Intrusive rocks from Polumir and Željin (Serbia):
two contrasting granitoid types

Milenko VUKOV

1University of Belgrade, Faculty of Mining and Geology, Belgrade, Serbia

Abstract. This paper outlines correlation of the most distinctive features of intrusive rocks from Polumir (granite from Polumir, Polumir granite) and from Željin (Željin granitoid). Although these two intrusions are notable similar in space (10-12 km) and time (beginning of Miocene), they are very different, even contrasting concerning their petrography, genesis and geotectonic. Mineralogy, petrology and chemistry of Polumir granite (P≈2.5 km²), and of Željin quartz diorite and tonalite, as well as of granodiorite and granite (P≈56 km²), i.e. properties that directly reflect on their genesis and geotectonic setting, are presented in this paper. Chemistry of biotite, the only mineral observed in both plutons, as the direct evidence of different physical-chemical conditions during consolidation and proof for their genetic contrast, is contributed.

Keywords: Polumir, Željin, biotite, genesis, geotectonic, I- and S- type
1 Introduction

In central Serbia, northern and north-eastern from the Kopaonik Mt. outcrops one large and a several smaller granitoid bodies. Among them clearly could be recognized two contrasting intrusions concerning their petrography, genesis and geotectonic known as Polumir granites and Željin granitoid (Fig. 1).

The term *granite of Polumir* is applied to igneous body discovered by erosion as seven smaller masses at the area of about 2.5 km$^2$, in south-eastern part of the Čemerno Mt. (below 1200 m altitude), between Padež and Ibar river. This term is not applied to fine-grained granite variety, mostly exposed as dykes, pegmatite and aplite in the central part of the Čemerno Mt. (above 1300 m altitude).

The term *Željin granitoid* is applied to particular igneous body discovered by erosion in the uppermost part of the mountain, which covers about 56 km$^2$. This term is not applied to a smaller exposures discovered in the following localities: Crvanj (1 km$^2$), Kovač (2.5 km$^2$), Kavanj (2 km$^2$), Drenj (1.7 km$^2$), Jošanička Banja (1.4 km$^2$).

Polumir granite outcrops about 10-12 km eastern from Željin intrusive body.

2 Analytical procedures

Results of wet chemical rock analyses (WC): 36 analyses of Željin granitoid (Contribution 1) and 10 analyses (already published) of Polumir granite [32]; X-Ray Fluorescence (XRF) analyses: 8 – of Željin [37] and 5 of Polumir [41] including 441 analyses of alkalis [33] performed by flame photometry method (FPM) are presented.

Chemistry of biotite, obtained by electron microprobe (EMP): 32 analyses of biotite from Željin rocks [34] and 15 from Polumir [41] are also presented.

Distinct features for these two intrusive bodies (their chemical-mineralogical-petrographic properties) were correlated including biotite chemistry, which as already was noted above, directly indicates on their petrography, genesis and geotectonic setting synchronously displaying their contrast on the best way.

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**Fig. 1.** Geological map of Kopaonik region and its surrounding ([22, 14, 18], simplified). Explanation: i – Carpatho-balkanides (Composite terrane), ii – Serbian-macedonian mass (ibid), iiia – Vardar zone (ibid), iiib – Dinarides (ibid); 1 – Mesozoic sedimentary and metamorphic rocks (T, J, K), 2 – Jurassic peridotites and serpentinites, 3 – Miocene volcano-sedimentary products, 4 – Tertiary granites, 5 – Mio-Pliocene sediments (Morava basin); 6 – faults
3 Results and discussion

3.1 Geological Setting

Both intrusions are considered (as well as Kopaonik granitoid body) in geotectonic sense to the Varadar zone [14]; actually to the Varadar zone Composite terrane [18]. Željin granitoid, including southern Kopaonik granitoid mass and outcrops of the adjacent substratum building «Kopaonik ridge» displays parquet texture as it most distinctive feature (Fig. 1).

Intrusive of Polumir (Polumir granite) is concordantly emplaced into biotite schists, i.e. into «Mršave Livade series» [26], actually into the upper part of «lower Studenica series» - Early Paleozoic [25], more probably Triassic in age [19, 22], primary built of clayey, marly, sandy and carbonaceous rocks. Granites and associated contact metamorphic rocks, including products of diabase-chert formation (J), were discovered inside one «tectonic half-window». These rocks are at east and at north in contact with overlying serpentinites (J). On south they are subsiding along a large sub-vertical fault extending ESE-WNW. Products of diabase-chert formation (J) are in contact with almost whole complex towards NW along faults. Endo-contact and external-contact effects are weak.

It was considered as Paleozoic – Late Hercynian in age ([30, 6]; Carboniferous [19] or Permian [26]. However, the age of 16-17±2 Ma [27, 31] was obtained by K/Ar-method on biotite finely considering it as Miocene in age. Results of the same method implied that the fine-grained «monzonites» from central parts of the Čemerno Mt. is younger – 9 Ma [13].

Intrusive of Željin (Željin granitoid) was tectonically emplaced, as well as Kopaonik granitoid, into the central parts of brachy anticline, the most notable structure of the Željin-Kopaonik anticlinorium [12]. This structure involves central parts of Kopaonik area following the NS direction from Kraljevo to Priština, slightly bending and dipping northward. The same orientation displays almost all the other formations. The entire substratum of granitoid is represented with Triassic ([22], earlier Pz) metamorphic series, composed primary of different pelitic-psammitic rocks and carbonaceous sediments that were not affected significantly during the intrusion of granitoid. Endo-contact phenomena are marked with a narrow cataclasis zone.

Željin granitoid was according to radiometric data (K/Ar-method on biotite) formed before 17.5-24 13 Ma [35].

3.2 Petrological Setting

Intrusive of Polumir (P=2.5 km²), is represented due to mineral composition (Fig. 2) with mesocratic (M=7-10 % vol.) two-mica granites (IUGS - [4]). Rocks are medium grained (1-3 mm), light in color to pale-pinkish, sometimes grayish blue and occasionally with well-developed schistosity. Their texture is hypidiomorphic granular. Main constituents are quartz, K-feldspar (orthoclase: Or=26.5-92.9Ab71-74,M=0.0-0.3); -2V=45-64°, Δ=0.10-0.12; microcline: -2V=78-86°, Δ=0.75-0.93; orthoclase-micro-perthite, microcline-micro perthite, plagioclase (An14-40,Ab68.0-84.1Or11-24.2, 2V=80-98°), myrmekite (An18.8-22.8Ab75-79.9Or11-1.9), biotite (-2V=11°) and muscovite (primary, -2V=39°). Neo-biotite, neo-muscovite and neo-albite (Ab65.5An14.0Or11.0) were noted also. Among accessory compounds were observed: apatite, monazite, xenotime, allanite, zircon and magnetite, while sericite, chloride and clay minerals are secondary minerals [32, 23]. Chemistry of these rocks considered them as acid to slightly alkali (Fig. 3).

Crystallization of these rocks took part at temperatures of about 660⁰C and pressures of 2-4 kbar. Most of them were emplaced in this level either as already crystallized masses or as rheomorphic, additionally heated and upward intruded granite mass [32]. These rocks underwent most probably a several remobilization phases, with the last one at T=400⁰C [32, 41].

Intrusive of Željin (P=56 km²) consists of light gray to dark gray rocks, of variable qualitative and mostly consistent quantitative mineral composition. Main constituents are: quartz, plagioclase (An33.2-45.7Ab53.1-65.7Or0.8-1.9), K-feldspar -orthoclase (Or88.5-91.7Ab79.9-11.3An0.1-0.5), myrmekite, biotite and hornblende. Accessory minerals are: epidote, allanite, sphene, apatite, zircon and magnetite; while secondary minerals are: calcite, sercite, chloride and clay minerals including almost 40 rare accessory minerals (found in heavy rare assemblage). Modal mineral composition (Fig. 2) considered these rocks as mesocratic (M=12-30% vol.) amphibole-biotite varieties of quartz diorite and tonalite (2. rock group, i.e. second) and subordinated – 15 % of the area (1. rock group, i.e. the first) varieties of granodiorite and (monzo) granite (IUGS – [4]).
Fig. 2. Q-A-P diagram (IUGS – [4]) and Q-(A+P)-M diagram for granitoid rocks of I-, S- and A-type in Australia (Bowden et al., 1984) and intrusive rocks from Polumir and Željin (modal analyses)

Fig. 3. SiO$_2$–(Na$_2$O+K$_2$O) diagram (TKPK - [2]) for Polumir and Željin intrusive rocks (WC analyses)

Rocks exhibit hypidiomorphic granular texture, medium grained, rarely fine grained and porphyroid, but myrmekitic, symplectic or poikilitic texture (porphyry-poikilo-blastic) occur also. Their structure is massive, in places schlieren, foliated (sometimes almost schistose) and banded. Chemistry of these rocks considers them as intermediate to slightly acid normal alkali-calcoalkali rocks (Fig. 3).

Mineral constituents of this intrusive were crystallized during the two sub-phases. In the first one were formed all essential constituents, excluding K-feldspar: hornblende, biotite, plagioclase, epidote and sphene (i.e. quartz diorite and tonalite – K$_2$O<2.42 %), at following conditions - T=700°C, P$_S$=7(8) kbar, h=24-25 km, P$_{H2O}$=6.6 kbar, H$_2$O=13-14%, f$_{O2}$=10-18.5 bar. When hornblende, biotite, epidote and major part of plagioclase crystallized, Željin magma, actually mixture of magma and already formed crystals, intruded in shallower levels and late magmatic mineral homogenisation took part at T=630-640°C, P=5 kbar and h=18 km (?). Later on, due to K-feldspar metasomatism (along foliation planes), at T=560-600°C, P$_S$<4-5 kbar, crystallized K-feldspar [36] producing some small granodiorite and granite (K$_2$O>2.42 %) occurrences.

3.3 Biotite

Physical-chemical conditions during genesis of both igneous bodies are the best recognizable using biotite that synchronously indicates on their genetic consideration.

Biotite of Polumir corresponds concerning Si:Al ratio and (Mg+Fe):Al to two-mica granite, while biotite from Željin corresponds to biotite granite (Fig. 4). Biotite of Polumir crystallized at lower pressure-temperature conditions while the later crystallized under some higher pressure-temperature conditions – higher potassium potential (Fig. 5).
Biotite of Polumir ($X_{Al2O3}=15.14$, $X_{FeO}=18.56$, $X_{MgO}=11.67$ [41]) greatly differs from Željin biotite ($X_{Al2O3}=15.14$, $X_{FeO}=18.56$, $X_{MgO}=11.67$ [40]) due to distinct oxide amounts and corresponding discriminants [1]. Those from Željin are analogous to orogenic, calc-alkaline I-type granitoid complexes [40] while those from Polumir correspond to peraluminous collision complexes of S type. Calc-alkaline character of biotite in Željin rocks and its peraluminous character in rocks from Polumir are in agreement with chemistry of country rocks (Fig. 6). Biotite from Polumir rocks are with its chemistry similar to those in granites of Serbia, actually to Bukulja and Cer granites («fine grained, leucocratic» and «muscovite-aplitic» [40]).

The amount of Al$^{VI}$ is lower in Željin biotite (0.121-0.467), than in Polumir (0.691-1.006), reflecting [29, 9, 88] that the first one is of I-type and that the other is of S-type (>0.5). Higher TiO$_2$ contents in biotites from Polumir ($\Sigma=3.20$), than in Željin biotite ($\Sigma=2.50$), is additionally in agreement with TiO$_2$ content in I- and S-type [10].
3.4 Genetic and geotectonic setting

There are a plenty mineralogical and petrochemical criteria for distinguishing I- and S-granitoid types proposed by numerous authors (mostly for granitoid rocks of southeastern Australia – Lachlan Fold Belt, for example, [9, 10, 43, 46, 7, 8, 28, 44, 45, 11, 5, etc.]). In this paper we have used only some of these criteria, reachable and the mostly instructive.

Table 1. Average chemical composition of granitoid rocks I- and S-type (Australia) and of Polumir (P) and Željin (Ž) intrusives

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>S-type</th>
<th>Ž(1g.)</th>
<th>Ž(2g.)</th>
<th>I-type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>71.84</td>
<td>69.08</td>
<td>64.07</td>
<td>59.40</td>
<td>67.98</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.25</td>
<td>0.55</td>
<td>0.59</td>
<td>0.78</td>
<td>0.45</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>16.41</td>
<td>14.30</td>
<td>16.03</td>
<td>17.43</td>
<td>14.49</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.68</td>
<td>0.73</td>
<td>2.24</td>
<td>3.36</td>
<td>1.27</td>
</tr>
<tr>
<td>FeO</td>
<td>1.08</td>
<td>3.23</td>
<td>3.26</td>
<td>4.65</td>
<td>2.57</td>
</tr>
<tr>
<td>MnO</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>MgO</td>
<td>1.00</td>
<td>1.82</td>
<td>2.36</td>
<td>2.83</td>
<td>1.75</td>
</tr>
<tr>
<td>CaO</td>
<td>1.83</td>
<td>2.49</td>
<td>4.65</td>
<td>5.73</td>
<td>3.78</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.43</td>
<td>2.20</td>
<td>2.62</td>
<td>2.90</td>
<td>2.95</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.46</td>
<td>3.63</td>
<td>3.13</td>
<td>1.95</td>
<td>3.05</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.03</td>
<td>0.13</td>
<td>0.01</td>
<td>0.07</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Trace elements (ppm)

P – Polumir (10 WC analyses); Ž – Željin (Contribution 1; 1g. – Rock of the 1. group – metasomatic, 2g. – rock of the 2. group – primary); I-, S – referent rocks from Australia [10]: I - I-type (532 analyses); S – S-type (316 analyses).

1. Following criteria indicate that Polumir intrusive is S-type:
   - relatively high content of quartz and K-feldspar (Fig. 2);
   - narrow and high range of SiO₂ content (Table 1; Fig. 3);
   - common muscovite present;

![Fig. 6. ACNK–ANK diagram (Maniar & Piccoli, 1989) for Polumir and Željin intrusive rocks. Explanations: ANK – Al₂O₃/(Na₂O+K₂O) mol.; ACNK - Al₂O₃/(CaO+Na₂O+K₂O) mol. (XRF analyses)]](image-url)
- the absence of enclaves (including mafic).

2. Željin intrusive is I-type concerning:
- relatively low quartz and K-feldspar content (Fig. 2);
- wide range of SiO₂ content (Tab.1; Fig. 3);
- common presence of amphibole;
- presence of mafic enclaves (fine grained diorite/gabbro with quartz to quartz diorite; in size few tens of cm, rarely up to 150 cm).

On contrasting character of these two intrusives implies some other discriminants, united as:
1. *Alumina content* (defined as: norm. corundum: diopside; Al/(Na+K+Ca); etc.

Most of Željin rocks (>72 % of population) does not contain normative corundum or its amount is <1 %, analogous to its amount (absence) in I-type [9]. Polumir granite, on contrary completely corresponds to S-type as normative corundum is ordinary and present in significant amounts (2.45-8.36 %).

Ratio Al/(Na+K+Ca) / is coinciding completely with previous mentioned, whereas Polumir granite displays notable Al «excess» compared with referent S-type granites (Fig. 7).

2. *The amount of alkali* (defined as: K/(Na+K) and K2O-Na2O/.

K/(Na+K) ratio implies, as well as the K-feldspar ratio towards sialic minerals that Polumir granite corresponds to S-type. Primary Željin rocks (2. group) are analogous, as up to now, with I-type, while metasomatic rocks (1. group – K2O>2.42 %) only receive some features of S-type (Fig. 8).

![Fig. 8. Combined diagram of: (a) frequency K2/(Na+K) and (a) correlation of K2/(Na+K) – Fe3/(Fe3+Fe2) I- and S-type granites from Australia (Takahashi et al., 1980), and intrusive rocks from Polumir (granite) and Željin (1 – granodiorite and granite; 2 – quartz-diorite and tonalite) (WC analyses)](image)

![Fig. 9. K2O–Na2O (mas.) diagram of I- and S-type granites from Australia [9] and intrusive rocks from Polumir and Željin (FMP analyses)](image)

Amounts of K2O and Na2O (K2O>3.09 %, Na2O<2.70 %) distinctly consider rocks of Polumir as S-type [9], and from Željin as I-type excluding some of metasomatic derived (Fig. 9).

3. *Calcium amount* (defined as CaO % mas. and C/(A+C+F) - C=Ca; A=Al-Na-K; F=Fe+Mg).

Contents of CaO in entire samples including average values for intrusive rocks of Polumir and Željin (Table 1) are notable higher (4.65 %, followed with higher content and more basic plagioclase), i.e. notable lower (1.83 % followed with lower content and more acid plagioclase) than average values for corresponding rocks of I-type (3.78 % [10]), i.e. of S-type (2.49 %).
Synchronously with its consolidation, or just a little later (h=24-25 km), consolidation of Polumir magma took part. Syn-collision Polumir magma generated during the collision of two continental (micro) plates. Possibility of additional influence of deeper Željin magma should not be excluded.

Conclusions about geotectonic setting of investigated intrusive bodies are in well agreement with the already existed opinion [16, 17] about the existence of volcanic arc and micro plates collision in investigated area.

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4 Conclusions

Biotite chemistry, chemical, mineral and normative rock composition reflects that these two intrusive bodies, very close in space and time are contrasting. Željin intrusive corresponds to calc-alkaline orogenic I-type, whereas Polumir is peralkaline syn-kinematic S-type.

The amount of Al\(^{IV}\) and TiO\(_2\) in biotite, as well as content of Al\(_2\)O\(_3\), FeO and MgO are in agreement with their contrasting character. Additionally, amounts of Si:Al and (Mg+Fe):Al, are analogous to their mineral assemblages - biotite-amphibole, i.e., muscovite-biotite, while Fe(Fe+Mg) and Al(\(\text{Si+Al}+\text{Fe+Mg}\)) implies on some higher PT-conditions during crystallization of minerals within Željin intrusive body.

Intrusive rocks from Polumir display characteristics of S-type i.e. have relative high quartz and K-feldspar amounts followed with narrow but high range of SiO\(_2\) content (correspond to granites), muscovite presence is ordinary while enclaves are lacking. Intrusive rocks from Željin display characteristics of I-type i.e. have relative low quartz and K-feldspars amount followed with a wide range of SiO\(_2\) content (correspond to tonalite and granodiorite), usually contain amphibole while mafic enclaves are often.

Some significant petrochemical parameters reflect on their contrasting character too:

Alumina content - in Željin rocks normative corundum is lacking or present in negligible amounts (typical for I-type), while Polumir rocks display notable “excess” of Al(\(\text{Na}+\text{K}+\text{Ca}\)) compared with the referent S-type samples.

Alkali amount - \(K{}_{2}O/Na{}_{2}O\) or \(K_{2}O+Na_{2}O/Al_2O_3\) clearly distinguish Željin rocks as I-type and Polumir rocks as S-type, although metasomatic Željin rocks (1. group) only receive some features of S-type.

Calcium contents /CaO; C(\(\text{A}+\text{C}+\text{F}\))/, are either completely in agreement or some higher than in referent rocks from Australia.

Ferri:ferro ratio \(\text{Fe}^{3+}:\text{Fe}^{2+}\)/ is the least instructive in Polumir rocks, while is higher in Željin rocks than in referent samples of I-type.

Investigated intrusives were formed in different geotectonic settings according to R1- and R2-parameters, amounts of Rb, Nb and Y, with taking into account their age. Željin granitoid corresponds to preplate collision type, i.e. its magma was formed in volcanic arc in the “moment” when it overturned into the continental margin. Polumir intrusive corresponds to syn-collision type but its magma derived synchronously or little later than Željin one, during the continental (micro) plates collision.

References

and mineral resources of the Kopaonik. Fifth Meeting of geologists of FNRJ, geological guide-book, 36 pp., Belgrade (in Serbian), 1962.


