ABSTRACT

This study reports and discusses new radiometric ages, petrographic and volcanological observations and whole rock geochemical data of the rocks of the Rudnik Mts. volcano-intrusive complex. The complex belongs to the Serbo-Macedonian metallogenic belt and hosts a Pb-Zn-Ag deposit. Two distinct igneous events are distinguished. The first occurred, >30 Ma and was mainly characterized by extrusive and shallow intrusive dacites and andesites and was unrelated to mineralization. The second igneous event occurred <23 Ma and was highly heterogeneous in terms of its volcanic products and petrographic varieties, but with a strong predominance of quartzlatites. The dacite-andesites (first event) and the quartzlatites (second event) are geochemically similar and both display a calc-alkaline affinity and highly incompatible element enriched patterns on spider diagrams. However, the younger quartzlatites are richer in K₂O, Rb and Ba and poorer in Sr. Along with other petrochemical characteristics; this is taken as evidence that mixing between ultrapotassic lamprophyre/lamproite magma and an acid calc-alkaline (dacite-like) magma were essential petrogenetic processes of the second event. The proposed simplified volcanological model suggests that mixing was responsible for triggering strongly explosive volcanic activity and for providing the conditions for active hydrothermal and mineralization processes. The observed link between a specific magmatic phase and ore deposit formation can be a general phenomenon in the Balkans, and must be addressed by further and more advanced studies.

Keywords: Quartzlatite, Dacite, Magma mixing, Serbo-Macedonian metallogenic province

1. INTRODUCTION

The Balkan sector of the Alpine-Himalayan orogenic belt is probably one of the best regions to study the relationship between magmatism and the formation of ore deposits. Two roughly subparallel magmatic and metallogenic belts stretch through this region. The eastern one is referred to as the Banatite-Timok-Srednjegorje magmatic and metallogenic belt; it is Late Cretaceous in age, and is associated with andesite to basaltic andesite, presumably subduction-related volcanic rocks, and is characterized by the Cu-Au±Pb-Zn metallogeny of huge porphyry systems and high sulphidation epithermal gold deposits (JANKOVIĆ, 1997; VON QUADT et al., 2001, 2005; CIOBA-NU et al., 2002, etc). The western belt stretches along the main axis of the Balkan Peninsula and is named the Serbo-Macedonian metallogenic (and magmatic) province (JANKOVIĆ, 1966/67, 1984). It is Cenozoic in age and is associated with predominantly Pb-Zn-Ag±Sb±W metallogeny.

The Cenozoic Serbo-Macedonian magmatic and metallogenic province is spatially and temporarily associated with magmatic rocks that have a wide compositional spectrum, from basalts to rhyolites and from tholeiitic to alkaline series (e.g. CVETKOVIĆ et al., 2004; PRELEVIĆ et al., 2005; MLA-DENOVIĆ et al., 2015). This compositional heterogeneity was the reason why at many places in this province, the interplay between magmatic and mineralization processes has only been vaguely established. A plethora of petrographic types and highly variable volcanogenic facies have prevented the researchers from reconstructing the rock petrogenesis in sufficient detail, which was the main prerequisite for better understanding of the link between magmatism and mineralization.

Over several decades recently, knowledge about the age, origin and evolution of Cenozoic magmatism in the central Balkans has seriously improved (CVETKOVIĆ et al., 2000a, b, 2001, 2004, 2007, 2013; JOVANOVIĆ et al., 2001; PRELEVIĆ et al., 2000, 2001a, b, 2004, 2005, 2007; KORONEOS et al., 2011; SCHEFER et al., 2011; BOROJEVIĆ ŠOSTARIĆ et al., 2012; MLADENOVIĆ et al., 2015, among others). These studies provided a solid basis for refining the existing tectonomagmatic models and for making important steps forward in recognizing those magmatic processes that were essential for the formation of ore deposits. Although this information has already provoked new studies which suggest that some events of Cenozoic magmatism were more important for mineralization than others (e.g. BOROJEVIĆ ŠOSTARIĆ et al., 2012, 2013; CVETKOVIĆ et al., 2014; MLADENOVIĆ et al., 2015), there are still many places where the true links between igneous pro-
cesses and the formation of ore deposits remain poorly constrained.

In this paper we focus on the Rudnik Mts. volcano-intrusive complex that is situated in the very central part of the Serbo-Macedonian metallogenic province. It is our opinion, that this area is where the relationship between the magmatic evolution and mineralization is very clear, albeit still insufficiently known. So far, there is only a simplistic view about the general contemporaneity of the Cenozoic volcanism and mineralization (e.g. TOŠOVIĆ, 1997, 2000; POPOVIĆ & UMEJLIĆ, 2015). By reporting and discussing new radiometric age data, petrographic and volcanological observations and data on major and trace element whole rock concentrations, we try to reconstruct the magmatic evolution of the complex in unprecedented detail. We offer a volcanological model according to which the mineralization processes were genetically related to a younger igneous event that itself was controlled by magma mixing processes.

2. REGIONAL GEOLOGY AND GEOTECTONIC SETTING

It is widely accepted that the general geotectonic setting of the central Balkans was principally related to the formation, evolution and closure of the Mesozoic (Neo-)Tethys (see SCHMID et al., 2008; ROBERTSON et al., 2009; CVETKOVIĆ et al., 2016). Cenozoic geodynamics of this area evolved after the final consumption of Tethyan relics, and this geodynamic regime is still active today. The final Tethyan closure gave rise to the consolidation of the complex Dinaride – Albanide – Hel- lenide – Carpathian – Balkan section of the larger Alpine–Himalayan orogenic belt. The orogenic processes were controlled by continuous N- to NW-directed movements of the Adria plate that acted as an African promontory. Albeit generally compressive, this geodynamics involved regional-scale plate reorganizations, and this made it possible for certain regions to evolve into strike-slip or even purely extensional tectonic styles. These geotectonic regimes, which were highly variable on the regional to local scale, were responsible for the formation of Cenozoic magmatism and the accompanying continental depositional systems along this orogen.

The Cenozoic magmatism of the central Balkan Peninsula developed over a basement mostly composed of remnants of the Tethyan lithosphere and crust. These remnants occur along a mega-suture composed of dismembered ophiolite thrust sheets, fragments of the underlying metamorphic basement of distal African plate, lithologically strongly heterogeneous accretionary prism assemblages and various overlying overstep sequences, mainly flyschs.

The Rudnik Mts. volcano-intrusive complex is located in central Serbia, around 80 km south of Belgrade (see inset in Figure 1). It is a NNW-SSE elongated area that predominantly consists of two large masses of volcanic and shallow intrusive facies and an orefield located in-between (Figures 1 and 2). The immediate basement of the complex is composed...
Middle Miocene marginal facies conglomerates that grade into dark-reddish sandstones (FILIPOVIĆ et al., 1978). The terrigenous material contains abundant volcanic detritus that most likely originated by reworking of the rocks of the adjacent Rudnik Mts. volcano-intrusive complex.

3. SAMPLING AND ANALYTICAL TECHNIQUES

3.1. K-Ar AGES

Four K-Ar analyses of biotite and two of K-feldspar mineral separates, as well as one K-Ar analysis of an unspecified mixture of mafic minerals were undertaken in the Laboratory for K-Ar age dating of the Institute for Nuclear Research of the Hungarian Academy of Sciences in Debrecen (Hungary). Mineral separation involved crushing of whole rock samples and sieving to obtain the appropriate fraction. The separation was performed using a Franz magnetic separator and heavy liquid separation. Potassium concentrations were determined using flame photometry while applying an Na internal standard as well as Asia 1/65, LP-6, HD-B1, GL-O inter-laboratory standards. The samples were treated in an Argon extraction line using RF fusion in molybdenum crucibles. A 40Ar spike was added using a gas pipette system and the gas cleaning was done using Ti and SAES getters and liquid nitrogen traps. Ar isotope ratios were measured in the static mode, using a 15 cm radius magnetic sector mass spectrometer. Details about the instruments and methods can be found in BALOGH (1985). The radiometric ages were calculated according to the atomic constants of STEIGER & JAEGER (1977). Analytical errors represent one standard deviation, i.e. 68% analytical confidence level.

3.2. U-Pb ZIRCON DATING

Uranium, thorium and lead isotopes were analysed using a ThermoScientific Element 2 sector field (SF)-ICP-MS system coupled to a Resolution M-50 (Resonetics) 193 nm ArF excimer laser (ComPexPro 102F, Coherent) system at Goethe-University Frankfurt. Data were acquired in time-resolved peak-jumping pulse-counting/analogue mode over 356 mass scans, with a 20 s background measurement followed by 21 s sample ablation. Details about measurement conditions can be found in GERDES & ZEH (2009).

3.3. MAJOR AND TRACE ELEMENT ANALYSES

Major oxides and trace element analyses were carried out in the ACME Laboratories Ltd. Vancouver, Canada. Concentrations of major element oxides were determined by ICP atomic emission spectrometry, with detection limits of approximately 0.001–0.04% (accuracy 2–5%), whereas trace element and rare earth elements (REE) concentrations were measured using ICP-mass spectrometry (detection limits 0.01–0.5 ppm, accuracy 10–15% or better for trace elements and 1–5% for REE). STD SO-17 was certified in-house against 38 Certified Reference Materials including CANMET SY-4 and USGS AGV-1, G-2, GSP-2 and W-2 (KARSLI et al., 2007). The analyses are considered accurate within the limits for major elements.
4. RESULTS

4.1. FIELD OBSERVATIONS AND ROCK PETROGRAPHY

The following volcanic facies comprise the wider area of the Rudnik Mts. volcano-intrusive complex: 1) extrusive and shallow intrusive dacite and andesite, 2) extrusive and shallow intrusive quartzlatite, 3) monzogranite, 4) quartzlatite-rhyodacite pyroclastic rocks, and 5) basaltoid rocks. The spatial distribution of the most abundant volcanic facies is given in the simplified geological-volcanological map (Figure 1). In the following text we present the major petrographic and volcanological characteristics of the above listed rock facies that are grouped according to their radiometric age and geochemistry (see below). In addition, the spatial distribution of ore bodies within the Rudnik Mts. Orefield is illustrated in Figure 3 and a short description of mineralization types is given in subsection 4.1.6.

4.1.1 Extrusive and shallow intrusive dacite and andesite

Dacite and andesite rocks occur as shallow intrusive facies in the north-westernmost part of the complex, and are best exposed in the Vidačevica quarry (see Figure 1). Petrographically very similar dacite-andesite rocks are also found in boreholes near Stragari, outside of the complex, around 10 km east of the Rudnik Mts. Orefield. The rock mass in the Vidačevica quarry is generally polygonally jointed but along its periphery the rocks are platy jointed and display a pronounced fluidal fabric. The dacite is holocrystalline porphyrytic and polyphyric (>50 vol. % of phenocrysts) with seriate textures and consists of phenocrysts of plagioclase, quartz, biotite and amphibole, and microphenocrysts of the same minerals (Figure 2a). Quartz is relatively rare, subhedral and often shows embayments as effects of resorption. Biotite is slightly more abundant than amphibole. They are very fresh and show typical pleochroism, whereas opacitisation is only weakly developed. These volcanic rocks contain abundant crustal xenoliths (Figure 2a, inset). The xenoliths range from a few cm to a few dm in length and represent fragments of various schists, gneiss and amphibolites. Some xenoliths show the effects of contact-metamorphism along their margins.

4.1.2. Extrusive and shallow intrusive quartzlatite

Extrusive volcanic facies of quartzlatitic composition are predominant in the Rudnik Mts. volcano-intrusive complex. There are two large quartzlatitic masses that extend in a NNW-SSE direction and are separated by the Rudnik Mts. Orefield (Figure 1). In addition, there is a relatively large volcanic mass situated several kilometres east of the Rudnik Mts. Orefield.

The extrusive quartzlatites are exposed in many places and in particular in the Ćeramide active quarry. They are platy to polygonally jointed and often show evidence of planparallel and fluidal fabric. The roof parts of these extrusions are represented by highly porous rocks and have a tuff-like appearance. This was the reason that these rocks were erroneously interpreted as pyroclastic deposits (FILIPOVIĆ et al., 1978). The quartzlatite is porphyritic with variable phenocryst contents, but rarely above 30 vol.%. The phenocrysts are represented by quartz, plagioclase, sanidine, biotite and amphibole with apatite, zircon and opaques as accessories. The matrix is hypocrystalline and in some places the volcanic glass is replaced by micropoikilitic fine-grained textures (LOFGREN, 1971), which can easily be misinterpreted as holocrystalline (Figure 2b). Quartz is subhedral and often shows well developed embayments. Plagioclase is euhedral and tabular in shape and it very often exhibits so-called 'sieved' textures defined by the presence of tiny drop-like inclusions of glass (Figure 2b, inset). Such textures are commonly explained by partial resorption of plagioclase crystals, which implies nonequilibrium conditions during crystallization (NELSON & MONTANA, 1992). Sanidine is ubiquitously present, but it can be as 10 cm crystals and, therefore, rarely present in thinsections (Figure 2b). It is pale pinkish to white in colour and often shows typical Carlsbad-type twinning. Biotite occurs in the form of prismatic flakes, usually elongated in one direction, sometimes showing evidence of plastic deformation. It shows pleochroism in dark-red-brown colours. In some samples biotite contains needle-like sagenite inclusions and those biotite flakes usually show the effects of resorption (Figure 2c). Amphibole appears in prismatic and euhedral to subhedral phenocrysts. In some samples it is more abundant than biotite, in others it is almost totally lacking. One of the most important petrographic features of these quartzlatites is the presence of rounded to subrounded mafic microgranular en-
clavites. The clavites are lamprophyric in character and are rich in dark mica, sometimes accompanied by amphibole. In the south-eastern part of the complex a composite dome-like body composed of dacite – quartzlatite – leucominette occurs. This rock association is described in detail by PRELEVIĆ et al. (2000, 2001a).

Shallow intrusive quartzlatite occurs as a few metres to a few tens of meters thick discordant dykes or concordant sill-like bodies, which are mostly, emplaced within Cretaceous flysch sediments (Figures 1 and 3). The dykes often appear on the surface, but they are abundant in the Rudnik Mts. Orefield, in particular in the underground mine. The Cretaceous sediments show the effects of contact-metamorphism, but without regularities between the contact-metamorphic grade and the thickness and orientation of these quartzlatite shallow intrusions. The contact-metamorphic rocks range in composition from only slightly thermally metamorphosed sandstones up to garnet- and axinite bearing skarns. Shallow intrusive quartzlatites are petrographically almost indistinguishable from the extrusive quartzlatites described above. They are hypo- to holocrystalline porphyritic in texture and show variable abundance of phenocrysts. Some dykes show chilled margins and are devoid of large sanidine phenocrysts.

Hydrothermal quartzlatite breccia represents a subgroup of shallow intrusive facies. They are spatially restricted to the Rudnik Mts. Orefield and are found both at the surface and in the underground mine, in the latter case in close contact with mineralization. They are clast-supported mostly monomict breccias with highly unsorted angular fragments that sometimes show jigsaw puzzle fit structures. The fragments are usually strongly altered and sometimes heavily mineralized, especially along the margins of the volcanic fragments (Figure 2d). The most important alterations are propylitization and silicification, whereas potassic alteration is subordinate. The fragments are cemented by highly variable material, from silicates, dominated by quartz and clay minerals through primary hydrothermal sulphides to supergene limonite.

Some breccias are polymict in character and consist of volcanic fragments of different textures, mineral compositions and the extent of alteration and mineralization as well as of those of adjacent contact-metamorphosed flysch sediments (Figure 2e). The polymict breccia sometimes contains remarkably fresh fragments of equigranular rocks similar to monzogranite that is a separate lithology described below.

4.1.3. Monzogranite

The presence of plutonic rocks of monzogranite composition was first reported by BRKOVIĆ et al. (1980) who described weak outcrops within the Rudnik Mts. Orefield. These outcrops most likely represent the internal portions of thicker shallow quartzlatite intrusions. During our field campaign these rocks are found exclusively as individual fragments in the polymict hydrothermal breccia described above.

The plutonic rocks show uniform petrographic characteristics and mineral compositions by displaying medium- to rarely fine-grained hypidiomorphic granular texture and massive and homogeneous fabric (Figure 2f). The monzogranite is composed of plagioclase, quartz, potash feldspar, biotite and subordinate amphibole. Plagioclase is subhedral and, along with biotite and amphibole, constitutes the main crystal network, whereas the interstitial spaces are filled by quartz and perthitic potash feldspar. Sphene, apatite, opaques and zircon are the most important accessory minerals. Rare fragments of these rocks exhibit inequigranular texture with larger potash feldspar oikocrysts, which makes these rocks petrographically similar to the shallow intrusive quartzlatite.

4.1.4. Quartzlatite-rhyodacite pyroclastic rocks

These rock facies occur only in the most northwestern part of the complex (Figure 1). In the wider area, they appear as irregular patches of volcaniclastic rocks that usually overlie Cretaceous flysch deposits and are transgressively covered by Mio-Pliocene lacustrine strata. They are not addressed in detail in this study, but according to our field observations in the most northwestern part of the complex as well as according to data from the Basic Geological Map of the SFR of Yugoslavia, Sheets Kragujevac and Gornji Milanovac (FILIPOVIĆ et al., 1978; BRKOVIĆ et al., 1980, respectively), these rocks correspond to rarely preserved unwelded to welded ignimbrites. More rarely, they represent various reworked and redeposited primary pyroclastic deposits (TERZIĆ & TERZIĆ, 1972). Dense juvenile fragments of these pyroclastic rocks are porphyritic with glassy to hypocrystalline groundmass and are petrographically very similar to the extrusive quartzlatites described earlier. Although the juvenile pyroclasts only rarely contain large sanidine phenocrysts, they are characterized by sieved plagioclase phenocrysts and often contain partially resorbed biotite and hornblende.

4.1.5. Basaltoid rocks

Basaltoid rocks of the wider Rudnik Mts. complex are studied petrologically in detail by CVETKOVIĆ et al. (2004) and PRELEVIĆ et al. (2005). These rocks have negligible volumes in comparison to the acid to intermediate rocks described above, and mostly occur as several metre thick dykes and sills or lava plugs, rarely as lava flows. They range in composition from calc-alkaline, medium- and high-K calc-alkaline basalts to those showing ultrapotassic affinity and displaying minette or lamproite petrographic characteristics. As previously mentioned above, PRELEVIĆ et al. (2000, 2001a) reported the presence of hybrid rocks in the southeastern part (Beli Kamen) of the complex and called them leucominette.

4.1.6. The Rudnik Mts. Orefield

Presenting detailed characteristics of the Rudnik Mts. polymetallic deposit is beyond the scope of this study. Therefore, in this subsection we only briefly summarize what is generally known about this complex deposit (MILIĆ, 1972; JANKOVIĆ et al., 2003; TOŠOVIĆ, 1997, 2000).

As it is shown in Figure 3, the Rudnik Mts. Orefield is an elongated area composed of contact metamorphosed clastic and carbonate flysch sediments. The contact metamorphic zone hosts several elongated areas of hydrothermal breccia and numerous quartzlatite dyke-like shallow intrusive facies. These rock facies, which have already been described above, are closely spatially associated to numerous orebodies, which indicates that mineralization is most likely associated with the same structures that were used by the quartzlatite magma.
The orebodies have variable morphology, most often, they are platy to vein- and lens-like. The orebodies range in size from $10 \, m^3$ to $7 \times 10^3 \, m^3$ or even up to $3 \times 10^5 \, m^3$. They display two general modes of occurrence: 1) gently dipping, up to 2 m thick lenses that can be traced for 150-350 m; they are mainly spatially associated to contact-metamorphosed limestone blocks within the flysch sediments, and 2) predominantly high dipping platy bodies located within the subvolcanic quartz-latites (MILIĆ, 1972).

TOŠOVIĆ (1997) recognized roughly two major stages of mineralization processes in this area. The first that occurred was skarn mineralization associated in time with formation of the contact metamorphic rocks. This mineralization is only locally developed but in some places contains significant amounts of scheelite, magnetite and subordinate cassiterite (STOJANOVIĆ et al., 2006). The skarn mineralization is overprinted by the formation of hydrothermal replacements and structure-controlled veins and lenses. During this stage the most important orebodies originated. The mineralogy of these orebodies is dominated by pyrrhotite which often shows transitions to Ni-bearing pyrrhotite, sphalerite, galenite, chalcopyrite and subordinate arsenopyrite. The Pb-Zn grade in these ore bodies is highly variable but mostly around 7-8 %. In addition, the ore contains up to 0.5 %, 150 ppm and 450 ppm of Cu, Ag and Bi, respectively (JANKOVIĆ et al., 2003).

4.2. K-Ar AND U-Pb RADIOMETRIC AGES

Seven so far unpublished K-Ar age determinations and 11 K-Ar ages published earlier are reported together in Table 1. A mixture of mafic minerals of the hydrothermally altered sample R-19 revealed the largest relative error of > 20 %. Because this sample is also characterized by low potassium contents and a low concentration of radiogenic argon, the obtained age of 39±9.2 Ma is discarded. However, given that this sample was very important with respect to defining the maximum age of the mineralization, zircons from the sample were analyzed by LA-ICP-MS on U-Pb. The results shown in Figure 4 gave a concordia U-Pb age of 22.99 ±0.28 Ma.

All other biotite and K-feldspar separates gave K-Ar ages with relatively small errors (< ±1.13 Ma), consequently, their ages are reliable and considered to be close to the time of crystallization. There are two groups of ages. One is Oligocene and was obtained on the extrusive dacite from the Vidačevica quarry (35.30±1.09 Ma) and on the shallow intrusive andesite in a borehole near Stragari (35.69±1.13 Ma). The other group is represented by the latest Oligocene to Early Miocene ages (roughly 19-23 Ma). They are obtained by various volcanic quartzlatitic facies that include massive (19.02±0.59 Ma) to porous (20.44±0.67 Ma) extrusive quartzlatites, unaltered quartzlatite, breccia from the underground mine (22.97±0.72 Ma), and monzogranite from a borehole in the Rudnik Mts. Orefield (23.14±0.73 Ma).

Such a bimodal distribution is observed in other available K-Ar ages. These data also show two ranges, one between 29

Figure 4. Concordia U-Pb diagram for zircons from a hydrothermally altered and mineralized sample R-19.

Figure 5. Total alkali vs silica classification diagram (A - LE BAS et al., 1986) and the SiO₂ vs K₂O diagram (B - PECCERILLO & TAYLOR, 1976) for studied rocks of the Rudnik Mts. volcano-intrusive complex.
rocks that are ultrapotassic to shoshonitic in character (FOL-

2) most rocks correspond to subalkaline and to high- to medi-

above 55 wt.%, with subordinate intermediate to basic rocks,

respond to acid to intermediate rocks with silica contents

2 vs K 2O diagram (PEC-

and leucominette rocks are taken from the literature

So far unpublished whole rock major and trace element con-

chemistry and the radiometric age of the volcanic and intrusive

field and petrographic observations presented above as

as new and previously published radiometric and geo-

chemical data provide conditions for better understanding the

origin and evolution of the Rudnik Mts. volcano-intrusive

complex. Previously, there was a strong mismatch between a

highly variable rock petrography and volcanic facies, on one

side, and fragmentary information about petrology and geo-

chemistry and the radiometric age of the volcanic and intrusive

rocks. In the following discussion we first establish the rela-

tionship between radiometric ages and the inferred rock com-

positions, then, we discuss the younger quartzlatite volcanic

event as the most significant in terms of the volume of volcanic

products and with respect to its significance for mineralization

5. DISCUSSION

The field and petrographic observations presented above as

well as new and previously published radiometric and geo-

chemical data provide conditions for better understanding the

origin and evolution of the Rudnik Mts. volcano-intrusive

complex. Previously, there was a strong mismatch between a

highly variable rock petrography and volcanic facies, on one

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tionship between radiometric ages and the inferred rock com-

positions, then, we discuss the younger quartzlatite volcanic

event as the most significant in terms of the volume of volcanic

products and with respect to its significance for mineralization

processes. Finally, we propose a simplified volcanological

model for the entire Rudnik Mts. volcano-intrusive complex.

5.1. THE TIME-COMPOSITIONAL

FRAMEWORK OF THE RUDNIK

MTS. VOLCANO-INTRUSIVE COMPLEX

The available radiometric analyses indicate that there is a cou-

pling between the age and the composition of the Rudnik Mts.

igneous rocks. The extrusive to subvolcanic dacite and andes-
ite rocks, which are strongly subordinate in volume, show an Oligocene age of around 35 Ma. This age is similar to an unpublished K/Ar age of around 32 Ma (Table 1) obtained on a petrographically very similar dacite from Slavkovica, located around 15 km west of the Rudnik Mts. (TERZIĆ & VUKOV, 1984). Alternatively, volcanic and shallow intrusive quartzlatite facies as well as monzogranite from a borehole are clearly younger and have radiometric ages ranging between 19 Ma and 23 Ma. The U-Pb zircon age of 22.99 ±0.28 Ma obtained from a strongly hydrothermally altered and mineralized hydrothermal quartzlatitic breccia delimits the maximum age of mineralization and suggests that formation of the ore deposit was temporarily and, most likely, also petrogenetically associated with the quartzlatites.

The available ages of basaltoid rocks of the wide Rudnik Mts. area range between 24 Ma and 32 Ma (CVETKOVIĆ et al., 2004; PRELEVIĆ et al., 2005), which suggests that basaltoid magmatism was likely active during the afore-mentioned events. Although there are no radiometric ages of basaltoid rocks younger than 24 Ma, there is solid evidence that mafic magma similar in composition to lamprophyre-lamproite co-existed with acid melts during the younger volcanic event when most of the quartzlatite originated. In particular, much textural evidence, such as the presence of mafic microgranular enclaves, sieved plagioclase phenocrysts, co-existing phlogopite (Mg#[molMg/Mg+Fe]tot up to 0.91) and biotite (Mg# up to 0.61) (PRELEVIĆ et al., 2001a), partially resorbed mafic phenocrysts as well as the occurrence of large composite eruptions in the area of Beli Kamen (PRELEVIĆ et al., 2000, 2001a), imply that mixing between a lamprophyric to lamproitic magma and a dacitic melt has played a significant role in the quartzlatite petrogenesis. According to their model, hybridization occurred after a lamproite-like magma had invaded the base of an already stratified chamber with dacitic magma; this induced turbulent fountains and formation of more mafic leucominette facies. Similar magma mixing processes were reported in the adjacent Miocene Borač complex (CVETKOVIĆ & PECSKAY, 1999; CVETKOVIĆ et al., 2001). Furthermore, they considered that the injection of lamproite-lamprophyre melts has served as a trigger for Plinian explosive activity.

The data from this study are insufficient to refine the model of PRELEVIĆ et al. (2001a) to any significant extent. However, our data can be used to illustrate relatively simple geochemical variations that imply magma mixing processes. Diagrams that show 5.2. QUARTZLATITE VOLCANISM: THE LINK BETWEEN MAGMATISM AND MINERALIZATION

The time and compositional constraints presented above demonstrate that the Rudnik Mts. volcano-intrusive complex is predominantly composed of various products of magma of quartzlatite composition, all of which formed roughly simultaneously <23 Ma ago. Furthermore, there are strong indications that these quartzlatite volcanic, subvolcanic and intrusive facies were emplaced via a continuous succession of volcanic events, which were ultimately followed by hydrothermal stages and precipitation of Pb-Zn mineralization. It is also almost indisputable that magma mixing has played a crucial role in the volcanic events that produced the Rudnik Mts. quartzlatites. The petrographic evidence has already been listed above and here we discuss additional aspects that are closely related to rock geochemistry, volcanology and, supposedly, to mineralization processes.

Petrological and geochemical consequences of mixing between lamproite- and dacite-like magmas have already been recognized and explained in other Cenozoic provinces of the Balkan Peninsula. The most comprehensive study was by PRELEVIĆ et al., (2004) on the hybrid rocks from the Veliki Majdan area in western Serbia, suggesting that magma mixing may be a common process for lamprophyre formation. PRELEVIĆ et al. (2000, 2001a) described similar processes near Beli Kamen in the southeastern part of the Rudnik Mts. volcano-intrusive complex. They recognized petrographic and geochemical transitions between leucominette and the rhyodacite part of the extrusion and attributed this to hybridization. According to their model, hybridization occurred after a lamproite-like magma had invaded the base of an already stratified chamber with dacitic magma; this induced turbulent fountains and formation of more mafic leucominette facies. Similar magma mixing processes were reported in the adjacent Miocene Borač complex (CVETKOVIĆ & PECSKAY, 1999; CVETKOVIĆ et al., 2001). Furthermore, they considered that the injection of lamproite-lamprophyre melts has served as a trigger for Plinian explosive activity.

The data from this study are insufficient to refine the model of PRELEVIĆ et al. (2001a) to any significant extent. However, our data can be used to illustrate relatively simple geochemical variations that imply magma mixing processes. Diagrams that show
different variation paths for dacite-andesite and quartzlatite rocks of the Rudnik Mts complex are given in Figures 7a, b. From the plots of MgO (wt.%) vs Zr (ppm) and MgO (wt.%) vs $\text{Al}_2\text{O}_3$ (wt.%)/Zr (ppm) diagrams it is evident that: 1) dacite-andesite rocks plot close to upper crustal compositions reflected by the composition of Cretaceous flysch deposits, 2) these rocks form trends of increasing Zr contents and $\text{Al}_2\text{O}_3$/Zr ratios with decreasing MgO contents, which implies the effects of assimilation plus fractional crystallization processes (AFC), 3) these trends are distinct with respect to the trends shown by quartzlatites, leucitite and basaltoid (lamprophyre-lamproite) rocks, and 3) the latter trends suggest compositional mixing between melts similar in composition to the most evolved dacite (the continuation of the dacite-andesite trend) and basaltoid (lamprophyre-lamproite) melts. This is exactly what is suggested by both field and petrographic evidence.

These mixing processes had very important consequences with respect to volcanic activity and mineralization. First, as already mentioned, it most likely provided conditions for triggering large-scale explosive eruptions that produced widespread pyroclastic products. Second, the injection of water-laden lamprophyre-lamproite melts may have delivered additional water to the resulting hybridized magma, and this could have been crucial for enabling secondary boiling, even in a magma that previously degassed via strong explosive activity. It can therefore be postulated that without these injections of mafic melts, the magma chamber would probably be emptied by explosions, but it would have occurred later and have not led to subsequent hydrothermal and mineralization phases. Finally, the mixing was responsible for the generation of a wide spectrum of volcanic facies and petrographic rock varieties. The volcanological and petrographic variability imposed great problems for earlier investigators, because their descriptions were overburdened by dozens of different rock varieties, such as: dacite, quartzlatite, rhyodacite, lamprophyre, lamproite, leucite, leucite basanite, minette, kajantine, trachybasalt, trachyandesite, latite, trachyte, and so on and so forth. Such a ‘flood’ of petrographic names prevented them from understanding the rock petrogenesis in sufficient detail and to produce valid tectonomagmatic interpretations.

Our volcanological observations indicate that the breccia occurring in the Rudnik Mts. Orefield most likely originated in response to hydraulic fragmentation events that are readily produced by subsurface decompression of fluids (e.g. CAS & WRIGHT, 1987). PHILLIPS (1972) produced a model for these brecciation processes and for the formation of mostly subvertical, pipe-or dyke-like brecciated zones. Given that these breccias appear at many places on the surface, it is likely that at least some of them represented diatreme-like structures that originated via phreatic explosions. The hydrothermal fluids that generated brecciation were also responsible for precipitating mineralization, and that is evident from the fact that ore is often deposited in the matrix of these breccias, i.e. some fragments are cemented by ore minerals. The presence of strongly polymict breccia can indicate that some of these rocks may be polyphase in origin and can be associated with tectonic processes as well. These processes can be responsible for the presence of equigranular monzogranite fragments within the polymict breccias.

The granular monzogranite facies probably represent parts of a presumably large unexposed magmatic body, whereas subvolcanic quartzlatitic bodies, which are found both in the underground mine and on the surface, can be apophyses of this intrusive.

5.3. A SIMPLIFIED VOLCANOLOGICAL MODEL

A schematic volcanological model for the Rudnik Mts. volcano-intrusive complex is given in Figure 8. The model summarizes in a most simplistic way all of the available information and proposes a possible succession of igneous processes from the early Oligocene to the Early Miocene.

The first igneous event occurred >30 Ma, when the extrusive and shallow intrusive dacites and andesites originated (Figure 8a). As evidence of explosive volcanic activity at this stage is lacking, the model assumes that the event was exclusively associated with extrusive to shallow intrusive activity.
Volcanic processes occurred after a repose period of several million years, by the beginning of the Miocene (~23 Ma). It is very likely that during this time, formation of lacustrine depositional systems also occurred (Figure 8b). This synthesis suggests that before the second magmatic event in the area of the present day Rudnik Mts. orefield a large and presumably stratified magma chamber existed (Figure 8c). Due to advanced magmatic differentiation, the roof parts of this magmatic chamber were extremely depleted in crystals and enriched in magmatic gases, whereas its internal parts were progressively less gas- and more crystal-rich. The model involves a scenario according to which the chamber hanging wall did not collapse due to a simple overpressurisation of the underlying gas-rich magma, but in response to injections of water-saturated lamproite-like mafic melts from beneath (Figure 8d). This triggered huge explosive volcanic activity that probably had Plinian to sub-Plinian characteristics and produced large eruption columns and various pyroclastic fall and pyroclastic flow deposits (Figure 8e). This stage left behind numerous relics of welded to non-welded ignimbrites and subordinately shaped subvolcanic intrusions (Figure 8f). The presence of granular textured monzogranite as well as strong contact metamorphic effects indicate that large masses of quartzlatite did not reach the surface, but remained to crystallize at shallow crustal levels. On crystallization of these magmatic masses, the igneous processes in the Rudnik Mts. area terminated.

The phase of formation of polymetallic mineralization followed the afore-mentioned magmatic events. The precipitation of mineralization was controlled by a large hydrothermal system that developed in the hanging wall of the solid but still hot magmatic intrusive body. As already argued above, this model proposes that incorporation of lamproite-like and water-rich mafic melts contributed greatly to the hydrothermal potential of the acid magma. Decompression of these fluids induced subsurface and superficial brecciation and deposition of ore minerals (Figure 8g).

### 6. Conclusions

This study demonstrates that there is still room for large improvements in our understanding of how igneous and metallogenic processes were linked during Cenozoic magmatism of the Balkan Peninsula. The main conclusions are as follows:

1. The Rudnik Mts. volcano-intrusive complex formed in two magmatic events.
2. The first magmatic event was associated with the formation of extrusive to shallow intrusive dacites; this phase occurred before 30 Ma.
3. The second event developed around 23 Ma. It was much more heterogeneous in terms of volcanic activity and magmatic products; this magmatism produced various products of quartzlatitic magma depending on the crystallization conditions.
4. One of the most prominent petrogenetic processes of the second event was mixing between a lamproite-like magma and dacitic melts; this process most likely triggered large explosive Plinian to sub-Plinian events.

5. According to the simplified volcanological model, magma mixing was crucial for mineralization processes in the Rudnik Mts. volcano-intrusive complex; injected lamproite-like and water-saturated melt provided conditions for a strong hydrothermal phase, formation of hydraulic breccia and precipitation of ore minerals.

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