Pre-Variscan granitoids with adakitic signature at west Getic basement of the South Carpathians (Romania): constraints on genesis and timing based on whole-rock and zircon geochemistry

Anca Dobrescu

Department of Regional Geology, Geological Institute of Romania
Caransebes Str. 1, 012271, Bucharest 32, Romania
E-mail: ancadobrescu2003@yahoo.com

Research on two strata-like intrusions from Slatina-Timiş (STG) and Buchin (BG) at West Getic Domain of the South Carpathians (Semenic Mountains) identified granitoids with adakitic signature in a continental collision environment. Whole-rock geochemical composition with high Na$_2$O, Al$_2$O$_3$, and Sr, depleted Y (<18ppm) and HREE (Yb < 1.8ppm) contents, high Sr/Y (>40), (La/Yb)$_N$ (>10) ratios and no Eu anomalies overlaps the High-Silica Adakites (HSA) main characteristics, though there are differences related to lower Mg#, heavy metal contents and slightly increased $^{87}$Sr/$^{86}$Sr ratios. Comparison with HSA, Tonalite-Trondhjemite-Granodiorite (TTG) rocks and melts from experiments on basaltic sources suggests partial melting at pressures exceeding 1.25GPa and temperatures of 800-900ºC (confirmed by calculated Ti-in zircon temperatures) as the main genetic process, leaving residues of garnet amphibolite, garnet granulite or eclogite type. The adakitic signature along with geochemical variations observed in the STG-BG rocks indicate oceanic source melts affected by increasing mantle influence and decreasing crustal input that may restrict the tectonic setting to slab melting during a subduction at low angle conditions. An alternative model relates the STG-BG magma genesis to garnet-amphibolite and eclogite partial melting due to decompression and heating at crustal depth of 60-50km during syn-subduction exhumation of eclogitized slab fragments and mantle cumulates. The granitoids were entrained into a buoyant mélange during collision and placed randomly between two continental units. U-Pb zircon ages obtained by LA-ICP-MS and interpreted as Ordovician igneous crystallization time and Variscan recrystallization imprint are confirmed by trace-element characteristics of the dated zircon zones, connecting the STG-BG magmatism to a pre-Variscan subduction-collision event. The rich zircon inheritance reveals Neoproterozoic juvenile source and older crustal components represented by Neoarchean to Paleoproterozoic zircons.

INTRODUCTION

Four Variscan granitoid plutons align from Serbia (in the South) to Romania (at North) as intrusions into the western Getic basement of the Alpine upper nappe in the South Carpathians. Small granitoids are randomly widespread among these plutons in the gneissic units of the Getic basement, some of them documented to be of Ordovician age (Balintoni et al., 2010, 2014 and references therein). Two strata-like granitoid bodies at Slatina-Timiş (STG) and Buchin (BG) situated in the northeast part of the Semenic Mountains (Fig. 1) caught our attention.

A B S T R A C T

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by their particular geochemical characteristics and age related issues. They have adakitic signature: geochemical characteristics common to High-Silica Adakites (HSA) and Tonalite-Trondhjemite-Granodiorite (TTG) rocks, ground to search for their genesis and significance related to regional tectonic setting.

Since 1990s topics on HSA and TTG rocks have been constantly approached, concluding on their similarities sufficient to be regarded as analogues (Drummond and Defant, 1990; Martin, 1999), but also revealing differences (Martin et al., 2005; Moyen and Martin, 2012). Their distinctive geochemical features (high Na₂O, Al₂O₃
Pre-Variscan granitoids with adakitic signature

The current tectonic models describe the South Carpathians as composed of three major units as a result of a thrust structure assembled during the Alpine collisional evolution. The lower continental Danubian Domain is a nappe system consisting of Neoproterozoic granites, metamorphic rocks and Paleozoic-Mesozoic sedimentary formations. The Severin oceanic crust is a tectonic mélangé of Jurassic ophiolites, flysch and bimodal alkaline igneous rocks. The upper Getic Domain is composed of several pre-Alpine basement gneissic formations overlain by late Carboniferous to Permian sedimentary rocks and a transgressive late Cretaceous cover (Balintoni, 1997; Balintoni et al., 2010; Iancu et al., 2005; Medaris et al., 2003; Sândulescu, 1984).

The Getic Domain basement was reconsidered, differently divided and renamed based on various lithotectonic visions. Known as the Sebeş-Lotru pre-Alpine terrane, according to Balintoni et al. (2010) it comprises a lower Neoproterozoic metamorphic unit (Lotru) and an upper Ordovician metamorphic unit (Cumpăna) with rocks assemblages dominated by orthogneisses and metabasites, local paragneisses, quartzites and carbonate rocks; various sedimentary, volcanic, mafic and ultramafic protoliths were metamorphosed in medium-high grade conditions (Iancu and Mărăuțiu, 1989). The two units were juxtaposed during the Variscan orogeny, sharing the foliation generated by the high-grade metamorphic event (Șăbău and Massone, 2003) and the P-T signatures specific to the individual tectono-stratigraphic units (Medaris et al., 2003). The same basement was renamed as Lotru Metamorphic Suite (LMS) and considered by Șăbău (1999), Șăbău and Massone (2003) as composed of three units. The uppermost Semenic Nappe (SN) consists of mica gneisses and schists; at its lower boundary, manganese silicate rocks, quartzites, tourmaline rocks, pegmatites and stratiad granitoids (like STG and BG) form a marker level called Delinești, spatially associated with ultramafics, amphibolites and eclogites. The intermediate Voineasa Unit (VU) contains amphibolites, high grade gneisses (Valea Cârpărea Complex: VCC) with eclogite inclusions and metagranitoids (Tilișca), a migmatized gneiss complex with eclogites and ultramafic lenses, a mafic terrigenous complex and an alkaline meta-igneous complex. The lowermost Arminş Unit (AU) consists of biotite-gneisses, leptynites, kinzigites, pegmatite segregation and a thin limestone body.

The Getic basement is intruded, at its western part, by four Variscan granitoid plutons (Neresnica and Brnjica in Serbia, Sicheviţa and Ponişaca in Romania) interpreted to form a major batholith buried beneath the Mesozoic and Cenozoic cover (Duschesne et al., 2008; Sândulescu et al., 2010; Iancu et al., 2005; Medaris et al., 2003; Sândulescu, 1984).

GEOLOGICAL BACKGROUND

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et al., 1978). Small granitoid bodies and migmatites are widespread in the gneissic units of the Getic basement (Balintoni, 1975; Iancu, 1998; related references in Iancu and Seghedi, 2018; Stelea, 2000), some of them documented as Ordovician (Balintoni et al., 2010, 2014 and references therein). Two granitoid bodies outcrop in the Precambrian-lower Paleozoic medium-high grade Getic metamorphic basement: STG to the East and BG to the North-East from the Poniasca pluton (Fig. 1). Field observations (Gridan, 1981; Săbău, 1999; Savu, 1997) describe them as relating concordantly to the host rocks in the axial zone of two anticline structures, sometimes folded together or penetrating discordantly in places. According to Săbău (1999), the granitoids appear as strata-like laying on the gneisses of VU and beneath the micaschists of SN, although the relationship with the host rocks is complicated. Gridan (1981) and Savu (1997) described the rock mineralogy and petrography; Savu (1997) advanced a genetic model presuming a primary trondhjemitic magma resulted from a metasomatized mantle source controlled by subduction. Dimitrescu (2007) considered BG as a prolongation of the Variscan Poniasca pluton, while Conovici (2000) placed Poniasca, Sicheviţa and Beljanica plutons in a southern terrane with a distinct evolution from the northern terrane (where STG and BG occur).

The intrusions of STG and BG outcrop on areas of around 2km long by 0.6km wide and 12km long by 1.6km wide, respectively. The rocks are medium-fine grained, mostly with gneissic structure (Savu, 1997), described petrographically as tonalites and granodiorites in STG and granodiorites, trondhjemites and granites in BG samples. The STG mineralogy is composed of deformed quartz, zoned plagioclase (An$_{15-27}$), reddish-brown biotite and less greenish-brown biotite, rare microcline, accessory hornblende, zircon, zoned allanite, apatite, titanite, rutile, monazite and magnetite, secondary minerals like epidote, clinzoisite, muscovite, chlorite, iron oxides and pyrite. The BG rocks consist of deformed quartz, zoned plagioclase (An$_{16-29}$), green to greenish-brown biotite, microcline, hornblende and primary epidote, accessory titanite, rutile, zircon, apatite, rare muscovite, monazite, and secondary epidote, chlorite and opake minerals. Aplites and rare pegmatites occur in the area; biotite-rich autholiths and partly assimilated crystalline schists are concordantly disposed along margins. Contaminated rocks with biotite-almandine-muscovite-sillimanite association were observed at some margins (Savu, 1997). The two intrusions are locally crossed by fine leucocratic veins.

**METHODS**

Eighteen powdered bulk-rock samples were geochemically analyzed by X-Ray Fluorescence (XRF) and Inductively coupled plasma mass spectrometry (ICP-MS). Whole-rock samples were analyzed for major elements by a JY24 Sequential Spectrometer (ICP-AES), while Si was determined using a Spectro Analytical X-Lab 2000 XRF spectrometer. Detection limits for most elements were less than 0.005 wt.% in the sample and analytical errors characteristically varied from 2% to 5%, depending on the element determined and its concentration. Trace elements (including REE) were determined on totally digested samples ICP-MS using a VG Elemental Plasma Quad II. Precision varied from 5 to 10%, depending on the element determined and its concentration. All analyses were performed in the Department of Earth Sciences at the University of Bristol (UK). Analytical details for major and trace element measurements may be found in Marshall et al. (2005).

Rb-Sr isotope analyses needed isotope dilution, chemical separation, and mass spectrometer procedures performed at Prospecţiune S.A. Laboratory, Bucharest (Romania). The isotope data were obtained using PS-LAG-CAFCH-RM-004 procedure on MI-1201T mass-spectrometer of solid-state ionization source and MIN-L and MIN-G international standards. $^{87}$Sr/$^{86}$Sr ratios were corrected for fractionation using $^{86}$Sr/$^{88}$Sr= 0.1194. Analytical details and method are fully described in Bayanova et al. (2009).

In situ U/Pb zircon geochronology was performed using ELA-ICP-MS (Excimer Laser Ablation Inductively Coupled Plasma Mass Spectrometry) on 12 zircon crystals from a BG rock sample and on a single zircon from a STG rock sample (Table 1, see the Appendix). The zircon structure was examined by cathodoluminescence (CL) at University of Milan (Italy). U/Pb dating was carried out at CNR-Istituto di Geoscienze e Georisorse (Unita di Pavia) using an ArF excimer laser ablation microprobe operating at 193nm (Geolas200Q-Microlas) coupled with the High Resolution-ICP-MS (Element-Thermo Finnigan). Analytical details and method are fully described by Tiepolo (2003) and Dobrescu et al. (2010).

Geochemical analyses on the dated zircons were obtained by Secondary-Ion Mass Spectrometry (SIMS) using Cameca IMS-1280 ion microprobe at Nordsim facility in Stockholm which allows in situ measurements of isotopic and elemental composition in selected micrometer sized areas of polished sections. Trace-element contents of the zircon zones were analysed using the method described in Whitehouse et al. (1999) and Whitehouse and Kamber (2005).

**RESULTS**

Whole-rock geochemistry

The chemical composition of STG and BG samples is listed in Table 1. STG rocks have 65.6-68.4 wt.% SiO$_2$,
high Al₂O₃ (16.5-17wt.%) and Na₂O (3.8-5.1wt.%), low-medium K₂O (1.4-3.8wt.%) contents and Na₂O/K₂O (1-3) ratios. BG rocks are more siliceous (67.7-73.6wt.% SiO₂) with higher Na₂O (4.6-6.4wt.%), K₂O (3.1-3.9wt.%) contents and Na₂O/K₂O ratios of (1.2-1.9). A/CNK values are of (0.99-1.26) for STG and (0.93-1.09) for BG (Fig. 2A). Trace-element behavior (Fig. 3A) shows Large Ion Lithophile Element (LILE) enrichment and depleted High Field Strength Elements (HFSE), with Nb-Ti negative anomalies. Medium-high Sr (554-966ppm), low Y (4-12ppm) and HREE (Yb of 0.38-1.23ppm) contents yield low to no Eu anomalies (Eu/Eu* of 0.79-1 for BG and 0.81-1.18 for STG). A range of Rb-Sr isotopic data has been obtained on 7 BG and 6 STG rock samples. The initial 87Sr/86Sr ratios were age-corrected at 464Ma (Dobrescu et al., 2010) and vary between 0.7045-0.7051 for BG and 0.7042-0.7060 for STG (Table I).

Geochronology: age data review

Nineteen zircon U-Pb age data obtained by ELA-ICP-MS on STG and BG samples have been already published (Dobrescu et al., 2010). The age data interpretation is revisited in this study in order to relate the different stages of zircon crystallization with tectono-thermal events that affected the Getic Domain basement.

The majority of the analyzed crystals has composite structures with inherited anhedral to subhedral cores surrounded by complex zoned overgrowths typical for deep-seated, slowly cooled granitic magmas and thinner outer rims; prismatic crystals with oscillatory zoning without inherited cores were also described (Fig. 4). The oldest inherited xenocrystic core is Neoarchean (2.5Ga) correlating with 2.4-2.6Ga ages encountered in orthogneisses and metagranites from the Sebeş-Lotru terrane (Balica, 2007) and with 2.5-2.7Ga detected in the upper low-grade Caraş terrane (petrographically similar to the Sebeş-Lotru terrane and presumed to have the same origin), interpreted as of Saharian provenance (Balintoni et al., 2009). Corroded cores of Paleoproterozoic to lower Neoproterozoic ages (1878±57, 1857±56, 1055±39, 858±32Ma) are relicts contemporary to those detected by Balintoni et al. (2010) as detrital zircons in the upper Cumpăna unit, interpreted as of northeastern Gondwanan provenance. The Neoproterozoic age of 858Ma is close to the single inherited age (of 866Ma) evidenced in the Poniasca pluton (Duchesne et al., 2008). Ages at 677±29, 600±22, 589±23 and 583±22Ma on well-developed concentric zoned cores are assigned to the main source for BG, contemporary with the Cadomian protoliths from the lower part of the Sebeş-Lotru terrane, with possible

| Sample | Rock type | Location |
|--------|-----------|----------|
| BG     | granitoid  | Semenic Mts. - S Buchin village N49° 49’ 18” E28° 52’ 30” |
| STG    | granitoid  | Semenic Mts. - Slatina-Timis valley N49° 42’ 53” E28° 57’ 15” |

**TABLE 1. Location of the dated samples**

**FIGURE 2.** A) Rock/magma type classification for the STG-BG samples in A/CNK [molAl₂O₃/(CaO+Na₂O+K₂O)] vs. SiO₂ diagram (Chappel and White, 2001). B) Variation trends of STG and BG contents in P₂O₅ vs. SiO₂ diagram.
Pan-African affinities (Balintoni et al., 2009). Despite the limited number of dated crystals, the inherited BG zircons record the whole range of ages encountered in the Getic basement rocks (Balintoni et al., 2014; Stoica et al., 2016). The relics are overgrown by Ordovician and Variscan zircon rims which imply that the inherited zircons were entrained at the source stage. The ages of the oscillatory zoned overgrowths (a dominant feature of igneous zircons– Vavra, 1990) at 493±19 and 465±17Ma for STG and 462±18 and 434±19Ma for BG were interpreted as intrusion time-span, though data are relatively scattered and do not allow to unequivocally define an intrusion age. The four data yield a concordia age at 463.6±18Ma (1σ; MSWD= 0.04) (Dobrescu et al., 2010) which makes STG and BG contemporary to several rocks belonging to the Cumpăna unit of the Sebeş-Lotru terrane (Capălna orthogneiss of 458.9Ma, Latoriţa orthogneiss of 466.0Ma) (Balintoni et al., 2009, 2010, 2014) and to Tilişca granitoid (474-460Ma) (Săbău and Negulescu, 2012) which belongs to the VCC of the underlying VU. The ages coincide with a major pre-Variscan tectono-thermal event responsible for the incorporation of high-pressure rocks in the metamorphic complexes (Săbău and Massone, 2003). The dark-grey (low CL intensity) outer rims, some with “flow zones”, convoluted zoning and transgressive recrystallization-seeming front more developed in the crystal edges, range between 357±15 and 309±12Ma. They were interpreted as subsequent growths due to the peak metamorphic conditions that affected the Getic basement at 358-316Ma (Medaris et al., 2003). This effect is also present on zircons from other Ordovician metagranitoids in the Sebeş-Lotru terrane which suffered Variscan partial or total resetting during an eclogite-grade metamorphic event (Balintoni and Balica, 2010).

Zircon geochemistry and significance

Zircon is one of the minerals in igneous and metamorphic rocks that host for significant fractions of the whole-rock abundance of U, Th, Hf and REE, elements used as source and process indicators or parent isotopes for age determination. Compositional investigation on zircon crystals is related to zircon role in igneous and metamorphic petrogenetic processes (Hoskin and Schaltegger, 2003; Rubatto, 2002). Based on these considerations, the trace-element geochemistry of the dated zircon zones from STG and BG samples was used to verify the accuracy of the age interpretation for each process that generated the zircon growth.

According to Grimes et al. (2007), zircon trace-element signature may provide information on magma sources, discriminating between crystals formed in oceanic crust from those formed in continental crust. In this regard, the BG zircon cores with ages of 677-583Ma, interpreted as belonging to the main source, have two of the U/Yb ratio of extremely low values (<0.1) that “are almost certainly derived within a MORB-type setting” whereas other two ratios have low values, typical for lower crust (Grimes et al., 2015). All the inherited zircons plot in the field of ultramafic, mafic, intermediate and alkaline rocks in the Hf vs. Y diagram (Fig. 5A).

The study on trace elements of BG and STG zircons (Table II) as petrogenetic process indicators was meant to check the accuracy of the age data interpretation. The most developed oscillatory zoned areas at 493-434Ma have low U (114-396ppm) and Th (110-241ppm) contents and Th/U ratios of 0.5-1 (≥0.5) typical for igneous crystallized zircons (Hoskin and Black, 2000). Rich HREE, positive Ce and strong negative Eu anomalies (Fig. 5B) confirm the characteristics of zircons generated by igneous
growth (Hoskin and Schaltegger, 2003). The outer rims of 357-309 Ma have high to very high U (553-3891 ppm) and Hf (9037-9952 ppm) contents, extremely low Th/U (0.032-0.200) ratios, depleted HREE contents and no/small positive Ce anomalies along with no/small negative Eu anomalies (Fig. 5C), in obvious contrast with trace-element behavior in the igneous crystallized zones. These characteristics represent completely recrystallized zircons (as described by Pan, 1997 in Hoskin and Schaltegger, 2003), the flat HREE patterns and the lack of significant Eu anomalies being typical for eclogite-facies zircons (Rubatto, 2002).

DISCUSSIONS

Comparative study and petrogenetic considerations

The limited STG-BG differentiation extent, the absence of basic and intermediate related rocks in the
area and the sample plot in the La/Yb vs. La diagram (Fig. 6) indicate that partial melting was the main genetic process. Besides, the presence of inherited zircons is an argument that thorough and extensive fractionation did not occur during ascent (Miller et al., 2003). Petrographically similar, the two granitoids have common I-type minerals like hornblende, green to greenish-brown biotite, epidote, zoned allanite, sphen and magnetite, contrasting with reddish-brown biotite and monazite as S-type minerals in the STG rocks. Major-element geochemistry of high Na₂O contents, A/CNK values of (0.93-1.09) with positive A/ CNK-SiO₂ correlation for BG samples and negative P₂O₅-SiO₂ correlation for both granitoid samples (Fig. 2A, B) are common features for I-type granites (Chappell, 1999, Clemens and Stevens, 2012). According to Clemens and Stevens (2012) initial ⁸⁷Sr/⁸⁶Sr ratios of less than 0.708, between 0.704 and 0.706 (Chappell and White, 2001) for both BG and STG rocks, are typical characteristics for I-type granites derived from juvenile oceanic crust source. Variations to peraluminosity for STG samples (including slightly higher ⁸⁷Sr/⁸⁶Sr ratios) indicate an increased continental material input.

Rocks with medium-high SiO₂, high Na₂O and Al₂O₃, low Y (<18ppm), medium-high Sr contents and Sr/Y ratios, low HREE (Yb <1.8ppm) and no Eu anomaly (Fig. 3B) differ from those produced by fractional crystallization in a typical calc-alkaline arc (high HREE, low REE fractionation and negative Eu anomalies) (Peacock et al. 1994). Most geochemical characteristics of STG-BG rocks overlap HSA and TTG patterns (Table 2) which were interpreted as results of amphibolite/eclogite partial melting in increased pressure conditions, leaving amphibole, garnet, clinopyroxene and plagioclase residual phases (Defant and Drummond, 1990; Martin et al., 2005; Rollinson and Martin, 2005). The differences from HSA (Table 2) consist in lower Mg# (18-20) values, Ni (1-5ppm) and Cr (7-16ppm) contents in STG rocks, increasing to

![Figure 5](image.png)

**Figure 5.** A) Hf vs. Y contents of the dated BG zircon zones relative to the fields of zircon composition defined by Shnukov et al. (1997) (in Belousova et al., 2002): I (kimberlites); II (ultramafic, mafic and intermediate rocks); III (quartz-bearing intermediate and felsic rocks); IV (alkaline rocks)= field VI in Belousova et al. (2002); violet rombs (inherited zircons), green squares (main source zircons); B) chondrite-normalized REE characteristics of zircon zones interpreted as igneous crystallized; C) chondrite-normalized REE characteristics of zircon zones interpreted as recrystallized.
Mg# (29-35), Ni (6-30ppm) and Cr (19-65ppm) in BG rocks, but still lower than those of slab-derived adakitic melts enriched in interaction with mantle wedge during magma ascent (Mg#>47, average Ni contents of 20ppm and Cr of 41ppm (Smithies, 2000; Martin et al., 2005). Such geochemical patterns mostly overlap Archean TTG and adakitic rocks as products of melts derived from thickened lower crust and melts resulted from experiments on wet mafic rocks (Fig. 7A, B). Similar characteristics are also present in magmas generated by slab melting during the rare cases of subduction at low angle where adakitic signature is coupled with low to slightly increasing mantle influence (Martin, 1999). Other indicators based on trace-element behavior are used in order to find out sources and P-T conditions for the STG-BG petrogenesis. As (Sm/Yb)N is a good marker of amphibole-dominated (Sm/Yb)N <4 vs. garnet dominated (Sm/Yb)N >5 fractionation in granitoids, its values from 2.8 to 9.4 indicate that residual assemblage is amphibole-rich, but mostly garnet-rich. Medium-high Sr contents and small/no Eu anomalies relate to minor plagioclase left in the residue. Decreasing Yb and Y while increasing Sr contents (Fig. 3A) may indicate increasing residual garnet/plagioclase ratios from STG to BG. Low HREE, (Gd/Yb)N >1 and La/Yb >20 indicate residual garnet that, together with negative Nb-Ti anomalies, relate to residual Ti-phase and low-Mg amphibole implying a garnet-bearing source-rock, probably of amphibolite type (according to Castillo (2012); Moyen (2009)) criteria). The analyzed samples in diagrams like Sr/Y vs. Y (Fig. 8A), La/ Yb vs. Yb (Fig. 8B) and La/Yb vs. Sr/Y (Fig. 8C) confirm the adakitic/TTG signature. The rocks plot within TTG and close to the adakite areas on Nb/Ta-Zr/Sr diagram (Fig. 8D), not far from the products of amphibolite batch melting (Foley et al., 2002); taking into account Rapp et al. (2003) conclusions on a typical Archean basalt source, the samples are close to the eclogite melting field. Considering the low HREE and Nb, medium Ta and high Sr contents, STG-BG rocks could be identified as medium-high pressure TTGs (according to Halla et al. (2009) and Moyen, 2011 in Moyen and Martin, 2012) in equilibrium with residual garnet+rutile and scarce plagioclase. Despite the Nb-Ti negative anomalies indicating residual rutile, its presence as a residual phase becomes questionable because the lack of negative Ta anomalies, clinopyroxene, garnet and biotite being alternative residual phases. Considering scarce residual plagioclase consistent with low H2O content in case of dehydrating melting at pressures up to 1.8GPa, residual garnet (stable above 1GPa) and absence of rutile (with lower stability limit at 1.5GPa (Xiong et al., 2011)), the presumed melting pressure is of 1-1.5GPa. According to Moyen (2009), the Sr/Y ratios may reflect the pressure melting or inherit the source-rock Sr/Y signature. Low Mg# (18.8-20) and Sr/Y ratios (48-87) in STG rocks may relate to melting of a low-Mg# source at pressures ≥1.3 up to ~1.8GPa (Fig. 9). The composition of BG rocks seems to adjust to a more mafic source with higher Mg# (29.4-34.5) and Sr/Y ratios (100-175) at pressures ranging from 1.3 to 1.5GPa. A comparison with experimental results of Qian and Hermann (2013) on hydrous mafic lower crust material (Fig. 3A), based on trace-element behavior and stable mineral phases, indicates a pressure melting of ~1.25GPa and temperatures of ~900°C. Melting in such conditions could produce negative Nb-Ti anomalies and Ta enrichment due to residual amphibole, garnet, scarce plagioclase and clinopyroxene over orthopyroxene as a main mineral residue. In STG case, because allanite is not stable at higher temperature as LREE enter the melt (Herman, 2002 in Qian and Hermann, 2013), its presence together with apatite, titanite and rutile in the rock may relate to a garnet amphibolite residue left after partial melting at temperatures around 800°C and pressure of ~1.5GPa. Lower REE contents of BG samples may indicate more residual titanite and allanite, while rutile presence at >1.25GPa and 900°C (Qian and Hermann, 2013) could adjust to a garnet granulite. However, most granulite crustal lithologies contain abundant plagioclase which would cause Eu anomalies in any melt separated from them. Therefore, the lack of Eu anomalies in STG-BG rocks argues against granulite sources (Girardi et al., 2012); instead, eclogite is a more possible source for BG magma, given the high Sr/Y and low Nb/Ta ratio significance (Rapp et al., 2003).

Zircon thermometry

In an attempt to find out the temperatures attained by STG-BG magma and check the estimated partial melting thermal conditions for its genesis, as well as to explain the rich zircon inheritance in the BG rocks, both zircon saturation thermometer and Ti-in zircons thermometer have been applied.
For intrusions with abundant inherited zircons, Miller et al. (2003) showed that zircon saturation temperature ($T_{Zr}$) provides useful approximation of melt-generation temperature. The calculated $T_{Zr}$ using the expression of Watson and Harrison (1983) range within 847-897°C for BG and 873-918°C for STG (Table I) which contain maxima for magmas that carry zircon crystals, placing them into ‘hot granites’ category. Contrary to the idea that ‘hot granites’ have little or no inheritance (Miller et al., 2003), BG rocks are rich in inherited zircons (no observation on STG sample).

In order to estimate the lower limit for the maximum temperature reached by magma and to evaluate the survival capacity of the inherited crystals, the Ti concentration of each dated zircon was used to apply the Ti-in-zircon thermometer (Watson and Harrison, 2005; Watson et al., 2006) on both inherited and neo-formed zircon crystals. Corrected Ti-in-zircon crystallization temperatures were calculated using the recalibrated Ti-in-zircon equation of Ferry and Watson (2007). The extremely low TiO$_2$/Zr ratios (0.0013-0.0031) of STG and BG rock samples indicate that melts have been severely TiO$_2$ undersaturated at near-liquidus conditions, fact that imply corrections of low $a_{TiO_2}$ values (0.1-0.3) applied to the Ti-in-zircon crystallization temperature formula (Schiller and Finger, 2019). Plausible crystallization temperatures were obtained using $a_{TiO_2}$ values of 0.3.

**TABLE 2.** Comparison between STG, BG, HSA and TTG rocks (data from Defant and Drummond, 1990; Martin et al., 2005; Moyen and Martin, 2012; Smithies, 2000). Av.= Average

| Geochemical characteristics | HSA          | TTG          | STG          | BG           |
|-----------------------------|--------------|--------------|--------------|--------------|
| SiO$_2$ (wt.%)              | ≥56          | ≥64          | 65.62–68.41  | 67.87–73.64  |
| Al$_2$O$_3$ (wt. %)         | ≥15 at 70% SiO$_2$ | >15         | 16.59–17.19  | 15.21–16.11  |
| Na$_2$O (wt. %)             | 3.5-7.5      | 3-7          | 3.86-5.17    | 4.62-6.40    |
| K$_2$O/Na$_2$O              | Av.= 0.47    | Av.< 0.44    | 0.33–0.98    | 0.51–0.82    |
| Sr (ppm)                    | >400         | 400-600      | 554-722      | 608–965      |
| Y (ppm)                     | ≤18          | <20          | 6-12         | 4–10         |
| Yb (ppm)                    | <1.8         | <1.8         | 0.38–1.23    | 0.41–0.88    |
| Nb (ppm)                    | 6            | ≤10          | 9.1–10.4     | 4.3–9.5      |
| (La/Yb)$_N$                 | ≥10          | >15          | 22.78–39.93  | 10.56-30.55  |
| Gd/Yb                       | 3.4          | 3.6          | 1.8–6.1      | 3–5.1        |
| Sr/Y                        | >40          | >40          | 48-87        | 100–175      |
| Mg #                        | Av.= 48      | Av.= 38-43   | 18-20        | 29.4-35      |
| Ni (ppm)                    | Av.= 20      | Av.= 18      | Av.= 2       | Av.=13       |
| Cr (ppm)                    | Av.= 41      | Av.= 34      | Av.= 11      | Av.=32       |
Silica-rich rocks infer $a_{SiO_2} = 1$, thus requiring no correction. The calculated temperatures for zircons crystallized from STG magma range between 759°C and 875°C and for zircons crystallized from BG magma between 911°C and 985°C (Table II). As for the inherited zircons, application of Ti-in-zircon thermometer is often hindered by the lack of information regarding their host rock and by the contrasting correction values proposed for $a_{TiO_2}$ (0.15-0.63), which would result in extremely different temperatures (Chamberlain et al., 2014). However, the BG inherited zircons seem to belong mainly to oceanic crust rocks identified in ultramafic, mafic, intermediate and alkaline rocks area (Fig. 5A). Consequently, the applied correction for $a_{TiO_2}$ is 0.7 (as proposed in Grimes et al., 2009). The calculated crystallization temperatures of the oldest BG inherited zircons range between 754°C and 921°C and those of zircons interpreted as belonging to the main source between 681°C and 853°C.

The highest crystallization temperature of the BG neo-formed Ordovician zircons (within 911-985°C interval) represents an estimate of the magma’s thermal peak and an indicator of the attained partial melting thermal conditions. The crystallization temperatures obtained on STG neo-formed Ordovician zircons fully confirm the partial melting temperatures estimated by the qualitative modelling on whole-rock geochemistry.

Usually, pre-magmatic zircons survive when magma temperature is not high enough to dissolve them or when kinetic effects hinder their dissolution (Bea et al., 2007). The temperatures calculated using Ti-in-zircon thermometer on neo-formed Ordovician zircon crystals of BG rocks reached and even exceeded 900°C. It seems that survival of old zircons was possible in this case despite the temperatures reached by magma, high enough (exceeding the BG rocks $T_{Zr}$ values of 847-897°C) to dissolve almost all the inherited zircons. Under equilibrium conditions, the temperature for total zircon dissolution in a magma roughly corresponds to $T_{Zr}$ which does not surpass 870°C (Bea et al., 2007). Among the dated zircons, there is only one exception of BG zircon core with crystallization temperature higher than the peak magma temperature, crystal that would have survived anyway. The rest of the old zircon cores survived because of other reasons. According to Bea et al., (2007) referring to the Central Iberian Cambro-Orovician igneous rocks with similar unusual situation, the explanation for the zircon survival when magma temperature exceeds their crystallization temperature is related either to kinetic effects that hinder their dissolution or to incomplete dissolution that could occur due to the short life-span of magmatic pulses.

**TECTONIC SETTING**

The geochemistry of STG-BG rocks characterized by adakitic signature was interpreted to originate mainly from partial melting of garnet-bearing rocks of amphibolite, eclogite and less probable of granulite type. The few peraluminous features and the rich zircon inheritance indicate addition of old continental crust/sediments to the source; on the other hand, low to increasing mantle influence affected the magmas. Usually, garnet amphibolite/eclogite/granulite rocks occur at 30-40km depth in the crust where partial melting could have triggered. According to Girardi et al. (2012), magmas of lower (La/Yb)$_{N}$ ratios with no Eu anomalies (as observed in STG-BG rocks) have deeper sources than 40km.
The analyzed samples on a tectonic discrimination diagram (Fig. 10) indicate magmas related to a volcanic arc setting; the rocks are LILE-enriched and HFSE-depleted (Nb-Ti negative anomalies), typical for subduction-related magmas. Granitoids with adakitic signature formed in a subduction setting are linked to slab melting within extremely limited conditions such as high geothermal gradient, relatively hot and young oceanic crust or fast/flat subduction and slab window, where dehydration melting of hydrated minerals occurs (Defant and Drummond, 1990; Gutscher et al., 2000; Yogođzinski et al., 2001). The peraluminous characteristics observed in STG rocks coupled with low #Mg and heavy metals contents may be interpreted as sedimentary input from the subducted plate and low mantle influence on a primordial magmatic pulse, followed by a metaluminous melt affected by increased mantle influence, as a second BG magmatic pulse. These geochemical features may restrict the tectonic setting to slab melting during a subduction at low angle. The sequence of magmatic pulses revealed by the intrusion age intervals at 493-465Ma for STG followed by 462-434Ma for BG and the trace-element behavior with frequent parallel trends support the hypothesis. The calculated depth of melting ($d_m$) at crustal/mantle limit in subduction-related arcs based on ([La/Yb]$_r$, ratios, on samples within 65-68wt.% SiO$_2$ range (protocol applied from Chapman et al., 2015 in Profeta et al., 2015) with [$d_m = 21.277 \ln (1.0204 ([La/Yb]_r)]$ formula, averages 69km for STG and 70km for BG. According to Balintoni et al. (2010), a tectonic extension took place since late Cambrian until ~470Ma followed by contraction between 470 and 450Ma, when a double subduction was presumed, continental arc granites emplacement being accompanied by metamorphism and deformation.

The occurrence of the STG-BG strata-like intrusions at the same level with eclogitic bodies in the LMS connects...
their history to the subduction-collisional geotectonic model of the emplacement of eclogites advanced by Săbău and Massone (2003). Related to this image, STG-BG could have formed by partial melting of garnet-bearing rocks in a tectonic mélangé at the continental crust/oceanic crust/mantle contact, where rocks with diverse thermo-baric evolution were put together during collision that occurred in front of a subduction zone, during Caledonian orogeny. The actual Getic basement contains strongly deformed metasediments, eclogites, ultramafic and mafic rocks, suggesting an accretion complex composed of oceanic and continental components (Conovici, 2000; Săbău and Massone, 2003). The lowest level basement lithology in the Semenic Mountains exhibits basic rocks and garnet-granulites (Conovici, 2000) which may belong to garnet-bearing residues left after generating melts of STG-BG type. The presumed P-T conditions for adakites/TTG genesis are close to the peak metamorphic conditions for some granulites which may represent residues of adakite/TTG magmas (Jiang et al., 2007; Nehring et al., 2009, 2010; Storkey et al., 2005 in Qian and Hermann, 2013). A more plausible scenario for the STG-BG magma genesis could be related to exhumation of high-pressure metamorphic rocks from the lower-crust (where these were tectonically first emplaced) into the upper crust. In order to quantify the crustal thickness/Moho depth (DM) and to find out the depth at which partial melting could have triggered, DM = 27.78 \ln[0.34(\text{La/Yb})_N] formula was applied (Hu et al., 2017). The results indicate ~60km calculated on STG samples and ~50km on BG samples. According to Săbău and Massone (2003) eclogites that occur in LMS, originating from both subducted oceanic crust and mantle cumulates, were emplaced in the upper crust by a succession of syn-subduction exhumation of detached slab fragments. During this process, garnet-amphibolites and eclogites could have been partially melted by decompression and heating at crustal depth of 60-50km, at P-T conditions of around 1.5GPa and 900-800ºC. The spatial disposal of eclogites and granitoids suggests that both types were enclosed in the buoyant mélangé from the subductive margins during the subduction-collision process and placed randomly between the two continental blocks (SN and VU).

CONCLUSIONS

The study on the STG-BG rocks identified granitoids with predominantly I-type and few S-type features, but also geochemical characteristics that approximate the adakitic signature. Qualitative modeling and whole-rock geochemistry provide benchmarks on residues and sources of garnet-bearing rocks of amphibolite and eclogite type, partially melted at pressures exceeding 1.25GPa and temperatures of 800-900ºC (confirmed by calculated Ti-in-zircon temperatures). Particularities related to low to slightly increasing heavy metals contents and \(^{176}\text{Sr}/^{187}\text{Sr} \) ratios along with rich zircon inheritance argue for an oceanic crust source affected by minor to increasing mantle influence, enriched with old crustal material. The geochemical differences between the two granitoids indicate that they could have formed from two distinct magmatic pulses generated by slab melting during a subduction process, under particular low angle conditions. An alternative model for the STG-BG genesis could relate to partial melting of garnet-amphibolites and eclogites due to decompression and heating at crustal depth (60-50km) and P-T conditions of around 1.5GPa and 900-800ºC, during syn-subduction exhumation of eclogitized slab fragments. The granitoids

![FIGURE 9](image-url) Samples of STG-BG on Mg# vs. Sr/Y diagram: melting models of MORB-type source (Mg#= 70) and felsic crustal source (Mg#= 40), each with low Sr/Y (=2) source (solid curves) and higher Sr/Y (=10) source (dashed curves) (Moyen, 2009).
must have been entrained into a buoyant mélange from the subductive margins during the collision and placed randomly between two continental units.

U-Pb zircon ages obtained on the newly formed crystals, interpreted as Ordovician igneous crystallization time and Variscan recrystallization imprints, were confirmed by the trace elements characteristics of the dated zircon zones, thus relating the STG-BG magmatism to a pre-Variscan subduction-collision event. The rich zircon inheritance reveals Neoproterozoic contribution to the source and recycling of older crustal components of Neoarchean to Paleoproterozoic ages.

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## TABLE I. Major oxide and trace element analyses of STG and BG bulk samples; major elements (wt.%), trace elements (ppm); Mg#=mol.100*MgO/(MgO+FeOtt); A/CNK=mol. ([Al2O3]/(CaO+Na2O+K2O)); (Eu/Eu*)=Eu3+/[Sm3+(Gd+Nd)*1/2]. TzR(K)=1.2900/(2.95+0.55*McIn(496000/2melt)), M=(Na++K+Ca)*A(CNK)

| Sample | STG-19 | STG-18 | STG-17 | STG-16 | STG-14 | STG-12 | STG-11 | STG-9 | STG-8 | BG-5 | BG-7 | BG-8 |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|------|------|------|
|         | Rock   | To     | Na     | Mg     | Al     | Si     | Fe     | Ti     | Nd     | Pr   | Eu   | Yb   |
|         |        |        |        |        |        |        |        |        |        |      |      |      |
| STG-19  | 65.62  | 85.88  | 16.89  | 66.88  | 67.29  | 67.77  | 67.85  | 68.21  | 68.34  | 68.98 | 70.24 | 70.65 |
| STG-18  | 4.97   | 4.63   | 0.47   | 0.45   | 0.47   | 0.43   | 0.46   | 0.43   | 0.36   | 0.34   | 0.33   | 0.32   |
| STG-17  | 0.19   | 17.59  | 19.61  | 16.65  | 17.00  | 16.63  | 16.07  | 16.11  | 16.00  | 15.79  | 15.58  | 15.48  |
| STG-16  | 8.55   | 36.62  | 95.66  | 95.66  | 96.47  | 97.00  | 97.29  | 97.62  | 97.80  | 98.30  | 98.63  | 98.92  |
| STG-14  | 75.00  | 63.00  | 100.00 | 99.99  | 99.99  | 99.99  | 99.99  | 99.99  | 99.99  | 99.99  | 99.99  | 99.99  |
| STG-12  | 0.95   | 2.22   | 0.95   | 0.95   | 0.95   | 0.95   | 0.95   | 0.95   | 0.95   | 0.95   | 0.95   | 0.95   |
| STG-11  | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   |
| STG-9   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   |
| STG-8   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   | 2.67   |
| BG-5    | 1.95   | 20.02  | 20.02  | 20.02  | 20.02  | 20.02  | 20.02  | 20.02  | 20.02  | 20.02  | 20.02  | 20.02  |
| BG-7    | 0.79   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   |
| BG-8    | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   | 0.80   |

### Notes
- Mg# = mol.100*MgO/(MgO+FeOtt)
- A/CNK = mol. ([Al2O3]/(CaO+Na2O+K2O))
- (Eu/Eu*) = Eu3+/[Sm3+(Gd+Nd)*1/2]
- TzR(K) = 1.2900/(2.95+0.55*McIn(496000/2melt)), McIn = (Na++K+Ca)*A(CNK)

### Print-Variscan granitoids with adakitic signature

A. Dobrescu

| Table I. | (La/Yb)N | Nd/Th | Na | #Mg | Ce | Yb | Er | Hf | Zr | O | STG |
|----------|----------|-------|----|-----|----|----|----|----|----|---|-----|
|          | 8.79     | 1.64  | 4.39 | 1.17 | 722 | 1.9 | 19.6 | 5.5  | 45 | 2 | 698 |
|          | 43.87    | 56.74 | 0.10 | 1.18 | 4.56 | 10.1 | 35.6 | 1.11 | 698 | 1.1 | -13 |
|          | 25.05    | 56.74 | 0.10 | 1.18 | 4.56 | 10.1 | 35.6 | 1.11 | 698 | 1.1 | -13 |
|          | 25.05    | 56.74 | 0.10 | 1.18 | 4.56 | 10.1 | 35.6 | 1.11 | 698 | 1.1 | -13 |
|          | 25.05    | 56.74 | 0.10 | 1.18 | 4.56 | 10.1 | 35.6 | 1.11 | 698 | 1.1 | -13 |
|          | 25.05    | 56.74 | 0.10 | 1.18 | 4.56 | 10.1 | 35.6 | 1.11 | 698 | 1.1 | -13 |
|          | 25.05    | 56.74 | 0.10 | 1.18 | 4.56 | 10.1 | 35.6 | 1.11 | 698 | 1.1 | -13 |
|          | 25.05    | 56.74 | 0.10 | 1.18 | 4.56 | 10.1 | 35.6 | 1.11 | 698 | 1.1 | -13 |
|          | 25.05    | 56.74 | 0.10 | 1.18 | 4.56 | 10.1 | 35.6 | 1.11 | 698 | 1.1 | -13 |
|          | 25.05    | 56.74 | 0.10 | 1.18 | 4.56 | 10.1 | 35.6 | 1.11 | 698 | 1.1 | -13 |

Pre-Variscan granitoids with adakitic signature

A. Dobrescu
### TABLE II. Trace element data (ppm) of STG and BG zircons (Cameca IMS 1280)

| Sample  | Age (Ma) | Pb (ppm) | Th (ppm) | U (ppm) | Th/U | Y (ppm) | Hf (ppm) | La (ppm) | Ce (ppm) | Pr (ppm) | Nd (ppm) | Sm (ppm) | Eu (ppm) | Gd (ppm) | Dy (ppm) | Er (ppm) | Yb (ppm) | Ti (ppm) | T$_e$ corrected (°C) |
|---------|----------|----------|----------|---------|-------|---------|----------|----------|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----------------------|
| BG-Z13  | 25.14    | 48       | 164.01   | 180.67  | 746.59| 0.24    | 413.6    | 9712.2   | 15.7     | 22.9    | 29.4    | 33.2    | 72.6    | 47.3    | 181.4   | 212.7   | 379.2   | 709.1   | 24.56               |
| BG-Z2   | 1876-1857| 56       | 141.06   | 100.95  | 394.94| 0.26    | 964.4    | 10389.0  | 0.1      | 2.8     | 0.6     | 2.7     | 17.0    | 2.2     | 87.4    | 346.3   | 780.0   | 1274.8  | 7.62                |
| BG-Z11-c| 1055     | 39       | 2.3      | 62.6    | 4.7    | 8.7     | 40.7     | 30.6     | 115.4    | 522.3   | 1715.1  | 3503.3  |
| BG-Z10  | 858      | 32       | 77.46    | 498.66  | 1097.4| 0.45    | 1638.9   | 9141.6   | 81.4     | 75.9    | 158.7   | 187.0   | 417.7   | 252.5   | 573.6   | 851.2   | 1653.9  | 3364.3  | 34.48               |
| BG-Z17-c| 677      | 29       | 11.93    | 34.63   | 114.55| 0.30    | 910.5    | 9801.1   | 0.3      | 3.6     | 0.6     | 1.7     | 9.2     | 5.7     | 30.0    | 212.0   | 996.3   | 3300.3  | 19.75   |
| BG-Z12  | 600      | 22       | 44.92    | 301.31  | 434.50| 0.69    | 1114.8   | 8436.3   | 0.0      | 21.8    | 1.0     | 4.1     | 27.6    | 7.0     | 117.3   | 438.2   | 1066.1  | 1936.5  | 9.69    |
| BG-Z4-c | 569      | 23       | 39.11    | 3.60    | 400.10| 0.01    | 201.8    | 7736.3   | 0.3      | 3.5     | 0.2     | 0.2     | 1.2     | 3.1     | 7.9     | 59.2    | 204.8   | 518.6   | 3.37    |
| BG-Z15-c| 583      | 22       | 0.2      | 17.6    | 0.8    | 2.7     | 15.1     | 5.0      | 72.7     | 282.8   | 716.2   | 1383.6  |
| STG-r   | 493      | 19       | 23.00    | 241.69  | 396.73| 0.61    | 3145.7   | 7584.5   | 1.0      | 15.1    | 1.2     | 3.1     | 19.9    | 2.2     | 950.0   | 438.8   | 995.8   | 1637.2  | 10.14   |
| STG-c   | 465      | 17       | 14.05    | 150.39  | 234.46| 0.64    | 1075.1   | 7218.1   | 47.2     | 98.3    | 28.9    | 27.5    | 82.4    | 4.4     | 327.4   | 1176.1  | 2608.9  | 3579.0  | 3.46    |
| BG-Z18-r1| 462     | 18       | 24.15    | 110.11  | 305.21| 0.36    | 1598.9   | 9236.6   | 0.0      | 3.2     | 0.7     | 3.5     | 24.8    | 1.6     | 1614.6  | 655.8   | 1454.4  | 2328.1  | 13.63   |
| BG-Z9   | 434      | 19       | 8.49     | 114.95  | 113.86| 1.01    | 2351.7   | 8621.9   | 0.2      | 5.9     | 4.4     | 17.1    | 100.9   | 4.8     | 357.5   | 1024.3  | 2001.7  | 2826.8  | 23.66   |
| BG-Z16  | 357      | 15       | 239.63   | 776.77  | 3891.18| 0.20   | 1891.8   | 8689.7   | 26.4     | 71.2    | 79.7    | 113.4   | 253.2   | 181.3   | 320.0   | 671.4   | 1703.7  | 3360.3  | 16.96   |
| BG-Z15-r| 338      | 15       | 0.1      | 19.3    | 0.6    | 2.0     | 12.7     | 3.8      | 51.7     | 238.2   | 689.2   | 1360.4  |
| BG-Z4-r | 331      | 15       | 57.16    | 28.98   | 893.55| 0.03    | 240.8    | 9047.5   | 0.5      | 0.3     | 0.4     | 0.4     | 1.5     | 2.8     | 9.4     | 75.9    | 124.6   | 181.1   | 2.17    |
| BG-Z11-r| 329      | 13       | 30.5     | 130.6   | 81.6   | 74.5    | 81.0     | 61.2     | 133.7    | 312.2   | 825.2   | 1641.2  |
| BG-Z17-r| 319      | 14       | 57.87    | 308.09  | 1878.02| 0.16   | 862.8    | 9952.5   | 12.0     | 31.5    | 26.4    | 29.4    | 57.2    | 58.6    | 109.3   | 250.8   | 752.2   | 1787.3  | 11.17   |
| BG-Z5   | 309      | 12       | 116.88   | 257.09  | 553.39| 0.46    | 1007.3   | 7733.1   | 26.3     | 37.5    | 50.6    | 59.7    | 137.5   | 92.3    | 201.8   | 403.6   | 898.0   | 1733.5  | 25.87   |