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Edited by

Saša Stojadinović

and

Dejan Petrović

November 29th – 30th 2021

Bor, Serbia

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STRATIGRAPHY AND AGE OF ROCK UNITS AND MINERALIZATION IN THE TIMOK MAGMATIC COMPLEX ANDTHE BOR METALLOGENIC ZONE – A REVIEW

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Abstract

This study reports of stratigraphy and geochronology of rock units and mineralization of the Timok Magmatic Complex (TMC) and the Bor Metallogenetic Zone (BMZ)which belongs to theLate Cretaceous Apuseni-Banat-Timok-Srednogorje Belt (ABTS, part of the Tethyan-Eurasian Metallogenic Belt).Existing data are supplemented and systematized by the latest geological, stratigraphic and mineral exploration.The TMC developed on a continental crust composed of different types of the Proterozoic to the Lower Cretaceous rocks. The TMC consists of the volcanic/magmatic, volcanogeno-sedimentary and sedimentary units. The sedimentary processes and magmatism lasted nearly continuously throughout nearly the whole Late Cretaceous. The sedimentation lasted from the Albian-Cenomanian to the Maastrichtian. Magmatism occurred in two phases from the Upper Turonian to the Upper Campanian: V1 (90-83 Ma), V2 (83-78 Ma), with a steady decrease in age from east to west. Cu-Au porphyry mineralization take place between 87-80 Ma. Major mineralizationis related to the V1 magmatic phasepredominantly developed in the easternmost part of the BMZ.

Keywords*: Timok Magmatic Complex, stratigraphy, aga data, volcanism, mineralization.*

1. INTRODUCTION

The Timok Magmatic Complex (TMC) almost totally overlap of the Bor Metallogenetic Zone (BMZ) which belongs to the Late Cretaceous Apuseni-Banat-Timok-Srednogorje Belt (ABTS, [1,2]) and together belong to the transcontinental Tethyan-Eurasian Metallogenic Belt [3].

Because the TMC and the BMZ as the entire ABTS are known to host some of the largest Cu and Au deposits in Europe, their geology has been frequently studied in the last several decades (e.g.,[4,5,6,7,8,9,10,11], among others). The studies covered various geological aspects of the origin and evolution of many parts of this belt and established solid genetic links between volcanic/magmatic processes and mineralization events. In this respect, the information based on stratigraphic relationships and high precision geochronology that includes Ar/Ar[5,6], U/Pb zircon dating (e.g., [4,9,11,12]) and Re/Os molybdenite dating [7] was of supreme importance.

In this study will be revised, supplemented and systematizedstratigraphy, geochronology and mineralization relationshipof the BMZ. The BMZ is famous for its large porphyry copper systems accompanied by high- and subordinate low-sulphidation epithermal Au ore deposits [13,14,15,16,17]. It has long been thought that the massive sulphide deposits had been mined out long ago, the recent discovery of a world class copper and gold deposit of ČukaruPeki seriously arouse new interests for further investigating the BMZ, both in the exploration and the scientific context[18,19,20].

2. GEOLOGY, STRATIGRAPHY, ROCK AND MINERALIZATION AGE DATA OF THE TMC AND THE BMZ

The areas of the BMZ and the TMC almost totally overlap (Figure 1). The geology of the TMC along with the main ore deposits within the BMZ, the available geochronology age determinations are given in Figure 1 and Table1. The stratigraphy and time space development of the TMC and relationship of published sediment formations and magmatic suites[21,8] are given in Figure 2. The TMC developed on a continental crust composed of different types of the Proterozoic to the Lower Cretaceous rocks, partially overlaid by Miocene and Holocene sediments. After continuous carbonate sedimentation from the Early Jurassic to the Lower Cretaceous, a new sedimentation period commenced with the Albian transgression. These Albian–Cenomanian sedimentation processeshad clastic character and were related to oscillations of the depositional environment (Lenovac Formation, [21], Figure 2). After a hiatus, the Turonian–Senonian evolution commenced with a newsedimentary cycle. The sediments overlie the Cenomanian clastites, started with basal conglomerate and continues continuously, over wide area in the TMC with clastic to carbonate sediments (OštreljFormation,[21], Figure 2). The lowest part of the sediments contains microfauna (*Helvetoglobotruncanahelvetica*), indicating the Lower to the Middle Turonian age [21].During the Upper Turonian tothe Senonian, the whole TMC area shows a considerable difference in the evolution between the eastward and the westward tectonic block (Figure 2, [22]).

The volcanism/magmatismoccurred in two phases from the Upper Turonian to the Upper Campanian: V1 (90-83 Ma), V2 (83-78 Ma), Figure 2, Table 1. It predominantly consists of extrusive volcanics, shallow intrusions and volcaniclastics that are at places associated with volcano-sedimentary and sedimentary rock series, with a steady decrease in age from east to west.

In the eastward block, predominate volcanic rocks of biotite-hornblende andesite (±dacite) compositions (TimokAndesite, V1, [8,12], I volcanic phase in Figure 1). These rocks stratigraphically overlie the Cenomanian siliclastic sediments or the Turonian clastic to carbonate sediments (Figure 2). The available U/Pb zircon ages of the Timok Andesite (V1) range 90-83 Ma ([4,9,12], Table 1). In the same time, the available U/Pb zircon ages and volcanological analyses reveal that the first volcanic phase (V1) can be split into two sub-phases: V1A and V1B [12].

The V1A sub-phase andesite can betermed plagioclase-hornblende phyric, has mostly holocrystalline groundmass and is substantially altered and mineralized. It is represented by coherent, brecciated and volcaniclastic facies. The age of V1A ranges widely from 90 to 85 Ma ([4,12], Table 1).

The V1B can be termed hornblende-plagioclase phyric andesite. It is a fresh, non-mineralized rock displaying holo- to hypocrystalline texture and occasionally fluidal fabric. The V1B is represented by coherent lava flows or shallow intrusions, monomictic breccia and volcaniclastic rock.The V1B sub-phase shows an age range of ~85 to 83 Ma ([4,12], Table 1).

During the volcanismand especially after its interruption, in a shallow water environment, andesite volcanics begin to be resedimented, transported and formedvolcano-sedimentary package - epiclastics. The epiclastics are represented by polymictic andesite breccia, volcaniclastic conglomerate and sandstone, which matrix is often composed of clay, fine grained sandstones or reddish marls.These rocks are known as the MetovnicaEpiclastite([8], Epiclastic in Figure 1), are usually interlayered with marls and siltstoneand sometimes, contain well-preserved microfauna the Coniacian–Campanian age [22,23,12].

The sedimentary series of the Oštrelj Formation are continuously developed and can be found over the Early Cretaceous rocks of the volcanic basement rock but also as underlying or overlying the V1 and V2volcanites and their epiclastic products (MetovnicaEpiclastite, Figure 2). The sediments are represented by layered to laminated grayish siltstones, marls, sandy limestones and calcareous sandstones and contain Turonian–Campanian micropaleontological content [21,12].

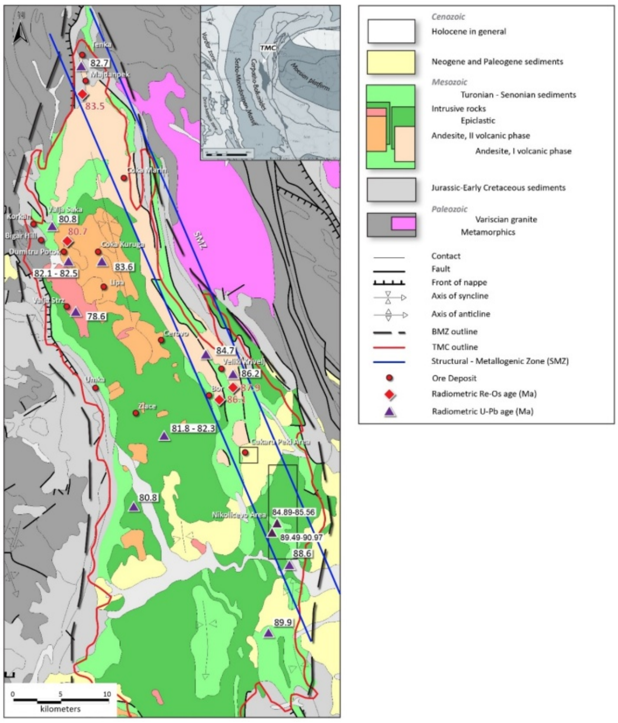

Figure 1. A geological-metallogenetic map of the Timok Magmatic Complex (TMK) and the BorMetallogenetic Zone (BMZ); the numbers are literature U/Pb and Re/Os age data [4,7,9,11,129]; theinset shows the regional geotectonic position; note that the legend is organized in the form of asimplified geological column.

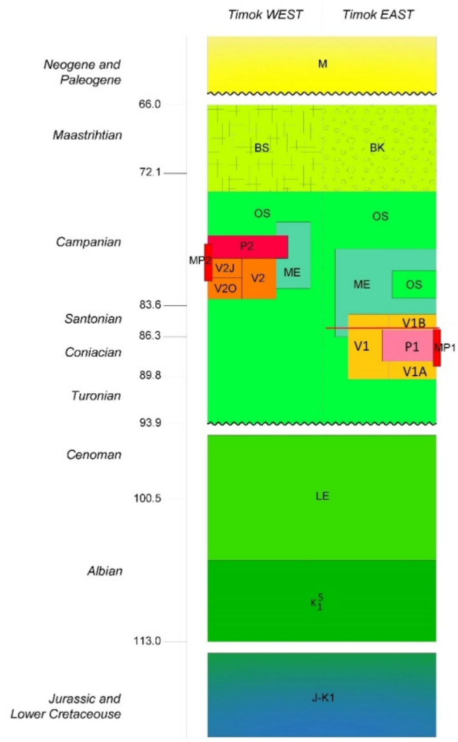

Figure 2.The stratigraphy and time space development of the TMC and relationship of sediment formations and magmatic suites [22,21,8]. On the left side is schematic stratigraphic chart with epoch and age in Ma. LE – Lenovac Formation, OS – Oštrelj Formation, V1 – Timok Andesite, volcanic/magmatic first phase, V1A–Timok andesite sub-phase, V1B – Timok andesite sub-phase, P1 – Shallow intrusions in V1, MP1 – Porphyry mineralization, ME – Metovnica Epiclastic, V2 – volcanic/magmatic second phase, V2O – Osnić basaltic andesite, V2J – Ježevica andesite, P2 – ValjaStržplutonite, MP2 – Porphyry and skarn mineralization, BS – Bukovo Formation, BK – Bor Clastic, M – Miocene sediments, TimokEAST – The eastward tectonic block, Timok WEST – the westward tectonic block Red line highlighted schematic unconformity of porphyry mineralization in the eastward tectonic block.

Towards the west of the TMC, the V1 andesite grade into the hornblende-pyroxene- to pyroxene andesite and basaltic andesite -V2 phase (Ježevica andesite and Osnić basaltic andesite,[8]). They are predominantly emplaced as submarine extrusive volcanics, shallow intrusions and associated epiclastic rocks (II volcanic phase in Figure 1). These volcanic rocksreveal U/Pb zircon ages range of 83-81 Ma, but related to andesite or trachyte dykes ([4], Table 2). They are also stratigraphically interlayered with the above mentioned the Senonian sediments (Oštrelj Formation, Figure 2) and are at places covered by their epiclastic products (Epiclastic in Figure 1). In the westernmost part of the TMC occur plutonic of monzodiorite-granodiorite-gabbrodiorite compositions (ValjaStržplutonite, [8],Intrusive rocks in Figure 1). This rock intruded in to the basaltic andesite and andesite and surrounding sediments (Figure 2). The plutonic rock is dated at 83-78 Ma (Table 1, [4,11]).

From the Upper Campanian to Maastrichtian, in the westward block of the TMC, reef sedimentation commenced (Bukovo Formation, [21]). At the same time, in the eastwardblock,coarse-grained and regressive clastites were deposited (Bor Clastic, ([21], Figure 2). This was the period when the TMCuplifted and its existence as an area of active volcanism/magmatismand marine sedimentation terminated[22].

Table 1 –Summary of rock and mineralization age data in the TMC [4,5,6,7,9,11,12], zr-zircon, ho-hornblende, bi-biotite, mo-molybdenite, wm-white mica.

Location	Lithology	Method	Age Ma	Volcanic phase
Majdanpek	Andesite-Dacite	U/Pb zr	85.2±4.2-86.0±7.2 [9]	V1A
VelikiKrivelj	Andesite dyke	U/Pb zr	86.17±0.15-86.29±0.32 [4]	
VelikiKrivelj	Andesite dyke	Ar/Ar ho	85.5±1.3 [5]	
Bor	Andesite	Ar/Ar ho	83.4±1.7-84.6±1.1 [6]	
Bor	Andesite	Ar/Arbi	89.0±0.6 [5]	
Nikoličevo	Andesite	U/Pb zr	89.49±0.42-90.97±0.39 [12]	
Gamzigrad	Andesite	U/Pb zr	88.6±8.0 [9]	
Lenovac	Volcaniclastic	U/Pb zr	89.9±6.0 [9]	
VelikiKrivelj	Cu-Mo Porphyry	Re/Osmo	87.88±0.5 [7]	
Bor	Andesite	Re/Osmo	85.94±0.4-86.24±0.5 [7]	
Bor	Borskareka Porphyry	Ar/Arwm	86.3±1-86.9±1.1 [6]	
Nikoličevo	Andesite	U/Pb zr	84.89±0.75-85.56±0.53 [12]	V1B
VelikiKrivelj	Andesite	U/Pb zr	84.66±0.5 [4]	
Majdanpek-Dolovi	Andesite dyke	U/Pb zr	82.73±0.03 [4]	V2
Brestovac cross road	Trachyte dyke	U/Pb zr	81.79±0.5-82.27±0.35 [4]	
Podgorac	Basaltic andesite	U/Pb zr	80.8±4.8 [9]	
Majdanpek	Cu-Au-Mo Skarn	Re/Osmo	83.37±0.4-83.77±0.5 [7]	
Majdanpek		Ar/Arwm	83.15[5]	
ValjaStrž	Monzonite	U/Pb zr	78.62±0.44 [4]	
ValjaStrž	Granodiorite	U/Pb zr	78.9±5.2-82.2±5.4 [9]	
ValjaStrž	Diorite	U/Pb zr	78.5±1.3-82.5±0.4 [11]	
ČokaKuruga	Diorite	U/Pb zr	83.6±0.5 [11]	
Dumitru Potok	Diorite	U/Pb zr	82.1±0.7-82.2±1.2 [11]	
KrakuRiđi	Diorite	U/Pb zr	80.8±0.6 [11]	
Dumitru Potok	Cu Porphyry	Re/Osmo	80.69±0.4-80.82±0.45 [7]	

The Bukovo Formation overlies theOštrelj Formation. There are moderate beddedsiltstonesand marls overlain by sandy limestones with intercalated layers of claystonesand contain Upper Campanian to Maastrichtian micropaleontological content [21].

The Bor Clastic are polymictic coarse to fine-grained conglomerate and sandstone.It is built by pebbles of the Upper Cretaceous volcanites and sediments originated from the TMC, pebbles of the Paleozoic metamorphic and igneous rocks, the Paleozoic sediments, the Jurassic and the Lower Cretaceous carbonate rocks, that originated from the basement of the TMC[24]. Micropaleontological content inthe Bor Clastic suggest the Upper Campanian to the Maastrichtian age [25,21,24].

The BMZ hosts more than hundred significant metallic occurrences out of which 22 have been recorded as ore deposits (see review of [16]. The location of 14 economically most significant ore deposits is indicated in Figure 1.

The world-class high-sulfidation Cu-Au deposit of Bor and ČukaruPeki-Upper zone and large porphyry Cu-Au deposits of VelikiKrivelj, Majdanpek,Bor-BorskaReka and ČukaruPeki-Lower zone are all situated along the eastern margin of the BMZ (Figure 1), more precisely inside a narrow structural-metallogenetic zone oriented SSZ-JJI (blue lines in Figure 1, [12]). In the same structural-metallogenetic zone occur smaller polymetalicepithermal deposits ofhigh-sulphidation, such as Čoka Marin [26], which do not exhibit obvious links to larger porphyry systems.

The western part of the BMZ is less promising and hosts generally different morphogenetic types of mineralization [11]. There are smaller porphyry Cu-Au, high sulphidation-style, polymetallic replacement, and skarn-type deposits connected with plutonic rocks (e.g.Tenka, Valja Saka, Umka, Dumitru Potok, ČokaKuruga, ValjaStrž, Lipa, among others, Figure 1). This zone also hosts a low-sulphidation deposit of Zlaće and a sediment-hosted Au mineralization Korkan-Bigar Hill ([27,11], Figure 1). In the last several years, in this part of the TMC occurrences of manganese ore were also reported and are interpreted as having been related to VMS/SEDEX-type of mineralization [16,11,28].

The age of porphyry mineralization andmineralized and hydrothermally altered andesitic host rocks clearly corresponds (Table 1). The porphyry mineralization ofVelikiKrivelj and Borska Reka deposits is associated with the V1A volcanics and may take place between 87-85.5 Ma roughly[6,7]. The porphyry-skarn mineralization of Majdanpek-Dolovi deposit related with andesitic dykes and dated around 83 Ma. The youngest dated mineralization is in the western part of the TMC, at Dumitru Potok deposit, range of 81-80 Ma and correspond with ValjaStrž plutonic.

3. CONCLUSION

The review of stratigraphy, time space development, relationship ofsediment formations and magmatic suites and available geochronology age determinationsof the TMC and the BMZ imposed the following conclusions:

- After a generally uniform development from the Early Jurassic to the Lower Cretaceous, during the Upper Turonian to the Senonian, the whole TMC area shows a considerable difference in the evolution between the eastward and the westward tectonic block.

- The sedimentary processes and magmatism lasted nearly continuously throughout nearly the whole Late Cretaceous.

- The volcanism/magmatism occurred in two phases from the Upper Turonian to the Upper Campanian: V1 (90-83 Ma), V2 (83-78 Ma).

- The available U/Pb zircon ages and volcanological analyses reveal that the first volcanic phase (V1) can be split into two sub-phases: V1A and V1B.The Timokandesite V1A is older (90-85 Ma) and is both in time and space associated to ore mineralization, whereas the V1B is younger (85-83 Ma) and clearly postdates the main mineralization event.

- The porphyry Cu-Au mineralization in the BMZ ranges widely from 87-80 Ma.

- The structural-metallogenetic zone along the eastern margin of the BMZ is probably one of the most prospective areas in Europe for exploration. The discovery testifies that even old and presumably well-investigated mining areas may host significant ore deposits that await to be found, in particular in deeper parts of the existing systems.

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