Geological settings of the Jajce bauxite bearing-area (Bosnia and Herzegovina)

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ABSTRACT

In the bauxite-bearing area of Jajce (Bosnia & Herzegovina), exploitation of karst bauxite has occurred for more than 40 years, during which time extensive geological and mining research was also conducted. Here, the geological map of the Jajce bauxite bearing-area (Bosnia & Herzegovina) at a scale of 1:25,000 is presented, accompanied by a geological column and regional geological cross-sections. The map shows the main stratigraphic and tectonic features and positions of the bauxite deposits of the area. This research area covers 343 km², divided into two structural units with four bauxite districts, Liskovica, Bešpelj, Crvene Stijene and Poljane. The Liskovica–Bešpelj structural unit is tectonically very complex, characterized by W–E trending structures in subvertical, vertical and overturned positions. The Crvene Stijene–Poljane structural unit is characterized by gentle folds and normal faults. The geological map summarizes all the available data and represents the necessary basis for further geological and mining research of the area.

1. Introduction

Bauxite-bearing area Jajce with area of 343 km² is located northwest from the city Jajce in the central part of Bosnia and Herzegovina (Southeastern Europe). Jajce is the biggest mining city in the northern part of Bosnia and Herzegovina. The most pronounced morphological structures in this area are canyons of the Vrbas and Ugar River with elevations between 260 and 388 m above sea level (m.a.s.l.), and mountain Ranča with highest peak Suvi Vrh (1433 m.a.s.l.) in the eastern part of the area. This region is well-known for the exploitation of karst bauxite mineral resources. The bauxite-bearing area of Jajce has been the subject of scientific geological and mining research for more than 40 years. Particularly important are the bauxite districts of Crvene Stijene, Bešpelj, Poljane and Liskovica (Main Map). Bauxite exploration is active in all bauxite districts except Liskovica, which was terminated in 2019. Over four decades, various research was conducted with the aim of finding new bauxite deposits, and to date, numerous geological research papers have been published, including: Marinković and Ahac (1979); Marinković and Đorđević (1981); Dragičević (1981); Tomić (1983); Papeš (1984); Dragičević and Velič (1994); Dragičević (1997), Dragičević and Velič (2002); Dragičević and Velič (2006); Galić, Krasić, and Dragičević (2015); Moro, Horvat, Tomić, Sremac, and Bermanec (2016), Budeš, Galić, and Dragičević (2018); Pavičić, Dragičević, and Ivki (2018) etc.

Through the research and bauxite exploitation activities, the terrain has been geologically mapped. The footwall and hanging wall strata of the bauxite deposits are stratigraphically defined. Structural and palaeogeographic settings are interpreted on the regional and local scale. Furthermore, more than one thousand holes were drilled (structural and exploration drill holes) and over 20 km of adits and mining tunnels were constructed. In the last 5 years, intense research was conducted to evaluate the footwall and hanging wall strata as a dimension stone (Bojčetić, Galić, Dragičević, Farkaš, & Pavičić, 2016; Dragičević, Galić, Pavičić, & Deljak, 2015; Galić et al., 2015). Based on the results of these studies, two quarries were opened and there is active exploration of dimension stone. Although all the aforementioned geological documentation exists, there is no systematic database collection of all of these geological data, and no geological map of the whole area has been published since Dragičević (1981). Therefore, this paper presents an integrated geological map of the Jajce bauxite-bearing region, covering an area of 343 km². The map and GIS database consist of all the available geological and mining data, and it serves as the base for planning future research and mining activities.

1.1. Geological settings

The bauxite-bearing area of Jajce includes four bauxite districts, Liskovica, Bešpelj, Crvene Stijene and Poljane (Main Map). Bauxite deposits originate from the...
terrestrial phase in the stratigraphic range from the Upper Albian ($K^6_1$) to the Coniacian – Maastrichtian ($K^3-6$). The Jajce area is, from a geological perspective, part of the northeastern margin of the Adriatic Carbonate Platform which existed from the end of the Lower Jurassic to the end of the Cretaceous periods (Dragičević, 1987; Dragičević & Velić, 2002; Vlahović, Tišlar, Velić, & Matičec, 2005). The fundamental stratigraphic and tectonic features of the study area were defined on the Basic Geological Map of Yugoslavia, sheet Jajce, 1:1,00,000 (Marinković & Ahac, 1979), in the explanatory notes for the same map, (Marinković & Đorđević, 1981), and on the geological maps of the bauxite-bearing area Jajce (Dragičević, 1981 and Papeš, 1984).

1.2. Stratigraphic succession
Since bauxite deposits are the primary subject of this research, the stratigraphic succession of the area can be subdivided into the footwall strata of the bauxite deposits, the bauxite deposits themselves and the hanging-wall strata to the bauxite deposits.

1.3. Footwall strata to bauxite deposits
The oldest rocks from the study area are shallow marine, well-layered Upper Jurassic limestones and dolomites ($J^2-3$). Most common are peloidal and recrystallized micrites. In the lower part of the succession, the most common algae are Clypeina jurassica, and in the upper part of the succession, Nerineeaen gastropods can be found. These gastropods mark the continued transition from Upper Jurassic limestones to thick series of shallow marine, lower Cretaceous limestones. Based on biostratigraphic dating and superposition, the limestones of the lower Cretaceous are subdivided into five units (Dragičević, 1981; Papeš, 1984) (chronostratigraphic units where letter is a symbol for system, number on the lower right position is series, upper right is stage and upper left is substage):
- Berriasian – Barremian ($K^{1-4}_1$)
- Aptian ($K^5_1$)
- Lower Albian ($K^6_1$)
- Upper Albian ($K^6_2$)
- Albian-Cenomanian ($K_{1,2}$)

Berriasian to Barremian ($K^{1-4}_1$) limestones are represented by fossiliferous micrites and dismicrites (Figure 1). They are white, fine-layered with bed thicknesses from 0.5 to 1.5 m and are very karstified. Their total thickness is more than 400 m. The upper boundary with the Aptian limestones ($K^5_1$) is marked by the appearance of an association of Orbitolines. Aptian limestones are light gray to pink fossiliferous micrites with bed thicknesses from 5 to 40 cm, and a total thickness of up to 170 m. Sedimentation of limestones from the Aptian continued into the Lower Albian. Lower Albian limestones ($K^6_1$) are described as micrites, pseudomicrites and dolomitic microsparites with Orbitolina and Mesoorbitolina foraminifera. The absence of these foraminifera marks the boundary between the Lower and Upper Albian limestones ($K^6_2$) (Dragičević, 1981).

1.4. Bauxite deposits
The end of the Lower Cretaceous and the beginning of the Upper Cretaceous, was characterized on the margin of the carbonate platform by intense compressional tectonics and an emersion which had regional impact.
The emersion lasted from the Upper Albian to the Coniacian – Maastrichtian, approximately 20 million years (Figure 2). During that period bauxites were formed on the diverse palaeorelief surface (footwall to bauxite deposits) across the study area. They represent a typical terrestrial formation (Figure 2). Through post-platform tectonic processes (folding and faulting), the deposits were brought to their present structural position (Pavičić et al., 2018) (Main Map). The spatial distribution of the bauxite deposits follows the orientation of the associated structural units (Main Map). In the study area, based on their shape, there are six types of bauxite deposits: lenticular, canyon-like, graben type, sinkhole type, canyon-like with a sinkhole at the end, and tectonized (Pavičić et al., 2018, bauxite types according to Bárdossy, 1982). The morphology and size of individual bauxite bodies mainly depend on the geometry and size of the palaeodepressions in the footwall strata and on the tectonic processes that affected the deposits. The tectonic influence on the shape of the bauxite deposits can be observed in the Crvene Stijene area, near to the Crvene Stijene-Bešpelj fault, where L-1 and L-5 deposits are elongated in the N-S direction by strike slip movement on the fault (see 3D geological models of these deposits in Pavičić et al., 2018). Reserves of individual bauxite deposits vary from 6.000 to 192.200 t in Bešpelj area, from 5.067 to 120.017 t in Crvene Stijene area and from 1.900–150.000 t in Poljane area (Rudnici boksita Jajce o.d.d., pers. inf).

1.4.1. Hanging-wall strata to bauxite deposits

The stratigraphic hanging wall of the bauxite deposits is mainly composed of carbonate clastics and limestones (Figure 2). Lithologically, there are numerous and diverse lithofacies (Figure 3). The most common types are carbonate breccia, conglomerates (Figure 3(A,B)). Clasts in the hanging wall breccias (that are directly on the bauxite deposits or palaeorelief) can exceed 1 m in size (Figure 3(A)) and since the clasts originate from the footwall limestones, can deceive the responsible geologist who is interpreting drill hole cores (so depth to the palaeorelief can be

![Figure 2](image-url)
underestimated) (Pavičić et al., 2018). In such cases, the depth of the palaeorelief would be underestimated. Also, directly beneath the palaeorelief, footwall limestones can be highly karstified, and look very similar to the hanging-wall breccia, so the distance to the boundary can then be overestimated (Pavičić et al., 2018). Clast sizes in conglomerates above the described breccias, vary from a few cm up to 50 cm (Figure 3(B)). Higher in the lithological column, they are covered by layers of calcarenite, argillaceous micrite and marl (Figure 3(C,D)). Frequent vertical and lateral changes of these lithofacies are common. In total, the Upper Cretaceous sediments can exceed 1000 m in thickness.

A boundary between the Upper Cretaceous and Paleogene (Pc) clastics is not precisely defined. In general, in the upper parts of the $K_{3}^{2-6}$succession, the absence of rudist breccias and coarse-grained sediments, and higher amounts of fine-grained sediments (marls, fine-grained calcarenites) can be observed. Based on nanoplankton analysis (see Dragičević, 1981), an assumption was made that sedimentation from the Upper Cretaceous continued into the Paleocene (Dragićević, 1981; Papeš, 1984). Miocene sediments are transgressive on all the older geological units (Main Map). The succession begins with transgressive conglomerates followed by sandstones, marls, clay and sporadically layers of coal. The thickness of the Miocene succession is approximately 200 m. Quaternary deposits are not significantly present in the research area and are usually represented by the alluvial sediments of larger rivers and debris material on slopes of the river canyons.

1.5. Tectonic settings

Tectonic settings are complex, as indicated by the numerous faults, anticlines, synclines and overturned structures. A variety of structures (Main Map) were formed during multiphase tectonic evolution of the area. Related to the bauxite districts, the area is subdivided into two structural units:

a) Crvene Stijene – Poljane Structural unit
b) Liskovica-Bešpelj Structural unit

The Crvene Stijene-Poljane unit is located in the central part of the bauxite bearing area and is characterized by Dinaric orientated structures (NW-SE). The area is characterized by horizontal to sub-horizontal strata (Figures 4 and 5(A), Main Map), relatively
gentle folds, high angle normal faults, sporadic strike-slip faults and low angle reverse faults (i.e. the Crvene Stijene-Bešpelj fault; Pavičić et al., 2018) (Main Map). Although the unit does not seem very tectonically disturbed, some significant fault movements were observed in the northern part of the Crvene Stijene district. On the fault between deposits L-22 and L-2, fault movement is estimated as being up to 180 m (Figure 4, Main Map) (Pavičić et al., 2018).

Furthermore, the most marked structure in the Poljane district is the syncline with a small interlimb angle between 10 and 30°. There are also overturned folds developed in the Flysch sequences (K₃−6) in the NE part of the Crvene Stijene-Poljane unit.

The second structural unit, the Liskovica-Bešpelj, is tectonically very complex, divided from the Crvene Stijene-Poljane by the N-S trending, Crvene Stijene-Bešpelj fault (Main Map). This unit is characterized by the E-W trend of its structural features. The main characteristic of the unit is folds and overturned folds, which resulted in subvertical to vertical (Figure 5 (B)) (Bešpelj district – see geological section C–D in Main Map) and even overturned strata (Liskovica district – see geological section A–B in Main Map). Normal and diagonal faults are the most abundant, with few strike-slip and reverse faults. The most significant faults have relatively large offsets, which confirms the very dynamic tectonic evolution of the structural unit (Geological sections A–B and C–D on Main Map).

1.6. Materials & methods

The research area covers 343 km² northeast of Jajce in central Bosnia & Herzegovina. Methods used to process the input data and compile the final map are described in recent papers (e.g. Abbà et al., 2018; Balestro, Fioraso, & Lombardo, 2013; Carmignani, Conti, Cornamusini, & Pirro, 2013; Hanžl et al., 2017). The topographic base is a national topographic map of Bosnia and Herzegovina at a scale of 1:25,000 made by Military-Geographical survey of former Yugoslavia. The geological cartographic base for the map is formed by combining two geological maps of the bauxite-bearing area of Jajce at a scale of 1:25,000 made by Military-Geographical survey of former Yugoslavia. The geological cartographic base for the map is formed by combining two geological maps of the bauxite-bearing area of Jajce at a scale of 1:25,000 (Dragičević, 1981; Papeš, 1984), and the basic geological map of Yugoslavia, sheet Jajce, scale 1:100,000 (Marinković & Ahac, 1979). Areas with known bauxite deposits, i.e. bauxite district were extensively investigated so geological maps of each bauxite district at a scale of 1:5000 were used for those areas (archive of Rudnici boksita Jajce). When maps of different scales covered the same area, the more detailed map was used (similar to Henrique-Pinto, de Assis Janasi, Borges Carvalho, de Oliveira Calado, & Grohmann, 2014). All input maps were in paper form, so they needed to be scanned, georeferenced and digitalized in vector form in ESRI ArcMap 10. Inconsistencies between base maps were resolved by applying more recent research with field work checks. All collected data, from the existing...
1.7. Discussion & conclusions

The presented geological map sheet summarizes the existing and reviewed data of 40 years of geological research of bauxites in the bauxite-bearing area of Jajce. The map was compiled based on all the available data and new collected data in the areas where geological settings were not clear. The constructed geological map represents an up to date set of summarized geological settings in the investigated area. In comparison with previous geological maps, it shows:

- Unified and more precise subdivision of lithostratigraphic units;
- Unified and a more precise surface distribution of lithostratigraphic units;
- All currently known bauxite deposits in the investigated area;
- Geodatabase with all available geological data (maps, sections, drill holes, adits, deposit contours);

Software

Fieldwork localities were prepared in Microsoft Excel then imported into geological geodatabase in ESRI ArcGIS 10.1. Geological geodatabase was created in Esri ArcGIS. Geological sections, column and final map layout were constructed in Adobe Illustrator CS6.

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No potential conflict of interest was reported by the authors.

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Geological sections were made based on sections from Dragićević (1981) with integration of new data for the interpretation of geological settings (especially fieldwork data and drilled holes in the bauxite district areas). A stratigraphic chart was compiled from the chart in Dragićević (1981) and stratigraphic data from Dragićević and Velić (2006) and Moro et al. (2016).
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