Stratigraphy and Geological Correlation, Vol. 12, No. 1, 2004, pp. 85–101. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 12, No. 1, 2004, pp. 94–113.

Geochronology of the Neogene–Quaternary Dacitic Volcanism in the Northwestern Lesser Caucasus (Georgia)

V. A. Lebedev*, I. V. Chernyshev*, M. M. Arakelyants*, Yu. V. Gol'tsman*, O. Z. Dudauri, and G. T. Vashakidze****

**Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Staromonetnyi per. 35, Moscow, 119017 Russia*

***Geological Institute, Academy of Sciences of Georgia, ul. Zoi Ruchadze 1, Tbilisi, 380093 Georgia*

Received August 8, 2002, in final form, January 30, 2003

Abstract—The isotopic geochronology of a representative collection of moderately acidic volcanics from the Dzhavakheti neovolcanic area in the northwest of the Lesser Caucasus (Georgia) is studied using the K–Ar and Rb–Sr methods. Three discrete stages of the regional volcanic activity took place in that area during the late Miocene (about 8–7 Ma), Pliocene (4–2 Ma), and Quaternary (800–about 50 ka). Moderately acidic volcanic rocks were most characteristic of the first and third stages, whereas basalts with subordinate rhyolite–dacitic lavas were typical of the second one. The K–Ar dates evidence for intermittent formation of the Dzhavakheti dacites formerly attributed altogether to one Goderdzi Formation. Pyroclastic units and intraformational dacitic flows exposed in the Kura River valley were formed in the late Miocene (7–8 Ma). The extrusive domes of the Amiranisgora and Chikiani volcanoes emerged at about 3 Ma. Dacitic lavas of the Dzhavakheti Ridge were erupted probably in the late Pliocene (about 2 Ma). Dacitic volcanism of the Samsari Ridge that commenced at about 800 ka had three discrete phases responsible for the formation of the "western range" volcanoes (800–700 ka), the Samsari caldera and other volcanoes of the main ridge (300–200 ka), and parasitic volcanoes and hyalodacitic lava flows (later than 50 ka). The volcanic activity in the Samsari Ridge continued up to the late Neopleistocene or, probably, to the Holocene. Accordingly, this area of the Dzhavakheti region is potentially hazardous with respect to volcanism reactivation. It was found out that plagioclase phenocrysts of the Dzhavakheti dacitic lavas contain the ^{40}Ar excess and differ in initial Sr and Nd isotopic ratios from the rock groundmass. These peculiarities previously noted for Quaternary lavas in other Caucasian volcanic centers appear to be also characteristic of Pliocene rocks. It is confirmed that the K–Ar dating of young volcanics, when applied to their groundmass, yields the most reliable results.

Key words: isotopic dating, geochronology, K–Ar method, Rb–Sr method, Lesser Caucasus, Dzhavakheti area, dacites, Neogene–Quaternary volcanism, stages of volcanic activity.

INTRODUCTION

Geochronology of the Neogene–Quaternary volcanism pertinent to the recent stage of the Earth development is of a great scientific and practical importance. A possibility to employ three to four methods of isotopic dating of young volcanic rocks (K–Ar, Rb–Sr, U–Io, ^{14}C) creates the quantitative (numerical) base for stratigraphy, geological mapping, regional geodynamic reconstructions, and theory of volcanogenic ore formation.

Specific aspects of isotopic dating of young volcanics are well known [1]. In geological and petrological practice, the method elucidates the real duration of volcanic processes and active life of volcanoes. The isotope dates determine periods of magmatic activity and time of the latest eruptions of Quaternary volcanoes and, thus, are important for the forecast possible catastrophes.

The last aspect greatly stimulated in the last 7–10 years the isotopic-geochronological investigations of the Quaternary volcanoes in Japan, North America, and the Mediterranean belt, the Caucasus included.

Methodically, the isotope dating of young, especially of Neopleistocene–Holocene (younger than 1 Ma) volcanic rocks is the most complicated, especially the K–Ar dating, which can be universally used for the entire Quaternary period, from its beginning up to 20–30 ka, i.e., to the Holocene. The modern K–Ar dating of Quaternary volcanics is based on mass-spectrometer facilities to measure minor amounts (0.00*n*–0.0*n* ppb) of the radiogenic ^{40}Ar.

In this work, we present the results of geochronological investigations of young volcanism in the Lesser Caucasus exemplified by rocks of the Dzhavakheti neovolcanic region. The work is a part of our systematic study on isotopic geochronology and geochemistry of the young Caucasian magmatism. The Dzhavacheti region (upland) is a typical volcanic area of Lesser Caucasus in Georgia and Armenia, where Neogene–Quaternary volcanics of different chemical composition and age are widespread.

According to the common opinion [2], the intense Neogene–Quaternary magmatism of Caucasus is of the late collisional type by geodynamic nature. It commenced the middle Miocene, when the Caucasian segment of the Alpine folded belt was involved in the process of “rigid” collision between the Arabian and Eurasian continental plates, and lasted to the Holocene.

Zaridze [3], Milanovskii and Koronovskii [4], and other researchers distinguished three stages of Neogene–Quaternary magmatism in the Caucasus: (1) the late Miocene–early Pliocene, (2) late Pliocene, and (3) late Pliocene–Anthropogene stages of volcanic activity. The first stage is most fully recorded in the Lesser Caucasus, whereas magmatic rocks of the second stage are widespread throughout the Caucasian segment. Volcanism of the third (Quaternary) stage was of a local significance and resulted in formation of the big Elbrus, Kazbek, Aragats, and others stratovolcanoes.

On the base of isotopic-geochronological data recently obtained in the Greater Caucasus, time limits and occasionally durations of stages and phases of the magmatic activity have been determined. At the first stage (9.5–8.3 Ma) laccoliths of the Pyatigorsk area [5] were formed. According to results obtained by Arakelyants *et al.*, [6] and in later works [7], the second stage (about 4–2 Ma) resulted in origin of numerous hypabyssal granite intrusions (the El’dzhurtu, Tepli, Songutidon and other massifs) and ignimbrites of the Verkhnii and Nizhnii Chegem plateaus. Chernyshev *et al.* [8] published the first reliable K–Ar dates for Quaternary volcanics of the Kazbek area and Elbrus volcanic center. These and radiocarbon dates [9] showed that recent volcanism in the Greater Caucasus developed in three discrete phases during the last 450 ka. One more phase of explosive activity in the Elbrus area was also suggested. Thus, summarizing the available isotopic-geochronological information, we can distinguish three stages of magmatic activity in the Greater Caucasus, which took place in (1) the late Miocene (9.5–8.3 Ma), (2) Pliocene (4–2 Ma), and (3) Quaternary (900–0 ka).

The systematic isotopic-geochronological study of the Neogene–Quaternary volcanism of Lesser Caucasus has not been carried out until recently. Single age estimates were insufficient for geochronological scales and reconstructions. The progress in geochronology of young magmatism in the region was also decelerated by a considerable amount of material erupted during the last 10 m.y. and widespread here from the Adzhariya to Nagornyi Karabakh. The west–east succession of the Erushet-Arsiani, Dzhavacheti, Aragats, Gegam, Vardenis, Syunik and Araks volcanic zones are distinguishable in the region [10]. In the south, the volcanic province of the Lesser Caucasus is contiguous with the Kars and Ararat zones of similarly young magmatism. The products of Neogene–Quaternary magmatic activity in the Lesser Caucasus demonstrate a wide petrochemical spectrum from olivine basalts to rhyolites and obsidians. In this work, we discuss the results of isotopic-geochronological investigations of moderately acidic to intermediate volcanic rocks of the Dzhavakheti area, which are commonly united into the Goderdzi Formation [11].

BRIEF GEOLOGICAL REVIEW OF THE DZHAVAKHETI VOLCANIC AREA

The Dzhavakheti volcanic area (Fig. 1) is located in the central part of the Lesser Caucasus mountain system. It is bordered by the Gek-Tapa (Egnakhag), Shirak and Bazum ridges in the south, by upper courses of the Kura River in the west, and by the Trialeti Ridge of Paleogene volcanogenic–sedimentary deposits in the north. The eastern boundary of the young volcanic area coincides with the Tsalka–Gomere–Dmanisi–Stepanavan line, and three large flows of basaltic lava slope down from that line for tens of kilometers along the Mashavera, Khrami and Debed river valleys, being traceable up to the Khrami River mouth.

The Dzhavakheti Upland represents a medium to high mountainous land with the maximal peaks of about 3300 m high (the Didi-Abuli and Samsari mountains of the Samsari Ridge). The area represents a combination of mountainous plateaus and volcanic ridges with separate central volcanoes, extrusive domes, and intermountain depressions.

The basement of the Dzhavakheti area is composed of Cretaceous and Paleogene volcanogenic–sedimentary deposits, which are exposed in separate erosional windows in many places. In the east (the Khrami valley), there are exposures of the Khrami massif of Paleozoic granitoids. In the largest part of the region, the basement is overlain by Neogene–Quaternary volcanics, which are a few hundred meters thick.

According to modern views on geology of the region, the young volcanics of the Dzhavakheti area constitute the Goderdzi ($N_1^3 - N_2^1$), Akhalkalaki ($N_2^3 - Q_E$) and Kechut (Q_{II-III}) formations [12]. The formations ages correspond to time ranges of three stages of the Caucasian young volcanism, as established by Milanovskii and Koronovskii [4].

The Goderdzi Formation includes mainly intermediate and moderately acidic rocks. The Mio-Pliocene volcanism occurred in the vast territory from the southern fault of the Adzharia–Trialeti fold system in the north to the Lake Van in the south. Due to the general explosive character of volcanism, the Goderdzi Formation is composed of pyroclastic material and infrequent lavas. The classic Goderdzi sections are in the Erushet–Arsiani and Kars areas outside the Dzhavakheti Upland. Their basal beds representing by thin basic lava flows are overlain by thick pyroclastic unit of andesite–dacitic lava flows. The sections are crowned by andes-

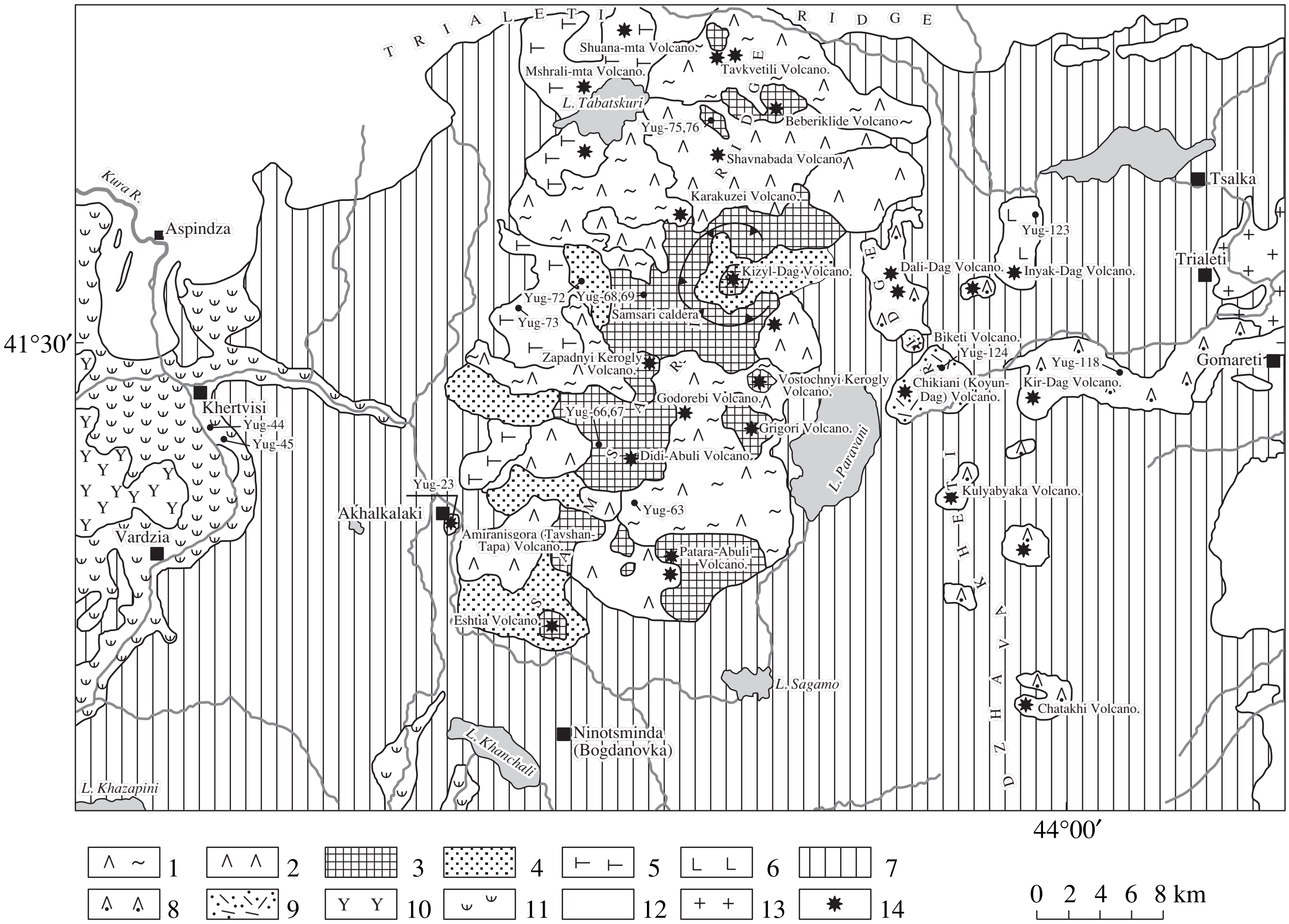

Fig. 1. Schematic geological map of the Dzhavakheti volcanic area (after Skhrtladze [11], Dzotsenidze and Kuloshvili [34], and Tutberidze [10]). (1–5) Quaternary volcanics of the Samsari Ridge: (1) hyalodacites (Phase III of volcanic activity), (2) pyroxene–plagioclase dacites (Phase II), (3) amphibole–plagioclase dacites (Phase II), (4) pyroclastics (Phase II), (5) two-pyroxene–amphibole–plagioclase dacites of the volcanoes of the "western range" of the Samsari Ridge (Phase I); (6) basaltic andesine of the Inyak-Dag Volcano (N_2); (7) basalts, basaltic andesites and andesites of the Akhalkalaki Formation (N_2); (8) dacites of the Dzhavakheti Ridge (N_2); (9) rhyolites, obsidians, perlites (N_2); (10) andesitic and dacitic lavas of the Goderdzi Formation (N_1); (11) pyroclastic rocks of the Goderdzi Formation (N_1); (12) Paleogene–Cretaceous volcanogenic–sedimentary deposits; (13) Paleozoic granitoids of the Khrami massif; (14) volcanoes.

itic and dacitic lavas. The Goderdzi Formation of the Erushet–Arsiani area is referred to the Mio-Pliocene based on stratigraphic data and floral remains [11].

In the Dzhavakheti region, pyroclastic rocks and andesitic lava flows of the Goderdzi Formation are exposed in the Kura and Paravani river valleys, where they are overlain by basalts of the Akhalkalaki Formation. Extrusive domes and volcanoes of the Samsari and Dzhavakheti ridges were also referred to the Goderdzi formation. These structures predominantly composed of dacites are confined to two large submeridional faults. Thus, the intermediate and moderately acidic rocks of the Dzhavakheti region are included into the Goderdzi Formation. It was supposed that dacitic lavas of the Samsari and Dzhavakheti ridges constitute upper parts of the formation, and that its lower pyroclastic part is not exposed here [11]. However, some geological peculiarities of the Dzhavakheti region evidence against the idea to unite all moderately acidic volcanics into the single formation. For instance, the dacitic lavas underlie basalts of the Akhalkalaki Formation in the Kura and Paravani river valleys and overlie them near the Korkhi-Ordzha Village. The late Miocene age of the Samsari Ridge volcanoes was doubted by Milanovskii and Koronovskii [4] and by other researchers earlier. Up to recently, the age problem of all moderately acidic rocks of the Dzhavakheti region was unsolved because of their different positioning in the Goderdzi Formation sections.

The Goderdzi pyroclastics are overlain by olivine basalts and basaltic andesites of the Akhalkalaki Formation. Lava flows of the latter leveled the ancient relief and formed the large Akhalkalaki, Tsalka, Gamer and other lava plateaus. Sequences of up to 20 lava flows of the Alkhalkalaki Formation, which are locally up to 300 m thick in total, can be observed in ravines of the Kura, Paravani and other large rivers. Fauna-bearing lacustrine deposits in the middle part of the Akhalkalaki Formation (near the town of Akhalkalaki) reliably indicate the late Pliocene–Eopleistocene age of the basalts [13]. The youngest structures of the Akhalkalaki Formation are numerous cinder cones and andesitic lava flows, which occur as small hills on the basaltic plateaus [12].

The youngest deposits of the Dzhavakheti Upland are pyroxene dacites and hyalodacites of the Kechut Formation. Lava flows of this composition, which lope down from parasitic centers of the Samsari Ridge volcanoes, are neither long nor thick. Characteristic "stone chaos" on the flow surfaces and good preservation of the eruption centers suggest the young age of the Kechut Formation. The middle–late Neopleistocene age estimated for the formation [12] has not been proved however by either paleontological evidence or geochronological data.

Thus, the geological structure of the Dzhavakheti Upland is indicative of three stages of the young volcanic activity separated by considerable hiatuses.

FORMER GEOCHRONOLOGICAL DATA

Remains of a prehistoric man found in the Dmanisi area in the last decade, stimulated works on age determinations for the Akhalkalaki basalts. The time span of two plateau basalt sequences that was determined by the K–Ar and $^{40}Ar/^{39}Ar$ methods [14] is 2.9–1.8 Ma. This is consistent with the fauna-based age of the Akhalkalaki Formation. The other $^{40}Ar/^{39}Ar$ date (3.60 ± 0.06 Ma) was obtained for plagioclase phenocrysts from the lowest basalt flows of the Toki section in the Paravani valley [15]. The isotopic-geochronological investigations of volcanic rocks from the Aragats area [16] yielded the K–Ar date of 2.5 ± 0.2 Ma for the plateau basalts of the Akhutyan canyon in Armenia, which are analogues of the Akhalkalaki Formation rocks in the Dzhavakheti Upland. Accordingly, the Akhalkalaki Formation age should be within the range of 3.6–1.8 Ma (middle–late Pliocene). Paleomagnetic study of the Akhalkalaki basalts [17] revealed regular reversals of magnetic polarity in their sequence.

The age of the Akhalkalaki plateau basalts is the minimum age limit for the Goderdzi pyroclastics and lavas in the Kura and Paravani valleys. In the 1960s–1980s, two K–Ar dates for the Goderdzi pyroclastics were obtained in the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM), one of 8.0 ± 1.5 Ma (ignimbrite, the Vardzia area, collection of E.K. Ustiev) and the other one of 6.6 ± 0.4 Ma (rhyolitic tuff, the Vardzia area, collection of V.N. Volkov). The K–Ar dating of the Goderdzi pyroclastic rocks that was done at the same time in the Geological Institute, Academy of Sciences of Georgia (GIN), approximately indicated their Mio-Pliocene age [18]. Stankevich [19] published paleomagnetic data for pyroclastics of the Goderdzi Formation in the Khertvisi Village area and for volcanoes Samsari, West Kerogly, and Ivan-Tepe of the Samsari Ridge, which, as mentioned above, are assigned to the upper part of the Goderdzi Formation. The Samsari Ridge volcanoes and the Late Quaternary volcanoes of the Kazbek area have similar paleomagnetic parameters, which essentially differ from those of the Goderdzi pyroclastic rocks and cast doubts on their coeval origin. The only obsidian dome of the Chikiani (Koyun-Dag) Volcano in southern Georgia, which was also referred to the Goderdzi Formation, was dated at 2.2–3.0 Ma by the fission track method [20]. This structure is therefore closer in age to the Akhalkalaki Formation rather than to the Goderdzi pyroclastics. In general, the volcanics referred to the Goderdzi Formation have not been systematically studied, and their age remains uncertain.

Geochronological investigations of the Kechut Formation volcanics have never been carried out. A single date of 0.37 ± 0.15 Ma (middle–late Neopleistocene) was obtained for hyalodacites of the Tavkvetili Volcano in GIN (Rubinshtein *et al.*, 1972).

PETROGRAPHY AND CHEMICAL COMPOSITION OF THE ROCKS STUDIED

In 1999–2000, the joint expedition of IGEM and GIN collected representative samples of volcanic rocks of different age and composition from different parts of the Dzhavakheti volcanic area. Described below are predominantly the samples of volcanics of the Mio-Pliocene Goderdzi Formation, lavas of the Samsari and Dzhavakheti ridges, volcanic rocks of the Kura valley, and some extrusive structures of the region included. Samples of the youngest Kechut Formation were also studied. Localities of sampling sites are shown in the schematic geological map of the Dzhavakheti Upland (Fig. 1) and in Table 1.

The Dzhavakheti volcanics can be divided into several petrographic groups.

Biotite–amphibole–plagioclase dacites of the Amiranisgora (Tavshan-Tapa) Volcano (samples Yug-2 and Yug-3). Phenocrysts constitute in total 10–15% of the rock volumes. Plagioclase of andesine composition occurs as occasionally zoned prismatic and xenomorphic crystals. Some crystals are partly resorbed. Plagioclase phenocrysts vary in size from 0.1 to 8 mm. Elongate, less frequently isometric crystals of basaltic hornblende are 0.2 to 1.2 mm in size and larger (up to 2 mm). Their idiomorphic hexagonal forms are rare, and absence of secondary opacite indicates hypabyssal origin of the rocks. Scarce biotite (its greatest abundance was recorded in the contact zone of extrusions) occurs as single elongate crystals 0.2 to 0.4 mm in size. The groundmass represents to 85–90% of the rocks. It is commonly hyalopilitic and locally fluidal, when ori-

Table 1. Brief characteristics of the studied geological samples from the Dzhavakheti volcanic upland

Sample number	Rock	Geological object	Sampling site
Yug-2	Biotite–amphibole dacite (pink)	Amiranisgora (Tavshan-Tapa) Volcano	SE-E slope of Amiranisgora Volcano, altitude 1750 m
Yug-3	Biotite–amphibole dacite (gray)	"	"
Yug-44	Two-pyroxene dacite	Intraformational flow in the pyroclastics of the Goderdzi Fm.	2 km to the south of Khertvisi Village along the Khertvisi–Vardzia road
Yug-45	"	"	3 km to the south of Khertvisi Village along the Khertvisi–Vardzia road
Yug-63	Hyalodacite	Kechut Fm., lava flow of Goderebi Volcano	S slope of Didi-Abuli Volcano, Abuli–Vladimirovka road, 200 m below the pass between Didi-Abuli and Patara-Abuli volcanoes
Yug-66	Amphibole dacite (gray–pink)	Didi-Abuli Volcano	W-NW slope of Didi-Abuli Volcano, 2 km to the top; 5 km to NE of Buzaveti Village at altitude of 2600 m
Yug-67	Amphibole dacite (pink)	"	"
Yug-68	Amphibole dacite (gray)	Samsarid Volcano	NW slope of Samsari Volcano, locality on Samsari Volcano slope 4 km to NW of the top, altitude 2300 m
Yug-69	Amphibole dacite (pink)	"	"
Yug-72	Amphibole dacite (gray)	Pyroclastics of Samsari Volcano	Cave-town below Patara-Samsari Village, quarry
Yug-73	Two-pyroxene–amphibole dacite	Babakhngo Mt.	W slope of Babakhngo Volcano, Didi-Samsari–Merenia road, 1 km of Merenia Village
Yug-75	Amphibole dacite	Shanabada Volcano	N slope of Shavnabada Volcano, Tabatskuri-Tsalka Mt. road, 100 m of Krasnyi Arbovshchik yaila
Yug-76	"	"	Altitude 2172.3 m on N slope of Shavnabada Volcano, pass between Tabatskuri and Tsalka Mt.
Yug-118	Aphyric dacite	Kir-Dag Volcano lava flow	Pass between Tsalka Mt.–Gomareti Mt. across the ridge separating Tsalka and Gomareti plateaus
Yug-123	Aphyric basaltic andesite	Inyak-Dag Volcano lava flow	Tikilis area, 1 km of Tsalka Mt.–Lake Paravani to the south
Yug-124	Obsidian	Chikiani (Koyun-Dag) Volcano	NE slope of Chikiani Volcano, obsidian quarry

Note: Rocks are named based on their chemical composition.

ented microlites flow around the phenocrysts. Set in the glassy matrix are andesine microlites, small crystals of hornblende, ore minerals, and cristobalite. Traces of superimposed processes can be observed. Samples Yug-2 and Yug-3 differing the groundmass color (pink and gray respectively).

Two-pyroxene–plagioclase dacites from the intraformational flows of the Kura valley (samples Yug-44 and Yug-45). Phenocrysts of plagioclase, monoclinic and rhombic pyroxenes constitute more than 50% of the rock volumes. Idiomorphic prismatic and infrequent xenomorphic, partially resorbed crystals of plagioclase (andesine) vary in size from 0.1 to 1 mm, less frequently to 2.5 mm. The total plagioclase content is 50%. Plagioclase phenocrysts in Sample Yug-45 contain abundant gas–fluid and melt inclusions. Idiomorphic clinopyroxene crystals (up to 5% of the rock volume) range in size from 0.1 to 0.9 mm, less frequently to 1.5 mm. Small (0.1–0.5 mm) orthopyroxene crystals (less than 1%) show traces of alteration along transverse parting. Predominantly hyalopilitic groundmass is composed of plagioclase microlites and partly recrystallized glass with dusty inclusions of ore minerals. Amygdules in Sample Yug-45 are filled with aggregate of anisotropic matter.

Hyalodacite of the Kechut Formation from the lava flows of the Godorebi Volcano (Sample Yug-63). The rock is black, with conchoidal fracturing and porphyritic texture. There are phenocrysts of plagioclase and hornblende. Rare idiomorphic plagioclase crystals 0.3–0.4 mm in size constitute not more than 3 or 4% of the rock. Single hornblende crystals are entirely replaced by opacite. The hyalopilitic groundmass is composed

Table 2. Chemical composition of the studied volcanics of the Dzhavakheti area

Sample no.	SiO_2, %	Al_2O_3, %	Fe_2O_3, %	MnO, %	TiO_2, %	Na_2O, %	K_2O, %	CaO, %	MgO, %	P_2O_5, %	Rb, ppm	Sr, ppm
Yug-2	72.25	14.26	2.85	0.045	0.33	3.50	2.59	3.29	0.78	0.118	68	538
Yug-3	71.18	14.62	3.12	0.046	0.37	3.59	2.47	3.58	0.89	0.135	64	570
Yug-44	67.33	15.24	4.72	0.055	0.60	3.56	2.11	5.09	1.03	0.266	43	624
Yug-45	65.48	14.54	5.47	0.065	0.76	3.63	2.56	5.56	1.55	0.387	52	774
Yug-63	64.71	16.09	6.04	0.082	0.85	3.98	2.21	4.64	1.12	0.279	41	609
Yug-66	71.08	14.50	3.25	0.045	0.40	3.52	2.13	4.26	0.69	0.121	52	559
Yug-67	68.27	14.72	3.43	0.049	0.40	3.51	2.03	6.58	0.89	0.126	48	578
Yug-68	67.07	15.71	3.89	0.053	0.50	3.65	1.92	6.36	0.72	0.126	45	610
Yug-69	67.91	15.65	3.98	0.057	0.52	3.78	1.90	5.30	0.78	0.132	43	647
Yug-72	70.31	14.43	3.83	0.054	0.50	3.60	2.25	4.13	0.74	0.159	51	590
Yug-73	66.98	15.74	4.68	0.062	0.55	3.68	1.66	5.40	1.12	0.140	38	561
Yug-75	71.75	14.10	2.84	0.043	0.40	3.76	2.19	4.19	0.62	0.115	54	613
Yug-76	66.67	15.79	4.62	0.067	0.56	3.93	1.78	5.08	1.31	0.195	32	611
Yug-118	69.32	15.76	3.64	0.050	0.55	3.63	2.37	3.92	0.65	0.125	68	615
Yug-123	56.48	17.69	7.84	0.123	1.08	3.83	1.82	7.68	3.06	0.406	27	604
Yug-124	77.04	12.49	1.28	0.063	0.14	3.52	4.52	0.75	0.17	0.016	124	90

Note: Rocks are analyzed by A.I. Yakushev and T.M. Marchenko, IGEM, the X-ray fluorescent spectroscopy, spectrometer Philips PW 2400. Analytical results are recalculated for 100% tot.

predominantly of volcanic glass with dusty inclusions of ore mineral and oriented plagioclase laths.

Amphibole–plagioclase dacites of the Samsari Ridge volcanoes (Didi-Abuli, Samsari, Shavnabada) (samples Yug-66, Yug-67, Yug-68, Yug-69, Yug-72, Yug-75, and Yug-76). The summary content of plagioclase and basaltic hornblende phenocrysts ranges from 30 to 50%. Prismatic or resorbed xenomorphic plagioclase crystals occasionally show indistinct zoning. In phenocrysts, their size is between 0.2 and 1.2 mm. The content of plagioclase phenocrysts in dacite samples ranges from 10–15 to 45%. Hornblende phenocrysts 0.2–1.0 mm in size are partly or entirely replaced by opacite. Only central parts of hornblende crystals usually remain unchanged. The hornblende content is from 5 to 10–15%. Groundmass usually fluid is sometimes hyalopilitic and pilotaxitic. It is composed of volcanic glass, plagioclase laths, magnetite grains, and small occasional hornblende crystals. Rocks are lacking traces of secondary alterations.

Two-pyroxene–amphibole–plagioclase dacite of the Babakhngo Mountain (Sample Yug-73). The rock of porphyritic texture is gray and vesicular in places. It contains phenocrysts of plagioclase, hornblende, clinopyroxene, and orthopyroxene. The plagioclase phenocrysts are represented by indistinctly zoned idiomorphic prismatic crystals varying in size from 0.15 to 1.0 mm. The plagioclase of andesine composition constitutes to 25% of the rock. The basaltic hornblende phenocrysts (about 5% of the rock) are replaced partly or entirely by opacite. They are of prismatic habit and range in size from 0.1 to 2.0 mm. Isometric and partially resorbed clinopyroxene crystals (1–2% of the rock) are 0.1–0.2 mm in size and show reaction rims at the contacts with groundmass. Single prismatic crystals of orthopyroxene are up to 0.3 mm in size. The microlitic groundmass is composed of plagioclase microlites with subordinate amount of volcanic glass.

Weakly porphyritic dacite of the Kir-Dag Volcano (Dzhavakheti Ridge) (Sample Yug-118). This microcrystalline rock is pink–brown in color and porphyritic in texture. The content of phenocrysts do not exceed 10%. The phenocrysts are represented by idiomorphic and less frequent xenomorphic crystals of plagioclase (andesine) 0.3–0.7 mm in size and by single grains of hornblende entirely replaced by opacite. Plagioclase crystals are indistinctly zoned. The trachytic groundmass is composed of subparallel plagioclase laths and elongated magnetite crystals of, which completely substitute hornblende.

Basaltic andesite from the lava flow of the Inyak-Dag Volcano (Sample Yug-123). The rock is aphyric and microdoleritic in texture. It is composed of randomly oriented laths of fresh plagioclase and small isometric clinopyroxene crystals in between.

Obsidian of the Chikiani Volcano (Sample Yug-124). The rock is black, showing a weak glass devitrification in places.

Thus, the moderately acidic volcanics of the Dzhavakheti Upland can be classified into six petrographic types of dacites according to the phenocryst paragene-

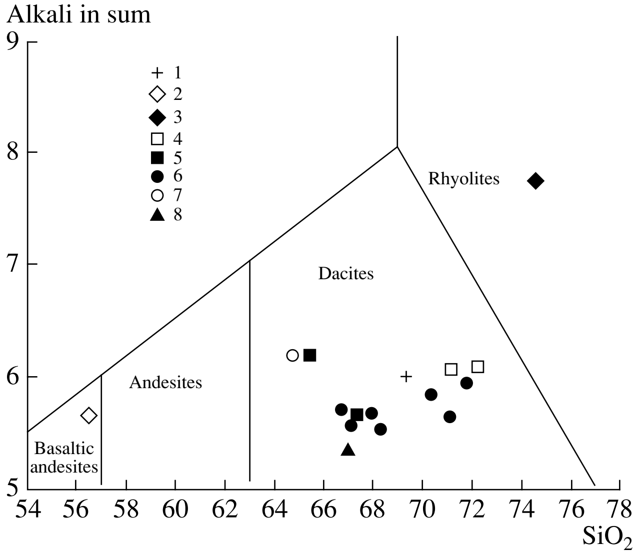

Fig. 2. The (Na_2O+K_2O)–SiO_2 classification diagram for the studied rocks of the Dzhavakheti area (fields for rock types are those recommended by the IUGS Subcommission on Systematics of Igneous Rocks [21]). Symbols for Figs. 2–5 and 7: (1) Kir-Dag (Dzhavakheti Ridge), (2) Inyak-Dag, (3) Chikiani, and (4) Amiranisgora volcanoes; (5) dacites, upper courses of the Kura River; (6) volcanoes of the Samsari Ridge; (7) hyalodacites of the Samsari Ridge; (8) Babakhngo Volcano (the western range of the Samsari Ridge).

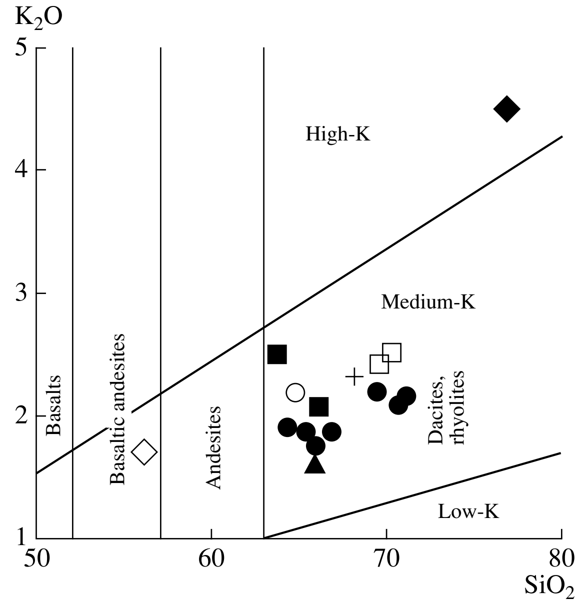

Fig. 3. The K_2O–SiO_2 classification diagram [21] for the studied rocks of the Dzhavakheti area (symbols as in Fig. 2).

sis These are biotite–amphibole–plagioclase, two-pyroxene–plagioclase, amphibole–plagioclase, and two-pyroxene–amphibole–plagioclase dacites, hyalodacites, and weakly porphyritic dacites of the Kir-Dag Volcano. The group does not include the Chikiani obsidians and Inyak-Dag basaltic andesites, which were also referred formerly to the Goderdzi Formation (for example, [11]).

In chemical composition, the majority of studied volcanics of the Dzhavakheti area corresponds to dacites with silica content varying from 64 to 72% (Table 2, Fig. 2). The exceptions are the obsidian of the Chikiani Volcano (Yug-124) and the rock of the lava flows from the Inyak-Dag Volcano (Yug-123), which correspond in composition to rhyolite and basaltic andesite respectively (Fig. 2). All the volcanics, except for the basaltic andesite Yug-123, have a high percentage of normative quartz (20–35%).

Among samples from the Dzhavakheti volcanic area, hyalodacite of the Kechut Formation (Yug-63) and rocks of intraformational flows in pyroclastic units of the Kura valley (Yug-44 and Yug-45) have the lowest silica content. The rocks of the Amiranisgora extrusive are most acidic. Volcanics of the Samsari Ridge (Fig. 2) are intermediate between them.

In SiO_2–K_2O classification diagram [21], data points of the Dzhavakheti volcanics studied are mostly concentrated in the field of rocks with moderate potassium content (Fig. 3). The only exception is the highly potassium Chikiani obsidian (Yug-124).

The studied rocks of the Dzhavakheti Upland (all the dacite varieties and basaltic andesite of the Inyak-Dag Volcano) belong to the calc–alkaline series (Fig. 4), whereas the Chikiani Volcano obsidian (Yug-124) belongs to the K–Na subalkaline series. This emphasizes a specific position of this magmatic rock among other intermediate and acidic volcanics of the Dzhavakheti Upland. Figs. 3 and 5 show variations of main oxides concentrations versus SiO_2 content in the rocks. It is clearly seen that contents of CaO, Fe_2O_3, P_2O_5, and TiO_2 diminish as the silica content increases. These trends are less pronounced for Al_2O_3, MgO, and MnO. It is difficult to specify any regular trend of K_2O and especially Na_2O concentrations in the studied volcanics.

In connection with the Rb–Sr method applied, the Rb and Sr concentrations in the Dzhavakheti rocks were analyzed (Table 2). It is natural that the Rb content is low in the Inyak-Dag basaltic andesite (Yug-123) and high in the Chikiani obsidian (Yug-124). The Rb concentrations in Dzhavakheti dacites range from 30 to 70 ppm.

Virtually all the studied Dzhavakheti dacites show the high Sr content, that is 1.5–2 times higher in average than the clarke values for intermediate and acidic rocks, whereas Ca-concentrations are usual for rocks of this type. It is remarkable that correlation between concentrations of these geochemically allied elements is absent (Fig. 6).

The Rb–Sr versus SiO_2 diagrams for the Dzhavakheti rocks are shown in Fig. 7. The Rb concentration

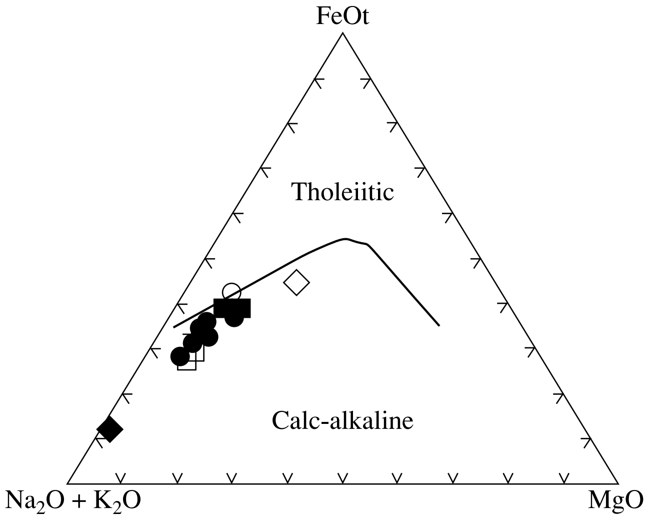

Fig. 4. The AFM diagram for the studied, moderately acidic volcanics of the Dzhavakheti area (symbols as in Fig. 2).

generally grows with the increase of silica content, whereas the Sr content is not silica-dependent.

The results obtained allow us to divide the Dzhavakheti volcanics referred previously to the Goderdzi Formation into three groups of rocks according to their petrographic and petrochemical features. The overwhelming majority of the volcanics is represented by calc-alkaline dacites, which build up the volcanoes of the Samsari and Dzhavakheti ridges and lava flows in the Kura valley. The Chikiani Volcano is composed of subalkaline acidic rocks. Basaltic andesites of the Inyak-Dag Volcano are similar in chemical composition to the plateau basalts of the Akhalkalaki Formation.

METHODS OF ISOTOPIC-GEOCHRONOLOGICAL ANALYSIS

We used both the K–Ar and Rb–Sr isotopic methods to study the volcanics of the Dzhavakheti Upland.

The largest part of geochronological dates is obtained by the K–Ar method. The K–Ar dating of young volcanics is based on measurements of ultraminor quantities of radiogenic argon, which usually constitutes an insignificant portion of argon in the samples. The Dzhavakheti volcanics were studied using a special technique developed in IGEM [22] and the highly sensitive mass-spectrometer constructed at that institute based on device MI-1201 IG of the Sumy NPO SELMI (Ukraine). The radiogenic argon was measured by the isotope dilution technique with the ^{38}Ar as a spike. The analytical procedure and precision allowed dating the samples weightings not more than 50 mg. The measurements were controlled by the regular analyses of standard samples: biotite–muscovite "Bern-4," basalt "1/76 Asia", muscovite "P-207," and atmospheric argon. The K concentration was measured by the flame spectrophotometry method.

The previous study of the K–Ar isotopic systematics for phenocrysts and groundmass of volcanics from the Greater Caucasus showed that the latter substance was best suitable for dating because the argon-saturated phenocrysts (especially with low K content) yielded overestimated ages [8]. The same effect is known for the Quaternary lavas of Japan, Italy, and North America, as is reported in foreign works [23]. Therefore, the groundmass freed of the phenocrysts was used for the K–Ar dating of the young Dzhavakheti volcanics. The whole-rock method was applied to samples Yug-44 and Yug-45, whose Miocene age was proved by preliminary studies. In addition, we studied the K–Ar isotopic systematics for phenocrysts from some samples of the Samsari Ridge volcanics. Prior to the isotope analysis, the dacite sample Yug-45 was treated in a weak HNO_3 solution to remove carbonate from amygdules.

The traditional ion-exchange chromatographic technique was used to extract Rb and Sr for isotopic analysis. Their concentrations were measured by the isotope dilution technique with the mixed spike ^{85}Rb + ^{84}Sr. The isotopic analyses were made using the mass-spectrometer Micromass Sector 54. The Sr isotope ratio for the standard sample SRM-987, which was regularly measured during the experimental runs, was 0.710248 ± 0.000011. Errors for ^{87}Sr/^{86}Sr and ^{87}Rb/^{86}Sr ratios in the samples studied are not greater than 0.003 and 1.7% respectively.

The Nd isotope composition, Sm and Nd concentrations were measured with the mass-spectrometer Micromass Sector 54. The ^{143}Nd/^{144}Nd ratio in the Nd standard of La Jolla, which was analyzed during experiments, corresponds to 0.511799 ± 0.000010. Errors for the ^{143}Nd/^{144}Nd and ^{147}Sm/^{144}Nd ratios in the samples studied did not exceed 0.018 and 0.09%, respectively.

Geochronological calculations are based on the decay constants recommended by the International Subcommission on Geochronology [24].

RESULTS OF ISOTOPIC-GEOCHRONOLOGICAL INVESTIGATIONS AND DISCUSSION

The K–Ar isotopic ages are determined for 22 samples of moderately acidic volcanics from the Dzhavakheti area. The results are shown in Table 3.

Dacitic Lavas of the Upper Course of the Kura River

The K–Ar whole-rock analysis was applied to date the intraformational two-pyroxene–plagioclase dacite flows in the pyroclastic unit of the Goderdzi Formation (Yug-44 and Yug-45, the Kura valley). The obtained dates (7.6 and 7.3 Ma) are concordant within the analytical error limits and correspond to the supposed age (late Miocene) of the enclosing Goderdzi pyroclastics. It should be noted that the dates are close to the K–Ar ages (8.0 ± 1.5 and 6.6 ± 0.4 Ma respectively) obtained previously in the laboratory of IGEM for ignimbrites of the Goderdzi Formation (collections of E.K. Ustiev and

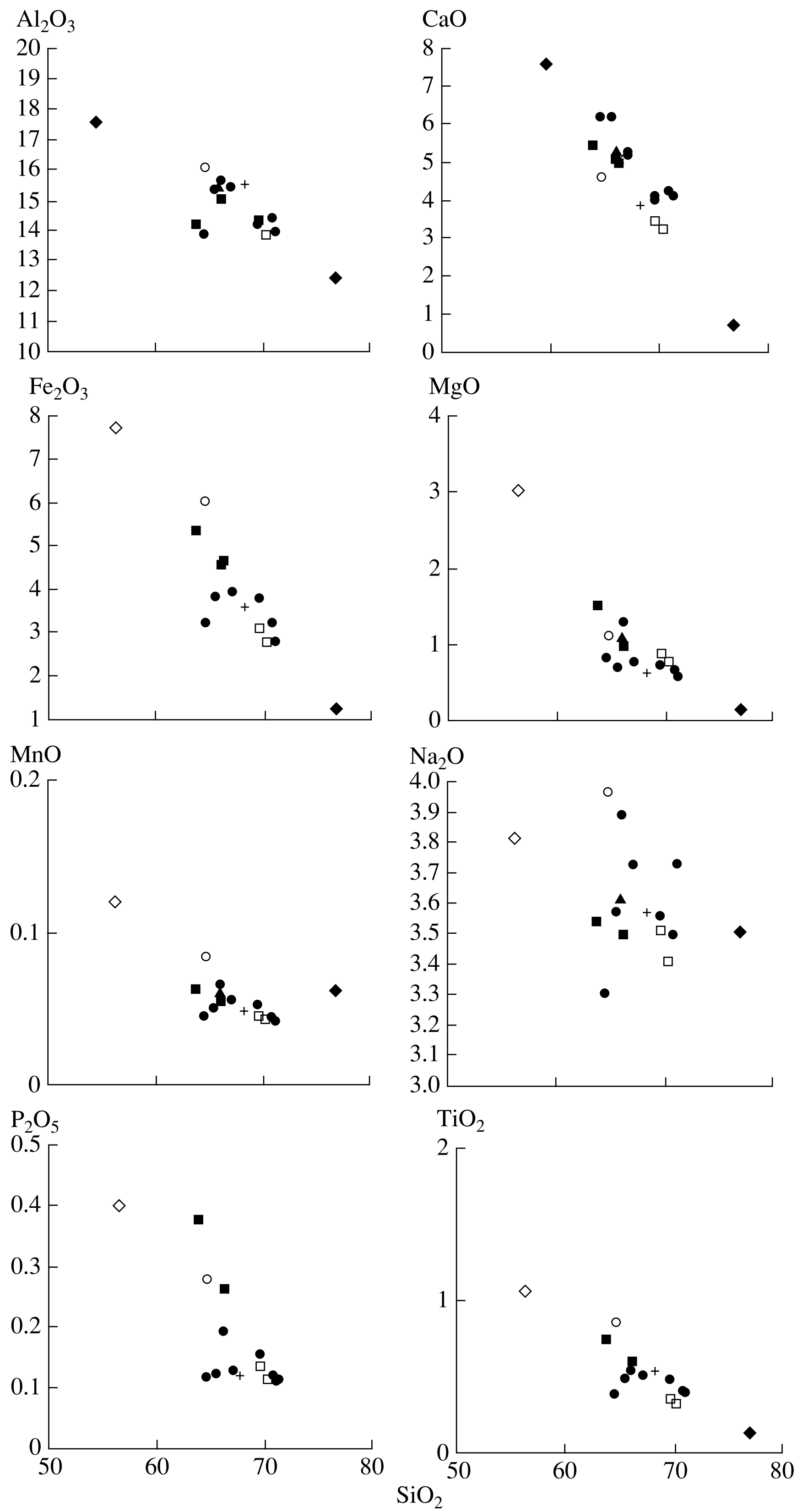

Fig. 5. Diagram of main oxides versus SiO_2 in volcanic rocks of the Dzhavakheti area (symbols as in Fig. 2).

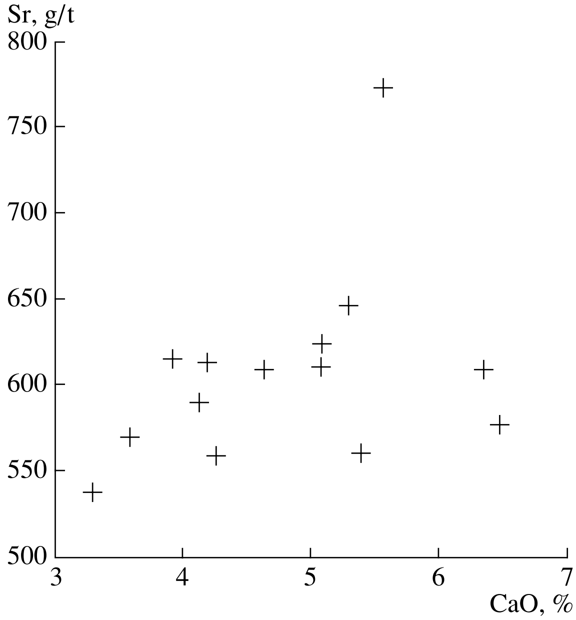

Fig. 6. The CaO–Sr correlation diagram for the studied dacites of the Dzhavakheti area.

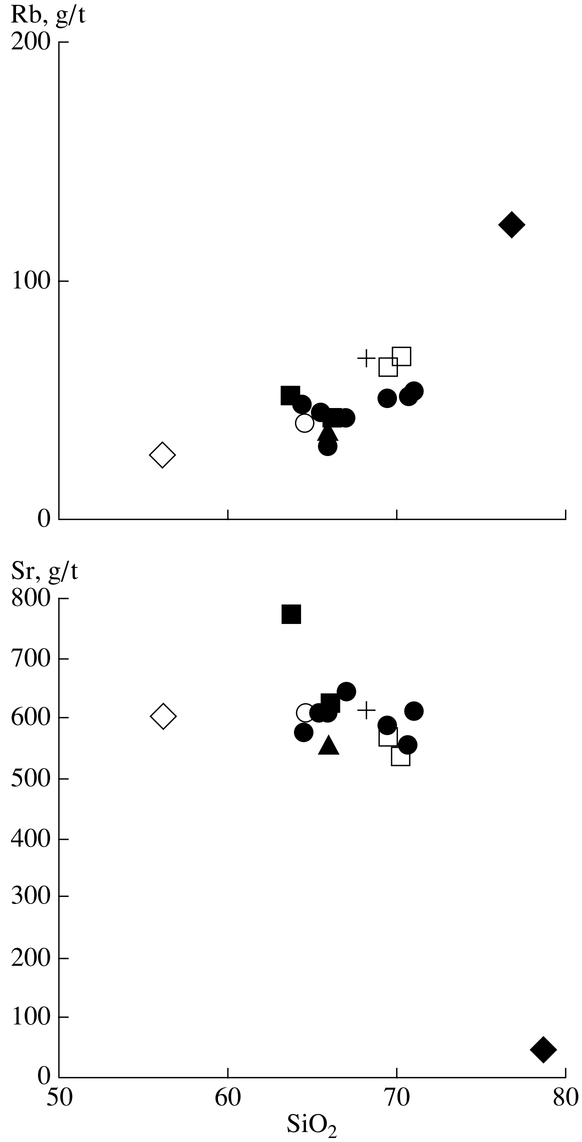

Fig. 7. Rb and Sr versus SiO_2 diagrams for the studied dacites of the Dzhavakheti area (symbols as in Fig. 2).

V.N Volkov, the Kura valley). As mentioned above, the late Miocene age of the Goderdzi pyroclastics was based on fossil flora found in the tuffs of the Erushet-Arsiani Upland joining to the Dzhavakheti area in the west. In this upland, the pyroclastics are widespread and traces of later magmatic processes are lacking. It is interesting that the K–Ar dating of teschenites from the Adzharia-Trialeti zone bordering the Dzhavakheti area in the north [25] yielded a close date of 7 ± 1 Ma. Thus, to the west of the Kura valley of southern Georgia, there was obviously a powerful impulse of predominantly explosive volcanism with subordinate eruptions of moderately acidic and even basic lavas (thin basaltic flows occur at the base of the pyroclastic unit in the Goderdzi Pass area) in the initial Late Miocene. To the east of the Kura valley (in the Dzhavakheti Upland), pyroclastic rocks are widespread along the Paravani valley up to the Toki Village area, where they underlie the basalts of the Akhalkalaki Formation. The established age (about 7.5 Ma) of the intraformational dacitic flows, which is likely close to that of the entire pyroclastic unit, the commencement time of the Late Cenozoic magmatic activity in southern Georgia after the considerable time gap since the Oligocene time.

The Amiranisgora and Chikiani Extrusive Domes

According to present views on geology of the Dzhavakheti Upland, dacitic lavas of the Samsari volcanoes and some extrusive structures composed of moderately acidic and acidic rocks are constituents, as mentioned above, of the Goderdzi Formation [11, 12]. These views are inconsistent with the K–Ar dates obtained for the Amiranisgora and Chikiani) extrusive structures composed of the most acidic volcanic rocks of the Dzhavakheti Upland.

The date of 2.7 ± 0.15 Ma was obtained for obsidian of the Chikiani (Koyun-Dag) Mountain (Yug-124, Table 3). The K–Ar date of 2.85 ± 0.2 Ma (Table 3, at the bottom) that is close within the error limits to the above date was previously obtained for the Chikiani rhyolites (collection of Volkov) by one of us in IGEM [26]. The fission track age of the Chikiani obsidian is 3.0–2.2 Ma [20]. Consequently, the recently obtained and previous dates obviously indicate the late Pliocene age (2.85–2.7 Ma) of the Chikiani rhyolite–perlite–obsidian extrusion. The available geochronological data on the Akhalkalaki Formation [27] suggest that the Chikiani Volcano is concurrent in age to the plateau basalts. On the contrary, there is a considerable time

Table 3. K-Ar isotopic ages of the samples from the Dzhavakheti volcanic area

Sample no.	Rock	Sample	K, % ±σ	$^{40}Ar_{rad}$, ppb ±σ	$^{40}Ar_{atm}$, %	Age, Ma ±1.6σ
Yug-2	Dacite	Biotite	5.35 ± 0.05	1.77 ± 0.06	58.1	4.8 ± 0.3
		Plagioclase	0.30 ± 0.015	not detected	100	–
		Groundmass	2.33 ± 0.03	0.44 ± 0.03	93.9	2.7 ± 0.3
Yug-3	"	Biotite	4.76 ± 0.07	1.39 ± 0.06	74.6	4.2 ± 0.3
		Groundmass	2.14 ± 0.03	0.48 ± 0.02	78.6	3.2 ± 0.2
Yug-44	"	Whole-rock	1.87 ± 0.03	0.99 ± 0.04	16.3	7.6 ± 0.4
Yug-45	"	"	2.35 ± 0.03	1.19 ± 0.05	15.8	7.3 ± 0.4
Yug-63	"	Groundmass	1.89 ± 0.02	0.003 ± 0.003	99.7	0.03 ± 0.03
Yug-66	"	"	1.90 ± 0.02	0.037 ± 0.004	97.5	0.28 ± 0.06
Yug-67	"	Plagioclase	0.45 ± 0.015	0.12 ± 0.01	85.5	3.7 ± 0.4
		Groundmass	1.71 ± 0.02	0.029 ± 0.004	98.4	0.24 ± 0.06
Yug-68	"	"	1.68 ± 0.02	0.021 ± 0.004	99.0	0.18 ± 0.07
Yug-69	"	"	1.74 ± 0.02	0.029 ± 0.005	99.0	0.24 ± 0.07
Yug-72	"	"	1.70 ± 0.02	0.023 ± 0.005	95.8	0.20 ± 0.04
Yug-73	"	"	1.68 ± 0.02	0.089 ± 0.009	91.4	0.76 ± 0.08
		Plagioclase	0.21 ± 0.015	0.12 ± 0.01	61.0	8.2 ± 0.7
Yug-75	"	Groundmass	1.92 ± 0.02	0.039 ± 0.004	97.1	0.29 ± 0.06
Yug-76	"	Plagioclase	0.28 ± 0.015	0.024 ± 0.006	93.0	1.2 ± 0.3
		Groundmass	1.66 ± 0.02	0.037 ± 0.004	98.1	0.32 ± 0.07
Yug-118	"	"	2.09 ± 0.02	0.33 ± 0.01	94.8	2.25 ± 0.10
Yug-123	Basaltic andesite	"	1.44 ± 0.02	0.21 ± 0.01	92.1	2.05 ± 0.10
Yug-124	Obsidian	Glass	3.90 ± 0.03	0.73 ± 0.03	10.5	2.7 ± 0.15
1549-1*	Rhyolite	Whole-rock	3.94 ± 0.04	0.78 ± 0.04	29.7	2.85 ± 0.20

* Sample of V.N. Volkov's collection.

gap (about 4.5 m.y.) between the formation of the Goderdzi pyroclastic rocks and the Chikiani extrusion. In addition, the Chikiani mountain rocks essentially differ in chemical composition from other Goderdzi dacitic lavas and show affinity with subalkaline K–Na series (Table 2). All these facts suggest that rhyolite–obsidian volcanism of the Dzhavakheti Upland corresponds to an independent Upper Pliocene volcanic formation.

The biotite–amphibole–plagioclase dacites of the Amiranisgora (Tavshan-Tapa) Mountain near the Akhalkalaki area are most acidic among dacites of the Dzhavakheti Upland (Fig. 2, Table 2). Their pink and gray varieties are undoubtedly coeval: the gradual color changes and the absence of intrusive contacts have been described by many authors (e.g., [11]) and observed by us. As dacites are composed of several appropriate mineral phases, they are the most suitable rocks for isotope dating. Therefore, we used both the K–Ar and isochron Rb–Sr methods to determine the age of Amiranisgora dacites. The results obtained faile however to date unambiguously the Amiranisgora extrusion time. The K–Ar ages for groundmass of two dacite varieties appeared to be very close: the pink dacite (Yug-2) is 2.7 ± 0.3 Ma old and the gray dacite (Yug-3) is 3.2 ± 0.2 Ma old. These dates approximate the age of the Chikiani rhyolite–perlite–obsidian extrusion. The biotite fraction of dacites yielded the much older K–Ar dates: 4.8 and 4.2 Ma for samples Yug-2 and Yug-3, respectively. It should be noted that the analyzed biotite fractions have anomalously low K content (4.8–5.4%) in spite of a high mineral purity (97–99%). The low K concentration (less than 6%) was also established for biotite fractions of the Kazbek Quaternary lavas [22]. As a rule, the K–Ar dating of these fractions yields ages older than those of the Kazbek lavas, and we doubted the biotite dates for the Amiranisgora Volcano. An attempt to date plagioclase from pink dacites failed, because phenocrysts of this mineral so saturated by atmospheric argon that the radiogenic increment cannot be diagnosed. The groundmass of pink dacites also revealed a considerable contamination by atmospheric argon (94% of the total content; Table 3). The abnormally high contamination of the Amiranisgora pink dacites by atmospheric argon may be a consequence of their specific formation, which caused the iron oxida-

Table 4. Rb-Sr isotopic ages of the samples from the Amiranisgora (Tavshan-Tapa) Volcano

Sample no.	Rock	Fraction	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr \pm 2\sigma$	$^{87}Sr/^{86}Sr \pm 2\sigma$
Yug-2	Pink dacite	Plagioclase	2.8	1620	0.00500 ± 0.00005	0.704094 ± 0.000015
		Amphibole	7	206	0.0960 ± 0.0007	0.704016 ± 0.000014
		Whole rock	70	585	0.3480 ± 0.0008	0.704062 ± 0.000015
		Groundmass	83	443	0.5418 ± 0.0013	0.704044 ± 0.000023
		Biotite	277	68	11.81 ± 0.03	0.704895 ± 0.000016
Yug-3	Gray dacite	Plagioclase	2.1	1667	0.00360 ± 0.00006	0.704122 ± 0.000015
		Amphibole	10	100	0.2859 ± 0.0008	0.704115 ± 0.000013
		Matrix	88	660	0.3888 ± 0.0010	0.704143 ± 0.000011
		Biotite	210	103	5.866 ± 0.023	0.705075 ± 0.000014

tion and appearance of abundant rock defects and micropores.

Almost all mineral components of the Amiranisgora dacites were dated by the Rb–Sr method (Table 4). Owing to presence of biotite, the mineral with high Rb/Sr ratio, we expected that the Rb–Sr dates may clarify significance of various groups of the K–Ar dates.

The Rb–Sr isotope analyses of different components and whole rock samples of the dacites (Yug-2 and Yug-3) showed that their Sr isotope composition is misbalanced. A similar phenomenon was reported for the Quaternary lavas of the Kazbek area and the Elbrus volcanic center of Greater Caucasus [28]. The initial $^{87}Sr/^{86}Sr$ ratio in plagioclases and whole-rock samples is more radiogenic than in the groundmass and amphiboles (Fig. 8). As for the biotite, the high content of radiogenic ^{87}Sr accumulated *in situ* “shades” to some extent the initial $^{87}Sr/^{86}Sr$ ratio in this mineral.

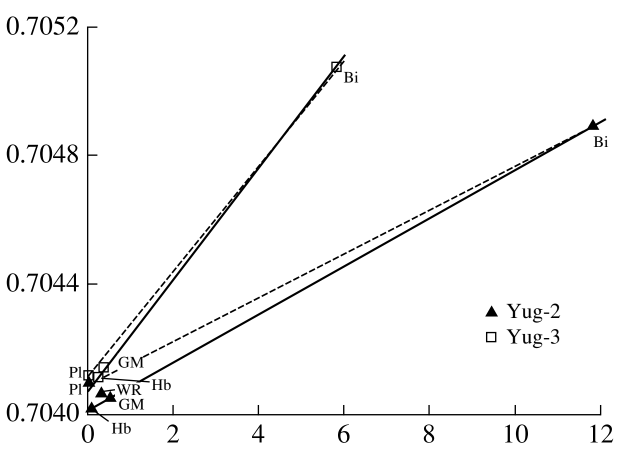

Fig. 8. Rb–Sr isochron diagrams for samples Yug-2 and Yug-3 (the Amiranisgora dacites). Sample Yug-2: Bi–GM–Hb isochron, age 5.3 ± 0.1 Ma, $I_0(Sr)$ = 0.704008 ± 0.000006, MSWD = 0.24; Bi–Pl isochron, age 4.78 ± 0.13 Ma, $I_0(Sr)$ = 0.704094 ± 0.000015. Sample Yu-3: Bi–GM–Hb isochron, age 12.0 ± 0.2 Ma, $I_0(Sr)$ = 0.704072 ± 0.000009, MSWD = 1.5; Bi–Pl isochron, age 11.4 ± 0.25 Ma, $I_0(Sr)$ = 0.704121 ± 0.000015 (Bi is biotite, GM groundmass, Hb amphibole, WR whole rock, Pl plagioclase).

Provided absence of the initial ^{87}Sr excess in biotite, the three-point isochron (biotite–groundmass–amphibole) for Sample Yug-2 corresponds to age of 5.3 ± 0.1 Ma. The $(^{87}Sr/^{86}Sr)_0$ value of 0.704008 ± 0.000006 calculated for biotite is lesser, in terms of minor measurement errors, than that established for the plagioclase. On the other hand, if assume equal $^{87}Sr/^{86}Sr$ initial ratios for biotite and plagioclase, then the biotite–plagioclase Rb–Sr age for Sample Yug-2 would be 4.78 ± 0.13 Ma. Assuming two possible values of the $^{87}Sr/^{86}Sr$ initial ratio in biotite, we can calculate the possible age range of 4.8–5.3 Ma for Sample Yug-2. The K–Ar biotite age of Yug-2 is close to this range and seems trustworthy. However, the same approach and calculations for Sample Yu-3 yielded the age range of 11.4–12.0 Ma that is completely unreal. Therefore, the Rb–Sr isochron ages, which actually characterize biotite, hardly correspond to the formation time of Amiranisgora dacites. The high Sr concentrations and, consequently, low $^{87}Sr/^{86}Sr$ ratios in biotite from both samples are to be noted. It was mentioned above that the Sr concentrations in all the dacites of the Dzhavakheti Upland greatly exceeded the clarke values.

The isotopic systems of mineral phenocrysts and groundmass in the dacites studied are unbalanced, as it is evident from the Sm–Nd parameters of plagioclase, amphibole, and groundmass (Sample Yug-2 Table 5). In the Amiranisgora dacites, amphibole is enriched in rare earth elements, whereas plagioclase is depleted. The Sm/Nd ratio expressed as $^{147}Sm/^{144}Nd$ isotopic ratio (0.06–0.16) varies significantly, and this is a consequence of rare earth elements fractionation during the dacitic magma crystallization.

Table 5 shows that amphibole and groundmass of dacite Yug-2 show similar Sm–Nd isotopic characteristics: $^{143}Nd/^{144}Nd$ = 0.51277–0.51281 (ϵ_{Nd} = 2.6–3.4), whereas the Nd isotopic parameters of plagioclase are shifted, like Sr concentrations, closer to the crustal values.

Table 5. Sm-Nd isotopic characteristics of phenocrysts and groundmass, Sample Yug-2 (the Amiranisgora pink dacite)

Sample	Nd, ppm	Sm, ppm	$^{147}Sm/^{144}Nd \pm 2\sigma$	$^{143}Nd/^{144}Nd \pm 2\sigma$	ϵ_{Nd}
Plagioclase	2.1	0.22	0.06480 ± 0.00006	0.51269 ± 0.00009	1.0
Groundmass	16	2.3	0.08590 ± 0.00002	0.512771 ± 0.000020	2.6
Amphibole	28	7.6	0.16310 ± 0.00006	0.512814 ± 0.000009	3.4

Thus, the geochronological data obtained show a complicated behavior of three isotopic systems (K–Ar, Rb–Sr, and Sm–Nd) in acidic volcanics. Therefore, the age of the Amiranisgora extrusive can be roughly estimated in the range of 3–5 Ma. There are two significantly different (with analytical errors taken into account) groups of dates falling into the intervals of 2.7–3.2 Ma (K–Ar ages for groundmass) and 4.2–5.3 Ma (K–Ar ages for biotite fractions and Rb–Sr ages for Sample Yug-2). The more precise dating of the Amiranisgora Volcano requires additional investigations. In our opinion, the K–Ar ages of groundmass are more reliable than those of biotite, because of the anomalous chemical composition of the latter (low K and Rb contents against high Sr concentration), the possible presence of excessive argon in biotite phenocrysts, as established previously, and unreliably old Rb–Sr age of biotite from Sample Yug-3. Most likely, the Amiranisgora dacites are 2.7–3.2 Ma old (late Pliocene). At that time, a weak impulse of magmatic activity in the Dzhavakheti Upland resulted in origin of some extrusive structures, e.g., of the Chikiani and Amiranisgora volcanoes composed of acidic and moderately acidic rocks of variable chemical composition. However, the older age of 4.2–5.0 Ma should not be excluded for the Amiranisgora extrusion, because the K–Ar isotope system in dacite groundmass might be disturbed, when it was subsequently heated by the Pliocene basaltic flows, resting on the volcano slopes. In this case, the dacite crystallization time is indicated by the K–Ar age of biotite, the isotopic system of which is more stable.

The Inyak-Dag Volcano

The basaltic andesite flow of the Inyak-Dag Volcano occupies a single hypsometric level within the Akhalkalaki Formation basalts. The K–Ar age (2.05 ± 0.10 Ma) of the basaltic andesite (Yug-123, Table 3) is close to that of the Akhalkalaki basalts (2.9–1.8 Ma, [14]). According to the chemical composition, geological position and age, the Inyak-Dag Volcano and its lava flows can be reliably referred to the plateau basalts (Akhalkalaki Formation) of the Dzhavakheti Upland

The Kir-Dag Volcano (Dzhavakheti Ridge)

The close K–Ar date (2.25 ± 0.1 Ma) was obtained for weakly porphyritic dacite flow of the Kir-Dag Volcano (Sample Yug-118, Table 4). The Kir-Dag Volcano is located on the eastern slope of the Dzhavakheti Ridge. The lava flow forms a low range between the Tsalka and Gomareti plateaus composed of the Akhalkalaki basalts. Its terminal part overlies the Khrami granitoid massif producing alterations at the contact. The dacitic lavas of the Dzhavakheti Ridge were previously considered as older than the plateau basalts ([11] and others). However, the dates obtained indicate that the Kir-Dag dacites are of the same age as the Akhalkalaki Formation basalts. We interpret the Dzhavakheti dacites, including the Kir-Dag rocks, as derivates of basaltic melts of deep-seated origin, or as products of magma mixing with old crustal material, e.g., with rocks of the Paleozoic Khrami massif exposed in the nearest proximity of the Kir-Dag Volcano. The Kir-Dag dacites were likely formed at the terminal stage of the Pliocene magmatic cycle in the Dzhavakheti volcanic area. The stage was characterized by volcanism of basaltic to basaltic andesite composition. The objects of interest for further isotopic-geochronological investigations are dacitic lavas of other volcanoes of the Dzhavakheti Ridge, which are supposed to be coeval with the Kir-Dag lavas.

Volcanoes of the Samsari Ridge

Unexpected results of K–Ar dating were obtained for seven samples (Yug-66, Yug-67, Yug-68, Yug-69, Yug-72, Yug-75, Yug-76) of amphibole–plagioclase dacites from Didi-Abuli, Samsari, and Shavnabada volcanoes of the Samsari Ridge. As noted above, rocks of these volcanoes were considered as members of the Mio-Pliocene Goderdzi Formation buried under basalts of the Akhalkalaki Formation. However, the dates obtained indicate with confidence the Late Quaternary age of dacitic lavas from the Samsari Ridge. The dates for groundmass of the studied samples vary in a narrow range from 180 to 320 ka (Table 3). Probably, the K–Ar ages would be even in a narrower range, if the rocks were not so strongly contaminated by atmospheric argon (96–99% of the bulk argon). This prevents the radiogenic argon to be more precisely determined and, as a consequence, we obtain the increased range of the K–Ar dates.

Interestingly, the age of pyroclastic rocks of the large Samsari caldera (Yug-72, 0.20 ± 0.04 Ma) is identical to that of the dacitic lavas forming the volcano itself (0.18–0.24 Ma). This is compatible with a gradual transition between the pyroclastic facies and dacitic lavas [11]. In addition, gray and pink varieties of the Samsari dacitic lavas yield similar dates being almost

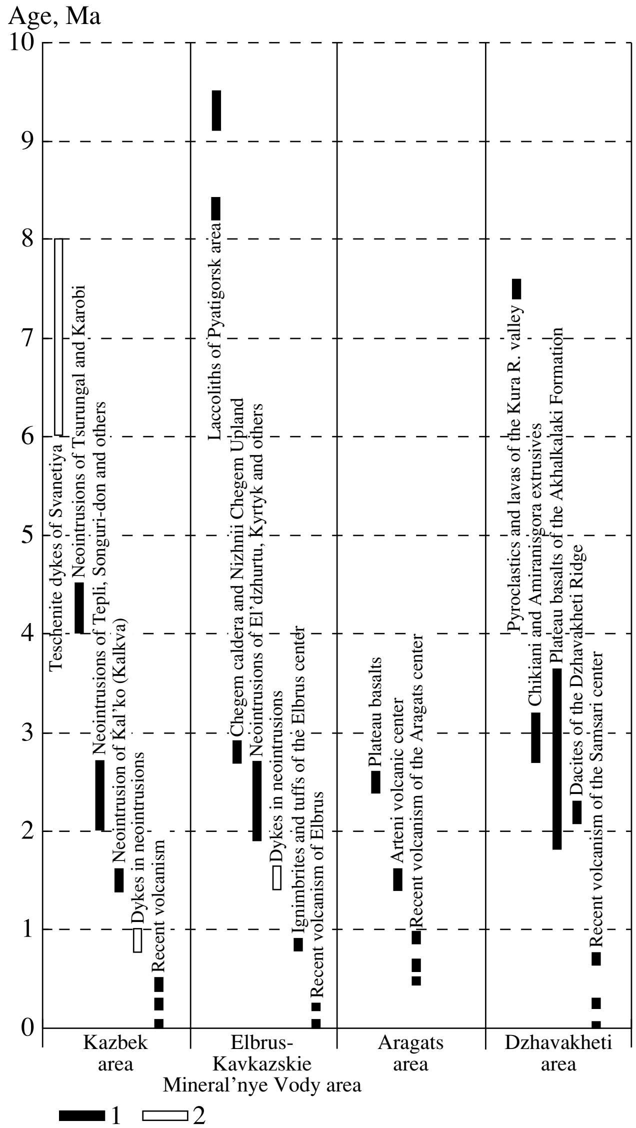

Fig. 9. Geochronology of the Neogene–Quaternary magmatism in some regions of the Caucasian segment of the Alpine belt (this work and data of Arakelyants *et al.* [6]; Borsuk *et al.* [5]; Hess *et al.* [7]; Kostitsyn and Kremenetskii [34]; Ferring *et al.* [14]; and Chernyshev *et al.* [1]): (1) proved and (2) supposed (single dates) stages and phases of magmatic activity (column lengths correspond to stage durations).

equally saturated by atmospheric argon. In distinction, the pink lavas of the Kazbek area appeared unsuitable for the K–Ar dating, as they are contaminated by atmospheric argon to the much greater extent. The Quaternary age of the Samsari volcanoes is also evident from paleomagnetic records studied by Stankevich [19], which are similar to those in recent lavas of the Kazbek area and Elbrus center [29]. The Samsari volcanic structures are weakly eroded, and there are even crater remnants at some mountaintops (e.g., at the Didi-Abuli top). As mentioned above, the assignment of the Samsari volcanics to the Mio-Pliocene Goderdzi Formation [11] was previously doubted by Milanovskii and Koronovskii [4] and by other authors. Nevertheless, the idea of Skhirtladze [11] was commonly accepted after discussion.

In distinction from the Dzhavakheti Ridge predominantly composed of Pliocene basaltic lavas, among which local acidic eruptions took place about 3–2 Ma ago (the Chikiani, Kir-Dag and other volcanoes), volcanoes of the Samsari Ridge originated, according to K–Ar dates, at the final, Quaternary stage of magmatism in the Lesser Caucasus. Thus, it is evident that submeridional deep-seated faults, to which the Dzhavakheti and Abul-Samsari ridges are confined, became activated in different times.

Hyalodacites of the Kechut Formation

The K–Ar dating of hyalodacite (Sample Yug-63) from lava flow of the Godorebi Volcano that is referred to the so-called Kechut Formation implies the late Neopleistocene and even Holocene age (30 ± 30 ka) of this structure. As noted above, the extremely young age of hyalodacites is evidenced by many geomorphological features. These lavas usually erupted from parasitic fissures like those on slopes of the Samsari Ridge volcanoes and less frequently from the main crater, e.g., in the Tavkvetili Volcano in the northern part of the Samsari Ridge. It seems rational to apply other methods (e.g., of radiocarbon dating) in addition to K–Ar age determinations in order to get a deeper insight into the latest stage of volcanism in the Dzhavakheti area. The radiocarbon dating is applicable for fossil remains, which document breaks between lava eruptions and may be found.

The Babakhngo Volcano ("Western Range" of the Samsari Ridge)

The K–Ar dating of dacite (Yug-73, Table 4) from the Babakhngo Mountain yielded an interesting result. This volcanic structure is an element of a low mountain range stretching along the western slopes of the Samsari Ridge and locally separated from it by intermontane depressions, where villages of Samsari, Olaverdi, Buzabeti, Abuli and others are located. The range restricts distribution of basalts of the Akhalkalaki Formation within the synonymous plateau (Fig. 1) and probably is associated with the submeridional fault zone. The K–Ar date of 0.76 ± 0.08 Ma for the dacite groundmass corresponds to the Eopleistocene–Neopleistocene boundary time. The date is the only one and needs to be verified after additional analysis of rocks from the "western range." It is noteworthy that this phase of volcanism (0.76 ± 0.08 Ma) in the Dzhavakheti area, which was caused probably by activation of submeridional fault under the range, is correlative with the activity impuls in the adjacent Aragats area about 700 ka ago [16]. According to our data, the Aragats Volcano originated at the same time.

Phases of the Quaternary Volcanism of the Dzhavakheti Area

Thus, the K–Ar dating of dacitic lavas of the Samsari Ridge indicates their Late Quaternary age. The revealed three phases of volcanism took place in the early Neopleistocene (800–700 ka), middle Neopleistocene (300–200 ka), and late Neopleistocene–Holocene (younger than 50 ka). The last two phases coincide with periods of volcanic activity in the Kazbek area and Elbrus center of Greater Caucasus [8]. The coincidence suggests synchronism of recent volcanic manifestations and interrelation between volcanic impulses in the Greater and Lesser Caucasus. However, in the Aragats area bordering the Dzhavakheti area in the south, the volcanic activity terminated about 450 ka ago [16]. On the contrary, some active volcanoes of the eastern Anatolia (e.g., the Nemrut cone) erupted in the historic time. Consequently, the Quaternary volcanism in the Lesser Caucasus led central eruptions, and the irregular volcanic impulses were of variable intensity in different volcanic areas.

According to the results obtained, the Samsari Ridge is a young volcanic center, and it was incorrect to attribute dacitic lavas and pyroclastic rocks of the ridge to the upper Miocene Goderdzi Formation. Nevertheless, the Goderdzi Formation rocks may be locally exposed within the Samsari Ridge, since even Paleogene deposits crop out here in some erosion windows. Additional investigations of the Dzhavakheti area are needed to detect here rocks of that formation and to determine the easternmost distribution limit of the Goderdzi pyroclastic rocks.

The problem of independent Kechut Formation composed of hyalodacite lavas appears to be a separate object of discussion on the Samsari Ridge geology. It seems reasonable to distinguish a single Late Quaternary volcanic complex of the Samsari Ridge, which is composed of two-pyroxene–amphibole–plagioclase dacitic lavas (Phase I of volcanic activity), amphibole–plagioclase dacitic lavas (Phase II), and the hyalodacite lavas (Phase III).

The dates obtained and geomorphological manifestations of the recent, possibly Holocene volcanism imply that the central part of the Dzhavakheti Upland is an area of potential seismic hazard. The further works should be oriented toward the comprehensive isotopic-geochronological study of the Late Quaternary volcanism in the Samsari Ridge in order to understand the periodicity of eruptions and the variations in volume and composition of erupted material during the volcanism evolution. This study will be of a great prognostic importance for the entire Caucasian region.

The K–Ar Isotopic Systematics for Plagioclase Phenocrysts of the Samsari Ridge Quaternary Lavas

Studying the Quaternary dacitic lavas of the Samsari Ridge, we continued our work on the K–Ar isotope systematics for phenocrysts in young volcanic rocks, which are usable for isotopic dating. The K–Ar isotopic ages were determined for groundmass and plagioclase phenocrysts of three samples (Yug-67, Yug-76, and Yug-73; Table 4). The plagioclase dates are of a wider range (from 1.2 to 8.2 Ma) and much older than the groundmass dates, which more reliably define the formation time of dacitic lavas. Similar results were formerly published [8] for volcanic rocks of the Kazbek area and Elbrus center, which yielded the essentially older K–Ar dates plagioclase phenocrysts in the late Neopleistocene lavas (1.5 Ma) and Eopleistocene ignimbrites (15 Ma). Along with the radiogenic argon excess, plagioclase phenocrysts of all studied volcanics from the Greater Caucasus contain abnormally high concentration of radiogenic ^{87}Sr, as compared with the other rock fractions [28]. The same is typical of the Pliocene dacites of the Amiranisrora Volcano. In discussion on possible causes of this phenomenon, there were mentioned the occurrence of plagioclase xenocrysts [30], the excessive argon capture during phenocryst crystallization [23], and some other factors [28]. In our opinion, the argon excess in phenocrysts may be produced by the following mechanism. Being heated by melts, rocks surrounding intermediate magmatic chambers lose a considerable amount of radiogenic argon. The argon partial pressure increased in the magmatic fluid phase may result in both the argon saturation in the liquid phase and the argon capturing by phenocrysts during their crystallization. After eruption, the degassing magma loses the argon excess, whereas mineral phenocrysts retain a part of it. If this hypothesis is correct, the argon excess in phenocrysts should be dependent to the great extent on composition and age of the host rocks. In addition, different mineral phases are likely able to capture variable amounts of excessive argon at high temperatures. For example, analysis of the Elbrus volcanics showed that the ^{40}Ar excess in clinopyroxene is only 0.02 ppb against 0.86 ppb in plagioclase with a higher K content [31].

Thus, summarizing the available data on the K–Ar isotope systematics for plagioclase phenocrysts in the young Caucasian volcanics, we should conclude that this mineral is unsuitable for isotope dating of most Neogene–Quaternary volcanic rocks.

CONCLUSION

The isotopic-geochronological investigations of moderately acidic Neogene–Quaternary magmatic rocks from the Dzhavakheti area of the Lesser Caucasus showed that one more area of young volcanism in the Caucasian segment of Eurasia, namely the Samsari volcanic center, is of the Late Quaternary, but not of the early Pliocene age, as it was formerly assumed. The K–Ar dates outline three discrete phases of volcanic activity in the study region: the formation of "western range" volcanoes (800–700 ka), the origin of Samsari caldera and other volcanoes in the main ridge (300–

200 ka), and the formation of parasitic volcanoes and hyalodacite lava flows (earlier than 50 ka). The dates obtained evidence for the volcanic activity in the Samsari Ridge until the late Neopleistocene and possibly Holocene. Accordingly, this part of the Dzhavakheti area is potentially hazardous one.

The isotopic-geochronological and petrochemical characteristics of the studied dacitic lavas from the Dzhavakheti Upland imply that the Mio-Pliocene Goderdzi Formation in its former scope is invalid. The late Miocene volcanics (7–8 Ma old) of the Dzhavakheti Upland are represented only by pyroclastic units with intraformational dacitic flows, which constitute the lower parts of exposures in the Kura and Paravani river valleys. The extrusive domes of the Chikiani and Amiranisgora volcanoes composed of subalkaline obsidians and biotite–amphibole dacites were formed in the Pliocene time. Dacitic lavas of the Dzhavakheti Ridge erupted in the late Pliocene, simultaneously with plateau basalts widespread in the Transcaucasia. The Samsari volcanic center appeared at the final, Neopleistocene stage of volcanism and was active until the late Neopleistocene–Holocene time.

Thus, the total duration of Neogene–Quaternary magmatic activity in the Dzhavakheti Upland was about 7 to 8 m.y. All the dacitic volcanics, regardless their ages, belong to the calc-alkaline series with moderate potassium content. Some stages and phases of volcanic activity in the Dzhavakheti Upland are well correlative with concurrent events in adjacent volcanic areas of the Greater and Lesser Caucasus [31, 32] (Fig. 9).

ACKNOWLEDGMENTS

We are grateful to E.D. Bairova, V.N. Nikishina, A.I. Yakusheva, and T.M. Marchenko for their assistance in analytical work. The work was supported by the Russian Foundation for Basic Research, projects nos. 01-05-64082 and 02-05-06479mac and by the Ministry of Industry, Sciences, and Technology of the Russian Federation as a part of the Federal Central Scientific and Technical Programs (project 1.2.5 of the Program “Global environmental and climatic changes”).

Reviewers N.V. Koronovskii and E.V. Bibikova

REFERENCES

1. I. V. Chernyshev, M. M. Arakelyants, V. A. Lebedev, and S. N. Bubnov, Dokl. Ross. Akad. Nauk **367**, No. 6, 810 (1999) [Proc. Russ. Acad. Sci. **367**, No. 6, 810 (1999)]; I. V. Chernyshev, V. A. Lebedev, M. M. Arakelyants, *et al.*, Dokl. Russ. Akad. Nauk **384**, No. 1, 95 (2001) [Proc. Russ. Acad. Sci. **384**, No. 1, 95 (2001)]; I. V. Chernyshev, V. A. Lebedev, S. N. Bubnov, *et al.*, Dokl. Russ. Akad. Nauk **380**, No. 3, 384 (2002) [Proc. Ross. Acad. Sci. **380**, No. 3, 384 (2002)]; Geokhimiya, No. 11, 1 (2002) [Geochemistry, No. 11, 1 (2002)].
2. N. V. Koronovskii and L. I. Demina, Geotektonika, No. 2, 17 (1999) [Geotectonics, No. 2, 17 (1999)].
3. G. M. Zaridze, Soobshch. Akad. Nauk GrSSR, **5**, No. 9, 885 (1944).
4. E. E. Milanovskii and N. V. Koronovskii, *Orogenic Volcanism and Tectonics of the Alpine Foldbelt in Eurasia* (Nedra, Moscow, 1973) [in Russian].
5. A. M. Borsuk, V. V. Ivanenko, M. I. Karpenko, and I. V. Chernyshev, Dokl. Akad. Nauk SSSR **308**, No. 5, 1188 (1989) [Proc. USSR Acad. Sci. **308**, No. 5, 1188 (1989)].
6. M. M. Arakelyants, A. M. Borsuk, and L. L. Shanin, Dokl. Akad. Nauk SSSR **182**, No. 5, 1157 (1968) [Proc. USSR Acad. Sci. **182**, No. 5 (1968)].
7. J. C. Hess, H. J. Lippolt, A. G. Gurbanov, and I. Michalski, Earth Planet. Sci. Lett. **117**, Nos. 3/4, 393 (1993); Yu. A. Kostitsyn and A. A. Kremenetskii, Geokhimiya, No. 7, 925 (1995).
8. I. V. Chernyshev, M. M. Arakelyants, V. A. Lebedev, and S. N. Bubnov, Dokl. Ross. Akad. Nauk **367**, No. 6, 810 (1999) [Proc. Russ. Acad. Sci. **367**, No. 6, 810 (2001)]; I. V. Chernyshev, V. A. Lebedev, M. M. Arakelyants, *et al.*, Dokl. Russ. Akad. Nauk **384**, No. 1, 95 (2001) [Proc. Russ. Acad. Sci. **384**, No. 1, 95 (2001)];
9. A. A. Burchuladze, Ch. G. Dzhanelidze, and G. I. Togonidze, in *Actual Problems of Current Geochronology* (Nauka, Moscow, 1976), pp. 238–243 [in Russian]; O. A. Bogatikov, I. V. Melekestsev, A. G. Gurbanov, *et al.*, Dokl. Ross. Akad. Nauk **363**, No. 2, 219 (1998) [Proc. Ross. Acad. Sci. **363**, No. 2, 219 (1998)]; I. V. Chernyshev, V. A. Lebedev, S. N. Bubnov, *et al.*, Geokhimiya, No. 11, 1 (2002) [Geochemistry, No. 11, 1 (2002)].
10. B. D. Tutberidze, Doctoral Dissertation in Geology and Mineralogy (Tbilisi, 1993).
11. N. N. Skhirtladze, *Post-Paleogene Eruptive Volcanism of Georgia* (Akad. Nauk GruzSSR, Tbilisi, 1958) [in Russian].
12. G. M. Maisuradze and S. I. Kuloshvili, in *Problems of Geology and Petrology, Nov. Ser.* (Geol. Inst., Tbilisi, 1999), pp. 220–228 [in Russian].
13. D. G. Dzhigauri, in *Georgia of the Anthropogene Time* (Sakartvelo, Tbilisi, 1991), pp. 91–125 [in Russian].
14. C. Ferring, C. Swisher, G. Bosinski, *et al.*, in *Progress Report on the Geology of the Plio-Pleistocene Dmanisi and the Diliska Gorge, Republic of Georgia* (Paleoanthropol. Soc., New Orleans, 1996), pp. 5–6.
15. P. Camps, P. Ruffer, V. Shcherbakova, *et al.*, Phys. Earth. Planet. Inter. **96**, 41 (1996).
16. I. V. Chernyshev, V. A. Lebedev, S. N. Bubnov, *et al.*, Dokl. Russ. Akad. Nauk **380**, No. 3, 384 (2002) [Proc. Ross. Acad. Sci. **380**, No. 3, 384 (2002)].
17. P. Camps, P. Ruffer, V. Shcherbakova, *et al.*, Phys. Earth. Planet. Inter. **96**, 41 (1996); A. T. Goguitchaichvili, D. Z. Sologachvili, M. Prevot, *et al.*, Geol. Mijnbow **76**, 135 (1997).
18. M. M. Rubinshtein, Sh. A. Adamiya, D. I. Devnozashvili, *et al.*, Izv. Akad. Nauk SSSR, Ser. Geol., No. 4, 13 (1972) [Trans. USSR Acad. Sci., No. 4, 13 (1972)].

19. E. K. Stankevich, *Recent Magmatism of the Greater Caucasus* (Nedra, Leningrad, 1976) [in Russian].

20. A. N. Komarov, N. V. Skovorodin, and S. G. Karapetyan, Geokhimiya, No. 6, 693 (1972) [Geochemistry Intern., No. 6, 693 (1972)].

21. *Classification of Magmatic (Eruptive) Rocks and Terminology* (Nedra, Moscow, 1997) [in Russian].

22. I. V. Chernyshev, M. M. Arakelyants, V. A. Lebedev, and S. N. Bubnov, Dokl. Ross. Akad. Nauk **367**, No. 6, 810 (1999) [Proc. Russ. Acad. Sci. **367**, No. 6, 810 (1999)];

23. A. Matsumoto and T. Kobayashi, Chem. Geol. **125**, 123 (1995); P. R. Renne, W. D. Sharp, A. L. Deino, *et al.*, Science **277**, 1279 (1997); B. S. Singer, J. R. Wijbrans, S. T. Nelson, *et al.*, Geology **26**, No. 5, 427 (1998).

24. R. H. Steiger and E. Jager, Earth Planet. Sci. Lett. **36**, 359 (1977).

25. O. Z. Dudauri, M. G. Togonidze, and E.N. Bartnitskii, Soobshch. Akad. Nauk Gruzii **134**, No. 1, 137 (1989).

26. V.N. Volkov, M.M. Arakelyants, and Yu.G. Pupyrev, Izv. Akad. Nauk SSSR, Ser. Geol. No. 6, 3 (1985) [Trans. USSR Acad. Sci. Ser. Geol., No. 6, 3 (1985)].

27. C. Ferring, C. Swisher, G. Bosinski, *et al.*, in *Progress Report on the Geology of the Plio-Pleistocene Dmanisi and the Diliska Gorge, Republic of Georgia* (Paleoanthropol. Soc., New Orleans, 1996), pp. 5–6; P. Camps, P. Ruffer, V. Shcherbakova, *et al.*, Phys. Earth. Planet. Inter. **96**, 41 (1996).

28. S. N. Bubnov, I. S. Krasivskaya, A.K. Simon, *et al*., in *Proceedings of XXXII Tectonic Conference: "Tectonics, Geodynamics, and Processes of Magmatism and Metamorphism"* (GEOS, Moscow, 1999), pp. 106–108 [in Russian].

29. N. M. Dzotsenidze, *Thematic Report: "Geological and Paleomagnetic Study of Lava Accumulations in the Kazbegi Area of the Greater Caucasus"* (KIMS, Tbilisi 1985) [in Russian]; E. K. Stankevich, *Recent Magmatism of the Greater Caucasus* (Nedra, Leningrad, 1976) [in Russian].

30. B. S. Singer, J. R. Wijbrans, S. T., Nelson, *et al.*, Geology **26**, No. 5, 427 (1998).

31. I. V. Chernyshev, V. A. Lebedev, M. M. Arakelyants, *et al.*, Dokl. Russ. Akad. Nauk **384**, No. 1, 95 (2001) [Proc. Russ. Acad. Sci. **384**, No. 1, 95 (2001)].

32. M. M. Arakelyants, A. M. Borsuk, and L. L. Shanin, Dokl. Akad. Nauk SSSR **182**, No. 5, 1157 (1968) [Proc. USSR Acad. Sci. **182**, No. 5, 1157 (1968)]; I. V. Chernyshev, M. M. Arakelyants, V. A. Lebedev, and S. N. Bubnov, Dokl. Ross. Akad. Nauk **367**, No. 6, 810 (1999) [Proc. Russ. Acad. Sci. **367**, No. 6, 810 (1999)]; I. V. Chernyshev, V. A. Lebedev, S. N. Bubnov, *et al.*, Dokl. Russ. Akad. Nauk **380**, No. 3, 384 (2002) [Proc. Ross. Acad. Sci. **380**, No. 3, 384 (2002)].

33. N. M. Dzotsenidze and S. M. Kuloshvili, *Thematic Report: "Seismotectonic Structure of the Central Part of the Artvin–Bolnissi Block (Dzhavakheti Upland) when Searching for Earthquake Precursors"* (Geol. Inst., Tbilisi, 1975) [in Russian].

34. Yu. A. Kostitsyn and A. A. Kremenetskii, Geokhimiya, No. 7, 925 (1995).