposits of red karst bauxite in Montenegro are situated. Besides, outcrops of bauxite have relatively large extent in the area. Fieldwork and laboratory analyses were particularly important during the Project realization. Namely, the final results of the Project depended on the quality of fieldwork and laboratory research, thus a team of experts with proven experience was engaged to produce a high-quality geologic map of the region, to carry out measuring of geological columns and sampling of bauxite and other rocks.

According to the concept of the map production, the so-called structural drilling in the investigation area was envisaged, but unfortunately, it was not carried out due to lack of funds. During production of this map, there were certain dilemmas about methodology, particularly about criteria that significantly depend on understanding and explaining the genesis of red karst bauxite.

Therefore, this metallogenic-prognostic map is based on the opinion that karst red bauxites were formed *in situ,* by the process of bauxitization of alumosilicate material that had been previously transported, by means of eolian process, onto karst surfaces and deposited mostly in depressions – thus it was "preserved" from erosion and washing off [1]. According to our opinion, criteria for the map production for redeposited bauxite deposits are significantly different.

2. Methods for Production Metallogenic-Prognostic Map (MPM)

Realization of the project was preceded by the preparation of Instructions for preparation of metallogenic-prognostic maps of metallic and partly of nonmetallic mineral deposits proven in the area of Montenegro [9]. The anticipated explorations should be carried out within ore regions, through the following three phases of work: preparation phase, phase of realization of fieldwork and laboratory works and phase of construction of MPM. If several types of

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mineral raw materials of economic value occur within a region, explorations in scope of a single project are to be directed toward genetically similar mineral raw materials.

2.1. Preparation phase

The first phase included studying of all available published and unpublished documents and construction of synthetic geologic maps for the selected ore region. After that, previous data on reserves and quality for each bauxite deposit and occurrence were analyzed, as well as the data on mineralogical, petrographic and geochemical characteristics etc. Finally, the project of realization of the second phase was made. This phase lasts from 1 to 2 years.

2.2. Phase of realization of fieldwork and laboratory works

This is the hardest and most demanding phase of work, thus it would be necessary to engage experienced professionals from different fields. In this phase, a geologic map was made at a scale of 1:25,000 (working geologic map is based on topographic maps 1:10,000) and after a minor reduction of certain data, the final map was produced at a scale of 1:50,000. During production of the geologic map, numerous lithostratigraphic columns, as well as local detailed geologic columns – mostly in the immediate hanging wall of bauxite, were measured in the whole region. Particular attention was paid to surveying of all exposed profiles of bauxite bodies (deposits and occurrences) and to detailed sampling of bauxite for chemical, mineralogical, petrographic and geochemical analyses that were carried out in relevant laboratories and institutions. For the needs of production of geologic map and geologic columns of all formations in the footwall and hanging wall of bauxite, extensive sedimentological, micropaleontological and petrographic investigations were carried out.

Realization of the second phase was planned to last for six years (about 60 km^2 a year), but it lasted longer due to financial reasons.

2.3. Phase of production of Metallogenetic-prognostic map

The third phase of work on production of MPM basically represents cabinet work and it basically comes to data processing and analyzing the results of investigations obtained during the second phase and previous investigations. It is interesting that there are few published data on methodology of production of this type of geological documents. Namely, individual criteria, such as paleogeography of conditions of origin of red (karst) bauxite deposits, [2], [3], [4], are usually analyzed for certain regional geotectonic-metallogenetic units. This approach enables separation of the most prospective areas or the most prospective bauxite formations within the investigated units. Certain authors distinguish different lithological types in the footwall and hanging wall, and combination of these types provides criteria for regional zonation of the terrain according to the level of prospectivity [5].

a) Production of geologic-structural map and geological cross-sections

Geologic-structural map covers a square area of about 350 km^2. The area belongs to the NE limb of Nikšićka Župa anticline (Fig. 1), which is separated from the SW limb by a tectonic (reverse) dislocation. In a morphological sense, the terrain belongs to the SW slopes of Maganik Mt., whose altitude varies between 700 and 2,139 m. Geologic map was produced according to the lithostratigraphic principle.

The investigation area is made of geological formations of Permian, Triassic, Jurassic, Cretaceous, as well as Early Paleogene and Quaternary deposits.

Permian clastites and subordinate limestone are found within a small area in the valley of the river Gračanica. Twelve geological units of Triassic age are distinguished: two units in the Lower, six in the Middle and four in the Upper Triassic. Besides sedimentary (mostly carbonate) rocks, there is also a formation of volcanic (andesitic) rocks that belongs to the Middle Triassic. Occurrences and traces of red bauxites, which are transgressively overlain by Upper Triassic carbonates and clastites, occur locally on Middle Triassic carbonates. These bauxites, known *Triassic bauxites* are the oldest in the Dinarides, but these rocks have no economic value in Montenegro. Upper Triassic is represented by 400 to 600 m thick carbonate rocks. Limestone with Megalodon (Rhaetian age) is in the footwall of Jurassic bauxites. The area went through another continental phase that lasted from the end of the Upper Triassic to the middle Upper Jurassic. During that period, *Red Jurassic Bauxites* originated on carbonate paleorelief made of the Upper Triassic, Lower and Middle Jurassic and the earliest Upper Jurassic rocks (Jurassic sediments of the paleorelief occur in the marginal parts of the region).

Three biofacial zones (units) of Upper Jurassic transgressive carbonate sediments are recognized in the roof of Jurassic bauxite. Sediments of Lower Cretaceous and lowermost Upper Cretaceous age are about 1000 m thick. According to paleontological investigations, nine lithostratigraphic units are distinguished in this carbonate sedimentary sequence. Cretaceous sediments are disconformably overlain by a Cretaceous-Paleogene formation -Durmitor flysch. Remains of glacial drift (moraines) occur in the mountainous part of the region, while up to 100 m thick glacio-fluvial deposits occur in the lower terrains.

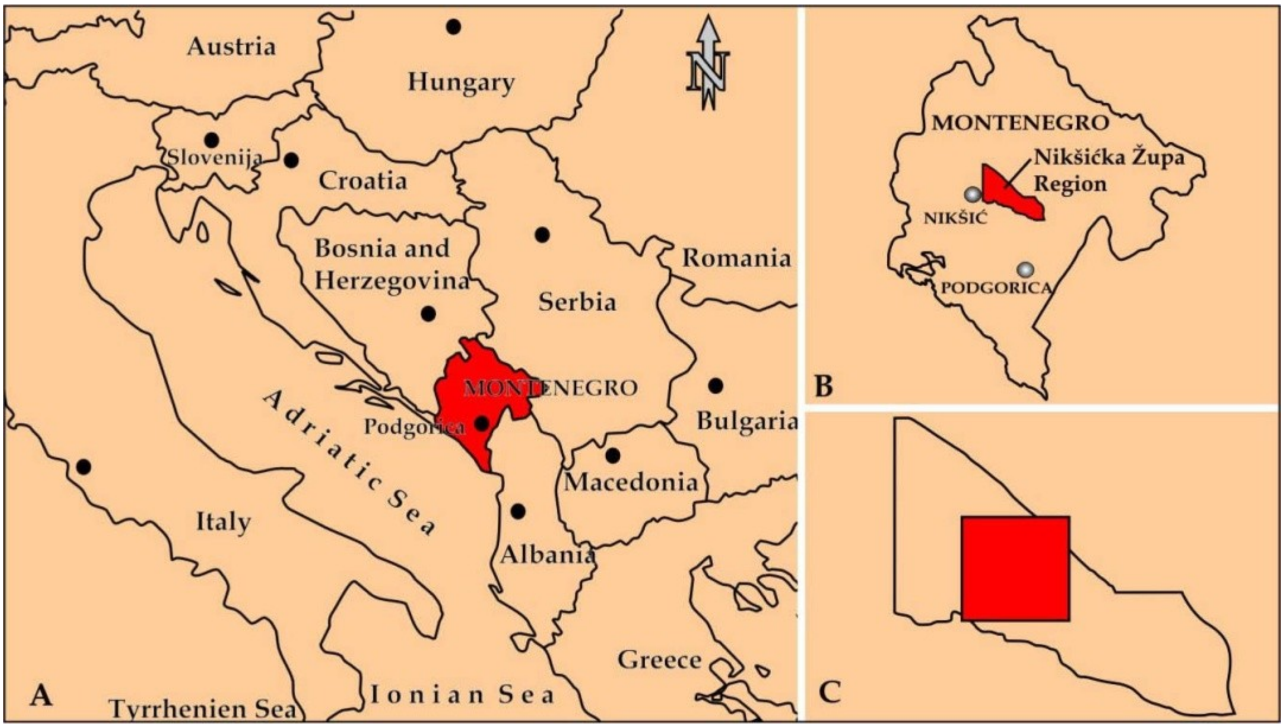

Fig. 1. Geographic position of Montenegro (A), Nikšićka Župa Region (B) and insert from the region presented on Figs. 2, 3, 4 (C).

Geological cross-sections at a scale of 1:25,000, at mutual distances of about 1 km, are approximately perpendicular to the strike of geological formations (S-N and SW-NE).

Thirty cross-sections were constructed. Geological cross-sections are particularly important for production of special-purpose maps: morphology, paleorelief, thickness of the hanging wall, tectonic features, etc.

b) Defining and working out the criteria and production of special-purpose maps

In order to produce MPM of the bauxite-bearing region of Nikšićka Župa, three groups of conditions were distinguished: geological, metallogenetic and paleomorphological. Climatic criteria were not analyzed, because they are precondition for bauxite formation.

Geological criteria

Geological criteria of particular importance are stratigraphy of bauxite footwall and hanging wall, as well as the tectonic setting of the region.

Stratigraphy of the bauxite footwall. Paleorelief of the Jurassic bauxite in the region of Nikšićka Župa is made of Triassic, Liassic, Doggerian and Oxfordian carbonate rocks. Triassic sediments belong to the Dinaridic carbonate platform and they are represented by the “Lofer” Formation with cyclic sedimentation in a shallow-marine environment. Liassic carbonate sediments belong to neritic facies as well, while Doggerian and Oxfordian deposits have subreefal-reefal character. Paleorelief is made of Triassic limestone for the most part, but there are also dolomitic limestone and dolomite (Fig. 2, C).

Stratigraphy of the bauxite hanging wall. Sediments in the immediate hanging wall of the bauxite are transgressive and they disconformably overlie paleorelief and bauxite. Primary karst bauxite deposits can be partly of completely redeposited, when bauxite occurs in the hanging wall sediments [1]. In the region of Nikšićka Župa, three superposition lithostratigraphic units are separated in the immediate hanging wall of bauxite (paleorelief): limestone with *Pianella grudii,* limestone and dolomite with *Clypeina jurassica* and limestone and dolomite with *tintinnids.* The first unit is the oldest. It was formed in the middle Kimmeridgian, in the morphologically lowest parts of the relief. Thickness of these sediments varies from 4 to 30 m. The second unit is made of shallow-water bedded carbonates of Kimmeridgian-Tithonian age, most often laminated with fenestral fabric and with ooidaloncoidal texture. Their thickness is in the interval from 4 to 200 m. The third unit with *tintinnids* is of Tithonian age. It is developed in the whole region and it is from 100 to 200 m, locally even up to 300 m thick. Only the highest parts of the paleorelief are disconformably overlain by sediments of the third unit. Thick carbonate deposits of Lower and Upper Cretaceous age are not discussed here, because they do not represent a direct indicator of conditions of bauxite formation. However, the above given data on composition and spatial position of Jurassic sediments in the immediate hanging wall of bauxite point to two important facts: that paleorelief was morphologically very diverse and that the process of Upper Jurassic transgression was gradual, i.e. that it has been lasting for at least two million years. Therefore, the map of morphology of reconstructed paleorelief of Jurassic bauxites (Fig. 2, D), which is discussed in detail under "Paleomorphological Criteria", is based on composition and thickness of sediments in the immediate hanging wall of bauxite.

Tectonics. Structural-tectonic influence on metallogeny of karst bauxites is manifested during both pre-ore and post-ore periods. Pre-ore tectonic influence refers mostly to the formation of structural and morphological antiformal **land** forms as a consequence of differentiation (evolution) of carbonate platforms or other continental environments, i.e. terrains. This aspect of tectonics was not particularly analyzed during production of MPM, because it was considered as a necessary precondition for bauxite formation.

Post-ore tectonics in the Dinarides is mostly related to the Cenozoic, while it was most intense during the Eocene and Oligocene [6], [7], [8], when major regional tectonic structures and reverse faults, napes and imbrications were formed. Region of Nikšićka Župa is situated in the High Karst tectonic unit, i.e. it comprises terrains of the NE limb of the tectonically separated anticline of Nikšićka Župa. Majority of N-S and NW-SE striking faults originated during the Neogene [7]. Only major tectonic dislocations and structures that significantly influence spatial position of paleorelief of Jurassic bauxite are shown on the geologic map and on special-purpose maps (Figs. 2, 3 and 4). Structural setting of the region is best visible on the map of paleorelief morphology (Fig. 2, A) and on the map of Jurassic bauxite roof thickness (Fig. 2, B). Data relevant for production of these maps (depth of paleorelief, thickness of roof sediments and fault dip angle) are obtained from geologic cross-sections. These maps only contribute to economic aspect of MPM in sense of providing graphical information on depth of paleorelief and thickness of hanging wall sediments, and for that purpose, the maps are shown in the final Metallogenetic-Prognostic Map (Fig. 4).

Metallogenetic criteria

Explanation and analysis of prospectiveness of the region of Nikšićka Župa are based on four metallogenetic criteria: concentration of bauxite in the region, quality of deposits and occurrences of bauxite, mineralogical composition and geochemical characteristics of bauxite.

Bauxite concentration in the region. The term bauxite concentration usually applies to frequency of occurrence and quantity of bauxite reserves in an area. However, for the needs of production of MPM, bauxite concentration was defined as the degree of concentration of bauxite reserves per unit area. In order to produce a map of bauxite concentration in the region for each deposit, bauxite body and occurrence, we indicated quantities of indentified bauxite reserves in million tons (Fig. 3, E). From the total 51.5 million tons of established reserves in the area, about 38 million tons (74%) is in the first zone that is 1 km wide and covers a square area of 15 km^2 (this is the zone of detailed exploration, with roof thickness from 1 to 200 m). In other words, bauxite concentration in the first zone is 2.5 million tons per square km, while it is the smallest in the internal parts of the region -0.25 million tons per square km. After that, we performed geometric interpolation of the whole region into six zones (classes) separated by isolines: 2.5, 2.0, 1.5, 1.0 and 0.5 that mark quantity of reserves in the zones they define. The map shown on Fig. 3,E was made in this way.

Bauxite quality. Bauxite quality can be expressed through the content of Al_2O_3 or SiO_2, but we decided to use the Si modulus to present it. The same principle as applied to bauxite concentration was used to calculate a value of Si modulus for each deposit and occurrence of bauxite (Fig. 3, F). The obtained data were interpolated for the whole region and isolines with modulus values 10, 8, 6, 4 and 2 were drawn. Six zones (classes) of bauxite quality were established in this way: >10, 10-8, 8-6, 6-4, 4-2, <2 (Fig. 3, F). Each class was scored from 1 to 6 points (see Table I)

Geochemical characteristics of bauxite, as a criterion for production of MPM, were not sufficiently studied, and such approach to processing of these data has not been found in the literature. We can expect more detailed research of this aspect of bauxite geochemistry in the future.

Mineralogical characteristics of bauxite were not used as a criterion for assessment of prospectiveness of the region of Nikšićka Župa. It is not necessary to specially emphasize it this criterion because it is, in a certain sense, contained in bauxite quality.

Paleomorphological criteria

Current knowledge on karst bauxite indicate that morphology of karst paleorelief represented one of the most important factors of bauxite formation, as well as of quality and quantity of the reserves. We must keep in mind that significance of morphologically higher and diversified , as well as of morphologically lower continental paleosurfaces is different for genetic types of primary (in situ) and genetic types of resedimented deposits of karst bauxite [1]. Particular importance of morphology and lithology of paleorelief for formation of bauxite in the area of Trans-Danubian Central Range in Hungary was stressed by Hungarian authors ([3], [4], [5]).

There are different possibilities of production of a map of karst bauxite paleorelief morphology, which is certainly a complicated job.

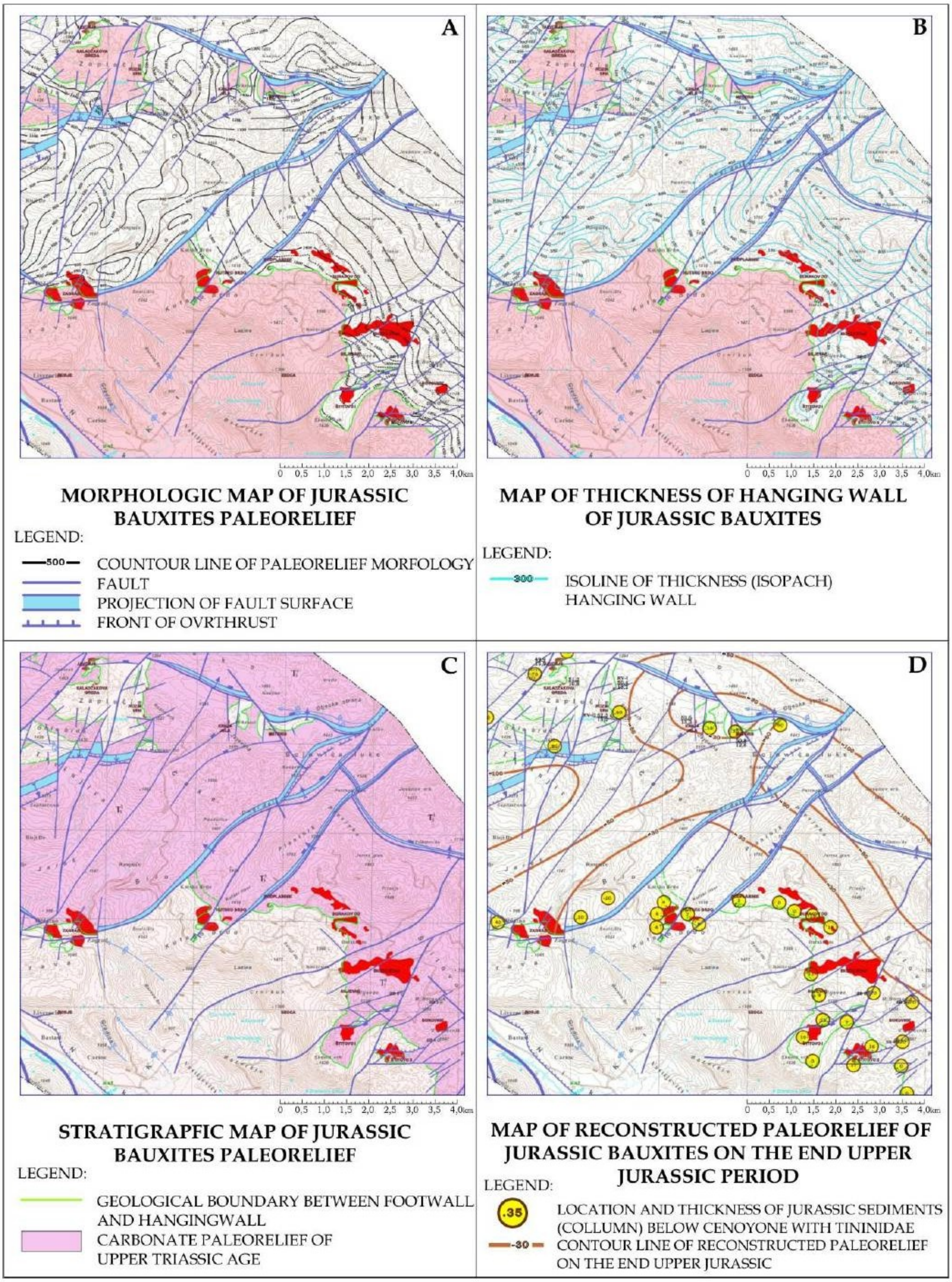

Fig. 2. Special maps (A,B,C,D) for production Metallogenic-Prognostic Map of Jurassic Bauxites in Nikšicka Župa Region.

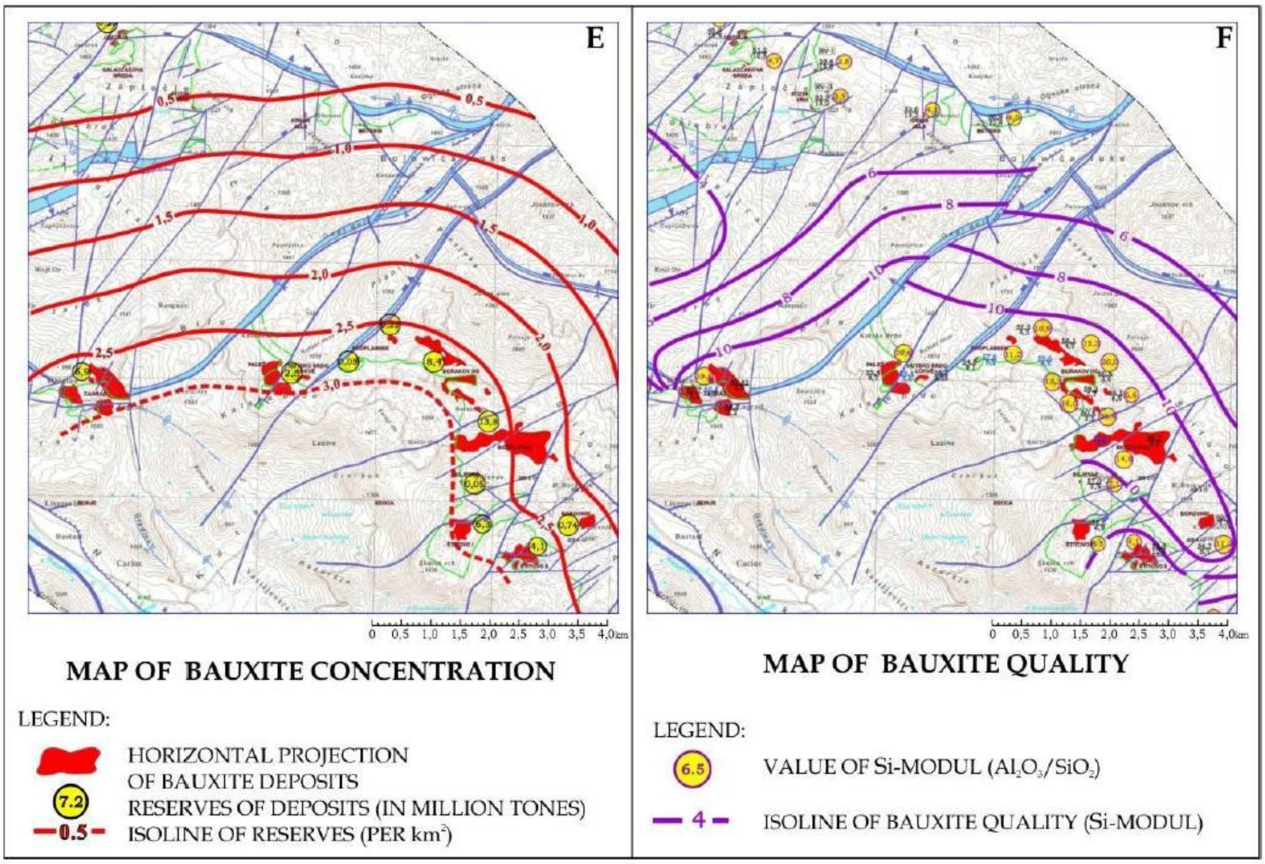

Fig. 3. Special maps (E,F) for production Metallogenic-Prognostic Map of Jurassic Bauxites in Nikšicka Župa Region.

This implies characteristics of paleorelief in the period of formation of karst bauxite deposits. During production of geologic map of the region of Nikšićka Župa, numerous detailed geologic columns were measured in the immediate hanging wall of bauxite where three sequences are distinguished, which is discussed in more details under criterion “Stratigraphy of bauxite hanging wall”. Data on roof thickness for the first two sequences were used for production of the map of reconstructed paleorelief in the first phase of Upper Jurassic transgression (Fig. 2, D). The “zero-” (uppermost) morphological level is marked by the contact between bauxite or paleorelief and the third sequence (limestone with as *tintinnids*), while construction of isolines of morphology is based on thickness data of the first and second (or only the second) sequences in the hanging wall sediments. In this way, paleorelief of Jurassic bauxites is morphologically divided into six levels: 0 to -30 m, -30 to -50 m, -50 to -100 m, -100 to -150 m, -150 to -200 m and below -200 m, which are shown on the map of reconstructed paleorelief (Fig. 2, D). The map shows that almost all large bauxite deposits occur in the interval from 0 to -50 m, and only one large deposit (“Liverovići”) is located in the interval from -50 to -100 m. Characteristics of the upper part of the deposit is that it is made of resedimented bauxite with interlayers of Upper Jurassic (hanging wall) limestone.

c) Analysis of prospectiveness factors

While working out the above discussed criteria, we came to the conclusion that assessment of prospectiveness of bauxite concentration (productivity) is largely influenced by four factors or indicators in the following order: morphology of reconstructed paleorelief, productivity of the region, bauxite quality and stratigraphy of the paleorelief. Each factor was previously analyzed in detail and presented graphically on special-purpose maps (Fig. 2. D, Fig. 3, E and F, Fig. 2, C). In order to quantify the factors, three of them were classified into six groups or classes that were given 1, 2, 3, 4, 5 or 6 points.

According to our opinion, stratigraphy of paleorelief is less important factor then the others, thus it was divided into three classes that were scored 1, 2 and 3 points (see Table I). Scoring was based on the principle that number of points increases with lower prospectiveness, i.e. the most prospective classes are scored one point and the least prospective are given 6 points (i.e. 3 points for the fourth factor).

d) Production of the base map

After the described special-purpose maps were finished, the next step in production of MPM was construction of the **base map**. We made a simplified geographic map of the region with general data on morphology of the relief, hydrographic network, main toponyms and settlements, road infrastructure, etc. General geological characteristics of the region are shown on this map: boundary between the footwall and hanging wall of Jurassic bauxite, projection of all known deposits and occurrences of Jurassic bauxite and previously defined structural-tectonic framework of the region.

e) Synthesizing data on the base map

Data from the special-purpose maps (Fig. 2 and 3) were synthesized in the following way: isolines of reconstructed paleorelief were copied to the base map and each class was marked with certain number of points; after that, isolines of reserves were copied (in different color) from the map of productivity and classes were marked with a number of points in the same color. Isolines of bauxite quality with each class marked by points (in the same color) were copied in the same way. Finally, boundaries between the main stratigraphic units (see Table I) were transferred from the stratigraphic map of paleorelief and the polygons were marked by points – with the same color as isolines. In this way, numerous irregular polygons were obtained by intersection of four types of isolines. These polygons were colored according to the number of points – from 4 to 23.

f) Construction of the final Metallogenetic-prognostic map

A synthesis of data from special-purpose maps provided data on the number of points in each class: I: 4-6, II: 7-11, III: 12-14, IV: 15-19, V: 20-22, VI: 23. Regional zonation of the bauxite-bearing area according to the level of prospectiveness was performed by constructing isolines (boundaries) of all classes (Fig. 4). Sequence of classes I to VI on MPM indicates the level of prospectiveness: the highest level of prospectiveness is marked by the first class, while the sixth class means the lowest prospectiveness level.

Metallogenetic-Prognostic Map includes the data on recent paleorelief morphology and thickness of the roof of Jurassic bauxite, because these data provide information on economic aspect of exploitation in this region. Therefore, isohypses of paleorelief and roof thickness are drawn in different colors on the map (see Fig. 4). Besides, the area of each level of prospectiveness is colored by a different color on the map. The map shown on Fig. 4 was finalized by making the legend and the accompanying content.

3. Explanatory Book

The final task in this Project is preparation of the Explanatory Book for Metallogenetic-Prognostic Map. This geologic document most often presents applied methods of investigation with detailed analysis of the results obtained during the map production. Considering the fact that detailed and complex investigations were carried out during the realization of the Project, the obtained results are presented within two sections in the Explanatory book: general and specialized sections. The *General Section* provides information regarding conception and methodology of research, geological setting, tectonics, mineral raw materials and explanation of genesis of red karst bauxite from which the concept and methodology of production of MPM largely depends. Criteria and methods of production of MPM, with detailed analysis of the obtained results are described in detail in the *Specialized Section* of the Explanatory book.

4. Conclusions

- Production of Metallogenetic-Prognostic Map is very complex job that demands experienced geologists of different specialties. This project is realized through three phases: preparation, fieldwork-laboratory works and finally cabinet work.
- In the first phase, it was necessary to fully understand and analyze the results of previous investigations and to make conceptually and methodologically clear project for realization of the second phase.
- In the second phase, which was the longest and financially most demanding phase, it was particularly important to maintain good quality of field and laboratory works.
- The third phase (production of Metallogenetic-Prognostic Map) demands a detailed analysis of criteria important for conditions and location of possible formation of deposits of a mineral raw material, bauxite in this case. Besides, a clear model of formation of deposits of certain genetic type must be kept in mind.
- Methodology of research is more or less different for different genetic types of the same mineral raw material, which particularly applies to different criteria for production of a Metallogenetic-Prognostic Map.
- Model of production of Metallogenetic-Prognostic Map that is described in this paper refers to the genetic type of karst bauxite formed *in situ*. Certain bauxite deposits in the region of Nikšićka Župa are partly resedimented in the first phase of the cyclic process of transgression in coastal areas. Therefore, process of redeposition is partial and it occurs only locally.
- Graphic design of special-purpose maps (related to certain criteria), as well of final Metallogenetic-prognostic map, implies creativity of the authors and contemporary technical solutions.

Table 1.

STRATIGRAPHY OF PALEORELIEF			QUALITY OF BAUXITE			BAUXITE CONCENTRATION			***Quantified factors of prospectiveness*** **MORPH. OF RECONST.PALEOR.**		
No of Points	Strat. Units	Class	No of Points	Si-modul Al2O3/SiO2	Class	No of Points	Reserves (mil.t/km2)	Class	No of Points	Depth (m)	Class
1	Strat.	1	1	>10	1	1	>2,5	1	1	0-30	1
1	Units		2	8-10	2	2	2,0-2,5	2	2	30-50	2
2	Lower	2	3	6-8	3	3	1,5-2,0	3	3	50-100	3
2	Jurassic		4	4-6	4	4	1,0-1,5	4	4	100-150	4
3	Middle+	3	5	2-4	5	5	0,25-1,0	5	5	150-200	5
3	Upper Jurassic		6	1-2	6	6	<0,25	6	6	< 200	6

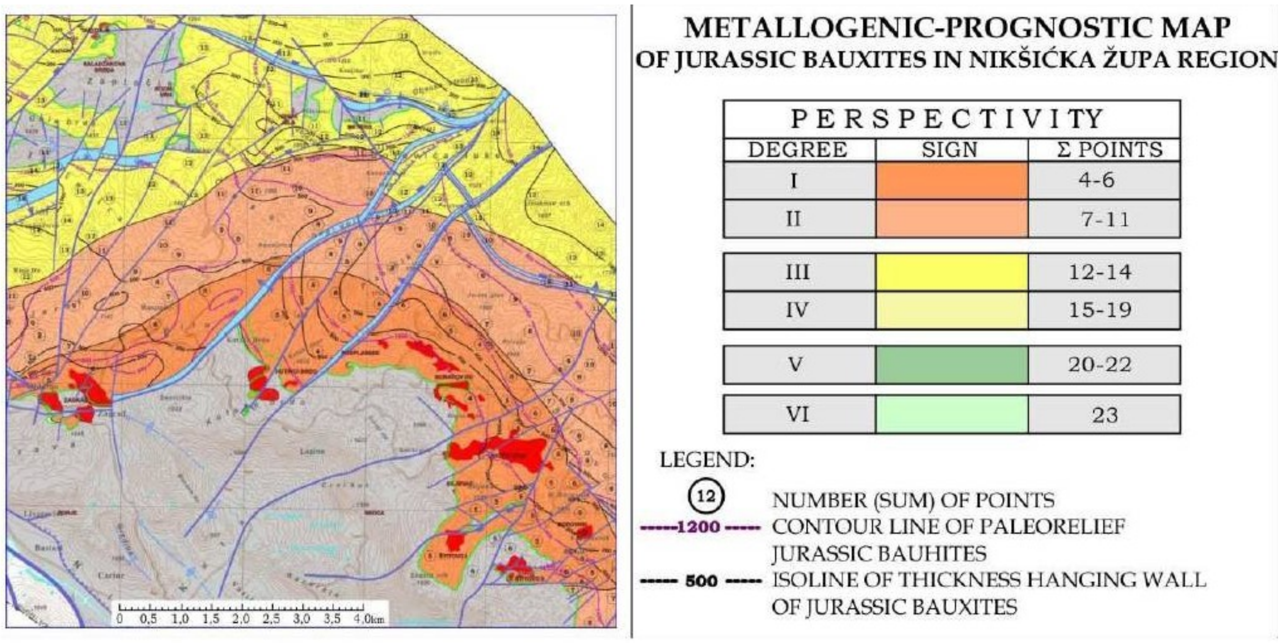

Fig.4. Metallogenic-Prognostic Map of Jurassic Bauxites in Nikšicka Župa region

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