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Late Cenozoic Collisional Volcanism in the Central Part of the Lesser Caucasus (Azerbaijan)

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Abstract

The chapter is devoted to petrogeochemical features of late Cenozoic collision volcanism of the Lesser Caucasus. It was determined that at the early and middle stages of crystallization of the rocks of the andesite-dacite-rhyolite association, amphibole fractionation played an important role in the formation of subsequent differentials. On the basis of computer modeling, it was found that when mixing andesite and rhyolite (taken as a contaminant) magma, it is possible to obtain a rock of dacitic composition. Under conditions of high water pressure, as a result of fractionation of olivine and pyroxene from primary high magnesian magma, high-alumina basalts are formed, which can be considered as the parent magma.Geochemical features of moderately alkaline olivine basalts indicate that the source of magma is metasomaticized, phlogopite-garnet-rutile containing lithospheric mantle. The evolution of moderately alkaline olivine basalts occurs due to changes in the composition of the main rock-forming and accessory minerals. Medium rock formations are formed by the assimilation of poorly differentiated primary magma by an acidic melt. The calculations have shown that proportion of melting rhyolitic melt separated from andesite substrate is close to 15%. After removal of the remaining melt, restite is entirely consistent with the composition of the lower earth crust.

Keywords

late Cenozoic collision volcanism · Lesser Caucasus · geochemical · petrological features · AFC – modeling

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1. Introduction

One of the pressing problems of collision zones of the study is to elucidate the evolution of magmatism occurring within them. Display magmatic associations, their petrochemical characteristics reflect the specificity of their manifestations, as well as the development of magmatism from magma generation to the evolution of magmatic melt in the Earth's crust. Materials on the distribution of rare and rare earth elements in different rock types, as well as other of their geochemical and petrological characteristics allow using the well-known models [1, 2, 3, 4, 5, 6, 7, 8] to analyze some aspects of the processes of birth, evolution, and crystallization of deep magmatic melts.

In this sense, the study of the geochemical characteristics of mantle and crystal sources of magmatism that have come out in a collision like the continent – the continent is quite topical. Therefore, the study late collision volcanism of the Lesser Caucasus is a theoretical and practical interest.

Such, more than 10 geodynamic models have been proposed on the genesis of Cenozoic collision volcanism including the Eastern Anatolian-Caucasian zone. The most popular models are: (1) lateral upper mantle flow of plume material from the East African rifts [3, 6]; (2) break-off of a subduction slab at the early collision (inversion) stage and, as a result, formation of an asthenospheric uplift under the growing collision orogen directly below the Moho boundary [2, 4, 5, 6, 9, 10]; (3) collision magmatism with a leading role of oxidation of deep fluids [1]; (4) Paleogene collision-riftogenic volcanoplutonic magmatism, which occurred from lateral compression of the lithosphere and uplift of a less compacted mantle substrate [11]; (5) relationship of late collision volcanism with longitudinal and latitudinal extension structures, which formed in the suture-collision zone during activation of an area along the junction zone [12]; and (6) collision-riftogenic origin of late collision volcanism with mantle metasomatosis playing a leading role [13].

Some of these models do not contradict each other and, as noted by Koronovskii and Demina [1], differ in the heat sources necessary for melting and mechanisms by which sources of late collision volcanism melt. On the basis of seismic tomographic, geological-petrochemical, and geophysical data, we have developed a geodynamic model that relates the geodynamic processes and magmatism at the late collision stage of the evolution of the Lesser Caucasus. We also used seismic and seismic tomographic data for the Lesser Caucasus and adjacent collision regions (Eastern Anatolia, northwestern Iran). Having developed the model and analyzed previous models, we tried to assess the role of lithospheric mantle and asthenosphere in the Late Cenozoic collision volcanism of the Lesser Caucasus.

Late Cenozoic geodynamics of the Alpine-Himalayan belt is defined sector of the Mediterranean collision of Eurasian and the Afro-Arabian megaplate [1]. According to modern concepts, folded structures of the Caucasus emerged as a result of their convergence. According to Koronovsky and Demina [1] in the Caucasian segment of the Alpine-Himalayan orogen Late Cenozoic volcanism manifested itself in an atmosphere of NS compression in the region, led to an accelerated movement towards the north of the Arabian plate due to disclosure in the Late Miocene (about 11–10 million years ago) the Red Sea [1]. This collision stage is divided into the stage of mild collisions (late Middle Eocene – Middle Miocene) and the stage of hard collisions (with the Late Miocene to present). This fragmentation of rigid crust was accompanied by volcanism; mark the sites of local stretching of the lithosphere.

Within the Lesser Caucasus Late Cenozoic volcanism covers part of the Transcaucasian transverse uplift (Akhalkalaki volcanic region, Kechut, Aragats volcano-structural sub-zones) and the eastern volcanic zone (Gegham, Vardenis, Syunik, Kaphan – in Armenia, Karabakh, Kelbajar, Nakhchivan in Azerbaijan) (Figure 1).

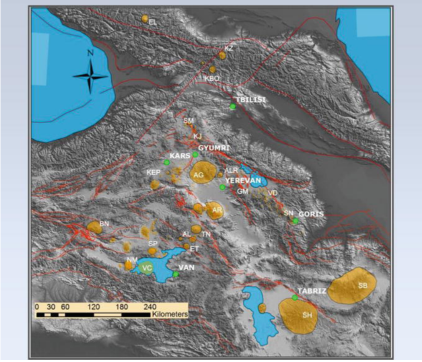

Figure 1.

The distribution of Neogene-Quaternary volcanoes in Eastern Anatolia, the Caucasus, North-West Iran.

Since the Middle Miocene, in these zones formed a high volcanic terrain, located on 2–3 km above sea level. Their association corresponds to the Caucasian age of folding, when the intense collision of the Arabian and Eurasian plates. Due to volcanic activity, there were formed many relatively large volcano-tectonic structures, such as Aragats, Ishygly, and others, erupting volcanoes of the central, central-type fracture (Figure 1).

Products of the Late Cenozoic volcanism in the Azerbaijan distributions upper river Terter and Akera are characterized by lava flows and pyroclastics varied composition.

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2. The late Cenozoic volcanism of the Lesser Caucasus

2.1 Neogene volcanism

Neogene volcanism in the Lesser Caucasus is mainly manifested itself, starting from the upper Sarmatian, Meotis-Ponte to the Upper Pliocene. However, Rustamov in the south-western part of Lesser Caucasus to carry a Molasse basin (Nakhchivan, Karadag) trachyandesite-teschenite and analcite alkaline basalt-trachyandesite, with the absolute age of 14–15 million years, volcanic fissure and concludes that the Neogene stage of volcanism in the region did not begin in the upper Sarmatians and in the Middle Miocene (based on determining the age of rocks with the K-Ar method, and by the stratigraphic position of the studied rocks) [11].

In the central part of the Lesser Caucasus upper-volcanogenic complex with a capacity of 200 m in the literature described as Agdzhagyz suite and submitted dacite, rhyolite, pyroclastic rhyodacites and their derivatives – dacite and rhyolite tuffs. The layers of fine-sedimentary rocks – carbonaceous shales, lignites are present between the volcanic rocks.

Volcanic complex with a thickness of 1150 m Meotis-Pont age first isolated as Basarkechar suite [14] and submitted dacite-trachydasite, andesite and trachyandesite, and latites (Figure 2). This complex with the angular and azimuthally unconformity lies at Agdzhagyz suite and places, Eocene and Cretaceous sediments. They overlap with an angular unconformity Upper Pliocene and Quaternary volcanic rocks in the volcanic highlands (Figure 2).

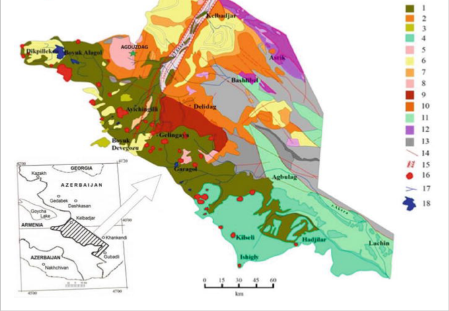


Figure 2.

Geological map of Late Cenozoic volcanic associations in the central part of the Lesser Caucasus (Azerbaijan), scale 1:100,000. Compiled by Imamverdiyev [13]. Volcanic association: Quaternary: 1 – trachybasalts, basaltic trachyandesites, and trachyandesites; 2 – tuffs, volcanic ashes, tuff breccias; 3 – rhyolites, perlite, and obsidian; Upper Pliocene-Low Quaternary: 4 – trachybasalts, basaltic trachyandesites, and trachyandesites; Upper Miocene-Low Pliocene: 5 – dacites, rhyodacites, rhyolites; 6 – andesites, trachyandesites, quartz latites, dacites, trachydacites (Basarkechar formation) 7 – dacites, trachydacites, rhyodacites and rhyolites (Ajagz formation); 8 – diorites, granodiorites, syenites; Upper Oligocene-Low Miocene: 9 – granodiorites, granites, monsonites, quartz syenites; Eocene: 10 – andesites, trachyandesites and their tuffs; 11 – granodiorites, monsonites, quartz diorites; Base rocks (Cretaceous): 12 – ophiolites; 13 – flysch; limestone's, sandstone's, tuffs; 14 – faults; 15 – Terter deep fault; 16 - largest centers of volcano eruption; 17 – rivers; 18 – lakes.

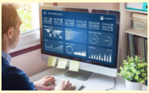
These volcanic complexes are distinguished in the differentiated andesite-dacite-rhyolite association [13]. Based on geological data, the age of association is defined as the Late Miocene-Low Pliocene. Volcanics of close age are also known in other regions of the Lesser Caucasus. For example, an Early Pliocene andesite-dacite association is developed within the Miskhan-Zangezur and Yerevan-Ordubad zones. Similar rocks are found within the Gegham and Vardenis highlands in Armenia.

2.2 Late Pliocene-quaternary acidic volcanic associations

Late Pliocene-quaternary acidic volcanic associations as independent volcanism are widely developed within the Caucasian segment of the Mediterranean belt. Within Azerbaijan, they are confined Kelbajar and Karabakh uplands and form a dome-shaped volcanoes, and a number of small extrusive domes (Kechaldag, Devegezy) with their lava flows composed of rhyolite, rhyodacites their subalkaline varieties, as well as obsidian and perlite (Figure 2).

The age of acidic volcanic rocks of the Lesser Caucasus in the studied region based on their stratigraphic position was considered late Pliocene-Akchagyl-Absheron [15]. This is confirmed by the absolute age. Thus, according to [16] age of rhyolite volcanic rocks Devegezy identified 0.61 million years, Kechaldagh 0.7 million years. Based on these data, the age of acidic volcanic rocks can be considered Quaternary.

Upper Pliocene-Quaternary volcanic associations with a more basic and medium composition, cover the entire Lesser Caucasus, form vast volcanic plateaus and large volcanoes and occupies about 5000 km^2 of surface area. These volcanic associations in the eastern area of Armenia and Azerbaijan within the differentiated form a continuous trachybasalt-basaltic trachyandesite-trachyandesite-trachyte series and cover Geghama, Vardenis and Syunik, Karabakh, Kelbajar highlands. In Armenia Kaphan zone has recently been formed basanite-tephrite-picro-bazaltic series.



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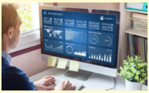
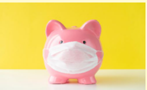
3. Research methods

This chapter used data from the Neogene-Quaternary volcanism of the Azerbaijan part of Lesser Caucasus based on the authors. Chemical analysis of rocks was determined by the Institute of Geology of Azerbaijan Academy of Sciences X-ray fluorescence method. Rare and rare-earth elements are in Geological and Geochemical Bronitsk expeditions in Russia. Microprobe analysis of mineral composition written in Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Moscow and Russian Geological Research Institute (VSEGEI), St. Petersburg. Measuring the isotopic composition of He performed in Geochemistry Institute of Academy of Sciences Russia, also used the data Sr and Nd [17, 18] performed on the material of Armenia and Georgia.

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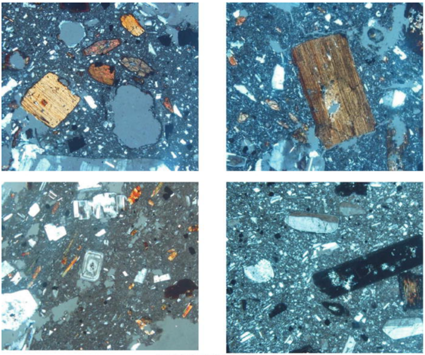
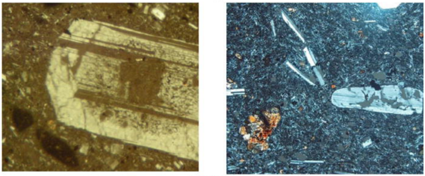
4. Petrography characteristics of the Late Cenozoic volcanic rocks

The rocks of the *andesite-dacite-rhyolite associations* form thin flows and subvolcanic body in the form of dikes, extrusions and other recent distributed along the Tartar, Lachin-Bashlybel, Istibulag-Agyatak deep faults (Figure 2).

Texture of porphyritic rocks, with high (25–30%) content of phenocrysts. In andesites, trachyandesites, latites phenocrysts are plagioclase, feldspar, clinopyroxene, and amphibole. In the more acidic varieties (dacites, rhyodacites, rhyolites their varieties), the proportion of dark-colored minerals decreases, leucocratic minerals also increased to 10%, there is quartz, biotite. The bulk of these rocks have hyalopilitic, glass texture (Figure 3).



Andesites, trachyandesites



Dacites

Figure 3.

Photomicrographs of the thin sections of rocks of the andesite-dacite-rhyolite association. Plagioclase and hornblende phenocrysts in andesites and trachyandesites, ×80, with an analyzer; zoned-plagioclase and quartz phenocrysts in dacites, ×80, with an analyzer.

The compositions of plagioclase in the rocks have An_{30-40} and are paragenesis with amphibole, biotite, clinopyroxene, and feldspar. Plagioclases second generation are relatively acid composition (An_{20-30}), crystallized on its own effusive stage. Feldspar in the rocks present in quartz latites, trachyandesites. The composition ranges from $Or_{55.3}Ab_{26.3}An_{0.3}$ to $Or_{73.4}Ab_{44.0}$ $An_{3.4}$ (Table 1). They belong to an intermediate structural-optical type and are monoclinic, but not homogeneous and presented albite and orthoclase phases. Composition of clinopyroxene varies from medium to acid rocks and the proportion of the component increases Fs: $Wo_{37.1-41.4}$ $En_{43.9-40.0}$ $Fs_{19-19.6}$ (for andesites), $Wo_{40.0-44.4}$ $En_{45.4-44.8}$ $Fs_{15.2-11.2}$ (for quartz latites), and $Wo_{41.7-42.7}$ $En_{36.3-34.6}$ $Fs_{22-22.7}$ (for dacites) (Table 1) [13, 19]. The compositions of amphiboles in the classification of B.E. Like [20] are responsible chermakit-, pargasit- and magnesian hornblendes.

Component	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
SiO_2	53.51	50.60	52.28	49.54	48.93	39.57	42.97	42.17	39.32	40.71
TiO_2	0.54	0.27	0.64	0.69	1.52	0.08	2.94	3.00	2.91	4.09
Al_2O_3	3.92	2.34	5.00	4.10	6.98	—	11.56	10.79	13.55	13.87
FeO*	8.46	12.12	7.63	7.53	7.96	14.94	12.08	14.29	12.77	11.51
MnO	0.22	0.25	0.13	0.18	0.13	0.28	0.14	0.25	0.16	0.10
MgO	14.63	12.81	15.09	15.46	13.72	44.86	13.11	13.06	12.91	14.44
CaO	18.50	20.43	18.65	19.94	19.97	0.22	9.94	10.68	12.06	11.70
Na_2O	0.52	0.47	0.56	0.64	0.53	—	2.48	2.76	2.88	2.63
K_2O	—	—	—	0.04	0.04	—	0.92	0.92	1.42	1.49
Total	100.27	99.65	100.0	98.11	99.58	99.95	96.14	97.92	97.99	100.54
Component	**11**		**12**		**13**	**14**	**15**		**16**	
SiO_2	58.47		64.59		62.87	57.06	52.52		51.39	
Al_2O_3	25.23		19.48		24.02	26.82	28.94		30.62	
FeO*	0.42		0.09		0.22	0.36	0.43		0.75	
CaO	7.16		0.17		5.55	8.68	13.17		12.99	
Na_2O	7.61		4.12		6.96	6.14	4.39		3.79	
K_2O	0.63		11.22		1.02	0.87	0.12		0.23	
Total	99.52		99.66		100.63	99.93	99.52		99.77	
Component	**17**		**18**		**19**	**20**	**21**		**22**	
TiO_2	1.10		4.14		5.49	6.10	5.41		11.10	
Al_2O_3	0.60		2.71		3.04	4.55	4.23		5.10	
Fe_2O_3	—		65.89		53.62	53.08	60.33		43.22	
FeO	91.0		14.02		28.39	19.60	15.68		17.76	
MgO	4.0		2.95		1.99	5.97	7.69		4.06	
Total	96.70		89.71		82.53	89.30	93.34		81.24	

Table 1.

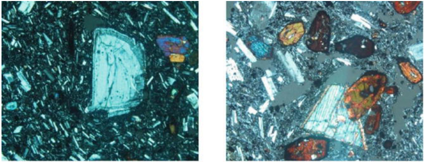
Chemical composition (wt %) of (1–5) clinopyroxene, (6) olivine, (7–10) amphibole, (11–16) plagioclase, and (17–22) magnetite from the late Cenozoic volcanic rocks [13, 19].

Note: Rocks: *Andesite-dacite-rhyolite association:* 11, 17 – rhyodacite; 1, 7, 12, 18 – dacite; 2, 8, 13, 19 – andesite; *trachybasalt-trachyandesites association:* 3, 9, 14, 20 – basaltic trachyandesite; 4, 10, 15, 21 – trachybasalt; 5, 6, 16, 22 – alkaline olivine basalt.

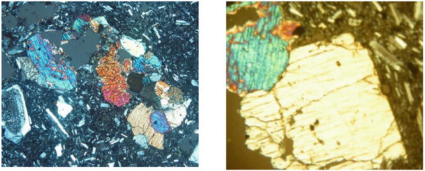
Analyses of rock-forming minerals were carried out at the analytical laboratories of the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Moscow State University; Moscow and Russian Geological Research Institute (VSEGEI), St. Petersburg on a Camebax microprobe. Magnetite was analyzed by conventional chemical techniques at Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences. Analysts A.I. Tsepin, V.K. Garanin, and V.S. Pavshukov.

The rocks of the *rhyolite association* of petrographic composition and structural and textural features are divided into crystallized – rhyolites, trachyrhyolites, rhyodacites and glass – obsidians and perlites. Phenocrysts crystallized rocks are plagioclase ($An_{30–40}$), quartz, less feldspar, biotite and hornblende. Number of phenocrysts is 5–10%.

The rocks of the *trachybasalt-trachyandesites associations* form a continuous series of differentiated trachybasalts to trachyandesites, sometimes comes to trachytes. Moderately alkaline olivine basalts are the most mafic rocks of the studied association. They are porphyritic and aphyric and contain phenocrysts of olivine, clinopyroxene, plagioclase, and amphibole. In places, sanidine megacrysts occur. The rock matrix is of pilotaxitic, hyalopilitic, and microlitic textures (Figure 4).



Trachyandesite



Basaltic trachyandesite

Trachybasalt

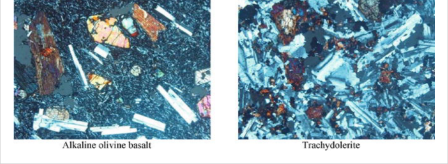


Figure 4.

Photomicrographs of the thin sections of rocks of the trachybasalt-trachyandesite association. Trachyandesite (one can see a glomeroporphyritic cluster of clinopyroxenes and opacitized hornblende, plagioclase, and clinopyroxene phenocrysts), ×80, with an analyzer; moderately alkaline olivine basalt with olivine, clinopyroxene, and plagioclase phenocsrysts, ×80, with an analyzer; crushed olivine in trachybasalt, ×80, with an analyzer; trachydolerite, ×80, with an analyzer.

Clinopyroxene rock associations more calcium and composition correspond to augite and salite. Plagioclases have relatively basic composition (An_{63-75}) (Table 1). Olivine in the mafic rocks is more magnesian (Fo_{83-87}) and corresponds to forsterite-chrysolite (Table 1). Olivine in trachyandesites and basaltic trachyandesites is more ferruginous (Fo_{61-70}).

The rocks occur as idiomorphic porphyritic crystals of apatite precipitates; the number of which reaches 0.5–1.25%, and fluoro-apatite. Often present as inclusions in phenocrysts of clinopyroxene and hornblende, indicating that the earlier crystallization.

In the rocks of andesite-dacite-rhyolite and trachybasalt-trachyandesites associations there are two types of inclusions: 1-inclusion, representing cumulates parent rocks, (pyroxenites, gabbro, hornblendites, etc.), 2-crustal inclusion - xenoliths of country rocks, trapped melts of crustal rocks (gabbro-amphibolites, quartz-diorite, quartz-feldspar rocks, etc.). Typical mantle inclusions in rocks associations are absent. Along with the rocks in the rocks of these associations are marked megacrystes sanidine, clinopyroxene, amphibole, phlogopite.

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5. Petrochemical features of the Late Cenozoic volcanic rocks

5.1 Andesite-dacite-rhyolite association

The association rocks form a continuous series from andesites to rhyolites by SiO_2 contents ($SiO_2 > 60\%$) (Table 2), and the ratio ($Na_2O + K_2O$)-SiO_2 [21] are the rocks of normal alkalinity (Figure 5) (some rocks – mid alkaline) in the diagram K_2O-SiO_2 [22] most of the samples falls within the high K calc-alkaline series, the diagram FeO */ MgO-SiO_2 composition points are located in the field calc-alkaline series.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Elements	40	8	15	100	190	194	106	74	96	12/13	6/174	OA 409	MA 19	105	129	132
SiO_2	61.09	62.1	62.32	62.99	63.75	63.89	64.81	65.99	68.19	73.99	75.51	76.75	77.01	51.23	48.35	48.88
TiO_2	0.59	0.49	0.58	0.6	0.81	0.75	0.6	0.52	0.27	0.01	0.01	0.08	0.09	1.39	1.2	1.57
Al_2O_3	15.7	15.41	16.9	16.6	14.81	17.15	17.03	16.41	15.77	13.48	13.79	12.85	12.67	16.49	15.77	15.86
Fe_2O_3	3.47	2.5	3.91	3.28	3.91	4.94	3.38	3.59	1.69	1.2	0.55	n.d.	n.d.	7.74	6.38	5.61
FeO	1.29	0.94	1.01	1.29	2.46	0.43	0.73	0.28	0.43	1.78	0.71	0.66	0.71	0.86	2.16	2.73
MnO	0.06	0.06	0.04	0.09	0.1	0.09	0.03	0.09	0.04	0.01	0.01	0.08	0.06	0.13	0.15	0.14
MgO	1.85	1.77	1.95	1.9	3.18	1.86	1.43	1.31	0.05	0.14	0.36	0.11	0.05	6.04	6.74	6.29
CaO	4.85	5.34	4.24	4.32	6.13	5.25	3.97	3.19	1.32	0.53	1.9	0.44	0.47	8.33	9.8	9.09
Na_2O	4.19	3.93	4.07	4.08	3.37	3.3	4.27	4.05	4.57	3.27	2.92	4.44	4.06	4.22	3.61	4
K_2O	3.54	2.73	2.95	3.08	2.37	1.87	3.47	2.55	4.14	4.87	3.96	4.59	4.86	1.42	1.96	1.92
P_2O_5	0.41	0.38	0.28	0.3	0.28	0.35	0.33	0.23	0.06	0.01	0.01	n.d.	0.01	0.65	1.03	1.18
LOI	0.81	1.96	0.54	0.46	0.13	0.83	0.47	0.96	0.27	0.38	0.54	n.d.	n.d.	0.7	1.5	0.93
Total	98.63	99.31	99.08	98.1	98.3	99.21	100.72	98.15	99.23	99.67	100.27	100	99.99	99.2	98.65	98.1
Rb	83	66	63	74	42	51	86	72	97	160	180	209	174	23	34	32
Li	20	14	19	19	19	8	12	14	13	67	70	n.d.	n.d.	9	9	9
Sr	1105	935	935	850	520	860	935	833	420	150	100	10	16	1190	1700	1700
Ba	1250	640	650	690	400	850	690	760	830	100	100	10	26	748	780	1060
Cr	120	180	180	180	n.d.	n.d.	180	100	n.d.	30	n.d.	3.13	2.75	346	412	270
V	170	40	60	60	150	110	40	100	40	n.d.	20	n.d.	n.d.	170	170	210
Ni	24	22	30	31	69	25	32	25	15	20	3	n.d.	n.d.	115	113	110
Co	20	30	35	16	34	24	3	15	9	5	3	0.1	0.2	31	29	50
Zr	178	150	160	150	130	160	170	150	240	100	80	83	86	n.d.	230	240
Nb	12	10	11	10	8	11	14	14	17	15	10	37	34	n.d.	20	18
Ta	0.84	0.82	0.72	0.94	0.46	0.77	1.4	1.1	1.2	n.d.	n.d.	3.11	2.71	0.85	0.92	0.92
Hf	4.8	4	3.6	3.3	3.8	4.3	4.7	4.2	6	n.d.	n.d.	3.87	3.51	4.7	4.6	5.2
Th	11	11	9.3	10	n.d.	10	18	16	5.2	25	31	37.3	34.5	3.2	2.6	2.6
U	2.7	4.7	5.7	4.4	4	4	5.4	3.3	14	9.3	12	12.1	10.2	4	4	4
La	45	37	43	36	23	47	47	38	47	33.5	36	23.5	30.7	40	65	63
Ce	88	73	77	76	57	91	87	74	78	60	59	41.4	53	81	130	130
Sm	4.2	3.6	3.9	4.2	7.5	5.1	3.6	4.4	5	3	2.8	2.42	2.51	5.3	9.5	9.8
Eu	1.2	1	1.2	1	1.6	1.6	1.1	0.95	0.79	0.2	0.65	0.1	0.16	1.7	2.5	2.5
Tb	0.67	0.43	0.56	0.58	1.1	0.9	0.44	0.42	0.57	0.6	0.68	0.15	0.13	0.88	1.5	1.3
Yb	1.2	1.3	1.4	1.5	3.6	1.8	1.3	1.3	1.4	2.3	2.3	1.3	1.32	2.4	2.7	2.4
Lu	0.19	0.18	0.2	0.2	0.69	0.23	0.17	0.17	0.18	0.32	0.42	0.24	0.22	0.42	0.39	0.33
Y	36	16	11	10	11	16	n.d.	11	29	10	10	11	11	31	30	34

	17	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
Elements	134	21	57	208	53	87	109	120	167	174	13	25	33	143	160	185
SiO_2	48.05	51.84	49.42	52.97	53.32	53.05	54.92	55.67	54.31	54.01	57.66	58.52	59.85	57.08	59.28	57.85
TiO_2	1.45	1.36	1.44	1.3	0.97	1.14	1.14	1.08	1.18	1.5	0.79	0.82	0.8	1.24	1.24	0.75
Al_2O_3	15.53	16.64	16.27	16.46	17.39	17.46	16.38	17.13	16.82	17.49	16.41	16.23	16.57	17.25	16.55	17.7
Fe_2O_3	3.55	6.11	7.16	7.04	6.11	5.66	4.54	6.59	5.02	5.79	4.09	4.8	4.88	4.62	4.95	3.79
FeO	4.46	1.01	0.72	0.3	0.57	1.65	2.59	0.43	2.17	2.46	1.87	0.87	0.5	3.09	1.3	1.88
MnO	0.13	0.11	0.12	0.12	0.1	0.13	0.1	0.12	0.12	0.12	0.05	0.09	0.11	0.11	0.1	0.13
MgO	6.81	4.42	5.27	3.65	3.81	4.12	3.76	4.66	3.84	3.37	3.18	3.23	2.67	2.29	2.79	2.77
CaO	9.19	8.58	9.1	7	7.17	6.71	6.88	6.24	6.66	6.8	6.25	6.24	5.61	6.09	5.82	6.12
Na_2O	4.18	4.14	3.22	4.39	5.03	4.27	0.7	4.22	4.78	4.53	3.85	4	4.38	4.53	4.65	4.53
K_2O	1.73	2.92	2.48	3.16	2.8	2.77	2.17	2.6	2.96	3.25	3.01	2.8	3.11	2.87	3.46	2.89
P_2O_5	1.13	1.31	1.04	0.93	0.82	0.83	0.94	0.58	0.75	0.94	0.57	0.68	0.79	0.68	0.76	0.44
LOI	1.79	0.61	1.9	1.1	0.14	0.35	0.85	0.41	0.19	0.44	0.64	0.4	0.35	0.27	0.2	1.15
Total	98	99.05	98.14	98.42	98.23	98.14	98.47	99.07	98.8	100.7	98.32	98.68	99.72	100.12	101.1	100
Rb	34	60	31	60	37	36	42	54	70	43	55	49	66	40	56	48
Li	9	14	9	13	12	12	13	14	14	13	10	12	16	14	17	15

Sr	1700	2635	2550	1900	1615	1615	1445	1020	1275	1785	1360	1275	1615	1647	1360	790
Ba	990	1300	1170	1170	1140	1000	1080	680	1100	1770	830	1060	900	900	1016	930
Cr	450	170	220	n.d.	157	200	224	280	n.d.	n.d.	160	188	100	n.d.	n.d.	n.d.
V	260	140	200	150	200	200	150	170	240	150	80	130	100	140	140	110
Ni	100	43	64	45	46	48	34	65	40	39	50	54	50	33	29	31
Co	24	26	50	45	19	50	22	45	55	35	45	16	20	40	19	13
Zr	250	200	220	250	180	210	250	190	250	250	190	180	220	207	200	160
Nb	20	28	27	23	10	21	18	19	23	22	18	13	18	21	23	15
Ta	0.96	1.2	1.7	1.5	0.8	0.99	n.d.	1	1.4	1.3	0.81	0.87	1	0.98	1.4	0.88
Hf	5.1	4.5	4.6	5.2	4.2	4.7	n.d.	4.4	4.8	5	4.8	4.5	5.3	4.7	4.7	4.3
Th	4.9	5.2	7.4	8.1	6.1	5.3	n.d.	5.6	6.4	6.5	6.3	6.5	8.8	5.6	9.5	9.7
U	4	4	4	3	4	4	n.d.	4	3	4	3.6	6.3	4	4	4	4
La	62	76	77	77	59	66	69	52	96	80	60	60	70	59	67	48
Ce	120	150	160	160	120	130	130	98	120	160	120	120	120	120	140	88
Sm	9.1	10	11	9.5	6.3	7.4	7.4	5.9	7.4	9.8	5.7	5.3	5.8	7.2	8.6	5.7
Eu	2.4	2.5	2.8	2.5	1.6	1.8	2	1.7	2.2	2.7	1.6	1.7	1.7	2	2	1.4
Tb	1.1	1	1.3	1.3	1	1.4	1.1	0.9	1.1	0.95	1.1	0.94	0.85	1.8	1.2	0.59
Yb	2.2	1.8	1.9	2.3	1.8	2.1	2	2	2.2	2	1.8	1.9	2	2.2	2.1	1.3
Lu	0.31	0.22	0.34	0.34	0.25	0.28	0.22	0.39	0.31	0.27	0.31	0.3	0.26	0.25	0.24	0.24
Y	29	16	23	23	20	24	21	19	27	25	14	15	19	16	19	15

Table 2.

Major (wt %) and trace-element (ppm) composition of a representative rocks of the Late Cenozoic associations in the Lesser Caucasus (Azerbaijan).

1–9 – andesite-dacite-rhyolite; 10–14 – rhyolitic association; 15–33 – trachybasalt-trachyandesite associations.

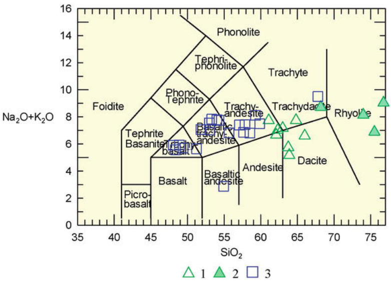

Figure 5.

Total alkali vs. -SiO$_2$ (TAS) classification diagrams [21] of Late Cenozoic volcanic associations of the Lesser Caucasus. In. 1 – andesite-dacite-rhyolite; 2 – rhyolitic association; 3 – trachybasalt-trachyandesite associations.

The rocks of this association are characterized by different contents of major elements. In volcanic rocks with increasing SiO$_2$ content decreases TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, MgO, CaO, and P$_2$O$_5$, due to fractionation of titanomagnetite, clinopyroxene, plagioclase, and possibly apatite. Weak rates increased content of K$_2$O. Na$_2$O is distributed evenly, but also an increase in the number of its slower rate. The reason for this pattern may be a potassium feldspar in the more acidic varieties of rocks.

5.2 Rhyolitic association

Rocks associations, in contrast to the previous rock associations, are characterized by ultra-structure and high alkalinity. There is approximately equal ratio of Na_2O and K_2O and low contents of CaO, MgO, and FeO (Table 2). In the normative composition of the rocks are calculated high content of salic components of quartz, feldspar, and corundum.

5.3 Trachybasalt-trachyandesite association

For silica rock associations form a continuous series from basalts to andesites (Table 2) and belong to the mildly alkaline series (Figure 5). In the diagram K_2O-SiO_2 composition points fall in the region high-K calc-alkaline and shoshonite series. In rock associations in the range of “trachybasalt-basaltic trachyandesite” with increasing silica content of TiO_2, MgO, Fe_2O_3, CaO, and P_2O_5 is reduced to a large extent, the contents of the same Al_2O_3, Na_2O decreases the slow pace. In the transition to trachyandesites content of these elements varies in a narrow range. The maximum content of MgO is observed in trachybasalts and alkaline olivine basalts and varies from 3.97 to 6.81% (Table 2), and the coefficient of $Mg^{\neq}$ (M) from 56 to 71. In subsequent decrease differentiates the content of MgO and “M.”

In the normative part of some mildly alkali olivine basalts and trachybasalts calculated normative nepheline and olivine, and in more acidic differentiates calculated hypersthene and quartz. Normative and mineral composition reflects the characteristic feature of the association: transition nepheline-normative, olivine containing mildly alkaline rocks to hypersthene-normative, and sometimes quartz-bearing alkaline rocks.

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6. Geochemical features of the Late Cenozoic volcanic rocks

The concentrations of rare and rare earth elements are in rocks of andesite-dacite-rhyolite association as a whole regularly changing. Thus, the concentration of lithophile elements increases from andesite to rhyolites (Rb from 44 to 128 ppm, Th 6 to 24 ppm) (Table 2). From the coherent elements in increasing the acidity of rocks in general, the content of V, Cr, Co, and Ni decreases. These elements are the same Sr form of silica negative dependence. Positive, but more vague correlation with silica form the content of Y and highly charged elements (HFSE – Nb, Zr, Hf). The above features show the leading role of crystallization differentiation in the association of rocks. As shown Dilek et al. [2] comparison of impurity elements rocks andesite-dacite-rhyolite association and the primitive mantle [23] shows the reduced content of Nb and Ta and elevated levels of lung large ionic lithophile elements (Rb, Ba, Th, La, Ce, and Sr) (LILE). Thus, in relation to the primitive mantle, there is a maximum Rb, Ba, Th, La, Ce, Sr, and negative Ta-Nb anomalies (Figure 6).

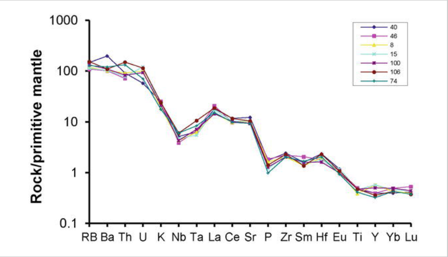

Figure 6.

Normalized to the primitive mantle [23] spider diagrams for the andesite-dacite-rhyolite association.

It is conceivable that this feature brings these rocks with subduction volcanic associations. From the same type of rocks of andesite-dacite-rhyolite association rocks rhyolite associations differ depleted femic components, a lower content of iron group elements, highly charged elements, and enrichment of ore elements in the earth crust, as well as lithophile elements (Pb, Th, U). The distribution of trace elements normalized to primitive mantle for the rhyolite showed that, like the rock of the previous association, rhyolite is enriched in LILE and depleted in highly charged elements. However, the nature of the schedule of rhyolites differs from the schedule of rocks of the previous association and is similar to the composition of the rocks of the earth's crust, which indicates a different genesis of the rocks of this association. In the rocks, trachybasalt-trachyandesite association occurs in about the same pattern as in the rocks of andesite-dacite-rhyolite association, but more clearly. Rocks of this association are inherent to the high content of Rb, Ba, La, Sr, as well as high values of La/Yb, La/Sm relations. Compared with the composition of primitive mantle [23], alkaline basalts are enriched in most LILE and some highly charged elements: Rb, Ba, Th, La, Ce, Sr, Zr (Figure 7).

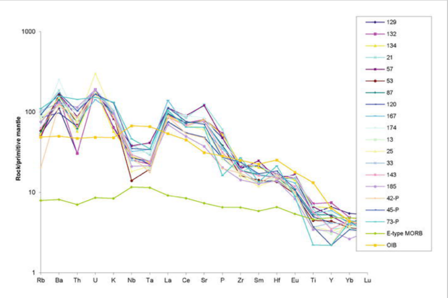

Figure 7.

Normalized to the primitive mantle [23] spider diagrams for the trachybasalt-trachyandesite association.

Geochemical data for this association show that the diversity of species association is due mainly to fractional crystallization. This is evidenced by: (1) with increasing SiO_2 content decreases compatible elements (Cr, Ni) and increasing concentrations of incompatible elements (Rb, Th, U) due to fractionation of olivine and clinopyroxene, and (2) revealed clear positive correlation connection LREE with phosphorus, calcium and fluoride, due to the concentration of light rare earth elements in apatite (the distribution coefficients of REE for apatite is 10–100). These data indicate that fractional crystallization is particularly important for trachybasalts and basaltic trachyandesites. In the process of differentiation of the content of trace elements naturally varies depending on the composition of the melt, its temperature, as well as the composition and crystal-chemical properties of rock-forming minerals. Content and types of spectra of these elements of the rock trachybasalt-trachyandesite associations of the Lesser Caucasus are close to the rocks of oceanic islands and the rift zones formed from the enriched mantle source. Similarity of plots, the distribution of elements on the primitive mantle may indicate comagmatic members of the association.

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7. Isotopic composition of the Late Cenozoic volcanic rocks

For the Neogene-Quaternary rocks of the Lesser Caucasus, we have obtained for the seven samples of volcanic rocks and their nodules isotopic compositions of He (Table 2). The highest ratio of $^3He/^4He$ ($^3He/^4He = 0.93 \times 10^{-5}$) is characteristic for alkali olivine basalts, which brings them to the mantle derivatives. Approximately, the same value is obtained for amphibole megacrysts from trachyandesite approaching the isotope ratios of primary helium mantle reservoirs ($1–5 \times 10^{-5}$) [24] and to the gases carbon sources, the most active areas associated with manifestations of modern volcanism of the Lesser Caucasus ($^3He/^4He = 10^{-5}$) [24]. A fractional difference between the rocks of trachybasalt-trachyandesite association, their nodules, as well as andesite of andesite-dacite-rhyolite association has lower values of helium isotopes (Table 3). These data indicate that differentiate the first association, incorporation, and andesite second association crystallized in the earth crust.

No samples	Rocks and minerals	$^3He/^4He \cdot 10^{-6}$	$^4He \cdot 10^{-6}$
132	Alkaline olivine basalte	9.29 (±1.46)	0.604 (±0.006)
21	Trachybasalte	1.76 (±0.27)	2.70 (±0.03)
13	Trachyandesite	1.05 (±0.18)	1.54 (±0.02)
15	Andesite	0.924 (±0.162)	2.36 (±0.02)
Nodules			
25-b	Pyroxsenites	3.33 (±0.49)	3.43 (±0.03)
13-m	Megacryste amphybole	9.39 (±1.42)	2.90 (±0.03)

Table 3.
Isotopic composition He in Late Cenozoic rocks of the Lesser Caucasus.

Unfortunately, Sr and Nd isotope data for Late Cenozoic volcanics in the Azerbaijani part of the Lesser Caucasus are absent. There is anecdotal evidence about the Armenian and Georgian part of the Lesser Caucasus. Chernyshev and his co-workers [17, 18] determined the absolute age of alkali basalts

Javakheti Plateau; they proposed a new version of the geochronological scale of the Neogene-Quaternary magmatism of the Caucasus. Dan precises absolute age of rhyolite volcanism for different volcanic highlands of the Lesser Caucasus [16]. Data above authors argue that the dominant role in the petrogenesis of lavas played by processes of fractional crystallization and contamination of the parent melts geochemically distinct from them, crustal matter [17]. A sour rhyolite volcanism developed in the context of tectonic and thermal activity of mantle lesions and relationship with the processes of local anatexis in the lower crust zones of metamorphism [16]. Our petrology and geochemistry data confirm these findings.

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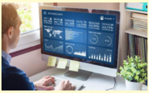

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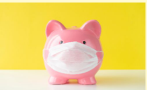

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8. Discussion of results

This section discusses the nature of the mantle substrate region under study as well as the origin of each of volcanic associations.

8.1 Mantle sources of the Late Cenozoic rocks

These isotopic compositions of Sr and Nd for late Cenozoic volcanic rocks of the Lesser Caucasus show that the primary melts to produce a mantle sources. Acid rock has mostly crustal origin. There have been offset mantle and crustal magmas. In general, this assumption is acceptable for the Azerbaijan part of the region.

A common feature for most of the Neogene-Quaternary volcanic rocks of the Lesser Caucasus is a relative enrichment in light REE and large lithophile elements (Rb, Ba), and weak depletion for heavy rare earth elements, as well as Nb, Ta, Hf [1, 2, 3, 7, 8, 13, 18, 25, 26, 27, 28, 29, 30, 31, 32, 33]. These geochemical data confirm the presence of restite of garnet in the magmatic source for the andesite-dacite-rhyolite and trachybasalt-trachyandesite associations. In addition, we believe in the petrogenesis of Late Cenozoic collision basaltoids important role played mantle substance metasomatically processed by previous subduction processes, as evidenced by the relatively high oxidized rocks associations.

Figure 8 $(Ce/Yb)_{MN} – Yb_{MN}$ shows the calculated line of equilibrium partial melting of garnet peridotite with different contents of garnet. Calculated trends melting portions of garnet peridotite, containing 2.5, and 4% garnet, borrowed from [34]. As seen from Figure 8, composition points of rocks of andesite-dacite-rhyolite associations are in the range of values with a relatively high degree of melting (3–10%) mantle source containing 4% garnet. Lineups alkali basaltoids trachybasalt-trachyandesite association on this chart are in the range of values with a low degree of melting (1–2.5%) garnet peridotite and, apparently, mantle source was more metasomatized [13]. It can be assumed that a lower degree of melting of the mantle of the substrate led to the association of basaltic melt at high alkalinity and a significant enrichment of the melt K, P, F, Ba, LREE due priority to the melting of phlogopite, apatite, amphibole, which are the main carriers of these elements.

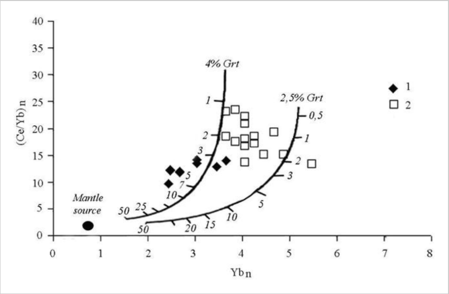


Figure 8.

Normalized to primitive mantle [23] the ratio of Ce/Yb-Yb in the Late Cenozoic basalts and andesites of the Lesser Caucasus. Calculated trends melting portions of garnet peridotite, containing 2.5 and 4% garnet [38]. The numbers along the curves – the percentage of melting. Legend: 1 – andesite-dacite-rhyolite association, 2 – trachybasalt-trachyandesite association.

At present, the association of these volcanic rocks is often associated with the association of subduction “windows” (slab-window) and sees the result of decompression melting of asthenospheric diapir. These volcanics differ from typical subduction magma and have geochemical characteristics of OIB sources. They are described for the active continental margin of North America, Philippines, Kamchatka, East Sikhote-Alin [35, 36]. For collision volcanics, this idea is developed [3, 4, 5, 6, 7, 8, 9, 10, 25, 26, 30, 31, 32, 33, 37]. Such rocks are called adakites. They are characterized by high ratio LREE/HREE and are formed by melting of garnet containing material (eclogite) oceanic plate.

Note that we also do not deny the delamination subduction lithospheric slab in the association of Late Cenozoic volcanic rocks of the Lesser Caucasus [2, 7, 8, 30, 31]. This is evidenced Seismic and some of petrology and geochemistry data. Part of Late Cenozoic andesite and dacite of the Lesser Caucasus can be considered derivatives adakites melts. They $(La/Yb)_n$ vary from 17.5 to 26.4, the concentration of Y from 6 to 13 ppm, Yb from 1.2 to 1.8 ppm. Figure Sr/Y-Y majority of species fall into the field adakites [38] (Figure 9).

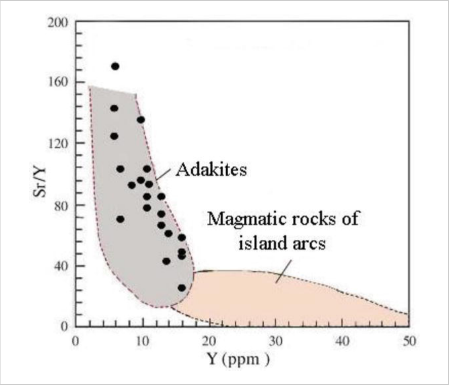


Figure 9.

Sr/Y vs. Y in the Neogene andesite-dacite-rhyolite association. The range of adakite and arc magmatic rocks is after [38].

Thus, it is found that the rocks of the Neogene andesite-dacite-rhyolite and Upper Pliocene-Quaternary trachybasalt-trachyandesite association smelt garnet sources at a depth of not less than 60–80 km [8, 33]. Not be excluded on the association of andesite melting subduction oceanic crust [39]. As Upper Pliocene-Quaternary acidic volcanic rocks, as shown by the full range of studies and published isotopic data for the region, the source of rhyolite-dacite magmas could serve as a rock granite-metamorphic layer, metamorphosed to amphibolite, and granulite facies metamorphism. The high concentrations of K, Li, Rb, Cs, U, Th, Rb and low Sr, Ba, Zr, Ti and light lanthanides, the presence of a deep negative Eu – anomalies may indicate relatively low levels of fusion substrate, in which a significant portion of plagioclase and accessories remained in the restite. The eastern part of the Lesser Caucasus (Vardenis and Syunik uplands) (Figure 1) $^{87}Sr/^{86}Sr$ are 0,70,444–0,70,811 [18].

8.2 The role of fractional crystallization in the formation of late Cenozoic volcanic rocks

Petrochemical data show that the association of andesite-dacite-rhyolite and trachybasalt-trachyandesite association of fractional crystallization occurred. Thus, in the rocks of andesite-dacite-rhyolite association with increasing silica content decreases femic rock-forming oxides, increasing the content of incompatible elements due to fractionation of dark-colored minerals and feldspars. However, fuzzy trends show the influence of processes of assimilation and crustal contamination on the association of these rocks. Thus, an attempt to get out of andesitic dacites and from dacitic rhyolites by fractionation of clinopyroxene, amphibole, biotite, magnetite, and feldspar failed [31, 32, 33]. Therefore, as will be shown below, apparently, the formation of these rocks is dominated by a single process of AFC, that is, assimilation and fractional crystallization.

We believe that fractional crystallization played a leading role in the association of rocks trachybasalt-trachyandesite association [13, 32, 33]. This is evidenced by the behavior of a number of rock-forming trace elements. For example, a change in slope of trends MgO-SiO_2, TiO_2-SiO_2, and Ni-SiO_2 in the field trachyandesite explained by fractionation of olivine, clinopyroxene, and magnetite.

Past balance calculations on a computer showed that the evolution of the melt occurred as a result of changes in the composition and quantity of rock-forming minerals. The results of balance calculation of fractional crystallization of alkaline olivine basalt-trachybasalts showed that the latter is obtained by fractionation of 19.8% Cpx, 57.6% Pl (An_{65}), 15.0% Ol (Fo_{84}) and 7.6% Mt. As seen from Table 4, the absolute and calculated values for major and trace elements in the whole match ($\Delta R^2 = 0.507$). The degree of fractionation at the same time is about 61%.

		SiO_2	TiO_2	Al_2O_3	FeO*	MgO	CaO	Na_2O	K_2O	P_2O_5
Parental magma	1	51.36	1.05	16.77	7.76	6.29	10.48	3.14	2.10	1.05
Calculated parental magma	2	51.76	0.84	16.68	7.80	6.31	10.46	3.36	1.61	1.14
Daughter magma	3	54.60	1.07	17.13	6.85	4.28	8.57	4.28	2.14	1.07

	Rb	Ba	Sr	V	Cr	Ni	Zr	Sc	Cu	La	Ce	Sm	Eu	Yb	Y
1	35	943	1871	105	315	105	240	11	73	63	130	9.8	2.5	2.4	19
2	44	953	1956	2119	575	56	151	22	73	158	112	7.5	1.5	0.8	12
3	64	1392	2821	150	182	46	214	21	101	81	161	10.7	2.1	1.1	17
D	0.01	0.01	0.04	1.99	4.02	1.53	0.08	1.12	0.16	0.03	0.05	0.08	0.09	0.11	0.11

Table 4.

Balance calculation for alkaline olivine basalt-trachybasalts (petrogenic elements recalculated to 100%).

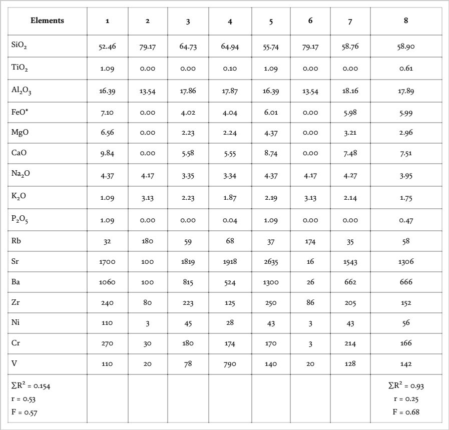
D – Bulk partition coefficient (are taken from [13, 40]).

Fractionation of the above minerals and amphibole leads to further differentiates associations and the result is a continuous differential series – trachybasalt-basaltic trachyandesite-trachyandesite. Possible further differentiation of the melt to the trachytes, trahyriodasites, that is, for example, in a large polygenic volcano Ishygly.

Although, FC simulation of least squares using the basic rock-forming oxides and some trace elements gives good results, the majority of trace elements do not conform to this model. Thus, the content of LREE and HREE for different types of rocks vary in narrow limits. At Harker diagrams micronutrients – SiO_2, where not all elements give a clear linear dependence. This suggests their association by other mechanisms, too.

8.3 The role of crust contamination in the formation of late Cenozoic volcanic rocks

By Imamverdiyev previously shown that the role of crustal contamination in the genesis of Late Cenozoic volcanic rocks of the Lesser Caucasus is negligible [13]. In other works [12, 18, 39] speculation is about a significant transassociation of the primary magmas of crustal processes. We obtained the last petrogeochemical data suggest involvement in petrogenesis Late Cenozoic volcanic enriched mantle source (lithospheric mantle) and a significant contribution to processes of crustal contamination. The calculations show AFC – a model of crustal material required for the appropriate changes to the source mantle composition of rocks trachybasalt-trachyandesite association can be achieved during the fractionation of basalts (degree of fractionation of F = 0.5–0.6) with the absorption of a large number of acid melt (the ratio of assimilation rock and cumulates r = 0.3–0.5) (Table 5). A similar pattern is observed for rocks of andesite-dacite-rhyolite association, but this shift is achieved with a high degree of fractionation (F = 0.7–0.9) and with a large number of acidic substances (r = 0.6). Obviously, with such volumes of assimilation acidic substances are not stored petrochemical characteristics of the primary rocks (andesites and basalts). Therefore, Harkers figures are not observed clear trends.



Elements	1	2	3	4	5	6	7	8
SiO_2	52.46	79.17	64.73	64.94	55.74	79.17	58.76	58.90
TiO_2	1.09	0.00	0.00	0.10	1.09	0.00	0.00	0.61
Al_2O_3	16.39	13.54	17.86	17.87	16.39	13.54	18.16	17.89
FeO*	7.10	0.00	4.02	4.04	6.01	0.00	5.98	5.99
MgO	6.56	0.00	2.23	2.24	4.37	0.00	3.21	2.96
CaO	9.84	0.00	5.58	5.55	8.74	0.00	7.48	7.51
Na_2O	4.37	4.17	3.35	3.34	4.37	4.17	4.27	3.95
K_2O	1.09	3.13	2.23	1.87	2.19	3.13	2.14	1.75
P_2O_5	1.09	0.00	0.00	0.04	1.09	0.00	0.00	0.47
Rb	32	180	59	68	37	174	35	58
Sr	1700	100	1819	1918	2635	16	1543	1306
Ba	1060	100	815	524	1300	26	662	666
Zr	240	80	223	125	250	86	205	152
Ni	110	3	45	28	43	3	43	56
Cr	270	30	180	174	170	3	214	166
V	110	20	78	790	140	20	128	142
$\Sigma R^2 = 0.154$ r = 0.53 F = 0.57								$\Sigma R^2 = 0.93$ r = 0.25 F = 0.68

Table 5.
Results AFC – modeling for rocks trachybasalt-trachyandesite association.

1 – alkaline olivine basalts (initial melt), 2 – rhyolite (assimilation rock), 3 – trachyandesite (hybrid), 4 – calculated composition of trachyandesites, 5 – trachybasalt (initial melt), 6 – rhyolite (assimilation rock), 7 – basaltic trachyandesite (hybrid), 8 – calculated composition (all analyses have been converted to 100%).

Below are the results of AFC – modeling for rocks trachybasalt-trachyandesite association.

As seen from Table 4, the intermingling rhyolite and basic rocks (alkaline olivine basalts and trachybasalt) may be formed basaltic trachyandesite and trachyandesite.

Summarizing the above data, the association of Late Cenozoic volcanic series of the Lesser Caucasus can be represented as follows.

Within the Lesser Caucasus in the late Cenozoic volcanism expressed high-K calc-alkaline, mildly alkaline, and partly alkaline associations. In Neogene time (Upper Miocene-Lower Pliocene), with decompression occurs anatexis metasomatized mantle and lower strata of basalt layer at a sufficiently large depth, which determines the enrichment of these melts with alkali, alkaline earth, and light rare earth elements.

This process resulted in association of basaltic melts, enriched in alkalis. Perhaps such a melt was formed at low degrees of partial melting (3–10%) of garnet peridotite or eclogite. We can assume that it corresponds subduction oceanic crust. In the future, as a result of growing tension mantle melts penetrated the upper layers of the earth crust, where it mixes basic and acid magma, with the association of hybrid andesite, andesite-dacite lavas (Figure 10). Progressive cooling of the deep source magma origin may be the cause of education dike fields in the region studied and possibly fractured outpouring mildly alkaline volcanism observed in the other parts of the Lesser Caucasus. Due to additional heating and the flow of volatiles formed fairly large volcanoes of calc-alkaline composition of Neogene age. Then Upper Pliocene-

Quaternary formed bimodal volcanism. Thus, the temporal spatial conjugation of crustal and mantle magmatism led to the introduction of mantle melts, under conditions of tension in the lower crust, which resulted in its melting and the association of acidic volcanic rocks rich in radiogenic Sr and Nd (rhyolite association). Simultaneously, in this situation, a change of scenery compression and tensile contributed to the development rifts depressions, arching and exercise slow differentiated and undifferentiated volcanic (trachybasalt-basaltic trachyandesite-trachyandesite and basanite-tefrite series). Thus, the evolution of the melt in the earth crust is dominated by a single process of AFC (assimilation and fractional crystallization). As the fractionation rare elements, intermediate rocks can be formed by mixing trachybasaltic and rhyolite melts.

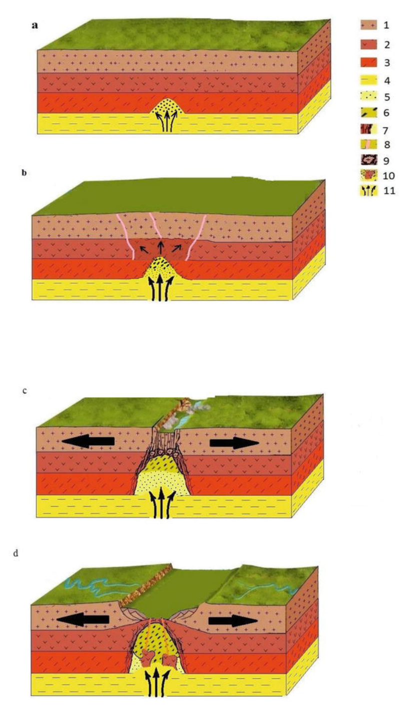


Figure 10.

Scheme of tectonic development and volcanism of the areas of matium magma formation at the Late Cenozoic stage of development of the Lesser Caucasus [8]. (a) Initial stage of mantle diapir growth; (b) Upper Miocene-Lower Pliocene stage; (c) in the Upper Pliocene is a new stage; (d) Upper Pliocene-Quaternary stage – stage of general extension. 1 – granite layer; 2 – basalt layer; 3 – mantle; 4 – astonesphere; 5 – metasomatized mantle; 6 – region anatexis; 7 – partially molten basalt layer; 8 – dykes; 9 – partially molten granite-metamorphic layer; 10 – partially molten material of the upper mantle; 11 – upward mantle fluid flows.

9. Conclusions

A distinctive feature of the investigated Late Miocene-Early Pliocene rocks of the Lesser Caucasus is that they are generally medium and acid. Volcanite composition meets mainly andesites and trachyandesites, dacites and trachydacites and also rhyolites. The volcanism was very powerful in relation to the attic tectonic activity of Late Miocene-Early Pliocene. During this period, there occurs Pre-Mesozoic base uplift and volcanism is mainly manifested in the central parts of the anticlinal zones of the Lesser Caucasus. The andesites and andesidacites with acid pyroclasts dominate in the products' composition at the beginning of the volcanic phase and at its end – andesite lavas. Magmatism of the main composition of high alkalinity has locally been manifested in the extreme parts of the anticlinal zones. Subvolcanic appearings of formation invaded after volcanogenic strata (Basarkechar suite) formation and have more acid composition. After active effusive-explosive activity of Meotian-Pontian-Early Pliocene volcanoes, more acid and viscous magma, cooling at a depth, rising along fractures at shallow depths hardened in the form of dikes and other subvolcanic bodies.

On the basis of nine petrogenic elements oxides (SiO_2, TiO_2, Al_2O_3, FeO^*, MgO, CaO, Na_2O, K_2O, P_2O_5) such independent groups as andesite-trachyandesite-quartz latites, dacite-trachydatsites and rhyodacite-rhyolites have been defined for andesite-dacite-rhyolite formation using factorial diagram.

It has been shown that with increasing SiO_2 content in the rocks composition, the content of TiO_2, Al_2O_3, FeO^*, MgO, CaO, P_2O_5 decreases due to fractionation of titanomagnetite, clinopyroxene, plagioclase, amphibole, and apatite. The calc-alkaline trend of andesite-dacite-rhyolite series is controlled not only by magnetite fractionation but also by the hornblende crystallization, having a high Fe/Mg ratio and by SiO_2 under saturation. First, it has been proved that the early hornblende crystallization in the Neogene magmatism evolution is the principal factor in the calc-alkaline series formation. This regularity is especially obvious during change of SiO_2 content between 60 and 64%. The slow increase of K_2O and Na_2O content in the rocks formation is explained by potassium feldspar crystallization.

In formation's volcanites with increasing SiO_2 content from andesites to rhyolites and with decreasing MgO quantity the coherent (compatible) elements as macroelements give a linear and sometimes expressed broken dependence. The figurative points of the homogenous inclusions are at the beginning of these dependence trends. These elements distribution in the rocks of formation is controlled by fractionation of rock-forming minerals and accumulative (homogenous) crystallization of the inclusions. The incompatible elements content (Rb, Th, Nb, Zr, Hf, LREE, etc.) is minimal in the deep-seated inclusions.

In rocks of formation the light lanthanoids prevail in relation to heavy, and therefore La/Sm, La/Yb relations are high. In medium rocks (quartz latites and andesites), it is defined approaching Eu/Eu* relation to unit (Eu/Eu* = 0.94–1.05) and in more acid rocks – Eu-minimum (Eu/Eu* = 0.58–0.63) that indicates on plagioclase fractionation. It has been established that the content of Ba and Ba/Y, Rb/Y, Th/Yb relations are rapidly increased in the formation's rocks. The formation's rocks enrichment with lithophylous and rare-earth elements caused by relatively high degree of fusion melting that enriched by fluids.

Based on the modeling, it was determined that as a result of high fractionation of the initial melt (F = 0.96) during mixing of 32.4% andesite and 63.4% rhyodacite; it is possible to obtain dacite of hybrid origin. The leading role of single process of Assimilation and Fractional Crystallization (AFC) is responsible for forming the igneous rocks of formation.

It has been shown that the enrichment of formation's rock with light rare-earth elements and many incompatible elements indicates on sufficiently important role of the enriched mantle matter in their formation. The high-alumina basalts can be considered as the parental magma for formation's rocks. Their formation is connected with fractionation in the environment of high water pressure from the initial high-magnesian melt of the olivine-clinopyroxene association.

So, the Neogene volcanic series formation of the Lesser Caucasus can be represented as follows.

At the beginning of the Late Cenozoic, the mantle metasomatism occurred as a result of regional compression in the lifting diapir. In the Late Miocene-Early Pliocene anatexis of the metasomatized mantle and lower parts of the basalt layer occurs due to decompression at sufficiently great depth that determines these melts enrichment with alkali, alkaline-earth, light rare-earth elements. As a result of this process, there is formed basalt melts enriched by alkalines. Further evolution of these melts occurs in conditions of continental Earth crust where medium-acidic rocks as steeply dipping dikes and volcanic edifices of the central, central-fractured type are formed due to melts differentiation (Figure 10).

The primary magma evolution was accompanied by fractionation of olivine-clinopyroxenic mineral associations and the appearance of high-alumina residual magma in the deep-seated foci. The last ones outcropping are accompanied by a stop at the intermediate foci, fractionation of plagioclase, clinopyroxene, amphibole, surrounding rock melting, crustal material contamination, and by hybrid magma formation.

The works area can be considered metallogenetically perspective in relation to new Au, Ag, Hg, As, Sb, Cu-Mo with Au, Pb-Zn, Cu-Pb-Zn fields and ore occurrences. The investigated area is also rich by non-metallic raw materials – tuffs, scorias, pumices, etc.

Therefore, for andesite-dacite-rhyolite formation, developed in the central part of Lesser Caucasus, rocks formation of high-potassium calc-alkaline series is specific unlike the rocks of calc-alkaline series of normal alkalinity. Rocks formation of andesite-dacite-rhyolite formation is caused by fractionation of the rock-forming minerals in the intermediate foci and later due to contamination of the differentiated basaltic melt by the surrounding rocks.

Single process of crystallization and assimilation caused the rocks buildup of the formation.

Two volcanic formations of the Late Pliocene-Quaternary age are separated at the end of the collision stage of development of the Azerbaijan part of the Lesser Caucasus, forming a bimodal association: 1 – rhyolite; 2 – trachybasalt-trachyandesite.

In the mafic volcanics of the behavior of major elements indicate their origin by fractionation of olivine, clinopyroxene, hornblende, basic plagioclase, apatite, magnetite. Acidic volcanic rocks associated with the formation of “dry” high temperature of the melt in the intermediate chambers are not of fractional crystallization.

The distribution of rare earth elements in rocks trachybasalt-trachyandesite formation indicates that the source was the metasomatic alteration of volcanic rocks containing garnet mantle. In the studied volcanics, $(Tb/Yb)_n = 1.7–3.0$ indicates the presence of garnet in the source of the primary magma.

In the rocks of rhyolite formation contents of rare earth elements is low (REE = 66–116 ppm), there is a pronounced low ratio of europium, which indicates that early removal of the molten plagioclase and alkali feldspar.

Trace element composition of the rocks trachybasalt-trachyandesite formation and their relationships complicate the model and determine the fractional crystallization of the magma mantle interaction with the substrate of the crust. In this substrate can be rhyolites, geochemical, and isotopic composition similar to the Earth’s crust and forming a spatio-temporal association with the rocks contrast trachybasalt-trachyandesite formation.

The simulation revealed that the evolution of moderately alkaline olivine basalts (considered a primary mantle melt the rocks trachybasalt-trachyandesite formation) occurs due to changes in the composition of the main rock-forming and accessory minerals. Average rock formations formed by the assimilation of poorly differentiated primary magma acidic melt. Geochemical features of moderately alkaline olivine basalts indicate that the source of magma is metasomaticized, phlogopite-garnet-rutile containing lithospheric mantle. It is very possible that the melting of such a source is rutile to a restaurant, and magma is depleted Nb and Ta.

The calculations have shown that the proportion of melting rhyolitic melt separated from andesite substrate close to 15%. After removal of the remaining melt restite entirely consistent with the composition of the lower crust. The typical ratio of rare earth elements is to confirm this.

These fact sheets, model calculations indicate various sources of education salic and mafic melts. Thus, the generation of mafic melt (moderately alkaline olivine basalt composition) came from a differentiated mantle protolith formation of a salic melt occurs during lifting mafic magma by melting of crustal substrate. On the other hand, the salic is going to melt in the top of the magma reservoir and prevents lifting heavier mafic magma, and in a short time in the melt is subjected to intermediate focuses differentiated. During subsequent evolution differentiated mafic melt reacts with rhyolitic melt, which entails the formation of secondary rocks.

Thus, the formation of bimodal volcanism in contrast, the central part of the Lesser Caucasus in the Late Pliocene-Quaternary period is as follows.

Temporary space conjugate crust and mantle magmatism led to the introduction of mantle melts under tension in the lower crust, which led to its melting and the formation of acidic volcanic rocks enriched in radiogenic *Sr* and *Nd* (rhyolite formation). At the same time in this situation, a change of scenery compression tensile contributed to the manifestation of poorly differentiated volcanism. At the same time, the evolution of the melt in the earth's crust is dominated by a single process of AFC (assimilation and fractional crystallization), and intermediate chambers became necessary mixing of mafic (trachybasalt) and salic (rhyolite) melts and created the conditions for the formation of intermediate rocks. However, due to different densities and viscosities of melts, salic mafic and such mixing occurred in small quantities.

Thus, in the petrogenesis of the majority of Caucasian young volcanic rocks has played a significant role lower mantle source material which is close to the tank "Common" with characteristic isotopic $^{87}Sr/^{86}Sr = 0.7041 \pm 0.0001$, $\ni_{Nd} = +4.1 \pm 0.2$; $^{147}Sm/^{144}Nd = 0.105–0.114$ and named "Caucasus" [17, 18]. The primary melt composition corresponds to K-Na moderately alkaline olivine basalts. The magma formed by the plume of the Caucasus in the atmosphere of Earth's crust formed the ever-increasing mantle diapir; he's at the very beginning of its process uplift served the development of large volumes of mantle fluids. Due to the hot magma mantle diapir melts the material of Earth's crust, magma is formed, which corresponds to the isotopic composition of the Earth's crust, and subsequently, to varying degrees due to contamination of the mantle and crustal magma formed hybrid rocks.

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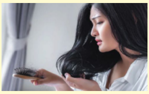
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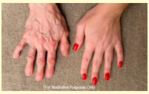
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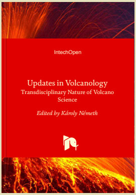

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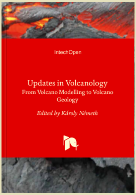

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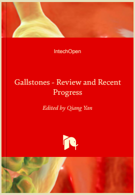

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