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Petrology

Thermal Evolution of Regional Metamorphism and Reconstruction of P-T Conditions in the Elbrus Subzone Infrastructure (Greater Caucasus)

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Abstract. The study addresses the thermal evolution of the Caledonian regional metamorphism of the infrastructure of the Elbrus subzone within the structural zone of the Main Range of the Greater Caucasus, in the Upper Svaneti segment, and reconstructs its P-T conditions. The research is based on geochronological data and detailed mineralogical-textural analyses of rocks from the gneiss-migmatite complex. To investigate the metamorphic rocks of the infrastructure, samples were collected in the Upper Svaneti area, within the basins of the Nenskra, Memuli, Dalari, Nakra, Sakeni, and Mestiachala rivers. Detailed microscopic, microprobe, and microstructural studies were carried out, and various geothermobarometric methods were applied. Based on the obtained petrological and thermobarometric data, it is suggested that the regional metamorphism of the Upper Svaneti infrastructure rocks corresponds to high-temperature amphibolite facies conditions and the transition zone to granulite facies (max. $T = 732°C$, $P \approx 3.37\text{-}4.17$ kbar). Evidence of partial melting followed by progressive cooling observed in the mineral assemblages indicates deep crustal melting and remobilization processes, as confirmed by direct petrological observations within this segment. © *2025 Bull. Natl. Acad. Sci. Georg.*

Keywords: Greater Caucasus, Elbrus subzone infrastructure, gneiss-migmatite complex, thermal reconstruction of metamorphism

Introduction

The pre-Alpine infrastructure of the crystalline basement of the Elbrus Subzone within the Main Range structural zone of the Greater Caucasus was formed during the Caledonian stage of regional metamorphism. It is represented by a gneiss-migmatite complex and syn- to post-metamorphic granitoids. From a petrological, mineralogical, geochronological, and geodynamical perspective, the constituent rocks of the infrastructure are relatively well studied (Somin, 1971; Shengelia et al., 2014; Shengelia et al., 2008; Gamkrelidze et al., 2012; Kakhadze, 1981; Gamkrelidze & Shengelia, 2005; Gamkrelidze et al., 2020). However, detailed thermal constraints of the metamorphism have not yet been systematically investigated. The main objective of the present study is to examine the thermo-dynamic conditions of high-temperature regional metamorphism developed in the Upper Svaneti segment of the Elbrus Subzone within the

Main Range zone of the Greater Caucasus. The research is based on geochronological data and detailed mineralogical and textural analyses of migmatites. Geothermobarometry was applied to determine the temperature and pressure conditions of metamorphism.

Brief Description of the Elbrus Subzone Infrastructure Rocks

The pre-Alpine infrastructure represents one of the units of the crystalline basement of the Elbrus Subzone and is represented by a gneiss-migmatite complex. U-Pb LA-ICP-MS zircon dating indicates that the rocks of the infrastructure correspond to three stages of regional metamorphism. The ages of 626 ± 16 Ma and 627 ± 19 Ma correspond to regional metamorphism associated with Cadomian orogeny (Gamkrelidze et al., 2020); however, this stage is not clearly evidenced by geological observations. High-temperature Caledonian regional metamorphism is indicated by ages of 457 ± 12 Ma and 461 ± 5.3 Ma, obtained for migmatites, and 468 ± 5 Ma and 471.7 ± 4.6 Ma, obtained for syn-metamorphic granitoids (Gamkrelidze et al., 2020; Tsutsunava et al., 2025). The final, low-temperature stage of regional metamorphism occurred during the Variscan orogeny (357.2 ± 5.9 Ma, determined using the same method). The infrastructure of the Elbrus Subzone is primarily composed of gneiss-migmatite complex and granitoids of sialic composition. The migmatites and para- and orthogneisses are predominant, while amphibolite occurrences are rare. The infrastructure is characterized by numerous syn- and post-metamorphic granitoid intrusions. CaO-rich rocks are represented by amphibole-, quartz-plagioclase-, and, occasionally, clinopyroxene-bearing amphibolites. The leucocratic parts of migmatites are mainly composed of quartz-feldspar aggregates, while the restites contain garnet, biotite, sillimanite, muscovite, feldspar, quartz, and, very rarely, cordierite and gedrite.

The degree of Caledonian regional metamorphism within the infrastructure of Upper Svaneti segment, according to previous studies, largely corresponds to the high-temperature amphibolite facies and also the low-temperature stage of the granulite facies, with pressures estimated 3.2-3.8 kbar (Kakhadze, 1981; Gamkrelidze & Shengelia, 2005). In the area adjacent to Upper Svaneti from the northern slope of the Greater Caucasus, within the same complex, exposures of granulite-facies metamorphic rocks are reported (Shengelia, 1968). These rocks are represented by garnet-sillimanite gneisses (Kintsigites), granitic granulites, and gneissic pyroxene (sahlite)-plagioclase-amphibole-bearing rocks.

Methodology

To study the infrastructure rocks, samples were collected in the Upper Svaneti area within the basins of the Nenskra River and its tributaries, the Memuli and Dalari Rivers, as well as the Nakra, Sakeni, and Mestiachala Rivers (Fig. 1). The samples from the authors' personal collections were also utilized.

To determine the mineral parageneses of the rocks, detailed microscopic, microprobe, and microstructural studies were conducted. Specifically, microscopic investigations were performed at the Alexandre Janelidze Institute of Geology; microprobe analyses were carried out using Cameca SX-100 and Cameca SX-Five FE electron microprobes, as well as SEM (Zeiss Sigma and/or Zeiss Auriga, Raman spectroscopy) at the Department of Geochemistry, Mineralogy, and Petrology, University of Warsaw, Poland. Micro-Raman and SEM studies were conducted at the University of Padua, Italy. More than 900 thin sections were described, from which representative samples were selected for microprobe analysis. A total of 906 point analyses were performed on garnet, 257 on biotite, 428 on plagioclase, 312 on muscovite, 179 on K-feldspar, as well as several additional analyses for other minerals.

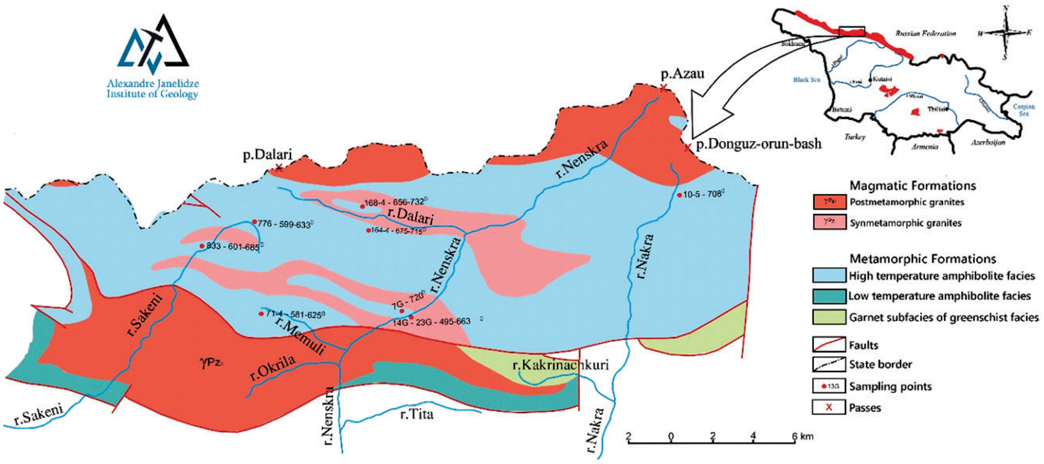

Fig. 1. Map of the crystalline basement of the Elbrus subzone of the Greater Caucasus Main Range zone within the Upper Svaneti (editors Korikovsky & Shengelia, 1999, with additions by the authors).

One of the objectives of the present study was the investigation of fine inclusions in garnets. For this purpose, SEM analysis was conducted, providing high-resolution visual data on the morphology, texture, and phase composition of the inclusions. Their shape, size, and internal structure were described in detail. The existing voids, mineral and vitreous components, and their spatial relationships were identified. Amorphous regions and crystalline phases – quartz, biotite, rutile, chlorite, and, very rarely, K-feldspar and graphite were clearly identified. For detailed chemical characterization, energy-dispersive spectroscopy (EDS/EDX) was applied, enabling both point and mapping analyses of elemental distribution in garnet grains and inclusions as well. Raman spectroscopy was employed as a primary method for identifying mineral and amorphous phases within the inclusions.

To determine the temperature conditions of metamorphism, three garnet-biotite geothermometers were used (Holdaway & Lee, 1977; Ferry & Spear, 1978; Perchuk & Lavrentyeva, 1981). Pressure conditions were estimated using a geobarometer (Perchuk et al., 1984), based on experimentally studied cation exchange equilibria between garnet, biotite, cordierite, and, partially, sillimanite, where Fe-Mg exchange occurs between garnet and biotite.

Results

The migmatites exposed in the Nenskra River valley are predominantly fine- to medium-grained stromatic metatexites, characterized by a well-developed alternation of melanosome and leucosome. The light bands are mainly composed of quartz, K-feldspar, and plagioclase, whereas the dark bands – of biotite, garnet, and sillimanite. Leucosomes contain euhedral K-feldspar crystals and thin quartz-feldspar films along the grain boundaries.

Based on microscopic and microprobe studies, the mineral parageneses of the metamorphic rocks were determined. The highest-temperature mineral parageneses of K_2O-rich metapelites are: Bt + Sil + Grt + Kfs + Pl + Gr, Bt + Sil + Crd + Kfs + Pl + Qz ± Gr, Bt + Sil + Kfs + Pl + Qz ± Gr and Ged + Cum + Bt + Pl; Relatively lower-temperature K2O-rich metapelites show the following mineral parageneses: $Grt_{92\text{-}95}$ + Bt_{66} + Ms + Pl + Qz, Grt_{91+92} + Bt_{62} + Pl_{14} + Crd + And ± Fi + Ms + Qz, $Grt_{78\text{-}82}$ + $Bt_{46\text{-}48}$ + Sil + Qz + Pl, but K_2O-poor metapelites – Grt + Crd_{43} + $Bt_{60\text{-}63}$ + Pl + Qz ± Spl.

To assess the grade and nature of regional metamorphism, several key minerals were described, including garnet, biotite, and muscovite.

In the studied garnets, the almandine content is 66-97 %, spessartine – 3-24%, pyrope – 6-12%, and grossular – 2-8%. Microstructural analysis revealed that garnet crystals often contain numerous tiny inclusions, giving them a cloudy appearance. Micro-Raman spectroscopy identified the presence of cristobalite, graphite, phlogopite, biotite, schamozite, carbonate, CH_4, and N_2 in the majority of these inclusions. In ten migmatite samples, profile microprobe analyses of garnet chemistry were performed across the entire grain diameter, including the garnet-biotite contacts. No clearly defined zoning was observed in garnet profiles; however, certain trends are noted. In most of these samples, a slight decrease in MgO and FeO contents and an increase in MnO content were observed toward the garnet crystal rims. SEM data also indicate local Mn enrichment at the edges of some garnet crystals. These features likely reflect post-peak metamorphic evolution of garnet, specifically replacement by biotite during retrograde metamorphism. FeO variations in the studied garnets are generally heterogeneous throughout the crystals, whereas MgO and MnO trends are relatively stable. It is known that, in general, such behavior is typical for pelitic migmatites and high-temperature metamorphic complexes.

Biotite is a widely distributed mineral in the metamorphic rocks of the Upper Svaneti infrastructure. Its paragenetic minerals are Grt, Sil, Ms, Pl, Kfs, and Qz, and very rarely Crd. Microprobe analysis was performed on 33 biotite crystals. Biotite is iron-rich; it is mostly characterized by high TiO_2 content (3-4%), corresponding to its formation during the prograde stage of regional metamorphism at temperatures of 550-730°C. During retrograde stage, TiO_2 content decreases to 1.95-0.49%. At the same time, the relative stability of Fe and Al_2O_3 in biotite indicates that the metamorphic processes were largely isochemical.

White mica appears in the metapelites of the Upper Svaneti infrastructure during both prograde and retrograde stages of regional metamorphism. It is in paragenesis with garnet, biotite, plagioclase, K-feldspar, and chlorite. The maximum temperature of white mica formation in the Upper Svaneti infrastructure corresponds to high-temperature amphibolite-facies conditions. In the highest-grade metamorphic samples, it occurs rarely and, if present, shows skeletal morphology. It is not in contact with quartz and is typically found near K-feldspar and sillimanite crystals. Microprobe analysis was conducted on 24 white mica crystals. Muscovite component clearly dominates in all cases, with contents 80-90% in 18 samples, 76-79% in 4 samples, and only 49.86% and 64.3% in 2 samples. Phengite component maximum values are 28.68% and 49.48%, while paragonite and margarite contents remain low, as expected. Notably, SEM analysis revealed the presence of green spinel inclusions in some sillimanite aggregates.

Crystallization temperatures of migmatites from the Elbrus Subzone infrastructure were calculated, as described above, using three garnet-biotite geothermometers (Table 1). Geothermometric calculations were performed on garnet-biotite pairs in a total of 15 samples. In two cases, calculations were carried out using a pair of garnet and inclusion of biotite within its crystal. The results obtained from all three geothermometers are very similar. The pressure conditions of metamorphism, recalculated using geobarometry (Perchuk et al., 1984), are as follows: 3.99, 4.17, 3.62, 3.50, and 3.37 kbar.

Discussion

High-temperature regional metamorphism of the Caledonian stage in the Elbrus Subzone infrastructure of the Main Range structural zone of the Greater Caucasus was responsible for initiating migmatization and partial melting processes in the rocks. It is noteworthy that the leucosomes of the studied migmatites contain idiomorphic K-feldspar crystals, along the edges of which thin quartz-K-feldspar films are observed. These can be interpreted as microstructures indicative of former melt presence. Below, an analysis of the data obtained in this study and the corresponding conclusions are presented.

Table 1. Mineral paragenesis and P-T conditions of metamorphism of the infrastructure rocks of the Upper Svaneti segment of the Elbrus Subzone

	Sample №	Paragenesis	Holdaway, Lee, 1977, T°C	Ferry, Spear, 1978, T°C	Perchuk, Lavrentyeva, 1981, T°C	Perchuk et al.,1984 P (Kbar)	Sampling location
1	7G	$Grt_{88}+Bt_{65}+Sil+Pl^{28}+Qz+Ilm$ [Chl+Ms]	659	706	665	3.99	Right bank of the Nenskra River
			668	720	672		
2	14G	$Grt_{91}+Bt_{63}+Sil\pm Ms+Pl^{5}+Qz$ [Chl]	562	556	586		Left bank of the Nenskra River
3	15G	$Grt_{93}+Bt_{64}+Sil+Ms+Pl^{12}+Qz+Ilm$ [Chl]	519	495	549		
4	16G	$Grt_{92}+Bt_{64}+Sil+Ms+Pl^{20}+Kfs5+Qz$ [Chl]	547	535	573		
5	18G	$Grt_{90}+Bt_{60}+Sil\pm Ms+Pl^{31}+Qz+Kfs^{6}$	564	539	588	4.17	
			556	548	581		
6	21G	$Grt_{90}+Bt_{66}+Sil+Kfs^{5}+Pl^{24}+Qz\pm Ms+Ilm$	604	620	621		
			628	656	640		
			632	663	643		
7	23G	$Grt_{89}+Bt_{64}+Sil\pm Ms+Pl^{16}+Kfs^{6}+Qz+Ilm$	604	619	620	3.62	
			601	615	618		
	23G - Bt in Grt		604	619	620		
8	164-4	$Grt_{87}+Bt_{61}+Sil+Ms+Kfs^{3}+Pl^{22}+Qz$	665	715	669		Dalari River (Right tributary of the Nenskra River)
			620	643	633		
			640	675	649		
9	168-4	$Grt_{89}+Bt_{67}+Sil+Ms+Kfs^{10}+Pl^{29}+Qz$	628	656	639		
			672	727	675		
			675	732	677		
10	10-5	$Grt_{89}+Bt_{68}+Sil\pm Ms+Kfs^{6}+Pl^{31}+Qz$ [Chl]	660	708	665		Nakra River
			654	698	661		
11	776	$Grt_{91}+Bt_{66}+Sil+Ms+Pl^{13}+Kfs^{7}+Qz$	551	540	577	3.5	Headwaters of the Sakeni River - Dalar Pass
			613	633	628		
			591	599	609		
			562	557	586		
11	833	$Grt_{90}+Bt_{65}+Sil+Ms+Kfs^{7}+Pl^{26}+Qz$	646	685	654		Headwaters of the Sakeni River
			592	601	610		
12	71-4	$Grt_{90}+Bt_{63}+Sil\pm Ms+Kfs^{9}+Pl^{32}+Qz$	579	581	600	3.37	Headwaters of the Memuli River
			608	625	623		
			584	589	604		
	71-4 - Bt in Grt		600	613	617		

Chemical zoning in garnets from the migmatites of the Elbrus Subzone is not clearly developed; only in some cases it reflects weakly expressed retrograde metamorphic processes, indicated by a trend of increasing Mn and decreasing Mg and Fe contents toward the crystal rims. The irregular, “jagged” profiles of Fe concentrations in garnet crystals likely reflect its sensitivity to changes in P-T conditions of metamorphism and may also suggest the episodic nature of metamorphic processes. Very rarely progressive zoning is also observed. The absolute majority of the studied garnets are characterized by high almandine content, which is typical of the high-temperature part of the amphibolite facies. In granulite facies conditions, garnet is usually characterized by a clearly expressed pyrope component. As noted above, garnets contain numerous tiny inclusions, which represent former fluid inclusions. Their presence confirms that the melt captured during metamorphism contained a significant amount of volatile components, which played an important role in its evolution.

The composition of the studied biotites (high titanium content and MgO ≤ 8.5%) is characteristic of pelitic or alumina-rich clayey rocks undergoing high-temperature, but not ultra-high-temperature, metamorphism. Under granulite facies conditions, biotite is typically thermally decomposed and is often replaced by orthopyroxene, especially in high-magnesium systems. When garnet is almandine-rich and biotite has MgO ≤ 8.5%, and if the reaction Ms + Qz → melt has not yet dominated and orthopyroxene has not formed, the metamorphic grade corresponds less to granulite facies and more to the high-temperature part of amphibolite facies.

As noted above, in the highest-grade metamorphic samples, muscovite is rare, displays skeletal morphology, is no longer in stable equilibrium with quartz, and begins to decompose. This indicates that partial melting conditions exceed the stability of Ms + Qz and reach the stability field of Kfs + Sil. Skeletal muscovite forms under high-temperature and relatively high-pressure conditions. During this stage, biotite, K-feldspar, and other minerals undergo melting, while muscovite crystallizes imperfectly, resulting in a skeletal habit. Such muscovite typically occurs at the high-temperature stage of amphibolite facies metamorphism and/or at the onset of granulite facies conditions.

Green spinel inclusions were observed in sillimanite aggregates. These may form either as a result of staurolite disaggregation or during the onset of anatexis and reactions with other high-temperature phases (Vielzeuf & Holloway, 1988; Holness, 1997). In the present case, the first scenario is less likely, as staurolite is extremely rare. It is more probable that green spinel developed within sillimanite aggregates through melt condensation or recrystallization under granulite facies conditions. It may also form during the transitional stage from the high-temperature part of amphibolite facies toward granulite facies. Green spinel develops also during the breakdown or transformation of garnet enclosed by sillimanite, a process that predominantly occurs in amphibolite- and granulite facies rocks or in transitional zones between them.

Investigations of the infrastructure rocks also revealed a few occurrences of cordierite. Cordierite is commonly formed during the metamorphism of pelitic rocks experiencing moderate heating and partial melting, yet not reaching the stage where more stable minerals, such as sillimanite, appear. In the upper part of the amphibolite facies and within granulite facies rocks, cordierite likely represents either the product of retrograde metamorphism or indicates a change in metamorphic conditions related to anatexis and subsequent late-stage cooling.

To determine the metamorphic temperature conditions, the Ferry and Spear (1978) garnet-biotite geothermometer was selected as the reference for the final results. This geothermometer is specifically designed for reliable interpretation in the high-temperature part of the amphibolite facies; it provides relatively stable results in the intermediate temperature range (≈500-700°C) and is well calibrated. Accordingly, based on this geothermometer, the maximum temperature reaches 732°C. Temperatures above 700°C indicate that the metamorphic grade exceeds typical amphibolite facies conditions; however, the absence of the Crd+Grt+Kfs paragenesis in Upper Svaneti migmatites demonstrates that it does not surpass the early stage of granulite facies. The lower temperature limit of 550°C corresponds to retrograde metamorphic conditions. During the Variscan orogeny in the Elbrus Subzone processes of diaphthoresis occurred, which are clearly recorded in the mineral assemblages: biotite is partially or completely chloritized, garnet exhibits chloritization along cracks, plagioclase is sericitized, and K-feldspar shows pelitization.

Conclusions

Within the Upper Svaneti segment, the metamorphic P-T conditions of migmatites in the Elbrus Subzone of the Main Range structural zone of the Greater Caucasus are as follows: the peak metamorphic temperature reaches 732°C, and pressure ranges from 3.37 to 4.17 kbar.

The proposed reconstruction of the regional metamorphism indicates temperature and pressure conditions corresponding to the upper part of the amphibolite facies and the transition zone toward the granulite facies.

These conditions are consistent with the initiation of partial melting processes at deep crustal levels, followed by subsequent slow cooling.

The results of this study provide a comprehensive insight into the petrogenesis of migmatites in the Caucasus. They are significant for reconstructing the tectonogenetic history of the Greater Caucasus structural zone, identifying metamorphic facies, and assessing the role of metamorphism in geodynamic processes. This work also contributes to the study of high-grade regional metamorphism and the thermal regime of melting in other metamorphic structural zones of the Caucasus.

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პეტროლოგია

იალბუზის ქვეზონის ინფრასტრუქტურის (კავკასიონი) რეგიონული მეტამორფიზმის ევოლუცია და P-T პირობების რეკონსტრუქცია

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შესწავლილია კავკასიონის მთავარი ქედის სტრუქტურული ზონის იალბუზის ქვეზონის ზემო სვანეთის სეგმენტის ინფრასტრუქტურის კალედონური რეგიონული მეტამორფიზმის თერმული ევოლუცია და რეკონსტრუირებულია მისი P-T პირობები. კვლევა ეფუძნება გნეისურ-მიგმატიტური კომპლექსის ქანების გეოქრონოლოგიურ მონაცემებსა და მიგმატიტების დეტალურ მინერალოგიურ-ტექსტურულ ანალიზს. ინფრასტრუქტურის მეტამორფული ქანების შესასწავლად, ნიმუშები შეგროვდა ზემო სვანეთის ტერიტორიაზე მდინარეების, ნენსკრის, მემულის, დალარის, ნაკრის, საკენისა და მესტიაჭალის აუზებში. ჩატარდა დეტალური მიკროსკოპული, მიკროზონდური და მიკროსტრუქტურული კვლევები. გამოყენებულია სხვადასხვა თერმობარომეტრი. მიღებული პეტროლოგიურ-თერმობარომეტრიული მონაცემების საფუძველზე, გამოთქმულია მოსაზრება, რომ ზემო სვანეთის ინფრასტრუქტურის ქანებში რეგიონული მეტამორფიზმი მიმდინარეობდა ამფიბოლიტური ფაციესის მაღალტემპერატურულ და გრანულიტური ფაციესისკენ გარდამავალ პირობებში (max. T=732°C, P≈3,37-4,17 კბ). მინერალოგიურ ასოციაციებში დაფიქსირებული ნაწილობრივი ლღობის ნიშნები და შემდგომი პროგრესული გაცივება მიუთითებს ღრმა ქერქის ლღობისა და რემობილიზაციის პროცესებზე, რაც ამ სეგმენტისთვის პირდაპირი პეტროლოგიური მტკიცებულებებით დადასტურდა.

REFERENCES

Ferry, J. M., & Spear, F. S. (1978). Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contributions to Mineralogy and Petrology*, 66, 113-117.

Gamkrelidze, I. & Shengelia, D. (2005). *Precambrian-Paleozoic regional metamorphism, granitoid magmatism and geodynamic of the Caucasus*. Nauchni Mir.

Gamkrelidze, I., Shengelia, D., & Tsutsunava, T. (2012). Pre-Alpine Geodynamics of the Caucasus, multistage regional metamorphism and granitoid magmatism. *Proceedings of the World Forum Natural Cataclysms and Global Problems of the Modern Civilization*, 208-217. London.

Gamkrelidze, I., Shengelia, D., Chichinadze, G., Okrostsvaridze, A., Lee, Y.-H., Beridze, G., & Vardanashvili, K. (2020). U-Pb LA-ICP-MS dating of zoned zircons from the Greater Caucasus pre-Alpine crystalline basement: Evidence for Cadomian to Late Variscan evolution. *Geologica Carpathica, 71*(3), 249-263.

Holdaway, M. J. & Lee, L. (1977). Fe-Mg cordierite stability in high grade pelitic rocks based on experimental, theoretical and natural observations. *Contributions to Mineralogy and Petrology,* 63, 175-198.

Holness, M. B. (1997). Partial melting of metapelites: Evidence from spinel compositions in anatectic rocks. *Journal of Metamorphic Geology, 15*(4), 471-484. https://doi.org/10.31577/GeolCarp.71.3.4

Kakhadze, R. G. (1981). Progressive regional metamorphic zonation in the Upper Svaneti. *Bull. Acad. Sci. GSSR, 104*(1), 97-100.

Map of Metamorphic Facies of the Crystalline Basement of the Greater Caucasus (1:200 000). (1999). Korikovsky, S. P. & Shengeli, D. M. (Editors).

Perchuk, L. L., & Lavrent'eva, I. V. (1981). Experimental investigation of exchange equilibria in the system cordierite-garnet-biotite. In Saxena, S.K., Ed. Kinetics and Equilibrium in Mineral Reactions, *Advances in Physical Geochemistry*, 3, 199-239.

Perchuk, L., Lavrentieva, I., Kotelnikov, A., & Petrik, I. (1984). The comparative characterization of the thermodynamic regimes of metamorphism in the Main Caucasus Range and the Western Carpathians. *Geologický Zborník, Geologica Carphatica, 35*(1), 105-155.

Shengelia, D. M. (1968). Granulite facies of the Greater Caucasus, *Izvestia of AN SSSR, Ser. Geol,* 7, 23-33.

Shengelia, D., Gamkrelidze, I., Tsutsunava, T., Chichinadze, G., Maisuradze, N., & Vardanashvili, K. (2008). About Geochemistry of Early Variscan Granitoids of the Main Range of the Caucasus. *Bull. Georg. Natl. Acad. Sci., 2*(2), 59-63.

Shengelia, D., Tsutsunava, T., Chichinadze, G., & Beridze, G. (2014). *Some questions on structure, Variscan regional metamorphism and granitoid magmatism of the Greater Caucasian terrane. Bull. Georg. Natl. Acad. Sci. 11*(1), 56-63.

Somin, M. L. (1971). *Pre-Jurassic basement of the Main Range and the Southern Slope of the Greater Caucasus*. Nauka.

Tsutsunava, T., Javakishvili, I., Cesare, B., Bartoli, O., Shengelia, D., Chichinadze, G., Beridze, G. (2025, April 27 - May 2). *New Insights on Partial Melting and Migmatization in the Greater Caucasus Main Range Zone* [Conference presentation]. EGU25, Vienna, Austria.

Vielzeuf, D., & Holloway, J. R. (1988). Experimental determination of phase relations in pelitic systems and their application to natural metapelites. *Contributions to Mineralogy and Petrology, 98*(2), 257-276.

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