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GEOPHYSIC MODEL OF THE EARTH'S CRUST AND GEODYNAMIC POSITION OF LEAD-ZINC DEPOSITS OF THE REPUBLIC OF NORTH MACEDONIA AND NEIGHBORING COUNTRIES

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A b s t r a c t: The north-westward direction of distribution of the Pb-Zn deposits in North Macedonia, Serbia and Greece corresponds to the trend of the average density and temperature of the upper mantle. A similar direction is also noted in the structure of the Moho. The thickness of the sedimentary layer of the upper crust varies from 7.8 km in the areas of Dinaride complexes and Serbo-Macedonian massif down to 100 m in the Vardar Zone. At the same time, the smallest thicknes is observed in the places of the densest distribution of Pb-Zn deposits. Blocks of the forming tectonic melange in the Vardar suture zone were squeezed up and eroded, which was possibly due to a decrease in the thickness of upper crust sedimentary layer and the lithosphere as a whole, as well as due to the high eclogitization of the lower ophiolite blocks. During the same period the deposits (Cu-Ni, SEDEX) previously formed due to ophiolites and rifts were exhumed as a result of uplifting and erosion processes and the new Cu-porphyry, skarn and / or vein (Pb-Zn) deposits were formed during the magmatic arcs formation. Thus, the local area of the Besna Kobyla–Osogovo metallogenic zone containing the Sasa and Toranica deposits is the most eroded. Based on this conclusion, the southern direction of the zone seems to be prospective for new Pb-Zn deposits under the surface

Key words: Balkans; North Macedonia; geodynamic situation; geophysical model; Earth's crust; deposit; lead; zinc; forecast

INTRODUCTION

The article discusses the results of studying the geodynamic conditions of the formation of Balkan Pb-Zn deposits by GIS methods, their relationship with the deep structure of the Earth's crust, the density and thermal state of the upper mantle. The GIS project prepared for this study includes cartographic material and an updated database of Pb-Zn deposits in Northern Macedonia and neighboring Balkan countries. This article is a continuation of our previous publication [Volkov et al., 2017]

To conduct GIS analysis, well-known methodological techniques were used, embedded in the analytical apparatus of ARCMAP and other mathematical-analytical systems. The most effective established methods for identifying and evaluating spatial relationships (raster algebra, fuzzy logic, probabilistic analysis, etc.) were used.

The new CRUST1.0 model is based on a database of the thickness of the Earth's crust according to the results of seismic studies. The crust model is inherited from the CRUST2.0 model [Bassin et al., 2000; http://igppweb.ucsd.edu/~gabi/crust2.html]. The types of crust were determined depending on the age of the foundation or tectonic conditions [Bouman et al., 2015] and for each cell of the network the Moho boundary depth, compression rate and shear rate, as well as density are given for 8 layers: water, ice, three-layer sedimentary cover and upper, middle and lower crystalline crust. The data of sedimentary layers mainly corresponds to the model [Laske and Masters, 1997].

The results obtained are of great importance for predicting new deposits.

DISTRIBUTION OF Pb-Zn ORE DEPOSITS

The metallogeny of the Balkans is due to the complex geodynamic evolution of the Thetis-Eurasian metallogenic belt (TEMP), which has been formed since the Mesozoic [Jankovich, 1977]. The polymetallic deposits of Serbia and North Macedonia within TEMP are concentrated in the Serbo-Macedonian Metallogenic Province (SMMP), which includes the Serbo-Macedonian massif, the Vardar zone and the eastern part of Dinarides. In the province, calc-alkaline magmatism is widespread, and among the deposits there are two main types: 1) porphyry Cu-Mo-Au and related epithermal (Au-Ag); 2) epi- and mesothermal polyreplacement and vein Pb-Zn (-Ag-Au) deposits in the carbonate formations of the Late Eocene–Oligocene, that extend through Serbia and Macedonia to Greece. The Greece deposits are located in the Rhodope and Serbo-Macedonian provinces, where the most economic are the vein (Kirki, Majarovo) and stratiform (Essimi) Pb-Zn deposits [Arvanitidis, 2010].

In the metallogene aspect the Vardar zone is most significant; the evolution of the zone was numerously studied [Serafimovski et al., 2002; Slovenec et al., 2002; Burchfiel et al., 2008, etc.]. The Vardar zone is located between the Serbo-Macedonian massif (SMM) in the east and Dinarides in the west. If its eastern boundary is marked sharply by longitudinal dislocations along which the SMM, that pulled over the Vardar zone [Resimić-Šarić et al. 2000], then its western boundary with Dinarides is not clearly defined.

The Vardar zone consists of tectonic blocks of crystalline schist, Jurassic serpentinized peridotite, gabbrodiabase, marine Triassic sediments, Jurassic and Cretaceous granites and calc-alkaline volcanic formations. The tectonic melange of the Vardar zone represents fragments of riftogenic complexes [Serafimovski et al., 2002] of the Mesozoic oceanic crust, that formed more than 150 million years ago. Melange rocks are characterized by a schistose and fine-grained shale-clay matrix with fragments of various rocks. Most of them are greywackes, ophiolites, quartzites and marbles, the youngest of them are of Late Cretaceous and Paleocene age.

In the Cretaceous, after the closure of the ocean and subduction of the oceanic crust under the crystalline complexes of the SMM in Late Jurassic, the mode of regional tectonic compression and the Cretaceous magmatic arcs forming in the Vardar zone [Slovenec et al., 2002] was replaced by extension mode [Burchfiel et al., 2008]. In the Middle Eocene – Oligocene, the extension mode and corresponding lithosphere decrease in the thickness became predominant and was accompanied by intensive intrusion of subvolcanic rhyolite and dacite porphyries (Figure 1). A study of the Sr-Nd-Pb isotopy in plutonic minette and kersantite analogues indicates their origin from a mantle source [Sokol et al., 2019], and Late Cretaceous volcanism within the Vardar zone is most likely intracontinental. The magmatism of the Jurassic-Pliocene age, which has determined the productive ore mineralization, intensified in the post-subduction period during alpine orogenesis [Serafimovski et al., 2002]. Eocene–Pliocene magmatism is the main factor in the emergence of numerous copper-porphyry, epithermal (Au-Ag) and metasomatic Pb-Zn deposits. Ore mineralization here is directly related to subvolcanic intrusions by dacitic and andesitic volcanism (Figure 1).

To the east of the Vardar zone is the Serbo-Macedonian massif (SMM), a geotectonic taxon folded at the base by metamorphic rocks of the amphibolite facies (mica, gneisses, micaceous schists, quartzites, marble and magmatites) and Paleozoic granitoids [Dimitrijević, 1997]. The depth of the roof of the complex is ~11 km. The upper SMM complex (to a depth of 5 km) is represented by Riphean-Cambrian green schists and weakly metamorphosed Ordovician-carboniferous strata. The thicknesses are broken through by granitoids of the Paleozoic and Tertiary age.

SMM is an accretionary prism consisting of shales, gneisses and marbles, which are often mineralized and penetrated by Variscian granites and contain polymetallic (Olimpias and Stratoni), Cu-porphyry (Skouries and Pontokerasia) deposits in Greece, Pb-Zn deposits Sasa, Toranica and Zletovo and Cu-porphyry Bučim and Borov Dol in North Macedonia, as well as the Lece polymetallic deposit in Serbia. Here the Pb-Zn deposits occur in carbonate rocks and are genetically relate to deep crustal faults.

To the west of the Vardar zone, at the base of the Dinaride system, the Mesozoic (sub-platform / shelf?) limestones are known, which are covered by siliceous schists and quartzites of the continental slope. The sequence is completed by ophiolite complexes represented by obducted blocks of ultramafic rocks with intratelluric xenoliths of the oceanic crust.

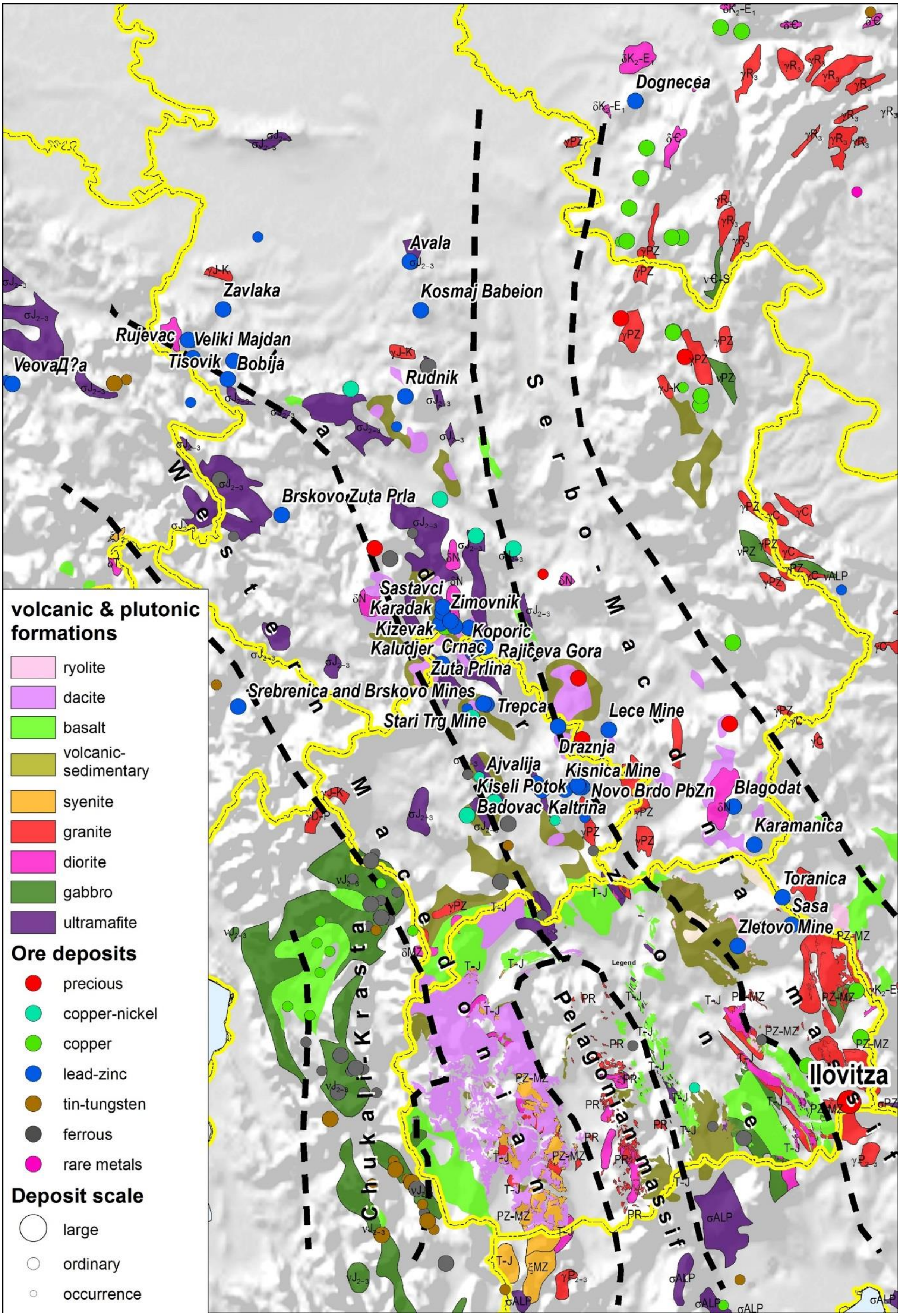

Fig. 1. Volcanic-plutonic associations and the distribution of ore deposits in the central region of the Balkan Peninsula (by [Asch, 2003])

In general, Dinarides complexes are characterized by passive margins and sub-platform conditions. It is this specificity that determines the discovery possibility of ores of types MVT and SEDEX. In the southeast, the Paleozoic-Triassic Dinaride complexes are represented by the West Macedonian zone. The formation of regional lithofacial complexes was accompanied by magmatic activity, which is associated with polyreplacement deposits and magnetite skarns (Mala Kropa), vein Pb-Zn occurrences in Tertiary trachy-andesites and underlying Late Paleozoic meta-sedimentary rocks (Srebrenica). In North Macedonia, the Pb-Zn deposits in West-Macedonian zone are unknown.

GEODYNAMIC SETTING OF POLYMETALLIC ORE DEPOSITS AND THEIR FORMATION FEATURES

Polymetallic deposits in the Balkan TEMP segment, as shown above, produced three geodynamic settings: suprasubduction, collisional and riftogenic [Jelenković et al, 2008].

Suprasubduction ore deposits are associated with linear horst-grabens over the subduction zone. The largest deposits are of skarn and pyrite (VMS) types. Sources of ore mineralization are the host rocks that compose the subducted plate and some of continental crust. Collision deposits located along the active continental margin are associated with rocks of volcanic-intrusive complexes, and the source of magma is the lower crust. The main deposits located in the Vardar zone and the SMM, could be converted into the skarn type at the period of the magmatic arc development.

Lead and zinc prevail in ores associated with early rifts, and mineralization refers to both the hydrothermal volcanic-sedimentary, stockwork and vein types associated with upper crustal magmatism, and to the VMS and vein types characteristic of ophiolite basalts.

Regarding the genesis of lead-zinc deposits in North Macedonia, Serbia and Greece, there is currently no common understanding on the sources and conditions of the formation of primary ores. Some researchers [Tufar, 1984] consider ores to be stratiform, syngenetic, having undergone regional metamorphism in the Tertiary period, while others [Dobrovolskaya, 1997, etc.] consider them to be epigenetic hydrothermal, associated with Tertiary magmatism. Often there are cases of coexisting ores of various mineral types in some ore deposits. Some of them are classified as VMS and partially in the porphyry or epithermal type (Bor, Chelopech), others (Sasa, Toranica) in the epi/mesothermal vein or skarn type. Such deposits may be determine as hybrid [Migineishvili, 2005] or polygenic and polychronous [Munkov et al., 2006].

The main industrial and scientific source in TEMPs are the large reserves of Au and rich Cu massive sulpide deposits, such as Chelopech (Bulgaria), Bor (Serbia) and Madneuli (Georgia), which are spatially relates to late Cu-porphyry ore-forming system and have common characteristics both with high sulphidation epithermal deposits and VMS deposits [Robertson and Karamata, 1994; Berza et al., 1998].

According to R. Migineishvili [2005], on the one hand, the Madneuli Cu-Au deposit has the typical features of Kuroko type pyrite-polymetallic deposit, and, on the other hand, is very similar to epithermal high sulphidation gold deposits. These ores are so peculiar that it has to be classified as a special type of hybrid field [Migineishvili, 2005].

Alexander Zavaritsky considered the Ural VMS deposits as metasomatic ores that precipitated from hydrothermal fluids coming from magmatic chambers. At the same time, he noted that "... great care is needed in interpreting the observed facts in order to find the right way to explain the genesis of pyrite deposits" [Zavaritsky, 1950]. These years and later there was an active discussion about the regenerated ore deposits [Schneiderhen, 1958]. This hypothesis was not very successful mainly because even the most ancient pyrite deposits, despite repeated metamorphism, were well preserved. However, it is difficult to imagine large VMS deposits without giant haloes of dispersed ore material, which, unlike massive ores, can easily be mobilized under the influence of hydrothermal fluids.

More recently, N. I. Prutsky [2004] proposed a regenerative model for the formation of vein polymetallic sulfide ores in many deposits of the Transcaucasian volcanic-plutonic belt, as a result of remobilization and redeposition of VMS deposits that were been fixed in a poorly permeable heat-insulating clay medium after productive hydrothermal-sedimentary precipitation stage. Large-scale metaregeneration was accompanied by both the scattering of primary large pyritic deposits and the enrichment of redeposited mineralization with a new more widers spectrum of impurity metals, including Au due to gold-bearing carbonaceous shale. The validity of this model is indirectly confirmed by the presence of the large Sadonsky, Zgidsky and recently explored Dzhamidonsky vein polymetallic deposits enriched with gold and silver of Late Jurassic age in the northern frame of the Lower Middle Jurassic Basin. In the southern frame of the Basin that is in Armenia there are numerous copper-gold vein deposits (Kafan ore district) of Middle Jurassic age.

Similar signs of ore regeneration are also characteristic of Pb-Zn deposits in North Macedonia. According to several isotopic studies, the ratio of Sr isotopes in volcanogenic rocks, despite the weak negative Eu anomaly in ores and host rocks of Sasa-Toranitsa, indicates the origin of volcanogenic material from the boundary zone between the lower crust and upper mantle [Tasev et al., 2013]. The endogenous sulfur source of the main sulfides in these deposits is indicated by isotopic ratios that range from –7.52 to +7.00‰. At the same time, values characteristic of biogenic sulfur (+14.12‰) were also recorded in the pyrite of the Sasa deposit [Serafimovski et al., 2005], which may indicate the presence of relics of primary exhalation VMS pyrite and, possibly, sphalerite-galena ores.

GEOPHYSIC MODELS OF EARTH'S CRUST

Sedimentary and magmatic formations and their metamorphic analogues in North Macedonia and neighboring Serbia and Greece compose a fragment of a large sedimentary layer of the upper crust, the global geophysical model of which has been developed in recent years [Laske et al, 1997, 2013]. The sedimentary nappe in the upper crust is the layer of undeformed rocks on a metamorphic and magmatic base, and its thickness is taken from the global CRUST 1.0 model [Laske et al., 2013].

The structure of the sedimentary cover reflects regional tectonics and clearly coincides with the location of orogenic belts and rift systems within the continental margins [Handy et al., 2019]. The sedimentary layer, in general, has a thickness from near zero values to two tens of kilometers. The global model of sedimentary complexes is digitized at a scale of 1×1^{o}. The layer has relatively low seismic velocities and densities, so its lower boundary reflects the seismic velocity changes abruptly.

The sedimentary layer of the upper crust in the study area includes alpine and older sedimentary and magmatic complexes [Heinrich and Neubauer, 2002]. In Figure 2A it is clearly seen that its thickness varies from 7.8 km in the areas of distribution of the Dinaride complexes and the SMM down to 100 meters in the Vardar zone. At the same time, the smallest thickness is observed in the places of the densest distribution of Cu-Ni, Pb-Zn, Co-Cr deposits.

The oldest structures of tectonic extension belong to the Late Cretaceous and Early Paleogene period were formed while the Vardar Ocean closed. Ophiolites are found in two zones – the Western belt in the Inner Dinarids [Dimitrijević, 1997] and the Eastern belt, that has the Vardar zone as its fragment. Lherzolite peridotite, gabbro-pyroxenite, and orthopyroxenite predominate in western ophiolite [Karamata et al., 1980]. The deposits associated with these ophiolite complexes mainly contain Ni-Co-Cu-Fe, Cu-pyrite, magnetite and minor gold mineralization. Eastern ophiolites consist mainly of magnesium peridotite and dunite, which are associated with significant Cr, Ni, Cu-pyrite, magnesite, chrysotile-asbestos deposits.

Subduction and post-collisional process in the Late Oligocene – Early Miocene led to the thickening of crust [Burchfiel et al., 2008] in the Dinarides area (see Figure 2B). At the same time, the blocks of tectonic melange having been forming in the suture Vardar zone were squeezed up and eroded, that, possibly, was associated with a thinning of the sedimentary layer (see Figure 2A) and the lithosphere as a whole due to the high probability of eclogitization of the lowermost ophiolite blocks. It was highly likely at that period the primary ore deposits (Cu-Ni, VMS, SEDEX, MVT?) were been exhumed as a result of erosion, and a new Cu-porphyry, Fe-Pb and Pb-Zn skarns, Pb-Zn-Ag replacement and vein ores have arisen due to tectonic-magmatic activity.

Important characteristics of the global model of the Earth's crust, which determine the geodynamic environment within the upper crust, are the density and thermal state of the lower crust and upper mantle. These basic properties were obtained by processing seismic data when studying deep horizons of the crust [Carlson et al., 1984; Christensen et al., 1995; Simmons et al., 2010; Hacker et al., 2015]. According to some authors [Hacker et al., 2015], the average composition of the lowermost crust does not have to be necessary mafic. This hypothesis is based on an analysis of the average composition of the rocks, the estimated heat flux (according to the state of U, Th and K in the rocks) and seismic properties [Rudnick et al., 1995, 2003, 2014].

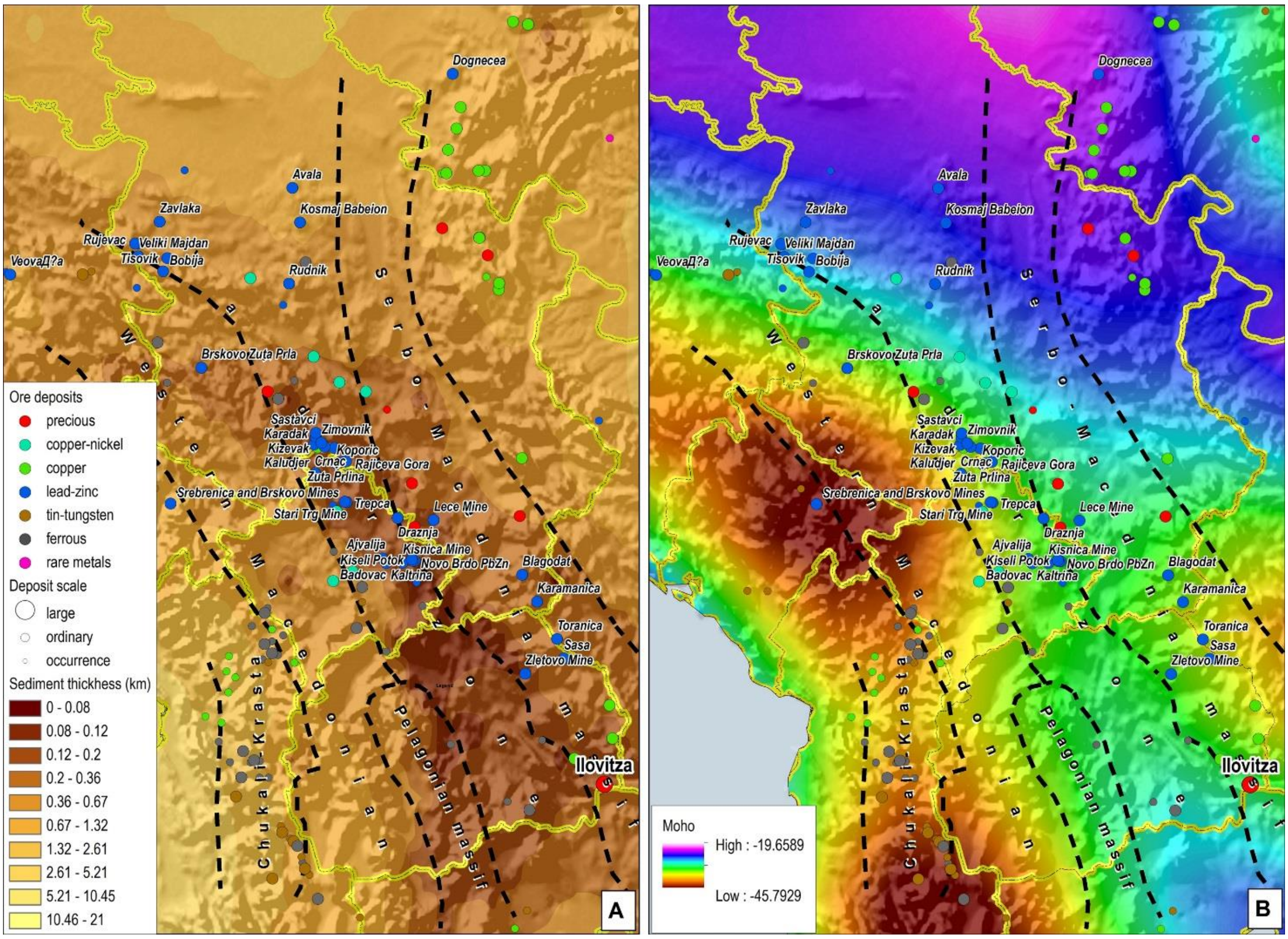

Fig. 2. The thickness of the sedimentary layer (A) and the surface of Moho (B) in the central region of the Balkan Peninsula (by [Laske et al., 1997; Bouman et al., 2015])

In this case, an increase in the melt acidity (formation of andesite and dacite magma) was likely achieved due to differentiation of the basaltic crust when mixing basaltic magma with silicon derivatives of a partial melt of the subducted mafic oceanic crust, delamination or relamination of the lowermost crust [Hacker et al. 2015].

It is natural to assume that the processes occurring in the lower crust are mostly due to the state of the upper mantle, the main characteristics of which are density and thermal regimes. A three-dimensional global model of the density of the upper mantle has been developed, corresponding to geodynamic and seismic observations [Artemieva, 2006; Simmons et al., 2010; Cammarano et al., 2017, etc.].

The temperature heterogeneity of the upper mantle, caused by subduction and convection, includes temperature differences, which can be explained by plumes. Asthenospheric convection in rifts and fault zones determines plume-like structures. Geophysical estimates of the average potential temperature of the upper mantle are about 1400 ºC. Areas of high density and low temperatures are usually assumed at the base of superplume structures [Simmons et al., 2010]. As well, the structural features of the lithosphere, stress, and gaps formation in the upper crust sufficiently determine the volume and place of volcanic activity [Anderson, 2000].

Figure 3 shows the distribution of density and temperature in the upper mantle corresponding to the thermal and density model [Sampietro et al., 2013; Cammarano et al,, 2017; Handy et al., 2019]. It is clearly seen that the main directions of thermal-density anomalies in the upper mantle do not quite correspond to the direction of the main geotectonic taxon elongation in the upper crust. The reason for this is the heterogeneous and disordered in time and space movement of various crust blocks during the alpine subduction [Botev et al., 1988]. At the same time, the north-west direction of the deposits spreading in northern Macedonia and Serbia is quite consistent with the trend of the average density and temperature of the upper mantle (Figure 3A,B). A similar direction is noted in the structure of the surface of Moho (the bottom of the crust), and it also corresponds to the direction of distribution of deposits (Figure 2B). This zone, passing between two blocks of increased lithosphere thickness, evidently trace a regional deep-seated fault zone, which at pre-Cretaceous time served as oceanic riftogenic structure of the Vardar zone, and later was inherited as subduction zone of the oceanic crust under the cratonic blocks of the Serbo-Macedonian massif.

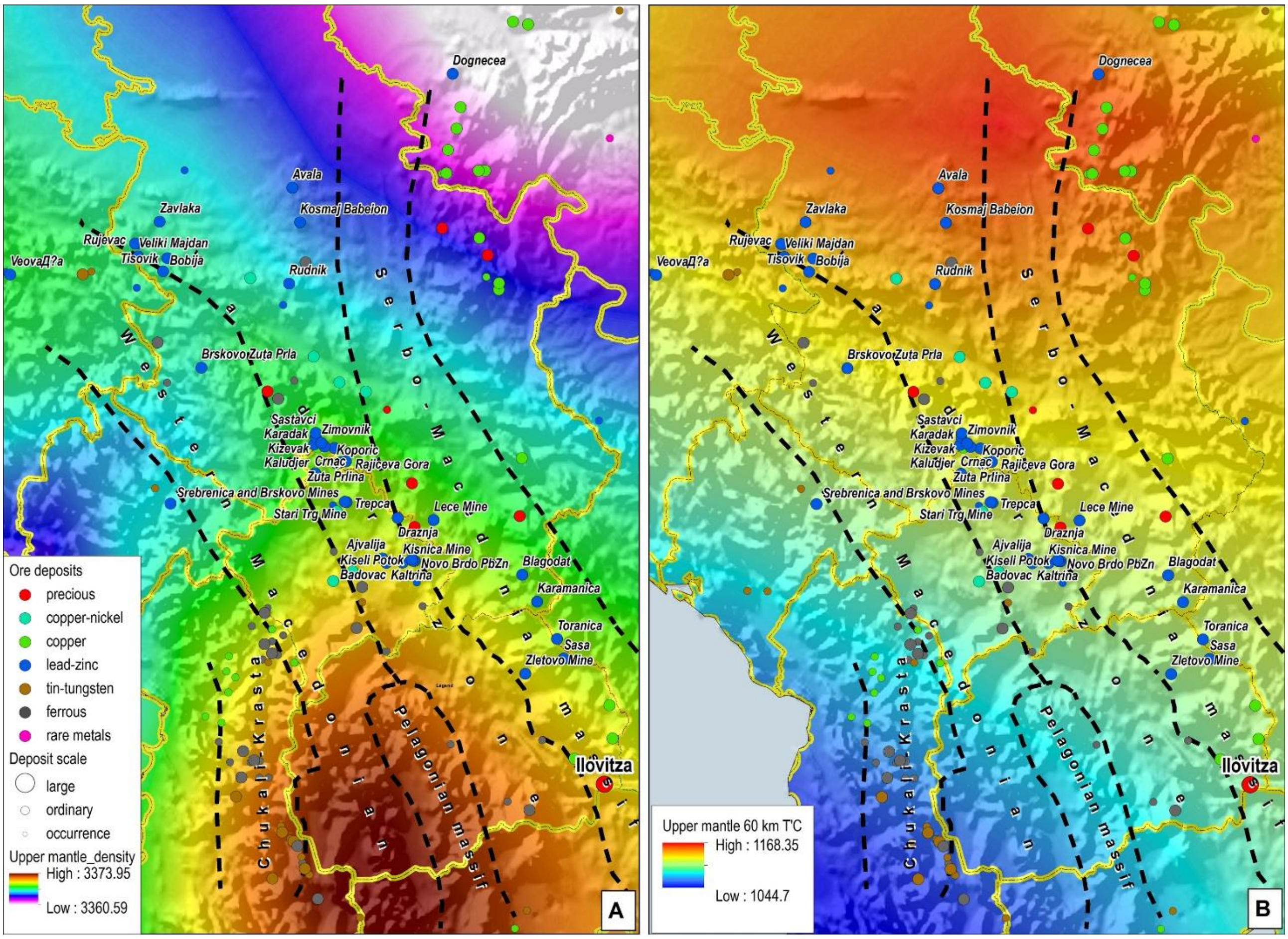

Fig. 3. Density (A) and thermal (B) model of the upper mantle in the central region of the Balkan Peninsula (by [Sampietro et al, 2013; Cammarano et al., 2017])

CONCLUSIONS

The results obtained are consistent with the ideas [Jelenković et al., 2008] that polymetallic deposits in the Balkan TEMP segment produced three geodynamic settings: suprasubduction, collisional and riftogenic.

It has been shown that the north-west trend of Pb-Zn distribution of deposits in North Macedonia and Serbia is quite consistent with the trend of average density and temperature of the upper mantle. A similar direction is also noted in the structure of the surface of Moho. However, these directions in the upper mantle do not correspond to the direction of the main geotectonic units in the upper crust, which is probably due to inhomogeneous and disordered in time and space movements of various crustal blocks during alpine subduction.

The performed study shows that the thickness of the sedimentary layer of the upper crust varies from 7.8 km in the distribution areas of the Dinaride complexes and the Serbo-Macedonian massif down to 100 m in the Vardar zone. At the same time, the smallest thickness is observed in the places of the densest distribution of Pb-Zn deposits. Blocks of the tectonic melange in the suture Vardar zone were squeezed up and eroded, that, possibly, was associated with a thinning of the sedimentary layer of the upper crust and the lithosphere as a whole due to the high eclogitization of the lowermost ophiolite blocks.

During the same period the deposits (Cu-Ni, SEDEX) previously formed due to ophiolites and rifts were exhumed as a result of uplifting and erosion processes and the new Cu-porphyry, skarn and / or vein (Pb-Zn) deposits were formed during the magmatic arcs formation.

Thus, the section of the Besna Kobila–Osogovo metallogenic zone, containing the Sasa and Toranica ore deposits, is the most eroded area. Based on this conclusion, the southern direction of the zone seems promising for the discovery for new Pb-Zn deposits that do not reach the surface.

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REFERENCES

Anderson, Don L. (2000): The Thermal state of the upper mantle; no role for mantle plumes. *Geophysical Research Letters*, Vol. **27** (22), pp. 3623–3626.

Artemieva, I. M. (2006): Global 1° × 1° thermal model TC1 for the continental lithosphere: implications for lithosphere secular evolution. *Tectonophysics*, Vol. **416** (1), pp. 245–277.

Arvanitidis, N. (2010): New metallogenetic concepts and substainability perspectives for non-energy metallic minerals in Central Macedonia, Greece. *Bulletin of the Geological Society of Greece*, Vol. **43** (5), 2437–2445.

Asch, K. (2003): The 1 : 5 Million International Geological Map of Europe and adjacent areas: Development and implementation of a GIS-enabled concept. – *Geologisches Jahrbuch*, SA 3, Stuttgart: E. Schweizerbartische Verlagsbuchhandlung.

Berza, T., Constantinescu, E., Vlad, S. N. (1998): Upper Cretaceous magmatic series and associated mineralisation in the Carpathian–Balkan Orogen. *Resour. Geol.*, Vol. **48**. pp. 291–306.

Botev, E. A., Burmakov, Ju. A., Treussov, A. V. and Vinnik, L. P. (1988): Crust and upper-mantle in homogeneities beneath the central part of the Balkan region. *Phys. Earth Planet. Inter.*, Vol. **51**, pp. 198–210.

Bouman, J., Ebbing, J., Meekes, S., Abdul Fattah, R., Fuchs, M., Gradmann, S., Haagmans, R., Lieb, V. (2015): GOCE gravity gradient data for lithospheric modeling. *Int. J. Appl. Earth Obs. Geoinform.*, Vol. **35**, pp. 16–30.

Burchfiel, B. C., Nakov, R., Dumurdžanov, N., Papanikolaou, D., Tzankov, T., Serafimovski, T., King, R.W., Kotzev, V., Todosov, A. & Nurce, B. (2008): Evolution and dynamics of the Cenozoic Tectonics of the South Balkan extensional system. *Geosphere*, Vol. **4** (6), pp. 919–938.

Cammarano, F., Guerri, M. (2017): Global thermal models of the lithosphere. *Geophys. J. Int.*, Vol. **210**, pp. 56–72.

Carlson R. L., Raskin G. S. (1984): Density of the ocean crust. *Nature*, Vol. **311**, pp. 555–558.

Christensen, N. I., Mooney, W. D. (1995): Seismic velocity structure and composition of the continental crust: A global view. *Journal of Geophysical Research*, Vol. **100** (B7), pp. 9761–9788.

Dimitrijević, M. D. (1997): *Geology of Yugoslavia*. – Geological Institute – GEMINI, Belgrade, Spec. Publ., Monograph, 197 p.

Dobrovolskaya, M. G., Serafimovski, T., Alexandrov, M. (1997): Textural-structural relations and sequence of ore formation of lead-zinc deposit Toranitsa (Macedonia). *Geology of Ore Deposits*, Vol. **39**, pp. 91–105.

Hacker, B. R., Kelemen, P. B., Behn, M. D. (2015): Continental lower crust. *Annual Review of Earth and Planetary Sciences*, Vol. **43**, pp. 167–205.

Handy, M. R., Giese, J., Pleuger, J., Schmid, S. M., Spakman, W., Onuzi, K., Ustaszewski, K. (2019): Coupled crust-mantle response to slab tearing, bending and rollback along the Dinaride-Hellenide orogen. *Tectonics*, Vol. **38** (8), pp. 2803–2828.

Heinrich, C. A., Neubauer, F. (2002): Cu-Au-Pb-Zn-Ag metallogeny of the Alpine-Balkan-Carpathian-Dinaride geodynamic province, *Miner. Deposita*, Vol. **37**, pp. 533–540.

Jankovich, S. (1977): The copper deposits and geotectonic setting of the Tethyan Eurasian metallogenic belt. *Mineral. Deposit*., Vol. **12** (1), pp 37–47.

Jelenković, R., Kostić, A., Životić, D., Ercegovac, M. (2008): Mineral resources of Serbia. *Geologica Carpathica*, Vol. **59**, pp. 345–361.

Karamata, S., Majer, V., Pamić, J. (1980): *Ophiolites of Yugoslavia*. *Ophiolite*, *Tethyan Ophiolites* (special issue), 1, 105–125.

Laske, G. and Masters, G. (1997): *A Global Digital Map of Sediment Thickness.* EOS Transactions American Geophysical Union, **78**, F483. http://igppweb.ucsd.edu/~gabi/sediment.html#sed

Laske, G., Masters, G., Ma, Z., Pasyanos, M. (2013): Update on CRUST1.0 – A 1-degree Global Model of Earth's Crust. *EGU General Assembly 2013*, held 7–12 April 2013 in Vienna, Austria, id. EGU2013-2658.

Migineishvili, R. (2005): *Hybrid Nature of the Madneuli Cu-Au deposit, Georgia* // IGCP Project 486, 2005 field workshop, Kiten, Bulgaria, 14–19 September 2005. Bulgarian Academy of Sciences Geochemistry, Mineralogy and Petrology. – Sofia, Vol. **43**, pp. 128–132.

Munkov, S. (2006): The ore belt "Osogovo-Besna Kobila" (ore formations, morphogenetic types of deposits and physicochemical conditions of forming). In: *Ann. of the University of Mining and Geology "St. Ivan Rilski", Geol. and Geophys.*, Vol. **49**, pp. 119–130.

Prutsky, N. I. (2004): *The Cimmerian Belt of VMS Deposits Geodynamic Formation and the General Metallogeny of the Greater Caucasus*. Abstract of the doctoral dissertation. – Novocherkask. 40 p. (in Russian).

Resimić-Šarić, K., Karamata, S., Popević, A., Balogh, K. (2000): The eastern branch of the Vardar zone – the scar of the main Vardar ocean. In: *Geology and Metallogeny of the Dinarides and the Vardar Zone* (eds. S. Karamata and S. Janković), Zvornik, pp. 81–85.

Robertson, A. H. F., Karamata, S. (1994): The role of subduction-accretion process in the tectonic evolution of the Mesozoic Tethys in Serbia. *Tectonophysics*, Vol. **234,**. pp. 73–94.

Rudnick, R. L., Fountain, D. M. (1995): Nature and composition of the continental crust: a lower crustal perspective. *Rev. Geophys.*, Vol. **33**, pp. 267–309.

Rudnick, R. L., Gao, S. (2003): Composition of the continental crust. See *Holland & Turekian*, pp. 1–64.

Rudnick, R. L., Gao, S. (2014): Composition of the continental crust. See *Holland & Turekian*, pp. 1–51.

Sampietro, D., Reguzzoni, M., Negretti, N. (2013): *The GEMMA Crustal Model: First Yalidation and Data Distribution*. ESA SP, 722 p.

Schneiderhen, G. (1958): *Ore Deposits*. Izd-vo Inostr. Lit., Moscow: 501 pp. (Russian translation).

Serafimovski, T., Tasev, G. (2002): Magmatism and mineralization in the Vardar zone compressional area, SE-Europe. *11th Quadr. IAGOD Symposium and Geocongress*, pp. 22–26.

Serafimovski, T., Tasev, G. (2005): Sulfur isotope composition of some polymetallic deposits in the Republic of Macedonia. *Geol. Maced*., Vol. **19**, pp. 1–11.

Simmons, N. A., Forte, A. M., Boschi, L., Grand, S. P. (2010): GyPSuM: A joint tomographic model of mantle density and seismic wave speeds. *Journal of Geophysical Research*, Vol. **115**, B12310

Slovenec, D., Pamic, J. (2002): Geology of the Vardar zone ophiolites of the Medvednica Mountain area located along the Zagreb–Zemplin line (NW Croatia). *Geologica Carpathica*, Vol. **53**, pp. 53–59.

Sokol, K., Prelević, D., Romer, R. L., Božović, M., Van den Bogaard, P., Stefanova, E., Kostić, B., Čokulov, N. (2019): Cretaceous ultrapotassic magmatism from the Sava-Vardar zone of the Balkans, Lithos. https://doi.org/10.1016/j.lithos.2019.105268

Tasev, G., & Serafimovski, T. (2013): REE in some Tertiary volcanic complexes in the Republic of Macedonia. *Geol. Maced*., Vol. **23**, pp. 17–25.

Tsirambides, A., Filippidis, A. (2016): Gold metallogeny of the Serbomacedonian-Rhodope metallogenic belt (SRMB). *Bull. Geol. Soc. Greece*, *L*, 11 pp.

Tufar, W., Strucl, I. (1984): The Sasa lead-zinc deposit (Macedonia/Yugoslavia) and its position in the Serbian-Macedonian ore province. *Syngenesis and Epigenesis in the Formation of Mineral Deposits*. Berlin; Heidelberg: Springer-Verlag, pp. 412–421.

Volkov, A., Serafimovski, T., Galyamov, A. (2017): Prospects of discovery of new deposits of lead and zinc in the Republic of Macedonia. *Geol. Maced*., Vol. **31**, pp. 41–48.

Zavaritsky, A. N. (1950): Metamorphism and metamorphic rocks of massive sulfide deposits. In: *Massive Sulfide Deposits of the Urals*. – Moscow: Publishing House of the Academy of Science of the USSR, pp. 7–18 (in Russian).

Р е з и м е

ГЕОФИЗИЧКИ МОДЕЛ НА ЗЕМЈИНАТА КОРА И ГЕОДИНАМИЧКА ПОЗИЦИЈА НА ОЛОВНО-ЦИНКОВИТЕ НАОЃАЛИШТА ВО РЕПУБЛИКА СЕВЕРНА МАКЕДОНИЈА И СОСЕДНИТЕ ЗЕМЈИ

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Клучни зборови: Балкан; Северна Македонија; геодинамичка ситуација; геофизички модел; Земјина кора; наоѓалиште; олово; цинк: прогноза

Северозападниот правец на дистрибуцијата на наоѓалиштата на Pb-Zn во Република Северна Македонија, Грција и Србија одговара на трендот на средна густина и температура во горната мантија. Сличен правец исто така е забележан во структурата на дисконтинуитетот Мохо. Моќноста на седиментниот слој во горната кора варира од 7,8 km во областите на комплексот Динариди и Српско-Македонскиот масив до 100 m во Вардарската зона. Во исто време,

најмалата моќност е забележена на местата со најгуста дистрибуција на наоѓалиштата на Pb-Zn. Блоковите на формираниот тектонски меланж во Вардарската зона биле притиснати и еродирани, што веројатно е поради намалувањето на моќноста на седиментниот слој од горната кора и литосферата како целина, како и последица на високата еклотизација на долните офиолитски блокови. Во истиот тој период наоѓалиштата (Cu-Ni, SEDEX) формирани претходно во офиолитите и рифтовите биле откриени како резултат на издигнувањето и процесите на ерозија, а биле формирани и нови порфирски бакарни наоѓалишта, скарновски и/или жични наоѓалишта на Pb-Zn за време на формирањето на магматските лакови. Така, локалното подрачје на металогената зона Бесна Кобила–Осогово, каде што се наоѓаат наоѓалиштата Саса и Тораница, е еродирано. Врз основа на овој заклучок, се чини дека јужната насока на зоната е потенцијална за нови наоѓалишта на Pb-Zn под површината.