*Field Trip Guide*
*17th EGU Émile Argand Conference on Alpine Geological Studies*
*Fruška Gora, Serbia*

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# Cenozoic magmatism and metallogeny in Serbia: insights from the Rudnik volcano–intrusive complex

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**Key words:**
*Rudnik, Serbo–Macedonian Cenozoic magmatic–metallogenic province, post-collisional magmatism, skarn deposit, polymetallic mineralization.*

**Abstract.** This field guide accompanies the pre-conference field trip of the 17th EGU Émile Argand Conference on Alpine Geological Studies and presents key exposures of the Rudnik volcano–intrusive complex and the associated Pb–Zn–Cu–Ag skarn deposit in central Serbia. The excursion focuses on the relationships between Oligocene–Miocene post-collisional magmatism, hydrothermal activity, contact metamorphism, and polymetallic ore formation within the Serbo–Macedonian Cenozoic magmatic–metallogenic province. The principal field stops are located within the Rudnik volcano–intrusive complex and encompass quartz–latite volcanic and subvolcanic facies, diatreme breccias, contact-metamorphic rocks, and underground exposures of skarn-hosted sulfide mineralization. To place the Rudnik system within a broader volcanological context, the field trip also includes the nearby Borač volcanic complex, which preserves a more complete record of volcanic and pyroclastic facies associated with Oligocene–Miocene post-collisional magmatism in central Serbia. The selected localities provide complementary insights into the volcanic, subvolcanic, and hydrothermal processes that governed the evolution of magmatic–hydrothermal systems and associated Pb–Zn–Cu–Ag mineralization within the Serbo–Macedonian Cenozoic magmatic–metallogenic province.

**Апстракт.** Овај теренски водич прати претконференцијску екскурзију 17. EGU Émile Argand конференције о алпским геолошким истраживањима и приказује кључне изданке вулканско-интрузивног комплекса Рудник и са њим повезаног Pb–Zn–Cu–Ag скарновског лежишта Рудник у централној Србији. Екскурзија је усмерена на сагледавање односа између олигоценско–миоценског постколизионог магматизма, хидротермалне активности, контактног метаморфизма и формирања полиметаличних рудних лежишта у оквиру Српско–македонске кенозојске магматско-металогенетске провинције.Главни теренски локалитети налазе се у оквиру вулканско-интру-зивног комплекса Рудник и обухватају кварцлатитске вулканске и суб-вулканске фације, дијатремске брече, контактно-метаморфне стене и рудна тела сулфидне минерализације у скарновима. Како би се систем Рудника сагледао у ширем вулканолошком контексту, екскурзија обухвата и оближњи вул-

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**Кључне речи**:
*Рудник, Српско–македонска кенозојска магматско-металогенетска провинција, постколизиони магматизам, скарновско лежиште, полиметалична минерализација.*

кански комплекс Борач, који чува потпунији запис вулканских и пирокластичних фација повезаних са олигоценско-миоценским посткозионим магматизмом у централној Србији.
Одабрани локалитети пружају увиде у вулканске, субвулканске и хидротермалне процесе који су контролисали еволуцију магматско-хидротермалних система и са њима повезане Pb–Zn–Cu–Ag минерализације у оквиру Српско–македонске кенозојске магматско-металогенетске провинције.

## Foreword

This field guide accompanies the pre-conference field trip organized as part of the 17th EGU Émile Argand Conference on Alpine Geological Studies, held in Fruška Gora, Serbia, from 16th to 18th September 2026.

The Rudnik volcano–intrusive complex, located in central Serbia, represents a well-exposed example of post-collisional magmatism and associated ore-forming processes within the Serbo–Macedonian Cenozoic magmatic–metallogenic province. It hosts a Pb–Zn–Cu–Ag skarn deposit and provides insights into the interplay between magmatism, contact metamorphism, and sulfide ore mineralization.

Apart of the Rudnik volcano–intrusive complex and its associated ore system, this two-day field trip also includes the nearby Borač volcanic complex that preserves a more complete record of the volcanic and pyroclastic facies associated with Oligocene–Miocene post-collisional magmatism in central Serbia. The Rudnik volcano–intrusive complex provides excellent exposures of shallow intrusive facies, diatreme breccias, contact-metamorphic rocks, and polymetallic mineralisation. Together, the two complexes provide complementary insights into the volcanic, subvolcanic, and hydrothermal processes that controlled the evolution of magmatic–hydrothermal systems and associated ore-forming processes within the Serbo–Macedonian Cenozoic magmatic–metallogenic province.

The first day focuses on surface localities (FS 1–FS 3), whereas the second day includes a visit to the Rudnik underground mine (FS 4), providing a direct insight into skarn assemblages, ore bodies, quartz–latite dykes, and the subsurface continuation of the diatreme breccia (FS4).

For participants interested in more detailed information about the regional and deposit-scale context, the following references are recommended: Janković (1978), Prelević et al. (2001), Jelenković (2014), Cvetković et al. (2016), and Petrović et al. (2024).

## Introduction

Ore deposits in Serbia are located within the Alpine–Balkan–Carpathian–Dinaride segment of the Western Tethyan metallogenic belt (Janković, 1990; Janković, 1997). This belt records the tectonomagmatic transition from Mesozoic subduction to Cenozoic post-collision, following the closure of the Vardar Ocean and the collision between Eurasia- and Gondwana-derived units (Janković, 1978; Heinrich & Neubauer, 2002; Richards, 2015).

The Western Tethyan metallogenic belt consists of two major magmatic–metallogenic provinces in Serbia (Janković, 1990; Jelenković, 2014; Fig. 1). The first is the Carpatho–Balkanian province, part of the renown Apuseni–Banatite–Timok–Srednjegorie Belt; it is an Upper Cretaceous arc-related province (ca. 92–65 Ma), characterized by calc-alkaline magmatism and porphyry-, epithermal-, and skarn Cu–Au deposits (e.g. Bor, Majdanpek, Veliki Krivelj, Čukaru Peki, etc). The second is the Cenozoic post-collisional Serbo–Macedonian province (ca. 35–5 Ma), characterized by calc-alkaline to high-K calc-alkaline, shoshonitic, and locally ultrapotassic magmaism, and associated with vein-, skarn-, carbonate-replacement-, and locally porphyry Pb–Zn–Ag–(Cu–Au–Sb–W) deposits (e.g. Rudnik, Veliki Majdan, Trepča, Lece, Kiseljak, etc).

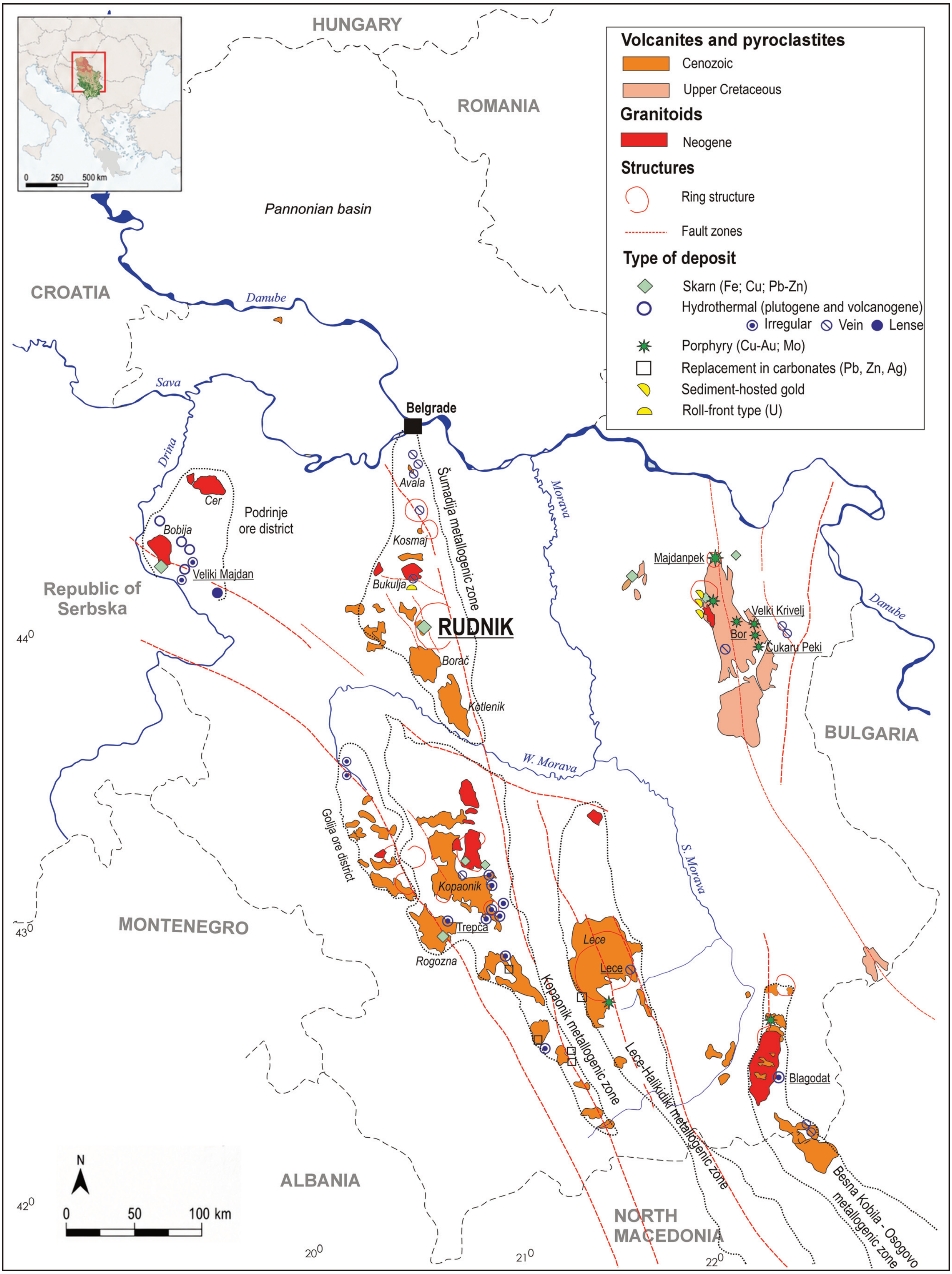


***Fig. 1***. *Volcano–intrusive complexes in Serbia and associated ore deposits. Modified after* JELENKOVIĆ *et al. (2008).*

Numerous studies have established a close temporal and genetic relationship between magmatism and polymetallic mineralization during the younger stages of Oligocene–Miocene magmatic activity in the Serbo–Macedonian Cenozoic magmatic–metallogenic province (e.g. Prelević et al., 2004, 2005; Palinkaš et al., 2013; Šoštarić et al., 2013; Cvetković et al., 2016; Hoerler et al., 2022, among others). This relationship was characterized by magma mixing, explosive volcanism, emplacement of shallow intrusions, and ore-forming hydrothermal activity, which all controlled ore formation. These processes are particularly well documented in the volcano–intrusive complexes of central and southwestern Serbia, notably at Rudnik, one of the best-studied systems, including Borač complex with its characteristic volcanic facies (Figs. 1, 2).

The Rudnik Pb–Zn–Cu–Ag skarn deposit represents one of the most economically important and geologically best-constrained polymetallic systems within the Serbo–Macedonian magmatic–metallogenic province of Serbia. Sulfide ore mineralization is closely linked to Oligocene–Miocene calc–alkaline magmatism and occurs as genetically related skarn-, vein-, and diatreme breccia-hosted ore bodies (Petrović et al., 2024). The deposit comprises more than 90 individual ore bodies and has been continuously mined since 1952. Cumulative production exceeds 15 Mt of ore, establishing Rudnik as one of Serbia's most important producers of lead, zinc, and silver concentrates (Jelenković et al., 2008).

## Geology of the Rudnik area

The Rudnik volcano–intrusive complex is an NNW–SSE-trending magmatic system composed of volcanic, subvolcanic, and intrusive facies (Cvetković et al., 2016). The Rudnik Pb–Zn–Cu–Ag skarn deposit, located in its central part, represents the principal ore system of the area (Fig. 2). The complex was emplaced into Lower Cretaceous (Barremian–Aptian) and Upper Cretaceous (Turonian–Senonian) flysch successions, while its more distal volcanic facies are spatially associated with Oligocene–Miocene sedimentary rocks (Fig. 2).

The complex records a two-stage Cenozoic magmatic evolution (Cvetković et al., 2016). The older Oligocene stage (≥30 Ma) is represented by dacitic to andesitic volcanic and shallow intrusive rocks that locally overlie and intrude the Upper Cretaceous flysch series. The younger Miocene stage (≤23 Ma) comprises quartz–latite lava flows, pyroclastic deposits, quartz–latite dyke-like subvolcanic intrusions and suposedly true intrusive facies in depth. Their close spatial association with the ore bodies reveals that sulfide mineralization was controlled by the same NE–SW-trending structures that acted as conduits for the emplacement of quartz–latite magma.

Quartz–latite volcanic facies are predominantly exposed in the northwestern and southwestern sectors of the complex, whereas the central zone is characterized by shallow quartz–latite intrusive bodies, including dykes, sills, and diatreme breccias spatially related to the ore deposit (Figs. 2, 3). The diatreme facies occur as polymict breccias composed of fragments of Upper Cretaceous sedimentary rocks, volcanic rocks, metamorphic basement rocks, and subordinate ultramafic rocks, enclosed within a strongly altered silicified, argillaceous, and carbonate-rich matrix. These breccias commonly occupy structural discontinuities and exhibit intrusive contacts, indicating a close relationship between fracturing, magma emplacement, and hydrothermal activity (Cvetković et al., 2016; Petrović et al., 2024). Volcanological observations indicate that the breccias exposed within the Rudnik ore field most likely originated through hydraulic fragmentation caused by rapid subsurface decompression of hydrothermal fluids (e.g., Cas & Wright, 1987). The hydrothermal fluids responsible for brecciation also played a key role in ore formation, as evidenced by the occurrence of sulfide mineralization within the breccia matrix, where rock fragments are commonly cemented by ore minerals. The mineralization is dominated by arsenopyrite and pyrrhotite, accompanied by subordinate chalcopyrite, galena, and sphalerite (Petrović et al., 2024).

The formation of the ore bodies was controlled by lithological contrasts, particularly at contacts between carbonate- and siliciclastic flysch units that provided favourable sites for skarn development. Contact metamorphism produced skarns, skarno-ids, hornfelses, metasandstones, and metamudstones,

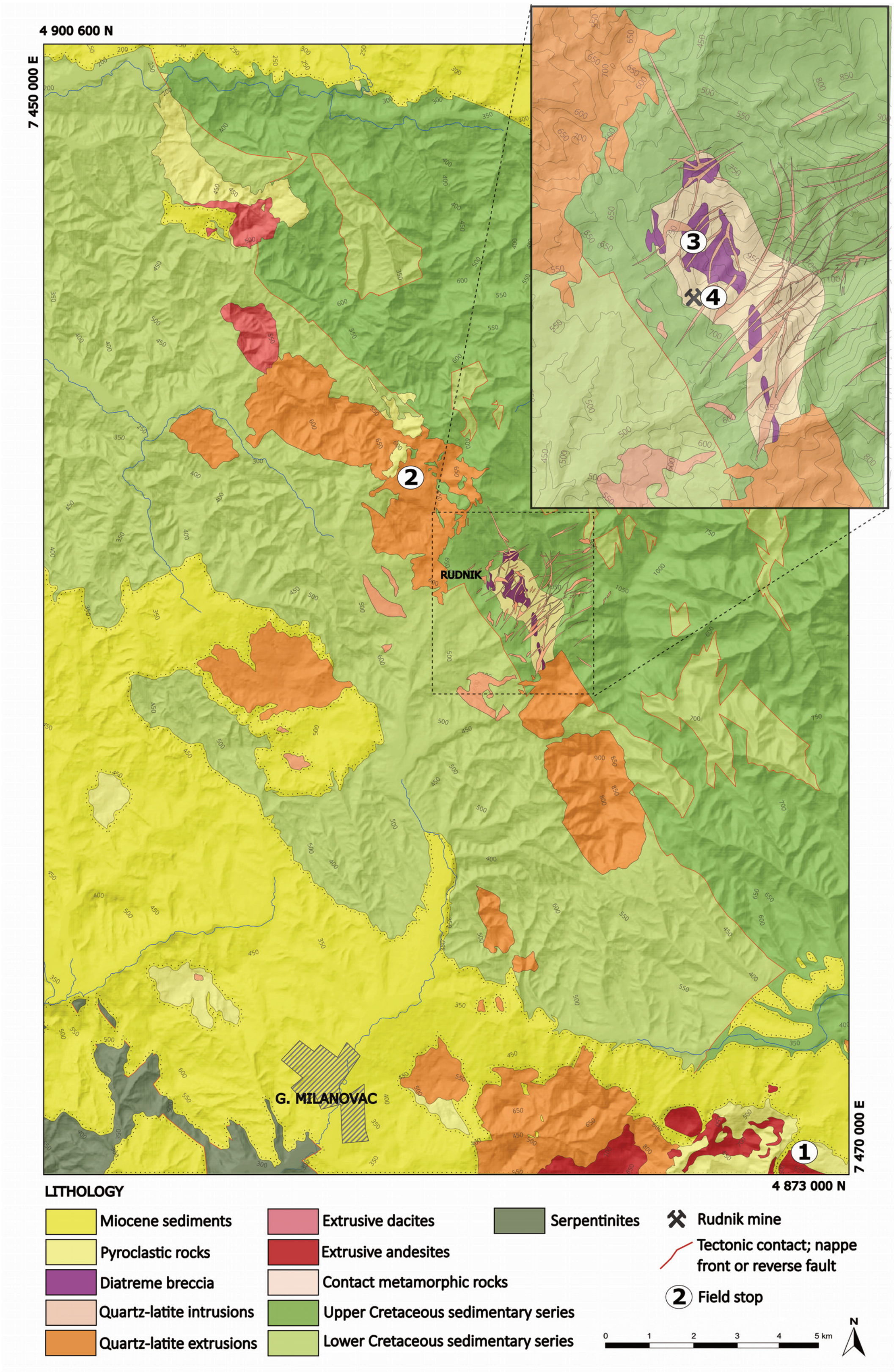


***Fig. 2.*** *Simplified geological map of the wider Rudnik deposit area and locations of field stops. The map modified after* Filipović *et al. (1978) and* Cvetković *et al. (2016).*

all derived from Upper Cretaceous flysch protoliths (Kostić et al., 2021). The skarns mostly correspond to epidote–zoisite and garnet–clinopyroxene skarns that are composed of epidote, coisite, quartz, calcite and actinolite (low temperature or retrograde skarns) as well as of garnet, quartz, calcite and clinopyroxene (high temperature or prograde skarns). It is noteworthy that the low-temperature hydrous skarn minerals are usually spatially associated with sulfide minerals and are sometimes found overprinting high-temperature anhydrous minerals of high-temperature prograde skarns (Petrović et al., 2024).

The sulfide mineralization is predominantly associated with quartz and calcite, and commonly appears in form of the stockworks and impregnations, more rarely as massive ore precipitated within the carbonate cement. The major sulfide minerals are pyrrhotite, sphalerite, galena, chalcopyrite, pyrite and arsenopyrite, among which pyrrhotite is most abundant (Stojanović et al., 2016). The main economic ore consists of Zn–Pb–Cu–Ag sulfide mineralization hosted in epidote-zoisite skarns in a relatively shallow zone up to 300 m from the ground surface, usually in the form of pseudo-layers, nests, veins and lenses (Popović & Umeljić, 2015). More rarely, the ore bodies are found in the diatreme breccias, where they have a more irregular geometry, usually as cone shaped forms that extend upwards over a vertical interval of ~ 100 m. The size of the ore bodies usually varies from 30–150 thousand tons to the biggest ones that amount to 300–900 thousand tons of ore. The average metal contents of the Rudnik skarn ores show considerable variations and range; Pb (0.94–5.66 wt%), Zn (0.49–4.49 wt%), Cu (0.08–2.18 wt%), and Ag (50–297 μg/g) (Stojanović et al. 2018).

The metamorphic–hydrothermal evolution of the Rudnik deposit comprises three stages (Petrović et al., 2024): (1) a pre-ore prograde stage characterized by garnet–clinopyroxene skarn formation; (2) a syn-ore retrograde stage marked by epidote–zoisite alteration and quartz–sulfide mineralization; and (3) a post-ore stage associated with calcite and quartz precipitation. The close spatial relationship between quartz–latite intrusions, skarn alteration, diatreme brecciation, and sulfide mineralization indicates that ore formation was genetically linked to the evolution of the younger phase of Rudnik magmatism. Fluid inclusion data document a progressive evolution from high-temperature, moderate-salinity fluids (~380–390°C; 12–16 wt.% NaCl equiv.) to lower-temperature, lower-salinity fluids (~180–200°C; 1–8 wt.% NaCl equiv.), reflecting fluid mixing, cooling, volatile redistribution, and increasing meteoric water involvement. Combined geological, mineralogical, and fluid inclusion evidence indicates that Rudnik represents a distal Zn–Pb skarn system formed by the upward migration of hydrothermal fluids derived from a deeper magmatic source.

## Field Stops

### FS 1 – Borač (volcanic domain)

The Borač volcanic complex represents one of the most important examples of Cenozoic volcanism in central Serbia. The volcanic products associated with the formation of the Borač caldera were ge-ne-rated after Plinian to sub-Plinian eruptionsthat produced rhyodacite/rhyolite pumice-fall deposits, un-welded ignimbrites, quartzlatite lava flows and domes as well as adjacent andesite lava flows, hyaloclastic deposits, and lamprophyre plugs and sills (Cvetković et al., 2001).

Rhyodacitic–rhyolitic pyroclastic deposits occur as rare relicts of pumice-rich fallout deposits and better preserved non-welded to weakly welded ignimbrites composed of highly vesicular pumice, volcanic ash, and crystal fragments of quartz, plagioclase, sanidine, and biotite (±hornblende). Quartz–latites are porphyritic in texture and contain phenocrysts of quartz, sanidine, plagioclase, biotite, hornblende, and augite set in a holocrystalline to hypocrystalline groundmass. Lamprophyric enclaves are common, particularly in the northern part of the complex. Lamprophyres are porphyritic rocks characterized by phenocrysts of diopside, phlogopite, and altered olivine set in a sanidine–oligoclase groundmass. Vesicles filled by epidote, chlorite, and calcite are common. Post-caldera andesites are porphyritic and contain phenocrysts of plagioclase, hornblende, hypersthene (±pigeonite), and augite.

The groundmass consists of microlites of the same minerals accompanied by minor titanite, apatite, and opaque minerals.

## FS 2 – Ostrvica (quartz–latite extrusive deeper facies)

Ostrvica (758 m a.s.l.) represents one of the most distinctive geomorphological features of the entire Rudnik area (Fig. 3a). The exposed quartz–latite rocks belong to the younger Miocene magmatic stage, which is genetically associated with ore formation in the Rudnik deposit (Cvetković et al., 2016).

Petrographically, the rocks are porphyritic, containing up to 30 vol.% phenocrysts of quartz, plagioclase, sanidine, biotite, and amphibole within a hypocrystalline groundmass. Quartz commonly displays embayed margins, while plagioclase frequently exhibits sieve textures indicative of crystal resorption and magma disequilibrium. Sanidine is rare but usually occurs as megacrysts, locally reaching several centimetres in length. A distinctive feature of the Rudnik quartz-latites is the presence of rounded to subrounded mafic microgranular enclaves of lamprophyric affinity, providing petrographic evidence of magma mingling, i.e. of the interaction between compositionally contrasting magmas during the evolution of the volcanic system.

## FS 3 – Prljuša (diatreme breccia)

The Prljuša locality exposes well-preserved polymict diatreme breccias in the central part of the Rudnik volcano–intrusive complex (Fig. 3b, c). The breccias infill a diatreme conduit that acted as a major conduit for hydrothermal fluids and provide an opportunity to examine the relationships between magmatic–hydrothermal processes, brecciation, and ore deposition within the Rudnik magmatic–hydrothermal system. They are exposed both at the surface and within the underground mine, where they are locally associated with sulfide mineralization. The breccias consist of sedimentary, volcanic (predominantly quartz–latite), metamorphic, and subordinate ultramafic clasts enclosed within a strongly altered, finely comminuted matrix (rock flour).

The clasts are commonly strongly altered and locally mineralized, particularly along clast margins. Hydrothermal alteration is dominated by silicification and propylitization, whereas potassic alteration is less common. The breccia matrix is cemented by quartz, clay minerals, sulfide minerals, and locally supergene limonite. Stockwork, disseminated, and locally massive sulfide mineralization occurs within fractured quartz–latite dykes and within the skarn-altered carbonate cement of the diatreme breccias. The ore assemblage is dominated by pyrrhotite and arsenopyrite, accompanied by subordinate sphalerite, galena, and chalcopyrite, reflecting a high-temperature hydrothermal system genetically related to Rudnik quartz–latite magmatism.

## FS 4 – Rudnik underground mine (ore deposit, contact metamorphic rock, diatreme channel)

The Rudnik underground mine provides a direct access to the principal ore-hosting setting of the Rudnik volcano–intrusive complex. The spatial distribution of ore bodies is strongly controlled by shallow quartz–latite intrusions, particularly dykes that locally reach several tens of metres in thickness and are pervasively affected by hydrothermal alteration and mineralization (Fig. 3d). The surrounding Upper Cretaceous sedimentary rocks exhibit the effects of contact metamorphism; however, no clear relationship has been recognized between metamorphic grade and the thickness or orientation of the quartz–latite intrusions.

Skarn assemblages and ore bodies occur along intrusive contacts and fracture-controlled zones, forming vein-, replacement-, and stockwork-type mineralization dominated by Zn–Pb–Cu–Ag sulfides. Underground workings provide a direct insight into the relationships between quartz–latite intrusions, skarn formation, and ore deposition. The mine also allows the diatreme breccia system to be traced through several underground levels, illustrating the role of brecciation in controlling fluid flow and mineralization (Fig. 3e).

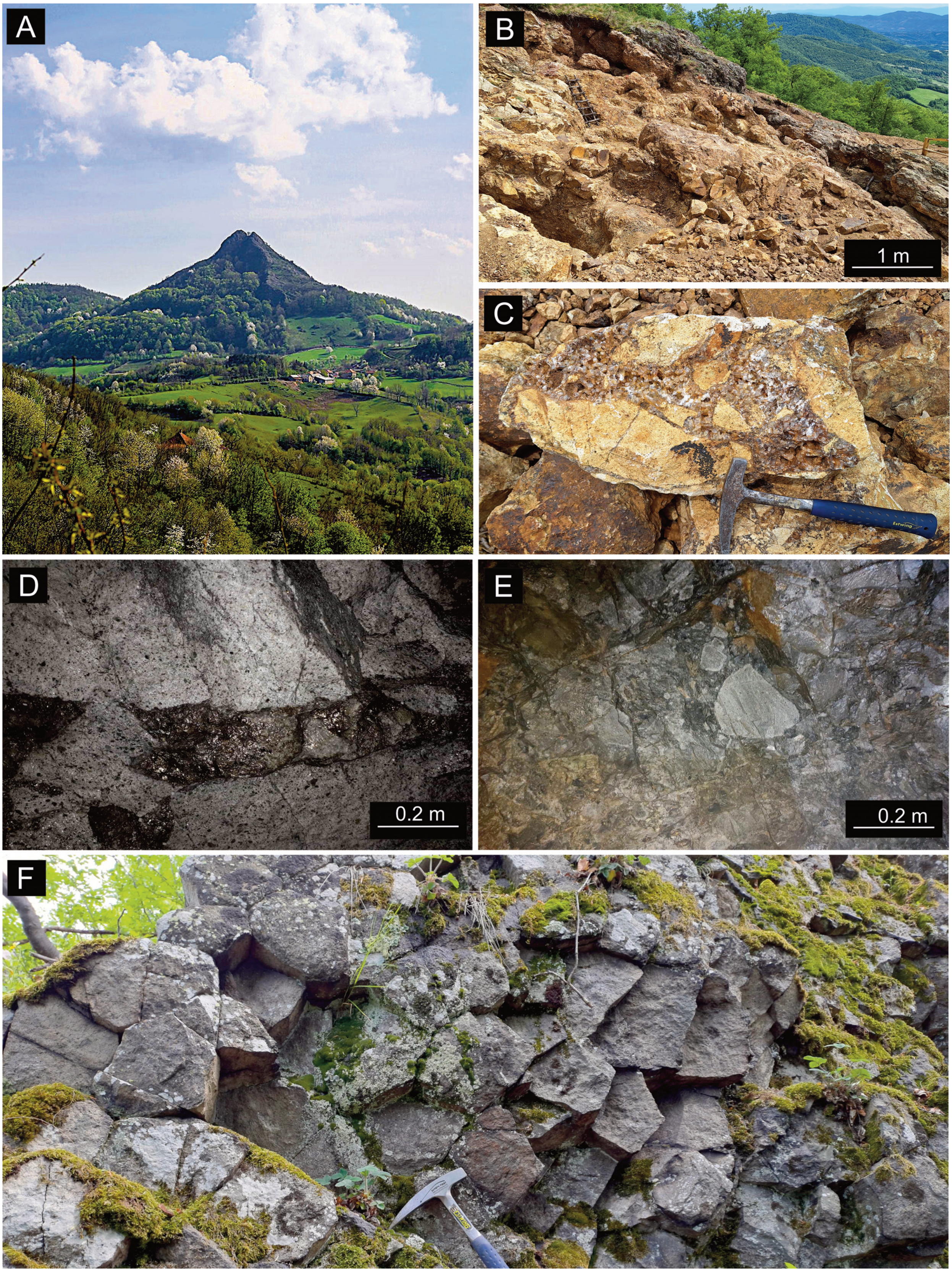


*Fig. 3. Key features of the Rudnik volcano–intrusive complex and field stops.* ***A)*** *Quartz–latite rocks exposed at Ostrvica, representing the younger Miocene magmatic stage (FS 2);* ***B)*** *Diatreme breccia with traces of historical mining activity (FS 3);* ***C)*** *Silicified diatreme breccia;* ***D)*** *Mineralized quartz–latite dyke exposed in underground mine workings (FS 4);* ***E)*** *Diatreme breccia clasts exposed in underground galleries;* ***F)*** *Columnar-jointed quartz–latite.*

Shallow intrusive quartz–latites are petrographically almost indistinguishable from their extrusive counterparts exposed elsewhere within the complex. They are characterized by porphyritic textures with variable phenocryst abundances and locally display chilled margins indicative of undercooling due to shallow emplacement. Some dykes lack the large sanidine phenocrysts commonly observed in the volcanic facies. Locally, quartz–latite bodies with well-developed columnar jointing are exposed underground (Fig. 3f). These cooling joints most likely formed during post-emplacement cooling and contraction of shallow intrusive bodies and are therefore unrelated to the earlier explosive diatreme-forming stage. Their occurrence provides further evidence for the close relationship between volcanic and subvolcanic processes within the Rudnik magmatic system.

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