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Phanerozoic continental crust evolution of the Inner Caucasian Microplate: The Dzirula massif

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In the Pre-Alpine Dzirula massif of the Inner Caucasian Microplate is coded a wide spectrum of the geodynamic and magmatic events taking place in the region and that's why it represents important and major structure for general geological interpretations. In the given work, on the example of the mentioned crystalline massif evolution are considered processes of the continental crust in Phanerozoic collisional orogens. We consider, that in Variscan consolidation Dzirula massif formations of the Neoproterozoic Pan-African tectonic-thermal events are observed, that are organically involved in the evolution processes of the Caucasian Phanerozoic collisional orogen and their role in these processes are probably caused by the migration of lithospheric residues to the north, that are formed as a result of Gondwana northern edge Late Ordovician destruction and opening of Palaeo-Tethys. Within the Dzirula massif, a Gondwana-derived Neoproterozoic gneiss-migmatite complex is situated obductively on ensialic island arc. In this Variscan collision-accretion structure, the crustal thickening and released water caused partial melting of the ensialic island arc, thus generating the granitoid melt, which intruded the overlying gneiss-migmatite complex. By the end of this process, the Dzirula massif resembled typical Phanerozoic continental crust.

Introduction

The Neoproterozoic marks the onset of modern plate tectonic systems (Stern, 2008), and as such   the crust-forming processes preserved from the Pan-African evolution of Gondwana records this critical time period. The early tectonic history is frequently overprinted by younger events, but some of these areas are exposed in basement uplifts within the Alpine orogenic belt. The Dzirula massif in the central part of the Inner Caucasian Microplate in the Republic of Georgia is one of these windows. It exposes pre-Alpine basement, and contains a wide range of granitoids of different pre-Alpine ages. Geochemical and geochronological data provided in this paper helps shed light on crust-forming processes and geodynamics in this critical age range.

Most continental crust was formed from mantle-derived magma before Late Proterozoic, and most intensively in the interval of 3.2-2.5 Ma (Taylor and McLennan, 1985) when the earth's crust was divided into granulite-basic and granulite-gneissic. Crust formation at the end of Proterozoic and the Phanerozoic occurred as a result of lithospheric thickening, and granite-forming processes were localized at subduction zones. Here the continental crust was formed as a result of lateral and vertical accretion of island arc complexes at active continental margins or by mantle-derived magmatic additions. The application of integrated isotopic studies of Nd, Sr, and Ar isotope systematics in the North American Cordillera (Allegre, Ben Othman, 1980; DePaolo, 1981; DePaolo et al., 1991; Samson and Patchett, 1991) in Lachland orogen in the Eastern Australia (Collins, 1998); in Meguma lithotectonic zone in the NE Canada (Clarke et al., 1992); in central Asia (Jahn et al., 2000); in the Shyok-Darbuk corridor of NE Ladakh, in India (Daga et al., 2010) have largely supported this view of crustal formation.

The Pre-Alpine consolidation Dzirula massif is a good example of Phanerozoic lithospheric thickening and continental crustal formation. It is located in the North side of the Caucasus Orogen and represents a complicated and the widest outcropped part of the Pre-Alpine crystalline basement. As a result of the collision and of generation new magmatic centers Neoproterozoic granite-migmatite complex and ophiolites, Cambrian tonalites, Late Paleozoic microcline granites and Triassic orthoclase gabbros (ricothites) were gathered within the borders of the Dzitula massif. In the pre-Cambrian crystalline schist structure and as well as in composition of Phanerozioc magamtites reflects the whole deformation and the new magmatic center generation processes. The significant part of the regional geological events, starting from the Neoproterozoic up to Alpine, it is clear that in the structure and composition of this massif is encoded. It therefore Dzirula massif represents an important object for investigation of Proterozoic to Phanerozoic continental crust evolution. Although well-mapped, there are few isotopic or geological studies of the area (Okrostsvaridze and Clarke, 2003, 2004; Zakariadze et al., 1998). We use these geochemical constraints to further constrain the geodynamic and continental crust-forming processes in this area.

Tectonic setting

The Caucasus represents the Northern segment of the Eastern Mediterranean orogen, which is expended over 1200 km between the Black and Caspian Seas, at the NW-SE direction. Currently it is an expression of continental collision between the Arabian and Eurasian lithospheric plates and its location represents the connecting segment between the Alpine and Himalayan mobile belts. Three major unites are distinguished Structurally in the Caucasian Construction: the

Greater and Lesser Caucasian mobile belts and the Inner Caucasian Microplate.

Paleomagnetic and palaeochemical as well as geological data indicate that within the oceanic area of Tethys, which separated Afro-Arabian and Eurasian continental plates, there were relatively small continental or subcontinental plates (terranes) having various geodynamic and geological histories (Gamkrelidze, 1997; Stampfli et al., 2002). During the Late Precambrian, Paleozoic and Early Mesozoic, these terranes underwent horizontal displacement within the oceanic area of Proto-Paleo- and Meso-Tethys, followed by accretion and ultimately merging with the Eurasian continent. The Arabian and Eurasian lithospheric plates are separated by the Greater Caucasian, Black Sea-Central Transcaucasian, Baibut-Sevanian (Lesser Caucasian) and Iran-Afghan terranes (Gamkrelidze, 1997), which in the geological past represented island arcs or microcontinents (Figure 1). The Black Sea-Central Transcaucasian terrane now is situated between the Greater and Lesser Caucasian mobile belts and we consider it as the Inner Caucasian Microplate.
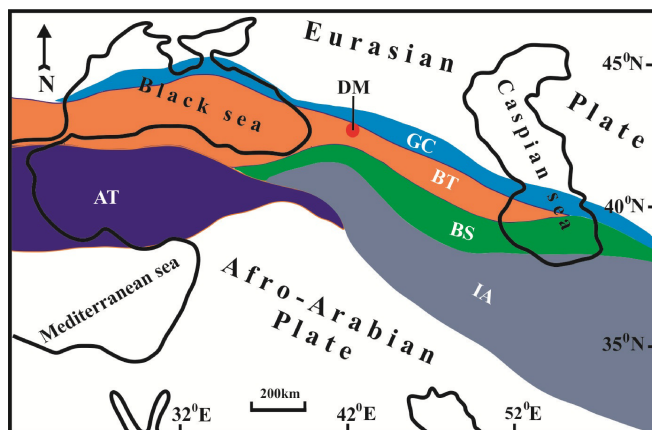

Figure 1. Tectonic zoning of the Caucasus and adjacent area on the basis of the terrane analysis (After Gamkrelidze, 1997). Terranes: GC – Greater Caucasian, BT – Black Sea-Central Transcaucasian, BS – Beiburt-Sevanian, IA – Iran-Afganian, AT – Anatolian. DM – Dzirula massif.

The Inner Caucasian Microplate consists of a pre-Alpine crystalline basement, exposed in the Dzirula and Khrami massifs, that is overlain by an Alpine, non-metamorphosed and moderately folded, nearly 10 km thick through Meso-Cenozoic volcano-sedimentary cover. The Dzirula massif reflects much wider and more interesting spectrum of geological processes, due to that we decided to study it.

Brief geological survey

The Dzirula massif is exposed in the northen part of the Inner Caucasian Microplate and occupies nearly 1200 km^2 at the current of erosion level (Figure 2). It is mainly constructed by Neoproterozoic plagiomigmatites, crystalline schists, and quartz-dioritic gneisses and ophiolites (gneiss-migmatite complex); Cambrian tonalities and granodiorites; Late Paleozoic anatectic microcline granites; and Late Triassic hybrid orthoclase gabbros (rikotites).

Most of the Dzirula massif is composed of the gneiss-migmatite complex. Its protolith was represented by crystalline schists, plagiogneisses and plagiomigmatites, which underwent the
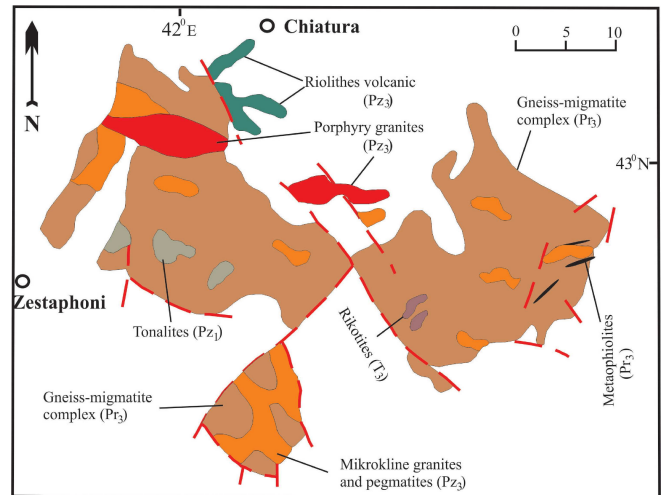
Figure 2. Schematic geological map of the Dzirula massif of the Inner Caucasian Microplate.

Grenvilian regional metamorphism. The wrinkled restites of these rocks, the size of which ranges between one to tens of meters, are found in the Neoproterozoic quartz-dioritic gneisses. Most are represented by metapelites, which underwent regional metamorphism to biotite-muscovite-gneiss, biotite-sillimanite-orthoclase and low-temperature garnet-cordierite-orthoclase facies (Gamkrelidze, Shengelia, 2005).

In the Cambrian, during Pan-African tectonic-thermal events, several tonalite composition bodies were generated in the gneiss-migmatite complex. Later, in the Upper Paleozoic Variscan tectonic-thermal events, numerous intrusions of microcline granites were emplaced, and most of the gneiss-migmatite complex transformed into granite-gneisses, granite-migmatites and porphyroblastic microcline granites.

The northeastern part of the Dzirula massif contains Neoproterozoic ophiolite fragments, and is known as the Chorchana-Utslevi Ophiolitic Zone (Gamkrelidze et al., 1981). The ophiolites are spatially related to the gneiss-migmatite complex, and are cut by the Upper Paleozoic microcline granites. A detailed study of this unit (Zakariadze et al., 1998) identified ultra-basic harzburgites that represent melting restites of tholeitic basalt; their Nd model age corresponds to 810±100 Ma. Later study indicated that not only the Chorchana-Utslevi ophiolitic zone overthrust, but the whole gneiss-migmatite complex overlies it in the Dzirula massif (Okrostsvaridze, Shengelia, 1996; Shengelia, Okrostsvaridze, 1998).

Field relations and granitoid petrography

The majority of the gneiss-migmatite complex of the Dzirula massif is constructed of quartz-dioritic gneisses (~70%). They are dark gray, medium grained rocks, with occasional plagioclase phenocrysts (4-5 mm). Mineral composition includes plagioclase, biotite, quartz, hornblende; secondary minerals include K-feldspar, muscovite, chlorite and epidote; accessory minerals include apatite, zircon, thorite and ore minerals. Quartz-dioritic gneisses are characterized by numerous oval inclusions of gabbro to diorite composition. Inclusions range between tens of centimeters to one meter and in some cases make 30-35% of the entire exposure. We consider that the xenoliths represent the restites of basic injections, which made ensialic protolith assimilation and hybridism.

Cambrian tonalities largest exposures are in the Macharula and Kvirila river gorges where they are exposed over a distance of 800 m. In both sections several tonalitie bodies intruded the gneiss-migmatite complex. The host rock undergoes selective melting and migmatization at the contacts, and biotite gneisses and migmatite inclusions are found in the tonalite intrusive bodies. Late Variscan quartz-muscovite-microcline aplite and pegmatite veins cut each of these features. The mineral assemblage of unchanged tonalites consists of plagioclases (oligoclase) biotite, quartz, and K-feldspar. Accessory minerals include apatite, zircon, thorite and Fe-Ti oxides. As a result of field and petrographic observation we find that tonalities may be the product of anatectic melting of biotite gneisses of the gneiss-migmatite complex.

Upper Paleozoic microcline granites are widely spread in the Dzirula outcrop and represent the product of the Variscan tectonic-thermal events. The gneiss-migmatite complex is saturated with numerous intrusions of these granites. In the northern part of the Dzirula massif, the largest of these granites is exposed; the Rkvia intrusive (~65 km^2) has a lens-like form of NW-SE orientation. The intrusion is composed of porphyritic granites with idiomorphic K-feldspars, the main mass of which is in a medium grained massive structure. The main minerals are plagioclase, k-feldspar, quartz, biotite and muscovite; secondary minerals are: muscovite, sericite, chlorite and epidote; accessory minerals are – zircon, apatite, monazite and ilmenite.

In the eastern part of the Dzirula massif, in the Rikoti river gorge, two small intrusives (thickness- 450 m and 250 m) of orthoclase gabbro are presented, which cross cut quartz-dioritic gneisses. Due to their exotic character the investigators called them the rikotites. Their contact zones are intricate because of Alpine tectonic processes, but partial melting products are detected in the approximately 2-meter wide contact zone. Inclusions of 10cm to 50cm diameters ellipsoid leucocratic quartz-orthoclase are characteristic of rikotites, the number of which decreases from the periphery to the centre. The inclusions are gradually displaced by orthoclase gabbros. Following the field work results, we assume that these acid rocks inclusions are xenoliths – the product of selection melting which were abducted by the intrusive on its way of moving. We relate gabbros magma enrichment by orthoclase and quartz to these processes.

Geochemistry and geochronology

Seventy samples of the Dzirula massif granitoids were collected for complex isotopic research. Major element, trace and rare earth element composition have been analyzed. Based on the petrographic and geochemical work, a subset of twenty four samples were analyzed for Sm-Nd, Rb-Sr and ^{40}Ar-^{39}Ar isotopic systematics. Sm-Nd and Rb-Sr investigations were carried out at the University of California at Berkeley Isotopic Research Centre. ^{40}Ar-^{39}Ar and major, trace and rare earth element composition determination was done at the laboratories of Dalhousie University (Canada).

Neoproterozoic quartz-dioritic gneisses have an average SiO_2 content of 64.08%, with relatively high Al_2O_3 (17.86%) (Table 1). In these rocks Na_2O (4.16%) is higher than K_2O (2.64%) and K_2O/Na_2O=0.64. Quartz-diorite gneisses are metaluminous rocks (Clarke, 1992) and according to A/CNK parameter (1.07) they are I-type (Chappel, White, 1974) or H-type (Castro et al., 1991) granitoids. The D_1-D_2 discrimination diagram (Figure 3) is consistent, indicating an I-type. REE concentration in quartz-diorite gneisses is relatively low. The trend has weak asymmetry and no expressed Eu negative anomaly (Okrostsvaridze, Clarke, 2003), which shows that in quartz-dioritic gneisses magma did not undergo significant fractional crystallization. In quartz-dioritic gneisses I_{Sr} parameter is quite relatively constant at 0.7044; this low value suggests a mantle source for these rocks (Table 2). In these rocks eNd parameter varies from –1.76803 to -2.19501. This shows that they were formed from the protolith which had comparatively low Sm/Nd parameters relative to chondrite. The Sm-Nd model age did not show reliable results (2376±600 Ma) (Table 3), but these results suggest that the protolith may have been middle Proterozoic formations. More reliable results were reached by Rb-Sr system, which corresponds to 686±74 Ma.

Table 1. Chemical composition (%) and some petrochemical parameters of the Dzirula massif granitoids and orthoclase gabbros (rikotites)

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	D_1	D_2	R_1	R_2
Quartz-dioritic gneisses														
Dz 10	64.44	0.84	17.69	6.46	0.07	1.53	4.55	3.96	2.08	0.28	2.3	-19.4	2667	1028
Dz 12	63.92	0.71	17.47	5.18	0.06	1.42	3.92	4.17	2.72	0.22	-1.7	-18.7	2517	997
Dz 13	63.89	0.55	18.42	4.64	0.07	1.47	3.70	4.35	3.14	0.16	-2.7	-16.4	2660	1153
Tonalites														
Dz 31	66.67	0.77	15.83	5.99	0.08	2.44	2.57	2.99	2.92	0.92	4.9	-7.4	2517	520
Dz 32	67.83	0.69	16.29	4.40	0.08	2.00	2.63	2.85	3.72	0.31	8.1	-9.3	2520	490
Dz 44	67.09	0.69	16.18	6.87	0.08	2.60	2.32	2.86	2.71	0.06	7.4	-6.4	2347	533
Dz 45	67.36	0.63	16.37	5.62	0.09	1.36	2.04	2.84	3.71	0.08	5.9	5.7	2410	628
Microcline granites														
Dz 2	72.25	0.27	15.09	2.57	0.04	0.59	1.23	3.55	3.78	0.15	10.4	-5.3	2548	450
Dz 4	71.01	0.56	16.35	2.15	0.07	1.16	1.34	2.16	3.69	0.06	8.3	-2.7	2775	482
Dz 9	74.79	0.07	14.71	1.15	0.06	0.18	0.61	3.65	4.17	0.22	14.6	2.7	2663	507
Dz 15	75.09	0.22	15.21	1.98	0.05	0.51	1.15	3.79	3.75	0.17	5.2	4.7	2733	466
Dz 16	71.88	0.017	15.49	1.74	0.04	0.42	1.15	3.31	5.52	0.15	13.6	-5.3	2365	493
Orthoclase gabbros (rikotites)														
R 20	46.6	0.964	9.87	11.75	0.21	10.84	14.95	1	1.76	0.38	-	-	-	-
R 21	51.02	0.718	7.12	10	0.174	11.99	15.68	1.08	1.11	0.03	-	-	-	-
R 23	50.25	0.7	6.40	9.26	0.195	11.79	17.48	1.25	0.87	0.06	-	-	-	-
R 26	51.57	0.817	16.57	8.36	0.156	4.63	7.99	2.16	2.02	0.43	-	-	-	-

Table 2 . Chemical composition of Rb, Sr, Sm and Nd (ppm) and some isotopic data of the Dzirula Massif granitoids and orthoclase gabbros (rikotites)

Sample	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	I_{Sr}	Sm	Nd	$^{147}Sm^{144}Sm$	$^{143}Nd/^{144}Nd$	εNd
Quartz-dioritic gneisses										
Dz10	89.27	387.51	0.4576	0.70872	0.70584	3.24	22.47	0.512362	0.11998	-1.76803
Dz12	97.64	402.23	0.5934	0.71023	0.70441	3.96	20.38	0.512379	0.11780	-1.96703
Dz13	110.22	416.89	0.7476	0.71172	0.70442	4.17	18.87	0.512071	0.12140	-2.19501
Tonalites										
Dz31	116.23	213.75	1.53879	0.72051	0.70920	6.48	38.45	0.512062	0.10410	-6.28938
Dz32	118.87	294.18	1.1432	0.71757	0.70891	3.98	17.08	0.512349	0.14394	-2.87918
Dz44	110.20	248.86	1.2529	0.71826	0.70877	7.10	39.63	0.512044	0.11064	-6.99145
Dz45	89.67	290.02	1.3833	0.71606	0.70882	9.30	48.56	0.512070	0.11823	-6.89080
Microcline granites										
Dz2	114.99	249.60	0.98124	0.71519	0.70722	5.86	33.29	0.51216	0.10863	-4.50135
Dz4	153.83	74.93	1.29801	0.71512	0.71460	8.08	45.59	0.51191	0.10947	-9.36967
Dz9	177.68	36.08	1.82012	0.71783	0.70668	1.20	4.17	0.51223	0.17722	-6.92835
Dz15	130.40	203.49	1.72948	0.71723	0.70671	5.08	23.20	0.51214	0.13525	-6.43603
Dz16	155.39	250.46	1.73452	0.71581	0.70665	3.92	23.31	0.51227	0.10387	-2.19580
Orthoclase gabbros (rikotites)										
R20	442.21	54.82	0.35032	0.70602	0.70497	7.06	33.62	0.51237	0.12968	+0.44803
R21	50.59	215.24	0.66948	0.70715	0.70514	3.60	13.88	0.51258	0.16417	-0.26030
R23	257.81	123.59	0.29257	0.70614	0.70526	6.19	26.67	0.51258	0.14327	+0.28341
R26	836.14	119.42	0.40361	0.70654	0.70533	6.88	37.17	0.51254	0.11421	+0.15332

Proceeding from these data and geological evolution of the region, we can assume that quartz-dioritic gneisses was formed in the Neoproterozoic at the Early Pan-African tectonic-thermal events.

In the Cambrian Tonalites SiO_2 (67.26%) is higher than in the Neoproterozoic quartz dioritic gneisses, but Al_2O_3 is lower (16.16%). In these rocks as compared to quartz-dioritic gneisses Na_2O concentration (2.88%) is relatively low but K_2O is quite high (3.26%). Cambrian tonalites are metaluminous rocks and according to A/CNK parameter (1.22) it is S-type granitoids (Okrostsvaridze, Shengelia, 1996). The D_1-D_2 discrimination diagram (Figure 3) is consistent, indicating an S-type. REE concentration is quite high, but with symmetric trends. They are enriched in lanthanides, comparatively poor in heavy REE and weakly expressed Eu minimum, which shows that crystal fractioning was not an important process in the development of these rocks (Okrostsvaridze, Clarke, 2004).

In tonalites I_{Sr} parameter varies from 0.7081 to 0.7082 which is a consistent with for the upper crust. The eNd parameter ranges from -2.8792 to -6.8906 (Table 2); suggesting a strong influence of upper crustal partial melts.

Rb-Sr isochrones of tonalites showed an age of 538±53 Ma which corresponds to Cambrian age. Biotite samples were also analyzed by ^{40}Ar-^{39}Ar method gave an Upper Paleozoic age of 306±2 (Table 3).

Table 3. Isotopic Ages (Ma) of the Dzirula massif Granitoid and rikotites (orthoclase gabbros)

Rock name	Quartz-dioritic gneisses	Tonalites	Microcline granites	Rikotites
Sm-Nd method	2370±600	-	-	278±48
Rb-Sr method	686±74	538±53	331±21	211±11
^{40}Ar-^{39}Ar method	309±5 (biotite)	306±2 (biotite)	303±4 (biotite)	219±4 (hornblende) 217±3 (biotite)

Proceeding from these data, we assume they tonalities could have been generated at Late Pan-African tectonic-magmatic events by melting of metapelites of the gneiss-migmatite complex.

Late Paleozoic Microcline granites have an average SiO_2 of 73.00%; Al_2O_3 is the lowest among the Dzirula massif granitoids (15.31%). Alkalinity is increased (Na_2O=3.49; K_2O=4.18) and K_2O/Na_2O parameter is equal to 1.20 which is typical upper crust granitoid data (Table 1).
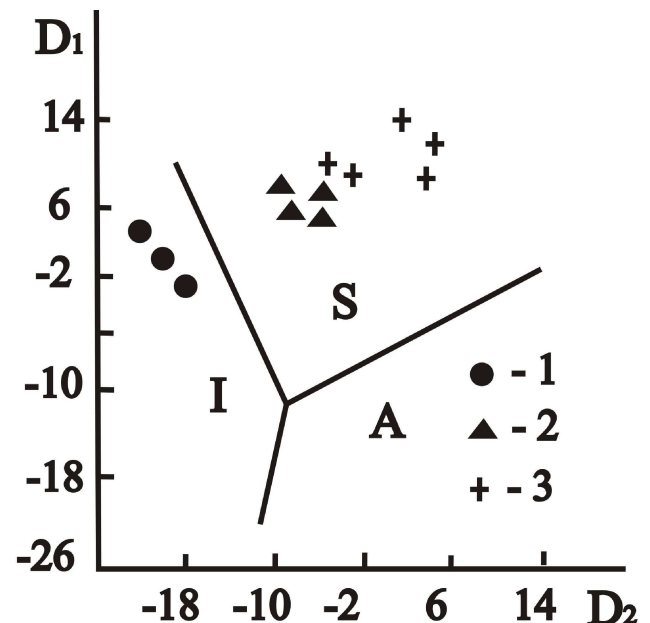
Figure 3. D_1–D_2 Discrimination diagram (Hassan, McAllister, 1992) for the Dzirula massif granitoids. Fields: I – type granites; S – type granites; A – type granites. $D_1 = 0.76Al_2O_3+2.91MnO-1.93Na_2O+1.95K_2O-18.50P_2O_5$; $D_2 = 0.37Al_2O_3+7.25TiO_2-54.08MnO-4.28Na_2O-0.55K_2O+45.81P_2O_5$. Conventional signs: 1 - quartz-dioritic gneisses; 2 - tonalities; 3 - microcline granites.

Upper Paleozoic microcline granites are metaluminous rocks (A/CNK =1.42) and according to it is S-type (Chappel, White, 1974) granitoids. The D_1-D_2 discrimination diagram is consistent, indicating an S-type (Figure 3).

REE distribution in microcline granites are characterized by sharp asymmetry; they show lanthanides high concentration and heavy REE low concentration. They have sharply expressed Eu minimum, which show that intensive crystal fractionation took place in magmatic system (Okrostsvaridze, Clarke, 2004). The I_{Sr} has a very wide range, from 0.70667 to 0.71460. This range suggests extensive incorporation of upper crustal rocks. eNd parameter ranges from -2.19589 to -9.36967; it shows that they were generated by melting of upper crust rocks.

The Rb-Sr isotopic age of microcline granites corresponds to 351±21 Ma (Tab.3). This is Early Carboniferous, correspondingly, the activity appears to be associated with Variscan tectono-thermal events. In microcline granites (sample Dz2, Dz9, Dz16) muscovite isotopic age was determined using ^{40}Ar-^{39}Ar method which is identical nearly in all samples and on average equals to 303±4 Ma, which, like the Tonalite ^{40}Ar-^{39}Ar data, also corresponds to Late Variscan.

Rikotites (orthoclase gabbros) represent protolith rocks which were low in Al_2O_3, Fe_2O_3, K_2O and high in CaO and MgO composition. Rb-Sr data of rikotites show 211±11 Ma. Same date of this intrusive was approximately by hornblende ^{40}Ar-^{39}Ar which corresponds to 219±4 Ma and by biotite dating using the same method in this intrusive - 217±3 Ma (Table 3). The Rb-Sr isotopic system in rocks is closed at 600-700^{0}C; ^{40}Ar-^{39}Ar system in hornblendes at 450-500^{0}C; in biotites 300-350^{0}C. From this we can conclude, that the results are in good correlation with each other and indicate ricotite intrusion took place Upper Triassic during the Cimmerian tectonic-thermal events, approximately in the interval of 210-220 Ma.

Summary of Geochemistry Findings

The geodynamic regime of formation of the Dzirula massif granitoids can be assessed with the R_1-R_2 multipartite diagram (Figure 4), quartz-dioritic gneisses figure points are located within pre-plate Collision granitoids field, while tonalites and microcline granites –
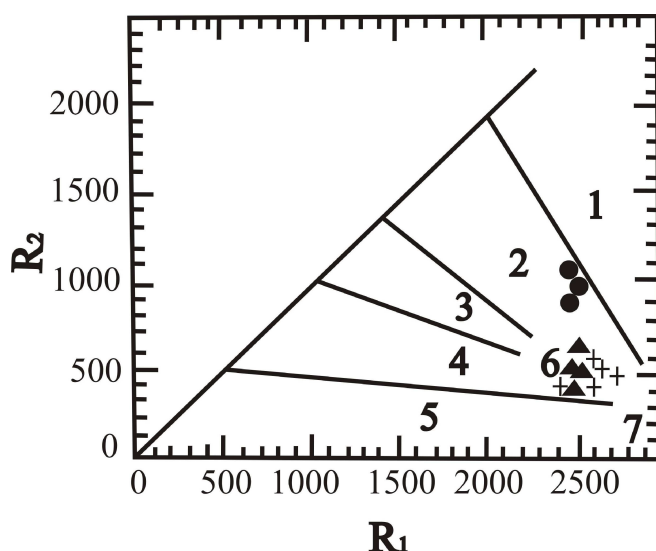

Figure 4. *R_1-R_2 discrimination diagram (Bachelor, Bowden, 1985) for the Dzirula massif granitoids $R_1 = 4Si-11(Na+K)-2(Fe+Ti)$; $R_2= 6Ca+2Mg+Al$. Conventional signs are identical to figure 3.*

within the syn-collision. The petrochemical investigation carried out showed, that the Dzirula massif granitoids are genetically different from each other. Quartz-dioritic gneisses belong to metaluminous I-type granites, which were formed in the volcanic arc geodynamic regime and in which magma crystal fractioning didn't take place. Tonalites and microcline granites represent petrochemically similar formations and belong to S-type paraluminous granites which were formed at syn-collision stage evolution of the orogen evolution.

On the εNd -I_{Sr} isotopic diagram quartz-dioritic gneisses figures points actually do not appear in the field of crust formations and only tonalities and microcline granites figure points follow the upper crust trend (Figure 5). εNd - Intrusive age (Ma) relation diagram shows clearly, that all the granitoid figure points investigated by us are located in the field of Phanerozoic crust (Figure 6), which clearly shows, that the Dzirula massif continental crust is Phanerozoic formation. According to granitoid petrogenetic types, isotopic age and εNd parameters it should be treated as typical Tethyside or collisional orogen (Windley, 1996).
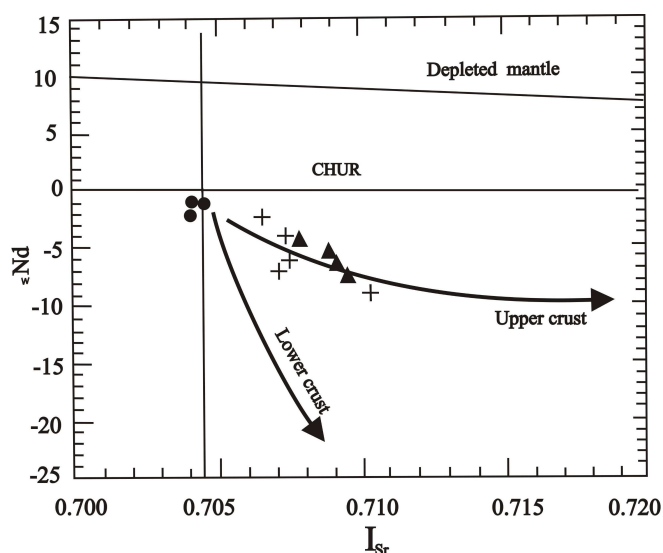

Figure 5. *εNd-I_{Sr} isotopic diagram (Jahn et al., 2000) for the Dzirula massif granitoids. Conventional signs are identical of figure 3.*
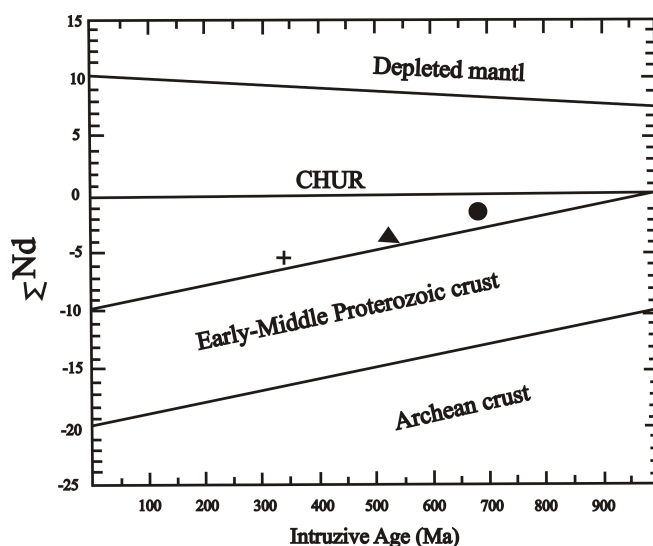

Figure 6. *εNd- I_{Sr} isotope diagram (Jahn et al., 2000) for the Dzirula massif granitoids. Conventional signs are identical of figure 3.*

Geodynamic Evolution of the Region

The geodynamic evolution of the Caucasian orogen, based on geological, paleofacies, paleobiogeographic and paleomagnetic data, centers on the closing of the Tethys oceanic basin at the end of the Alpine cycle as a result of collision of the Afro-Arabian and Eastern European plates (Gamkrelidze, 1991; 1997; Stampfli, Borel, 2002, Raumer et al., 2003). The Inner Caucasian Microplate, of which the Dzirula massif is a part, in these models is treated as microcontinent, island arc or terrane, which was situated in the inner oceanic portion of Tethys. Its genetic relation with any of the continental plates is not well understood. The new tectonic, petrogeochemical and isotopic data obtained from the Dzirula massif gave us an opportunity to constrain the relationship.

Relying on existing information and the data in this paper suggests that the Dzirula massif represents a vertically accretion structure which is constructed of two large formations: Gondwana-derived gneiss-migmatite complex (upper) and ensialic island arc (lower) (Figure 7).
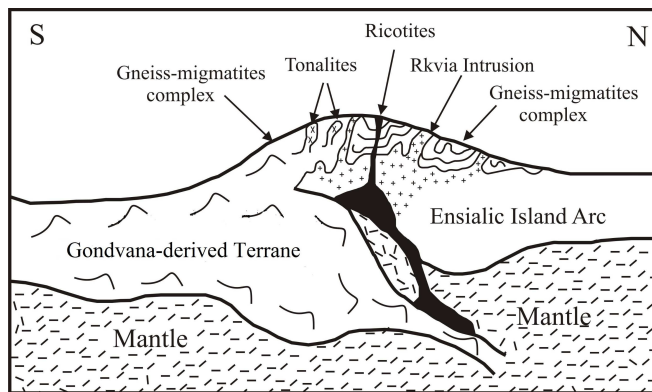
Figure 7.N Hypothetical geological cross section through the Dzitula massif. It is shown on the figure how gneiss-migmatite complex is overlaying ensialic island arc and how base granitoid magma sources are generated. Base magma generation possible model is shown by dark color.

The interrelation of granitoid genetic types and the geodynamic evolution of the region support this structure. In addition, the gneiss-migmatite complex is similar to the Arabian Plate Northern edge in age, composition and construction (Marzouki, Fyfe, 1979; Kroner, Stern, 2008). These authors indicate that the Northern part of Arabian Plate, situated to the south of the Inner Caucasian Microplate, represents a mosaic of microcontinents which were connected by Pan-African tectono-thermal events. Most are characterized by similar composition and tectonic development history to the Dzirula massif gneiss-migmatite complex. The intensive injection of the mantle material, metamorphism, ultrametamorphism and granite-forming processes were of the same character and took place in the intervals of 700-450 Ma. The Pan-African tectonic-thermal events at this time are characterized by a transitional regime, namely, the older inner plate processes are substituted by younger (Phanerozoic) plate edge regimes. Our data indicate that the gneiss-migmatite complex of the Dzirula massif is likely a Gondwana-derived terrane part and separated from the Arabian plate northern edge during the opening of the Palaeo-Tethys.

To make the idea more clear and convincing we will cite a comparison. The Tsakhkuniats massif, which reveals great similarities with Dzirula massif by its tectonic construction, composition and isotopic parameters, is exposed in the South of the Dzirulla massif, within the borders of Iran-Afganian terrane of Gondwanan origin. The above mentioned massif, as well as Dzirula, is constructed of the Neoproterozoic gneissic metabasalts-migmatites (Hancavan complex), which is obducted on gneiss-paraschist (Arzacan complex). The Hancavan Complex as well as Dzirula massif gneiss-migmatite complex also contains lenses of opiolitic serpentinites and is crossed by quartz-dioritic gneisses intrusive; its the Rb-Sr isotopic age is 685 ± 77 Ma and the Isr=0.703361 (Agamalian, 2004). The age of the Dzirula massif quartz-dioritic gneisses determined by the same method, corresponds to 686 ± 74 Ma and the Isr=0.70489. So, we can detect many similarities between these two massifs and proceeding from the geodynamic evolution analysis of the region, they are most likely to contains same Precambrian platform relics.

Discussion

This work has identified four distinct granitoid types in the Dzirula massif, including their spatial relationships, intrusion history, and ages. These data, combined with an understanding of the regional geodynamics, provides an understanding of granitoid melt generation and the evolution of the continental crust in the Dzirula Massif.

The Neoproterozoic gneiss-migmatite complex is the most widely distributed, and occupy the upper plate of the structure. This unit is composed of quartz-dioritic gneisses of I or H-type granitoids. The average isotopic parameters of these rocks (I_{Sr}=0.7044±0.0066; eNd = -1.976692) show that they belong to juvenile crust with a high percent of mantle component. The migmatite complex appears to have formed by partial melting of a subcontinental lithosphere by mantle-derived magmas. The age of quartz-diorite gneiss crystallization is 686 ± 74 Ma (Rb-Sr method), which corresponds to the Early Pan-African tectonic-thermal events.

The tonalites have a crystallization age of 538 ± 33 Ma (Rb-Sr age) which corresponds to Late Pan-African tectonic-thermal events. The tonalites are more evolved than the gneiss, being S type granitoids with higher REE concentrations. The tectonic discrimination diagrams indicate the syn-collisional granite field. The isotopic composition of the tonalites indicates a greater upper crustal character compared to the gneiss-migmatite complex (I_{Sr} = 0.7087±0.0011; eNd = -5.762702). The microcline granites have an age of 351 ± 21 Ma (Rb-Sr method), corresponding to the Variscan tectonic-thermal events. The gneiss-migmatite complex is intruded by the microcline granites at this time. These rocks are much more evolved than either the gneiss-migmatite or the tonalites. The microcline granites are biotitic-muscovite peraluminous S type formation and in tectonic discrimination diagrams its plots are in the syn-collision granite fields. The isotopic composition of the microcline granites also indicates a more developed continental crust. The I_{Sr} of these rocks ranges between 0.70667 and 0.71460, and eNd from -2.19589 to -9.96967.

Thus by the late Variscan, the crust of the Dzirula massif has evolved from a primitive composition to one more characteristic of more evolved continental crust. This development occurred during cycles of tectonic-thermal activity that lasted from the upper Proterozoic to the upper Paleozoic. As a result of these cycles, the ensialic protolith S type Upper Paleozoic microcline granites intrude into the mantle-crust hybrid I type Neoproterozoic gneiss-migmatite complex. Based on the geodynamic setting, the gneiss-migmatite

complex was overthrust onto the protolith of the microcline granite, and part of the ensimatic terrane subducted under this protolith (Figure 7). This collision led to release of water from the subducted terrane led to partial melting of the microcline granite protolith and formation of the granitoid melt which intruded into the overlying gneiss. This explanation is further supported by the presence of ophiolite fragments in the northern part of the Dzirula massif.

The fourth magmatic rock in the Dzirula massif is the rikotites (orthoclase gabbros). The age of the Rikotites by Rb-Sr method, the whole rock - 211±11 Ma; ^{40}Ar-^{39}Ar method hornblende - 219±4 Ma; by ^{40}Ar-^{39}Ar method - biotite is 217±3 Ma. The results indicate that the rikotites intruded into the Dzirula massif during the Upper Triassic, corresponding to the Cimmerian tectonic-thermal events. The rikotites, according to all data, belong to island arc formations that collided with the Dzirula massif area. The rikotites contain orthoclase and are potassium rich. The exotic composition of the rikotites provides further clues about the development of the Dzirula massif. The rikotites appear to have a mantle source, and partial melting and incorporation of the potassium-bearing granites or their protolith appear to have led to the potassium enrichment of the rikotites.

Conclusions

Field, petrochemical, isotopic, and geochronological investigation of the granitoids of the Dzirula massif illustrate continental crust forming processes from Upper Proterozoic to Upper Paleozoic. The formation of the continental crust in this area was episodic, occurring during three phases of tectono-magmatic events.

The data in this study also constrain the geodynamic history of the Inner Caucasian Microplate. These processes occurred in the closing process of Palaeo-Tethys and the opening of Meso-Tethys. Within the Dzirula massif, a Gondwana-derived Proterozoic gneiss-migmatite complex is situated obductively on ensialic island arc. In this Variscan collision-accretion structure, the crustal thickening and released water caused partial melting of the ensialic island arc, thus generating the microcline granites, which intruded the overlying gneiss-migmatite complex. By the end of this process, the Dzirula massif resembled typical continental crust. Later, in the Upper Triassic, the structure was further intruded by potassium rich gabbros (rikotites). Later, during the Alpine tectonic-thermal processes the Inner Caucasian Microplate merged with the Euro-Asian continental southern active edge.

Acknowledgements

References

Agamalian, V., 2004, The Lesser Caucasus Earth Crust formation and evolution in the collision zone of Palaeo-Tethys. Proceedings of the 5th International Symposium on Eastern Mediterranean Geology, pp. 17-20.

Allegre, C.I., Ben Othman, D., 1980, Nd-Sr Relationship in Granitoid Rocks and Continental Crust development: a chemical approach to Orogenesis. Nature, v. 286, pp. 335-343.

Bachelor, R.A. and Bowden, P., 1985, Petrogenetic interpretation of granitoiod rock series using multication parameters. Journal of Chemical Geoogy, v. 48, pp. 43-55.

Castro, A., Moreno-Ventas, J. and De La Rosa, J.D., 1991, H-type (hybrid) granitoids: A proposed revision of the granite-type classification and nomenclature. Earth Science Review, v. 3, no. 4, pp. 237-253.

Chappel, B.W., White, A.Y.R., 1974, Two contrasting Granite types. Journal Pacif. Geology, no. 8, pp. 173-174.

Clarke, D.B., 1992, Granitoid Rocks. London: Blackwell. 283 p.

Clarke, D.B., Chatterjee, A.K. and Giles, P.S., 1993, Petrochemistry, tectonic history, and Sr-Nd systematic of the Liscomb Complex Meguma Lithotectonic Zone, Nova Scotia. Canadian Journal of Earth Science, no. 30, pp. 449-464.

Collins, W.J., 1998, Evolution of Petrogenetic model for Lachlan Fold Belt granitoids: implication for crustal architecture and tectonic models. Australian Journal Earth Science, v. 45, pp. 83-500.

Daga, M.M., Rao, D.R. and Rai, H., 2010, Granite Magmatizm and Crustal Evolution of the Shyok-Darbuk corridor of NE Ladakh, India. Episodes, v. 33, no. 3, pp. 183-199.

DePaolo, D.J., Linn, A.M. and Solubert, G., 1991, The continental crust age distribution: methods of determining mantle separation age from Sm-Nd isotope data and application to the south-western United States. Journal Geophysical Research, no. 96, pp. 2071-2088.

Gamkrelidze, I.P., 1997, Terrane of the Caucasus and adjacent areas. Bulletin Academy of Science Georgia, v. 155, no.3, pp. 75-81.

Gamkrelidze, I.P., Dumbadze, G.D. and Kekelia, M.A., 1981, Ophiolites of the Dzirula massif and problem of Paleotethyse in Caucasus. Geotectonic, no. 5, pp.23-33.

Gamkrelidze I.P. and Shengelia D.M., 2005, Precambrian-Paleozoic regional metamorphism, granitoid magmatism and geodynamics of the Caucasus. M: Scientific World, 458 p.

Hassan, H.H. and McAllister, A.L., 1992, An integrated geological, geochemical investigation of uranium metallogenesis in selected granitic plutons of the Miramichi Anticlinorium, New Brunswick. Canadian Journal of Earth Science, no. 13, pp. 91-115.

Jahn, B., Wu, F. and Chen, B., 2000, Massive granitoid generation in Central Asia: Nd isotope evidence and implication for continental growth in the Phanerozoic. Episodes, v. 23, no. 2, pp. 82-92.

Marzouki, F. and Fyte, W.S., 1979, Pan-African plates: Additional evidence from igneous events in Saudi Arabia. Contribution to Mineralogy and Petrology, v. 60, no.3, pp. 219-224.

Okrostsvaridze, A.V. and Shengelia, D.M., 1996, New Data on the formation of microcline granites of Dzirula salient. Bulletin Academy of Science Georgia., v. 14, no. 1, pp. 93-95.

Okrostsvaridze, A.V. and Clarke D.B., 2003, The First Data on the Investigation of Sm-Nd and Rb-Sr Izotopic Systems of the Dzirula Salient Gneisses-Quartz-Diorites of the Black Sea - Central Transcaucasian Terrane. Bulletin Academy of Science Georgia, v. 168, no. 2, pp. 281-285.

Okrostsvaridze, A.V. and Clarke D.B., 2004, New data of isotopic investigation of magmatic rocks of Dzirula salient of Caucasian Inner Massif. Journal Rep. Russian Academy of Sciences, v. 398, no. 1, pp. 117-121.

Samson S.D. and Patchett P.J., 1991, The Canadian Cordillera as a modern analogue of Proterozoic crustal growth. Australian Journal of Earth Sciences, no. 38, pp. 595-611.

Roumer, I.F., Stampfly, M. and Bussy, F., 2003, Gondwana-derived microcontinents – the constituent of the Variscan Alpine collisional orogens. Journal of Tectonophysics, no. 365, pp. 7-22.

Shengelia, D.M. and Okrostsvaridze, A.V., 1998, New data on the construction of Dzirula salient of Pre-Alpine Georgian block. Journal Rep. Russian Academy of Sciences, v. 559, no. 6, pp. 800-803.

Shengelia, D.M. and Okrostsvaridze, A.V., 1998, New data on the construction of Dzirula salient of Pre-Alpine basement of Georgian block. Journal Rep. Russian Academy of Sciences, v. 559, no. 6, pp. 800-803.

Stampli, G.M., Borel, G.D., Cavazza, W., Mosar, J. and Ziegler, P.A., 2001, Palaeotectonic and paleogeographic evolution of the Western Tethys and Peri-Tethyan domain. Episodes, v. 24, no. 4, pp. 222-228.

Stern, R.J., 2008, Neoproterozoic crustal growth: The solid Earth system during a critical episode of Earth history. Gondwana Research, v. 14, issues 1-2, pp. 33-50.

Taylor, S.R. and McLennan, S.M., 1985, The continental crust: its evolution and composition. London: Blackwell, 312 p.

Windley, B., 1996, The evolving Continent, 3rd edition. Chichester: John Wiley and Sons, 526 p.

Zakariadze, G.S., Karpenko, S.F. and Bazilev, B.A., 1998, Petrology, geochemistry and Sm-Nd izotopic age of Pre-Late-Hercynian paleooceanic complex of Dzirula salient of Transcaucasian massif. Journal of Petrology, v. 6, no. 4, pp. 422-444.

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