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# Geochronology and Genesis of Subalkaline Basaltic Lava Rivers at the Dzhavakheti Highland, Lesser Caucasus: K–Ar and Sr–Nd Isotopic Data

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**Abstract**—The paper reports newly obtained K–Ar isotopic–geochronological data on the age of three lava flows (Khrami, Mashavera, and Kura), which begin at the Dzhavakheti volcanic highland in southern Georgia. All of the dated rocks, including those from the Kura Flow, which was previously considered as the Pleistocene, are demonstrated to have a Pliocene age. The lavas of the longest Khrami Flow were erupted at 3.25–3.10 Ma, and those of the Kura and Mashavera Flows at 2.20–2.05 Ma, a fact testifying to two pulses of volcanic activity at the Dzhavakheti Highland. The petrogeochemical and isotopic characteristics of the rocks ($^{87}Sr/^{86}Sr$ = 0.7039–0.7042; $\epsilon_{Nd}$ = 3.4–5.1) indicate that they are subalkaline within-plate basalts formed by the fractional crystallization of a basic mantle melt with the usually discontinuous selective or rarely continuous contamination with material that was not in geochemical equilibrium with the melt. The volcanics of the Khrami Flow are characterized by the less radiogenic Sr isotopic composition and the highest $\epsilon_{Nd}$ values, while the younger rocks of the Mashavera and Kura Flows have similar and more "crustal" isotopic signatures. The $^{87}Sr/^{86}Sr$ ratios of the Dzhavakheti subalkaline basalts are close to the initial Sr isotopic ratios of the Quaternary and Middle Pliocene dacite lavas from the same territory. Considered together with petrogeochemical and geological data, this suggests that all young rocks in Southern Georgia were produced in similar tectonic and geodynamic environments.

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## INTRODUCTION

This paper is a part of our systematic study of the geochronology and isotopic geochemistry of young magmatism in the Caucasus and is devoted to the dating of basaltic lava rivers of the Dzhavakheti neovolcanic area (highland), a volcanic area in the Lesser Caucasus in Georgia, Armenia and Turkey with widespread Neogene–Quaternary volcanic rocks of various composition and age.

The origin of basaltic lava rivers in valleys is a process typical of volcanic areas with active basic volcanism. The high temperature, low viscosity, and, as a consequence, high mobility of basaltic melts result in the spread of their lava flows for significant distances (from a few dozen to hundreds of kilometers) from the eruption centers. A well-developed hydrographic system is favorable for the spreading of lava flows for significant distances along river valleys. For example, in eastern Tuva (in the upper reaches of the Yenisei River) and southern Transbaikalia (in the basin of the Dzhida River), Neogene–Quaternary lava plateaus gave rise to large lava rivers as long as 200 km (for example, along the Malyi Yenisei River valley) [1].

The Dzhavakheti Highland is the only area in the Caucasus where basic Neogene volcanics form lava rivers. In contrast to basic volcanic rocks composing plateaus at the Dzhavakheti Highland, lava rivers in the highland are cut through all of their thicknesses by modern river valleys. This provides the opportunity of studying, in much detail, the vertical sections of the lava flows, which sometimes reach a few hundred meters in thickness. Isotopic–geochronological data obtained on the basaltic rivers are crucial for reproducing the evolutionary history of basic volcanism in the Lesser Caucasus, studying the lateral migration of eruption centers with time, and identifying the compositional trends of the melts.

According to the currently most popular viewpoint, active Neogene–Quaternary magmatism in the Caucasus is late collisional [2] and began in the Middle-Miocene, when the Caucasus segment of the Alpine Foldbelt was affected by the "rigid" collision of the Arabian and Eurasian lithospheric plates, and continued utill the Holocene inclusive. Geochronological dates obtained during the past decades constrained the ages of three stages of young magmatism in the Caucasus: (i) Late Miocene (9–5 Ma), (ii) Pliocene (4–2 Ma), and (iii) Anthropozoic (<1.5 Ma) [3–6 and others]. The first stage was clearly manifested in the Lesser Caucasus, whereas the magmatic rocks of the second stage are widespread throughout the whole Caucasian region. The final, Quaternary stage formed such large stratovolcanoes as Elbrus, Kazbek, and Ararat.

The products of the Neogene–Quaternary magmatism in the Caucasus are characterized by a broad spectrum of compositions, ranging from olivine basalt to rhyolite and mantle obsidian. Basic volcanic rocks in the Greater Caucasus are relatively scarce but are widely known in the Lesser Caucasus and belong to the Pliocene and, to a lesser degree, Anthropozoic episodes. As is well known, volcanic rocks in areas with typical collision-related magmatism (such as the Himalayas) are dominated by acid volcanics. Certain features of young volcanism in the Caucasus suggest that, starting in the Miocene, the region was characterized by a complicated combination of continental collision and initial rifting [7] or the within-plate environment of a mantle hot field [8].

Magmatic rocks in the Lesser and Greater Caucasus are still unequally characterized by geochronological data. In spite of some uncertain issues, the Greater Caucasus is represented by numerous isotopic dates, which constrain the overall time span of regional magmatism and its discrete stages and phases [3–5, 9, and others]. In the Lesser Caucasus, where Neogene–Quaternary volcanics are spread extremely widely (from Adjaria to Nagornyi Karabakh), the absence of systematic studies resulted in several problems with the dating of these rocks. Although numerous publications were devoted to various aspects of young volcanism in the Lesser Caucasus, the isotopic dates quoted in them are very scarce and often preliminary and insufficient to construct consistent detailed geochronological charts and to conduct evolutionary reconstructions.

During the first phase of our research, which was devoted to the complex geochronological and isotopic–geochemical study of Neogene–Quaternary magmatic rocks in the Lesser Caucasus [6, 10, 11], we dated the volcanic rocks of Late Quaternary volcanoes in the Aragats and Dzhavakheti areas. In the latter, for example, the volcanoes of the Samsari Range that erupted dacite lavas, which were previously thought to be Neogene, were dated at the Quaternary. In this paper we discuss the results of our isotopic–geochronological study of basaltic lava rivers in the Georgian part of the Dzhavakheti Highland.

## GEOLOGICAL OVERVIEW OF THE DZHAVAKHETI VOLCANIC AREA

The Dzhavakheti volcanic area (Fig. 1) in the central part of the Lesser Caucasus is now assumed to be bounded by the Gektap (Egnakhag), Shirak, and Bazumi ranges in the south, the upper reaches of the Kura River in the west, and the Trialeti Range, which is composed of Paleogene volcanic–sedimentary rocks, in the north. The eastern boundary of the young volcanics roughly coincides with the Tsalka–Gomareti–Dmanisi–Stepanavan line, except for three large basic lava flows, which descend outside this contour along the Mashavera, Khrami, and Debed river valleys for a few dozen kilometers.

Orographically, the Dzhavakheti Highland is a medium- to high-elevation mountainous area with maximum elevations of approximately 3300 m (mounts Didi-Abuli and Samsari in the Samsari Range) and is characterized by alternating plateaus and intermontane valleys and volcanic ranges with separated central volcanoes and volcanic domes.

The basement of the Dzhavakheti area consists of Cretaceous and Paleogene volcanic–sedimentary rocks, which are exposed in isolated erosion windows widespread in the area. In the east, the Khrami River valley cuts through the Khrami Massif of Paleozoic granitoids. Almost everywhere in the area, the basement rocks are overlain by Neogene–Quaternary volcanics up to a few hundred meters thick.

The initial phase of Late Cenozoic volcanism at the Dzhavakheti Highland produced the Late Miocene Goderdzi Formation, which is dominated by pyroclastic rocks with subordinate amounts of lavas of andesite–dacite composition. The classic cross section of the Goderdzi Formation are exposed outside the Dzhavakheti Highland, in the Erusheti–Arsiani and Kars areas. The Mio-Pliocene age of the Goderdzi Formation in the Erusheti–Arsiani area was proposed based on stratigraphic evidence and on results obtained on floristic remnants [12]. Within the Dzhavakheti area, the Goderdzi Formation includes pyroclastic rocks and andesitic lava flows cropping out in the valleys of the Kura River and the Paravani River, its right-hand tributary, where these rocks are overlain by basalts of the Akhalkalaki Formation. Our recently obtained geochronological data [11] testify that the volcanics of the Gordezi Formation were erupted within the time span of 8–7 Ma.

The peak of volcanic activity at the Dzhavakheti Highland corresponded to the Middle–Late Pliocene and was related to the formation of volcanic fields of basic composition, whose material is combined within the scope of the Akhalkalaki Formation [13]. Olivine basalt and basaltic andesite flows practically leveled off the ancient topography and formed extensive lava plateaus: Akhalkalaki, Tsalka, Gomareti, and others. The valleys of large rivers (Kura, Paravani, and Khrami) cut the volcanic rocks of the Akhalkalaki Formation throughout their whole thicknesses, which locally reach 300 m, and expose the vertical sections of up to twenty (and locally even more) alternating lava units. Rocks in many exposures show inversions of their magnetic polarity. Near Akhalkalaki and at some other sites

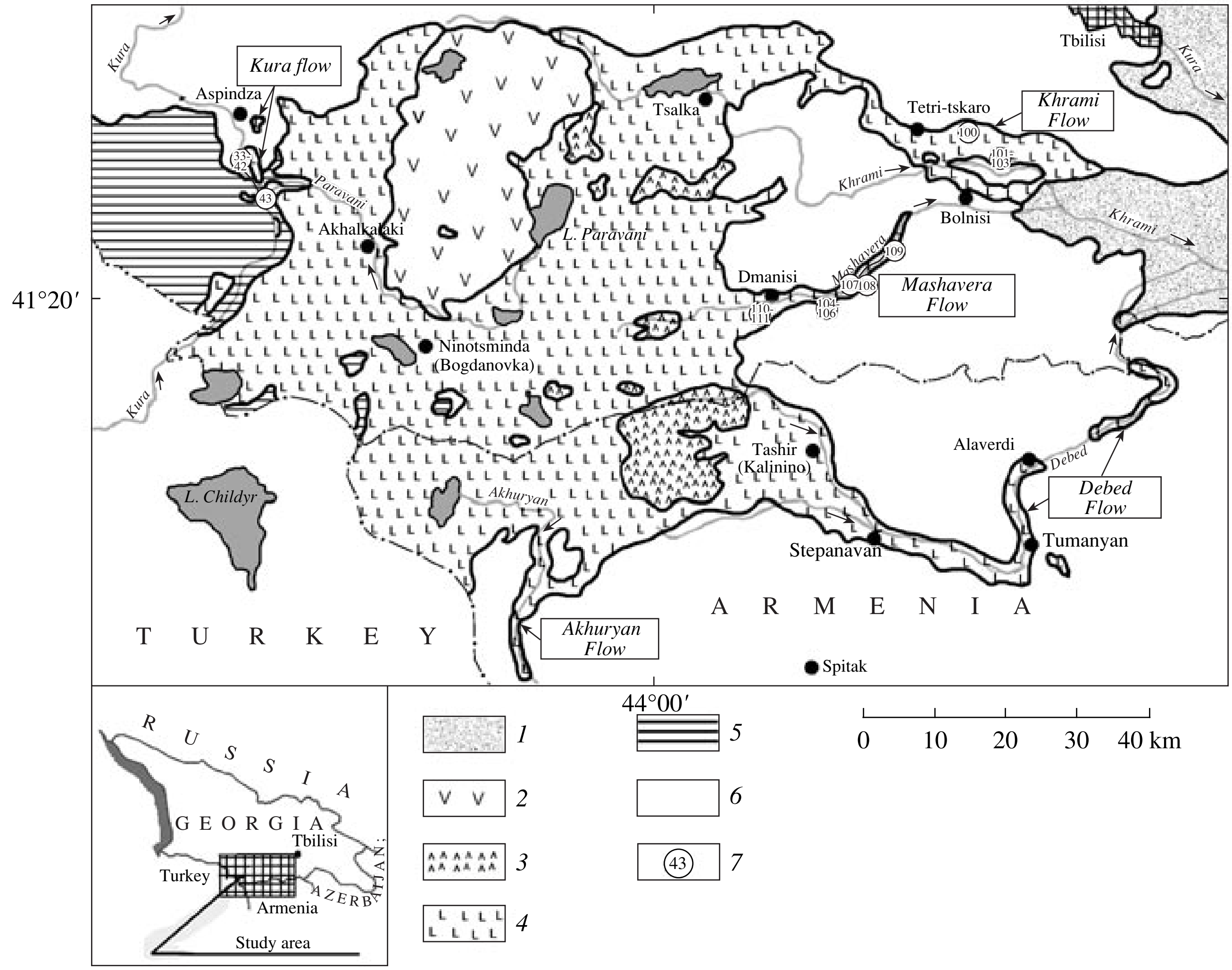

**Fig. 1.** Schematic geological map of the Dzhavakheti neovolcanic area (prepared with the use of the large-scale geological maps and materials of V.A. Lebedev). (*1*) Quaternary sedimentary deposits; (*2*) Late Quaternary dacite volcanics of the Samsari Range; (*3*) Pliocene andesite, dacite, and rhyolite of the Dzhavakheti Range; (*4*) Pliocene volcanic rocks of the Akhalkalaki Formation (basalt, subalkaline basalt, basaltic andesite, and andesite); (*5*) Late Miocene volcanics of the Goderdzi Formation (andesite and dacite); (*6*) pre-Neogene magmatic and sedimentary rocks; (*7*) sampling sites and their numbers.

with exposures of the middle part of the Akhalkalaki Formation, the latter contains a unit of lacustrine deposits with faunal remnants, which makes it possible to reliably date the basalts at the Late Pliocene–EoPleistocene [14].

The character of the volcanic activity, the local geomorphology, and significant volumes of erupted material at the high mobility of basic magmas were favorable for the origin of lava rivers up to tens of kilometers long and up to tens of meters thick (sometimes up to a few hundred meters thick) in integral thickness along the valleys of the Kura, Khrami, Mashavera, Debed, and Akhuryan rivers. Our research was centered mostly on studying the lava rivers in the Kura, Khrami, and Mashavera valleys that extend across the Georgian part of the Dzhavakheti Highland.

The longest lava river in this region, which is referred to as the Khrami Flow in the literature [13], begins near Tsalka town and extends for more than 60 km, fills the ancient valley of the Khrami River, and ends near its modern mouth. The lava river reaches its greatest width (close to 10 km) near the town of Bolnisi. Now the bottom of the flow in its upper and middle parts occurs at elevations of a few hundred meters above the modern Khrami riverbed. The tail of the flow is mapped as separated lava remnants and blocks beneath the sedimentary deposits of the Kura depression. The Khrami Flow has its maximum thickness (>100 m) in its upper reaches, where it comprises more than ten lava units, whereas its middle part (near town Tetri-tskaro) consists only of three lava units of total thickness of a few dozen meters.

The second longest lava river in the area is the so-called Mashavera Flow [12], which is 35–40 km long. It begins in the eastern slope of the Dzhavakheti Range and then fills the ancient valley of the Mashavera River between Dmanisi and Bolnisi. In contrast to the Khrami Flow, the Mashavera Flow is relatively narrow (<2 km) but has an almost unchanging thickness of >100 m virtually throughout the whole of its length. Geomorphologically, it is usually divided into three terraces, with the uppermost one exposed in the slopes of the Dzhavakheti Range, the middle one occurring at the level of the town of Dmanisi (Dmanisi Plateau), and the lower one composing a valley lava river in the strict sense of this term. The bottom of the Mashavera Flow in its middle part occurs only a few dozen meters above the modern level of the Mashavera River. In the vicinity of Dmanisi, the lava flow is cut throughout its entire thickness by the Mashavera River and its right-hand tributary Pinazeuri.

The shortest (no more than 15 km), but the thickest, (a few hundred meters) lava river in the area is referred to as the Kura Flow and fills the ancient valley of the Kura River from the mouth of the Paravani River to town Aspindza and the village of Rustavi. Its width does not exceed 2 km. The flow rests on a Paleogene sedimentary sequence and is exposed within only a few dozen meters above the modern flow line of the Kura River.

The lava rivers were provisionally dated based on paleomagnetic and geomorphological considerations, with the latter often applied even regardless of tectonic motions that took place in the Lesser Caucasus in the Late Cenozoic. In the geological literature, the basalts of the Khrami Flow were usually attributed to the Pliocene, those of the Mashsavera and Debed Flows were dated at either the Pliocene or the Pleistocene–Holocene, and the rocks of the Kura Flow were described as having a Pleistocene–Holocene age [12, 13, and others]. Depending of their surmised age, the volcanic rocks of the lava rivers were either included into the Pliocene Akhalkalaki Formation or ascribed to the Late Quaternary formations of this area.

The products of moderately acid and acid volcanism formed during the Pliocene evolutionary stage of the Dzhavakheti area occur locally. They compose relatively small volcanoes in the Dzhavakheti Range in the central part of the territory, near the basic lavas of the lower part of the Akhalkalaki Formation, and the lavas of its upper part overlie them. Our dates obtained for the dacite lavas of the Dzhavakheti Range vary from 2.7 to 2.2 Ma [11]. These rocks were previously included into the Late Miocene Goderdzi Formation [13].

Volcanism of the final (Quaternary) stage in the Dzhavakheti area began at approximately 800 ka. Reliable isotopic–geochronological data on this stage were obtained only on rocks from the Samsari Range [10, 11]. We subdivided this stage into four phases, with the youngest of them dated at the terminal Neopleistocene–Holocene (volcanoes Godoberi and Tavkvetili). The eruption products in the Samsari Range and those of Pliocene volcanoes in the Dzhavakheti Range were previously included into the Late Miocene Goderdzi Formation [12, 13, and others].

## EARLIER DATES FOR THE PLIOCENE BASALT LAVAS OF THE DZHAVAKHETI HIGHLAND

Previously published isotopic–geochronological data on basic lavas from the Dzhavakheti Highland are extremely scarce. The dates obtained at the Geological Institute of the Academy of Sciences of Georgia more than three decades ago were of reconnaissance character due to methodological difficulties during the dating of young rocks. Nevertheless, the basaltic lavas of the Akhalkalaki Formation were dated at the Pliocene [15].

The finds of remains of prehistoric humans near Dmanisi in the mid-1990s called for dating of the Mashavera Flow, on which the prehistoric man site was found, and the lavas of the Gomareti and Akhalakalaki plateaus. The basic rocks were dated at 2.9–1.8 Ma by the $^{40}$Ar/$^{39}$Ar method [16, 17], and their age is in good agreement with the faunal age of the Akahlkalaki Formation. At the same time, the $^{40}$Ar/$^{39}$Ar dates presented in [18] for plagioclase phenocrysts from the lowermost basaltic flows in the stratigraphic section of the formation exposed near the village of Toki in the Paravani River valley are 3.60 ± 0.06 Ma. When studying volcanics in the Aragats area in Armenia [6], the plateau basalts exposed in the canyon of the Akhuryan River, which are analogues of the Akhalkalaki Formation in the Dzhavakheti Highland, we dated them at 2.5 ± 0.2 Ma (K–Ar). Hence, the aforementioned isotopic–geochronological data allowed us to assay the age of the basic volcanics of the Akhalkalaki Formation at 3.6–1.8 Ma. These data are consistent with the results of the paleomagnetic studies [18, 19].

## PETROGRAPHY AND CHEMISTRY OF THE ROCKS

During the 1999–2000 fieldwork organized by the Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, and the Geological Institute, Academy of Sciences of Georgia, we gathered a representative collection of rock samples at the Dzhavakheti volcanic area to characterize the volcanic rocks of the area of various ages and composition. This paper presents materials on some of these samples, including samples of volcanic rocks from three basaltic lava rivers at the Dzhavakheti Highland that are known in the literature as the Kura, Mashavera, and Khrami Flows. The sampling sites of rocks dated in the course of this research are shown in the schematic geological map of the Dzhavakheti Highland in Fig. 1 and are listed in Table 1.

The lavas of these flows consist of porous or massive subalkaline basalts (subalkaline leucobasalts). These are porphyritic, more rarely aphyric rocks with intersertal, ophitic, doleritic, and, sometimes, pilotaxitic textures of the groundmass, with no more than 15% phenocrysts. All of the rocks contain phenocrysts of olivine and plagioclase, most rock varieties additionally, contain clinopyroxene phenocrysts, and, occasionally rocks (some lava varieties from the Mashavera Flow) also bear orthopyroxene (2–3%). Olivine phenocrysts up to 1.5 mm across are either unaltered or variably (sometimes completely) iddingsitized. Plagioclase phenocrysts (up to 2 mm) commonly consist of labradorite ($An_{55–70}$) and are usually zonal, with extensively altered cores. The clinopyroxene of the phenocrysts (up to 1.2 mm) is augite or, often, Ti-augite. Some lavas of the Mashavera Flow contain significant amounts of glomeroporphyritic aggregates of plagioclase or olivine and plagioclase crystals. The rocks of the Khrami and Kura flows occasionally bear aggregates of olivine grains. The groundmass of the rocks consists of plagioclase (commonly $An_{60–70}$), olivine, and clinopyroxene (augite or Ti-augite); the ore minerals (up to 8.5% of the groundmass) are magnetite, titanomagnetite, and, rarely, ilmenite. The rocks sometimes contain accessory apatite.

The volcanic rocks of the lava rivers at the Dzhavakheti Highland contain 48.7–52.7% $SiO_2$, 3.5–5.7% $K_2O + Na_2O$ at 0.9–1.4% $K_2O$. In the IAS classification diagram, their compositional data points fall mostly into the field of subalkaline olivine leucobasalts (Fig. 2) [20]. The position of the data points of these rocks in the $SiO_2$–$K_2O$ diagram indicates that the rocks are moderately potassic (Fig. 3). The overwhelming majority of the rocks affiliate with the K–Na and Na subalkaline series [22], with the lowest $K_2O/Na_2O$ ratios typical of the lavas of the Khrami Flow.

Volcanic breccia in sample YUG-43 (which was taken from a cliff exposure near the confluence site of the Paravani and Kura rivers, not far from the Khertvisi castle) basically differs from all of our other samples, and its composition corresponds to acid andesite (Table 1, Fig. 2). Some researchers believe [23] that this site hosts the eruption center that gave rise to the Kura Flow.

Our Na subalkaline lava samples from the Khrami Flow are characterized by a quite stable chemical composition (Table 1). Judging from their Mg# (0.54–0.56) and Ni contents (up to 126 ppm), these rocks are closer to the parental melt than the rocks of all other flows. With regard for the Sr and Nd isotopic compositions (see below), the rocks are also the closest to mantle magmas. The variations in the concentrations of major and trace elements in the lava units composing the Kosolari section of the Khrami Flow (from the bottom to top of the flow) are consistent with the model of the crystallization differentiation of the parental melt with the fractionation of plagioclase and, perhaps, also apatite during the initial phases of the process and of magnetite, olivine, and minor clinopyroxene amounts during the final phases. This follows from the increase in the MgO, $TiO_2$, Ni, and Cr contents from the lower (sample YUG-103) to middle (sample YUG-102) parts of the Kosolari section and the complementary decrease in the concentrations of $Na_2O$, $Al_2O_3$, and $P_2O_5$, as well as from the increase in the CaO and $Al_2O_3$ concentrations of the rocks from the middle to upper

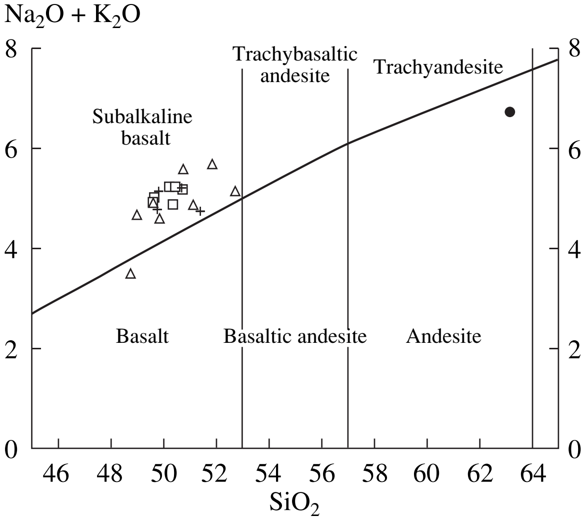

**Fig. 2.** $SiO_2$–($Na_2O$ + $K_2O$) classification diagram [20] for the examined rocks from the Dzhavakheti area. Crosses are basalts of the Khrami Flow, squares are basalts of the Kura Flow, triangles are basalts of the Mashavera Flow, and the circle is andesite from the Khertvisi volcanic center.

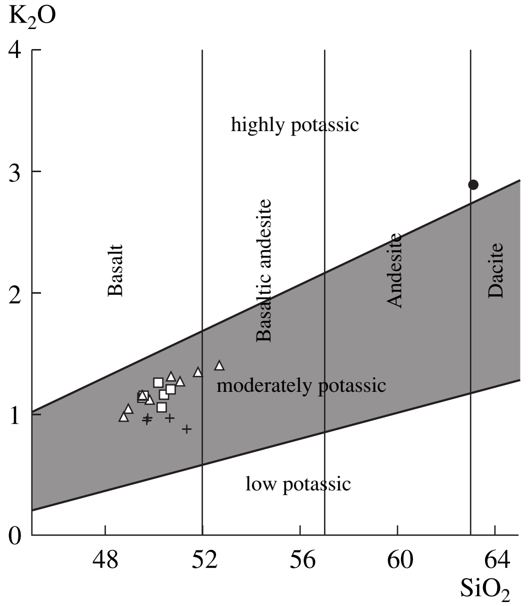

**Fig. 3.** $SiO_2$–$K_2O$ classification diagram [21] for the examined rocks from the Dzhavakheti area. See Fig. 2 for symbol explanations.

**Table 1.** Chemical composition of volcanic rocks from the lava rivers of the Dzhavakheti area

| Sample | $SiO_2$ % | $TiO_2$ % | $Al_2O_3$ % | $Fe_2O_3$ % | MnO % | MgO % | CaO % | $Na_2O$ % | $K_2O$ % | $P_2O_5$ % | Cr ppm | Sc ppm | V ppm | Co ppm | Ni ppm | Cu ppm | Zn ppm | Rb ppm | Sr ppm | Y ppm | Zr ppm | Nb ppm | Ba ppm | Cl ppm | Ga ppm | Sm ppm | Nd ppm | $^{87}Rb/^{86}Sr$ | $^{147}Sm/^{144}Nd$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YUG-33 | 49.56 | 1.41 | 15.78 | 12.08 | 0.16 | 6.51 | 9.19 | 3.82 | 1.13 | 0.29 | 109 | 23 | 138 | 34 | 93 | 75 | 74 | 17 | 536 | 32 | 180 | 17 | 438 | 167 | 20 | – | | 0.092 | |
| YUG-35 | 50.70 | 1.36 | 17.26 | 10.04 | 0.13 | 6.10 | 8.83 | 3.97 | 1.21 | 0.37 | 112 | 26 | 151 | 31 | 91 | 62 | 73 | 18 | 549 | 34 | 172 | 16 | 509 | 140 | 21 | 4.7 | 24.0 | 0.095 | 0.125 |
| YUG-39 | 50.44 | 1.50 | 17.52 | 9.88 | 0.13 | 6.07 | 8.73 | 4.08 | 1.17 | 0.38 | 114 | 23 | 143 | 37 | 83 | 59 | 64 | 17 | 505 | 34 | 177 | 17 | 345 | 91 | 23 | – | – | 0.098 | |
| YUG-40 | 50.18 | 1.62 | 16.16 | 11.71 | 0.15 | 5.67 | 8.76 | 3.97 | 1.26 | 0.44 | 84 | 21 | 153 | 38 | 82 | 67 | 86 | 12 | 539 | 34 | 197 | 20 | 462 | 158 | 17 | – | – | 0.065 | |
| YUG-41 | 49.62 | 1.58 | 16.53 | 11.79 | 0.15 | 5.87 | 8.93 | 3.87 | 1.15 | 0.36 | 77 | 20 | 146 | 39 | 74 | 93 | 99 | 12 | 555 | 34 | 190 | 18 | 456 | 124 | 19 | – | – | 0.063 | |
| YUG-42 | 50.33 | 1.58 | 16.85 | 11.36 | 0.14 | 5.52 | 8.81 | 3.82 | 1.06 | 0.37 | 84 | 22 | 158 | 31 | 75 | 91 | 89 | 11 | 506 | 36 | 189 | 16 | 403 | 107 | 20 | 3.2 | 19.4 | 0.063 | 0.105 |
| YUG-43 | 63.11 | 0.58 | 15.91 | 4.07 | 0.07 | 2.33 | 4.76 | 3.87 | 2.88 | 0.27 | 27 | 11 | 85 | 13 | 29 | 46 | 52 | 71 | 723 | 14 | 171 | 19 | 934 | 3153 | 19 | – | – | 0.285 | |
| YUG-100 | 49.78 | 1.40 | 17.59 | 10.34 | 0.13 | 6.56 | 8.68 | 4.18 | 0.97 | 0.36 | 146 | 21 | 135 | 45 | 126 | 77 | 65 | 16 | 530 | 34 | 190 | 11 | 362 | 116 | 20 | – | – | 0.087 | |
| YUG-101 | 51.38 | 1.38 | 17.25 | 9.80 | 0.13 | 5.67 | 8.95 | 3.87 | 0.88 | 0.33 | 148 | 27 | 158 | 39 | 122 | 82 | 63 | 12 | 449 | 34 | 160 | 12 | 329 | 242 | 23 | 2.8 | 15.1 | 0.077 | 0.117 |
| YUG-102 | 49.74 | 1.61 | 16.84 | 10.87 | 0.14 | 6.82 | 8.77 | 3.83 | 0.95 | 0.34 | 176 | 24 | 164 | 41 | 126 | 78 | 74 | 14 | 512 | 33 | 187 | 15 | 336 | 138 | 18 | – | – | 0.079 | |
| YUG-103 | 50.65 | 1.29 | 17.65 | 9.84 | 0.12 | 5.81 | 8.78 | 4.25 | 0.97 | 0.39 | 138 | 24 | 137 | 32 | 103 | 84 | 60 | 14 | 466 | 39 | 168 | 12 | 351 | 105 | 24 | 3.7 | 17.7 | 0.087 | 0.133 |
| YUG-104 | 49.56 | 1.59 | 16.78 | 11.38 | 0.15 | 5.91 | 9.49 | 3.75 | 1.15 | 0.23 | 141 | 29 | 227 | 28 | 72 | 60 | 68 | 22 | 349 | 34 | 153 | 9 | 372 | 124 | 18 | 3.4 | 15.8 | 0.182 | 0.137 |
| YUG-105 | 48.73 | 1.31 | 15.27 | 12.19 | 0.17 | 7.36 | 8.24 | 2.53 | 0.98 | 0.18 | 155 | 26 | 186 | 38 | 108 | 95 | 77 | 23 | 322 | 30 | 147 | 8 | 283 | 102 | 23 | – | – | 0.207 | |
| YUG-106 | 51.09 | 1.33 | 16.75 | 10.42 | 0.13 | 5.87 | 8.95 | 3.60 | 1.27 | 0.24 | 161 | 28 | 180 | 33 | 77 | 85 | 66 | 24 | 381 | 32 | 160 | 10 | 398 | 106 | 19 | – | – | 0.183 | |
| YUG-107 | 48.96 | 1.53 | 16.94 | 11.82 | 0.15 | 6.43 | 9.22 | 3.62 | 1.05 | 0.19 | 151 | 26 | 206 | 36 | 86 | 85 | 73 | 22 | 391 | 32 | 153 | 9 | 380 | 252 | 20 | – | – | 0.163 | |
| YUG-108 | 49.83 | 1.33 | 16.61 | 11.04 | 0.15 | 6.73 | 9.04 | 3.49 | 1.12 | 0.24 | 176 | 27 | 180 | 42 | 99 | 84 | 71 | 23 | 396 | 32 | 150 | 9 | 351 | 132 | 17 | – | – | 0.168 | |
| YUG-109 | 52.70 | 1.24 | 16.62 | 9.70 | 0.13 | 5.24 | 8.62 | 3.75 | 1.40 | 0.27 | 99 | 23 | 177 | 36 | 75 | 72 | 69 | 27 | 531 | 30 | 171 | 16 | 550 | 165 | 20 | – | – | 0.147 | |
| YUG-110 | 51.82 | 1.17 | 16.98 | 9.54 | 0.13 | 5.17 | 8.89 | 4.34 | 1.35 | 0.52 | 113 | 26 | 134 | 31 | 63 | 57 | 62 | 22 | 519 | 39 | 208 | 17 | 523 | 123 | 24 | – | – | 0.123 | |
| YUG-111 | 50.72 | 1.21 | 17.59 | 9.82 | 0.14 | 5.29 | 9.04 | 4.27 | 1.31 | 0.52 | 141 | 24 | 125 | 30 | 68 | 45 | 63 | 20 | 508 | 38 | 185 | 17 | 550 | 112 | 21 | 3.9 | 21.8 | 0.114 | 0.114 |

Notes: The analyzed material consisted of whole-rock samples. Analyses for major oxides and trace elements, except Sm and Nd, were conducted by XRF on a Philips PW 2400 spectrometer (analysts A.I. Yakushev and T.M. Marchenko). The Sm and Nd concentrations were determined by ICP MS on a VG Plasma Quad RPQ-2.3 (analyst S.A. Gorbacheva). Analyses of major oxides are normalized to 100%. Sampling sites and their position in the vertical sections of the lava rivers: YUG-33 is subalkaline basalt from the upper unit of the Kura Flow (Saro section); YUG-35 is subalkaline basalt from unit 3 of the Kura Flow (Saro section; YUG-39 is subalkaline basalt from unit 6 of the Kura Flow (Saro section; YUG-40 is subalkaline basalt from the lower unit of the Kura Flow (Saro section); YUG-41 is subalkaline basalt from the second unit (from the bottom) of the Kura Flow (Saro section); YUG-42 is subalkaline basalt from the third unit (from the bottom) of the Kura Flow (Saro section); YUG-43 is andesite from the Khertvisi volcanic center; YUG-100 is subalkaline basalt from the upper unit of the Khrami Flow (quarry near the village of Matsevani); YUG-101 is subalkaline basalt from the upper unit of the Khrami Flow (section near the village of Kosolari); YUG-102 is subalkaline basalt from the middle unit of the Khrami Flow (section near the village of Kosolari); YUG-103 is subalkaline basalt from the lower unit of the Khrami Flow (section near the village of Kosolari); YUG-104 is subalkaline basalt from the upper unit, lower terrace of the Mashavera Flow (section near Dmanisi); YUG-105 is subalkaline basalt from the lower unit, lower terrace of the Mashavera Flow (section near Dmanisi); YUG-106 is subalkaline basalt from the second unit (from the bottom), lower terrace of the Mashavera Flow (section near Dmanisi); YUG-107 is subalkaline basalt from the lower unit, lower terrace of the Mashavera Flow (section near village of Mashavera); YUG-108 is subalkaline basalt from the lower unit, lower terrace of the Mashavera Flow (section near village of Mashavera); YUG-109 is subalkaline basalt from the upper unit, lower terrace of the Mashavera Flow (section near township of Madneuli); YUG-110 is subalkaline basalt from the lower unit, second terrace of the Mashavera Flow (section near Danisi); YUG-111 is subalkaline basalt from the upper unit, second terrace of the Mashavera Flow (section near Danisi).

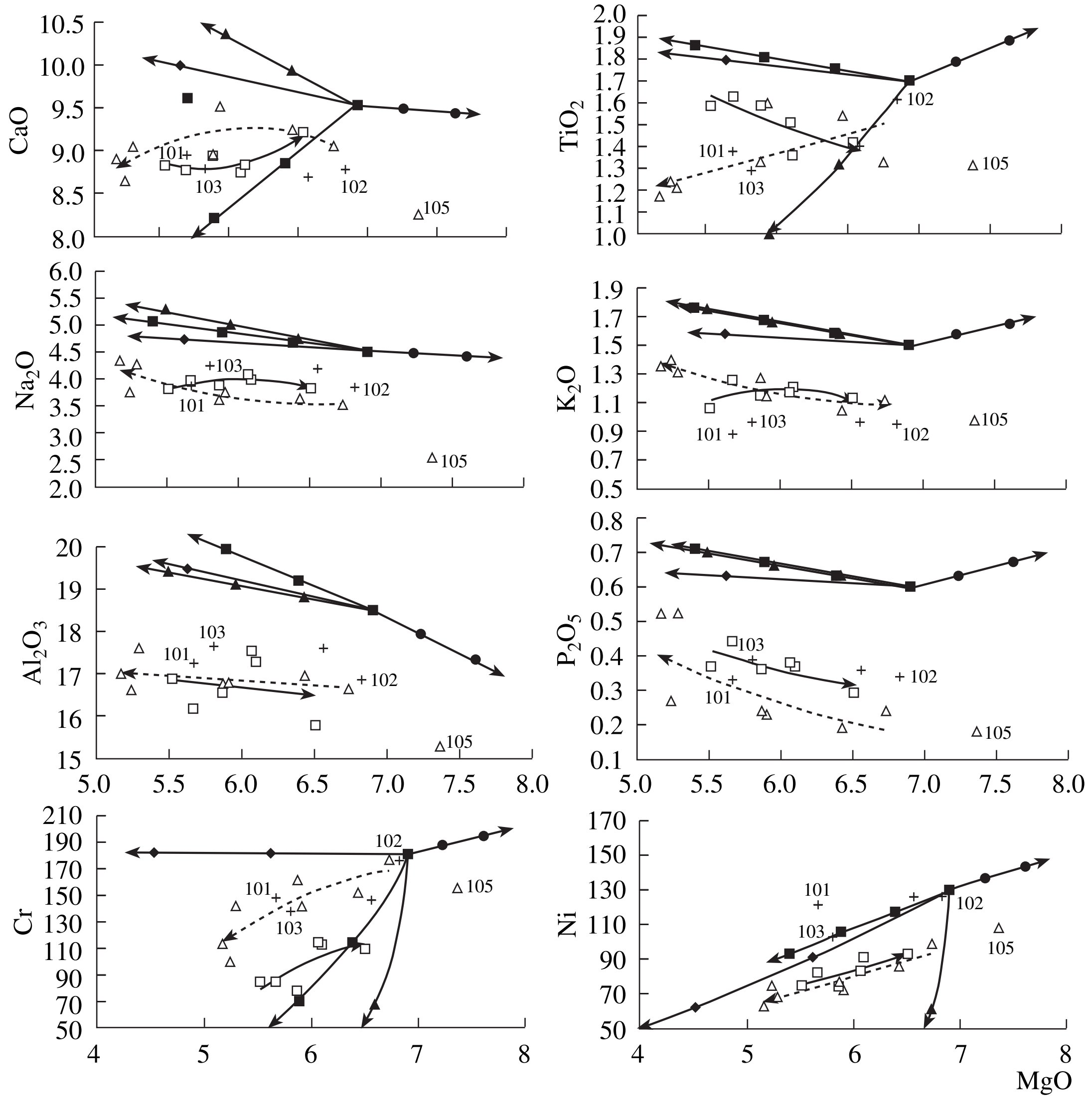

**Fig. 4.** Variations in the concentrations of major oxides (wt %) and some indicator trace elements (ppm) in rocks from the Dzhavakheti Highland as functions of their MgO concentrations. See Fig. 2 for symbol explanations. Numerals are our numbers of samples from the Kosolari section of the Khrami Flow and of basalt YUG-105 from the Mashavera Flow (Table 1). Solid lines with solid symbols are variations in the concentrations of major oxides and trace elements during the fractionation of the following minerals: circles—plagioclase; triangles—magnetite; squares—clinopyroxene; and diamonds—olivine. Approximating lines for the 2comps of lavas from flows: dashed lines—Mashavera Flow; solid lines—Kura Flow. The distribution coefficients used for the subalkaline basalts were compiled from the database available at *www.earthref.org*.

(sample YUG-101) parts of the flow and the concurrent decrease in the contents of MgO, TiO$_2$, K$_2$O, Ni, and Cr (Table 1, Fig. 4). The possibility of crystallization and the subsequent fractionation of apatite and plagioclase from the melt follows, for example, from the character of the decrease in the P$_2$O$_5$ concentration from the lower to middle parts of the Kosolari section. As can be seen in Fig. 4, this decrease could not be caused only by plagioclase settling from the melt.

Our K–Na subalkaline lava samples from the Kura Flow have relatively low Mg# (0.49–0.55) and, particularly, low Ni concentrations (74–93 ppm), which suggest that these rocks are more evolved than the volcanics of the Khrami Flow. The character of the variations in the contents of major oxides, Ni, and Cr in the vertical section of the lava river (from its bottom to top) is generally in good agreement with the crystallization differentiation model, with the inevitable fractionation of plagioclase from the subalkaline basaltic melt (Fig. 4).

The most chemically contrasting rocks compose the Mashavera Flow. Compared to the rocks of the Khrami and Kura Flows, they are richer in Rb (up to 27 ppm) and have lower K/Rb ratios and, in some varieties, lower contents of Sr (no more than 322 ppm) at Mg# = 0.51–0.55 and 63–108 ppm Ni. The least evolved rock (Mg# = 0.55 at 108 ppm Ni) was proved to be a tholeiite

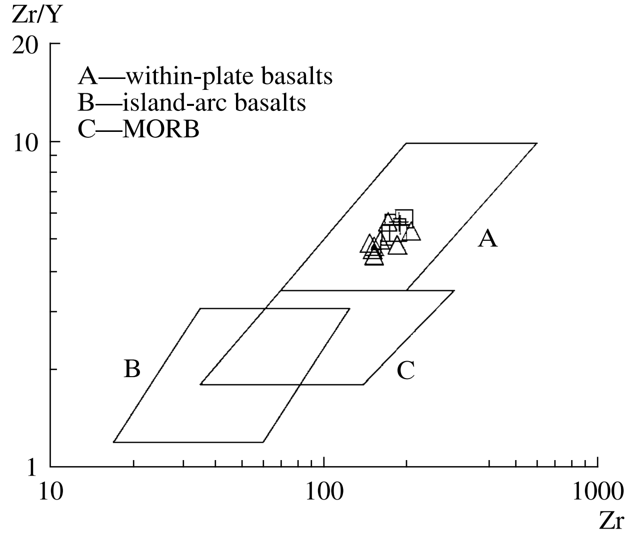

**Fig. 5.** Zr–Zr/Y diagram [26] for the examined rocks from the Dzhavakheti area. See Fig. 2 for symbol explanations.

olivine basalt from the lower unit of the lower terrace flow near Dmanisi (Table 1, sample YUG-105). Note that the subalkaline basalt of sample YUG-105 shows concentrations of some components that are not geochemically complementary to those in the lavas of the Mashavera Flow, as is particularly clearly pronounced in the MgO–$Na_2O$ and MgO–$Al_2O_3$ diagrams (Fig. 4). This rock also differs from other varieties in mineral composition: it generally contains 30–35% phenocrysts (whereas the other lavas bear no more than 10–15% phenocrysts) at the pervasive presence of orthopyroxene, a mineral that was not found in the other K–Na subalkaline basalts of the flow. Proceeding from the assumption that all lavas of the Mashavera Flow, except the subalkaline basalt of sample YUG-105, were derivatives of a single parental melt, their geochemical characteristics can generally be explained by the crystallization differentiation with the fractionation of clinopyroxene (perhaps, together with olivine and magnetite) from the melt. As can be seen from Fig. 4, the character of the increase of the $Na_2O$, $K_2O$, and $P_2O_5$ concentrations up the vertical section of the flow and the concurrent decrease in the concentrations of Ni, Cr, MgO, and $TiO_2$ can be adequately enough explained by the concurrent crystallization of clinopyroxene, olivine, and magnetite with their subsequent fractionation from the subalkaline basic melt.

In spite of the significant differences identified in the compositions of the parental magmas and their evolution, the contents of several elements (Y, Ti, K, and others) in the rocks of lava flows at the Dzhavakheti-Highland are fairly similar and are comparable with the concentrations of these elements in the trachybasalts of some Late Cenozoic volcanic centers and volcanoes in the Caucasian segment of the Alpine Belt. This pertains, first of all, to Ararat volcano, as well as to Tendyurek and Myus volcanoes south and southwest of the Dzhavakheti Highland [24, 25].

The geochemical characteristics of the volcanic rocks composing lava flows in the Dzhavakheti Highland generally correspond to the characteristics of subalkaline basalts of continental rifts and hotspots [22]. Similarities in the petrogeochemical parameters of the volcanics and their analogues in within-plate geodynamic environments are also clearly pronounced in the arrangement of the data points of the Dzhavakheti lavas in well-known petrochemical diagrams, such as the Zr–Zr/Y diagram [26], in which the data points plot within the field of within-plate basalts (Fig. 5).

## ISOTOPIC GEOCHRONOLOGY

Our earlier study of the K–Ar isotopic systematics of volcanic rocks from the Greater Caucasus suggests that the most suitable material for the dating of volcanic rocks is their groundmass from which all phenocrysts were removed. Phenocryst minerals often contain excess radiogenic Ar, so that the K–Ar dates obtained on these phenocrysts or on whole-rock samples with these phenocrysts were proved to be overestimates relative to the actual age of the rocks [4, 5]. This conclusion was also drawn from the results obtained on the K–Ar systematics of the youngest lavas in Japan, Italy, and North America [27 and others]. Because of this, in this research and in our earlier studies of young rocks from the Greater and Lesser Caucasus, the K–Ar dating of volcanic rocks was conducted using their groundmass alone, without phenocrysts.

We conducted the isotopic–geochemical examination of young volcanics from the Dzhavakheti Highland with the application of a specialized method of K–Ar dating developed at the Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences [4]. The measurements were carried out on a highly sensitive low-background mass spectrometric complex designed on the basis of MI-1201 IG (NPO SELMI, Sumy, Ukraine). The concentration of radiogenic Ar was determined by isotopic dilution with an $^{38}$Ar isotope as the spike. The accuracy of the measurements was monitored by the systematic replicate analyses of milligram samples of the following standards: biotite Bern-4, muscovite Bern-4, basalt 1/76, and rhyolite 1/65 Aziya. The K concentrations were determined by flame spectrophotometry. The geochronological calculations were conducted with the use of the decay constants recommended by the International Subcommission for Geochronology: ($\lambda_{\beta^-} = 4.962 \times 10^{-10}$ yr$^{-1}$, $\lambda_\varepsilon = 0.581 \times 10^{-10}$ yr$^{-1}$, $\lambda = 5.543 \times 10^{-10}$, and $^{40}$K/K = 0.01167 at %.

The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios were measured on a Micromass Sector 54 thermoionization multicollector mass spectrometer, the $2\sigma$ errors of the results were no greater than 0.003% for Sr and 0.002% for Nd. The accuracy of the measurements was monitored by the systematic analyses of Sr and Nd isotopic standards (SRM-987 and La Jolla, respectively). Elements for mass spectrometric analysis were extracted by ion-exchange chromatographic techniques. The Sr and Nd isotopic compositions were determined for the groundmasses of the rocks. Our earlier data on Neogene–Quaternary rocks from the Caucasus [4, 8] have revealed that the Sr and Nd isotopic compositions of the phenocrysts and groundmasses of young lavas are not in equilibrium. The main reason for this is, in our opinion, the hybrid genesis of their parental melts, whose compositions were formed with the participation of contamination and/or mixing of the parental melts with a geochemically distinct material. In the situation with contamination, some phenocryst minerals could be xenogenic, and it is quite probable that their Sr and Nd isotopic compositions differed from those in the parental (hybrid) melt. In the case of mixing, the parental magma was produced by the mixing of two geochemically distinct melts, and it cannot be ruled out that some phenocrysts of these subalkaline basalts could be diacrysts, which were formed before the derivation of the hybrid melt. Because of this, at least the Sr isotopic characteristics of the diacrysts can be inconsistent with the isotopic–geochemical features of the rocks. Over- or underestimated $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of the diacrysts, whose contents in the rocks could be as high as 15–20%, can significantly modify the compositions of the whole-rock samples, which was inconsistent with the isotopic characteristics of the parental melts. At the same time, the Sr and Nd isotopic composition of the rock groundmasses from which all phenocrysts (i.e., rock components responsible for the distortion of the isotopic composition of the parental magmas) were removed most closely approached the isotopic–geochemical characteristics of these magmas. The relatively young ages of the lavas (2–3 Ma) and their low Rb/Sr ratios led us to regard the measured $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios as corresponding to the initial ones. If the subalkaline basalts have the same Sr and Nd isotopic compositions of their phenocrysts and groundmass, this feature of rocks with an age of no older than 3 Ma so much the more allowed us to assume that the isotopic signatures of the groundmasses is identical to the initial signatures.

The Rb, Sr, Sm, and Nd concentrations were analyzed in the whole-rock samples because, in contrast to the Sr and Nd isotopic composition, the removal of phenocrysts from young volcanic rocks and the use of their separated groundmass for chemical analysis can result in a significant distortion of the petrogeochemical characteristics of these rocks. The Rb and Sr concentrations were measured on a Philips PW2400 (XRF), and the Sm and Nd concentrations were determined on a VG Plasma Quad RPQ-2 (ICP-MS). The $^{87}Rr/^{86}Sr$ and $^{147}Sm/^{144}Nd$ isotopic ratios were then calculated. Below, these values pertain to whole-rock samples.

## RESULTS AND DISCUSSION

### *K–Ar Geochronology*

The K–Ar dates of rocks from the Dzhavakheti Highland are summarized in Table 2. All of the lava rivers, including the Kura Flow, were dated at the Middle–Late Pliocene. Below we consider our results in detail.

**Khrami Flow.** The K–Ar dates of four samples of subalkaline basalts taken at the longest Khrami Flow coincide within the analytical errors and lie within the range of 3.25–3.10 Ma at an average of 3.19 ± 0.14 Ma ($2\sigma$), i.e., correspond to the Middle Pliocene. Available paleomagnetic data [19] indicate that basic lavas in the Khrami River valley are characterized by reverse magnetic polarity. Considered together with our K–Ar dates, this suggests that the lavas were erupted within the time span of the Mamut microchron of anomalous magnetic polarity of the Gauss chron. Hence, the Khrami Flow is the oldest among the lava rivers in the Georgian part of the Dzhavakheti Highland.

Three of the four dated samples represent the whole vertical section of the Khrami Flow near the village of Kosolari on the left bank of the Khrami River. The flow consists of lava units that conformably overlie one another (without stratigraphic discontinuity) and are not separated by units of sedimentary rocks. With regard for the analytical errors, the aforementioned closeness of the K–Ar ages of the rocks composing these units (samples YUG-101, YUG-102, and YUG-103) led us to conclude that the basaltic lavas were erupted and flowed along the ancient valley of the Khrami River without any significant interruptions during, at most, a few dozen to one hundred thousand years.

**Mashavera Flow.** We dated eight samples of volcanics from three vertical sections of this lava flow. Although these samples were more representative, their K–Ar dates are no more consistent than those for the Khrami Flow: all eight dates coincide within the analytical errors and yield an average value of 2.09 ± 0.12 Ma ($2\sigma$ scatter). With regard for earlier $^{40}Ar/^{39}Ar$ dates of basalts from a fragment of the Mashavera Flow near Dmanisi (2.0–1.8 Ma [16]), this result makes it possible to confidently date the Mashavera lava river at the Late Pliocene. According to available paleomagnetic data [19], the subalkaline basalts of the Mashavera Flow have a normal magnetic polarity. Taking into account our isotopic dates, it is reasonable to hypothesize that the lavas were erupted during either the initial phase of the Olduvai subchron or the Reunion microchron with a normal polarity.

The heterogeneity of the K–Ar ages of basalts from the Mashavera Flow can be interpreted as follows. Geomorphologicaly, the lavas of the Mashavera Flow compose three terraces (see above). We dated the volcanics that compose the second terrace near Dmalnisi (samples YUG-110 and YUG-111) and the lower terrace near Dmanisi (samples YUG-104 through YUG-106). The age values obtained for rocks from the bottom parts of the vertical sections of each terrace do not signifi-

**Table 2.** Results of K–Ar dating of rocks from lava rivers at the Dzhavakheti area

| Sample | K, % ± σ | $^{40}Ar_{rad}$, ng/g ± σ | $^{40}Ar_{air}$ (sam), % | age, Ma ± 2σ |
|---|---|---|---|---|
| | | *Khrami Flow* | | |
| YUG-100 | 0.63 ± 0.015 | 0.138 ± 0.004 | 73.0 | 3.16 ± 0.24 |
| YUG-101 | 0.56 ± 0.015 | 0.121 ± 0.003 | 81.0 | 3.10 ± 0.23 |
| YUG-102 | 0.70 ± 0.015 | 0.156 ± 0.003 | 67.6 | 3.22 ± 0.17 |
| YUG-103 | 0.49 ± 0.015 | 0.111 ± 0.002 | 69.0 | 3.26 ± 0.25 |
| Average | | | | 3.19 ± 0.14 |
| | | *Mashavera Flow* | | |
| YUG-104 | 0.91± 0.015 | 0.138 ± 0.004 | 86.7 | 2.18 ± 0.14 |
| YUG-105 | 0.86 ± 0.015 | 0.128 ± 0.003 | 83.6 | 2.15 ± 0.12 |
| YUG-106 | 0.98 ± 0.015 | 0.138 ± 0.003 | 79.4 | 2.02 ± 0.10 |
| YUG-107 | 0.99 ± 0.015 | 0.140 ± 0.003 | 81.4 | 2.04 ± 0.10 |
| YUG-108 | 1.00 ± 0.015 | 0.143 ± 0.004 | 75.4 | 2.06 ± 0.12 |
| YUG-109 | 1.22 ± 0.02 | 0.179 ± 0.003 | 72.5 | 2.12 ± 0.11 |
| YUG-110 | 0.85 ± 0.015 | 0.121 ± 0.003 | 68.5 | 2.06 ± 0.14 |
| YUG-111 | 0.81 ± 0.015 | 0.117 ± 0.003 | 66.2 | 2.09 ± 0.14 |
| Average | | | | 2.09 ± 0.12 |
| | | *Kura Flow* | | |
| YUG-33 | 0.95 ± 0.015 | 0.140 ± 0.002 | 72.2 | 2.11 ± 0.10 |
| YUG-35 | 0.86 ± 0.015 | 0.121 ± 0.002 | 77.7 | 2.03 ± 0.11 |
| YUG-39 | 0.76 ± 0.015 | 0.114 ± 0.004 | 72.6 | 2.15 ± 0.15 |
| YUG-40 | 0.96 ± 0.015 | 0.149 ± 0.003 | 67.9 | 2.23 ± 0.13 |
| YUG-41 | 0.98 ± 0.015 | 0.140 ± 0.003 | 62.1 | 2.05 ± 0.10 |
| YUG-42 | 0.81 ± 0.015 | 0.118 ± 0.004 | 72.4 | 2.10 ± 0.11 |
| Average | | | | 2.11 ± 0.14 |
| | | *Khertvisi volcanic center* | | |
| YUG-43 | 2.66 ± 0.02 | 1.42 ± 0.012 | 76.2 | 7.7 ± 0.2 |

Note: Rock names, sampling sites, and their position in the vertical sections of the lava rivers are listed in the note for Table 1. The analyzed material is rock groundmasses separated from phenocrysts.

cantly differ from the values for rocks from the upper parts of the same sections, and the K–Ar ages of rocks from both terraces are generally consistent (within the errors). This testifies that the lavas at different elevations were erupted roughly simultaneously, and hence, the Mashavera lava river was formed within a brief time span.

**Kura Flow.** We dated samples from the upper three and lower three lava units in the vertical section of the Kura Flow below the village of Saro. Our observations indicate that the flow consists of 15 to 20 individual lava units that are stratigraphically conformable and are not separated by units of sedimentary rocks. In spite of the viewpoint that the lava river can have a Pleistocene and even Holocene age [12, 23], our data undoubtedly constrain its age to the Late Pliocene. Consistent K–Ar dates for individual samples lie within a narrow range of 2.20–2.05 Ma (Table 2). With regard for the analytical errors, this testifies, as in the situations with the Khrami and Mashavera Flows, that the basaltic river, as a whole, was formed within a relatively brief time span, no more than a few dozen thousand years. The average age of the subalkaline basalts of the Kura Flow is 2.11 ± 0.14 Ma (2σ) and is very close, within the 2σ scatter of individual values, to the average age obtained for the Mashavera Flow (2.09 ± 0.12 Ma).

Although we determined that the Kura Flow in its Saro section was formed within a narrow time span, the rocks show systematic variations in their magnetic polarity [28]. From the bottom to top of the flow, the magnetization of the subalkaline basalts varies as follows: transitional ⟶ normal ⟶ transitional ⟶ reversed ⟶ transitional. The assumption that the lavas of the Kura Flow have a Late Quaternary age and the results of paleomagnetic studies led some Georgian geologists (for example, [19]) to recognize an individual episode of magnetic polarity inversion, which was referred to as Saro and ascribed to the boundary between the Early and Late Neopleistocene. However, our Pliocene K–Ar dates indicate that the lower portion of the Kura Flow was likely formed during the Reunion subchron (2.15–2.09 Ma) with normal polarity, the middle part of this flow was erupted between 2.09 and 1.95 Ma, during the Matuyama chron with reversed polarity, and, finally, its uppermost part was produced early during the Olduvai subchron with normal polarity. Thus, the magnetization inversions in the vertical sections of the Kura Flow are in good agreement with the universally adopted variant of the paleomagnetic chart of the Late Piocene, and the earlier idea about the existence of the Saro subchron with reversed polarity within the Brunhes chron seems to be groundless.

The Khertvisi volcanic center is interesting because it was sometimes thought to be the eruption center of the Kura Flow [23]. The K–Ar age of 7.7 ± 0.2 Ma (Table 2) coincides with the age of approximately 7.5 Ma that we previously obtained for volcanic rocks of the Goderdzi Formation that host the volcanic breccia of this center [11]. Thus, it is reasonable to think that the Khertvisi center (which is composed of andesitic breccia, Table 1) does not belong to the centers of Pliocene basic magmatism but was related to an older (Late Miocene) regional magmatic episode.

### *Sr–Nd Isotopic Systematics*

In order to study the Sr–Nd systematics of the rocks composing lava rivers at the Dzhavakheti Highland (Table 3), we selected rock samples from sites distant as much as possible from one another in the vertical section of the flow, i.e., rocks that have the most different ages. An additional criterion was the remoteness of the sampling sites from the contacts of the lavas with their host rocks (to minimize the possibility of the contamination of the subalkaline basalts during their contact interactions).

The subalkaline basalts YUG-101 and YUG-103 were sampled within the upper and lower units of the Khrami Flow in its vertical section exposed near the village of Kosolari. The rocks sampled in the Kura Flow (in its section near Saro village) also represent its upper (sample YUG-35) and lower (sample YUG-42) parts. The analyzed samples of subalkaline basalts from the Mashavera Flow (samples YUG-104 and YUG-111) were collected at two exposures at a considerable distance from each other, but the younger age of the rock of sample YUG-111 was not questioned.

The examined subalkaline basalts from lava rivers at the Dzhavakheti Highland exhibit fine differences between their Sr and Nd isotopic compositions. These differences are statistically significant, because the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were determined accurate to 0.002–0.003% (Table 3) and lie within the ranges of 0.7039–0.7043 and 0.51281–0.51290, respectively (or from +3.4 to +5.1 in terms of $\epsilon_{Nd}$). In a Sr–Nd isotopic correlation diagram, their data points plot within the field of the depleted mantle of the “common” type ($^{87}Sr/^{86}Sr \approx 0.7035$, $\epsilon_{Nd} \approx +5$ [92]), which is thought to be the possible source of most subalkaline basalts of mantle plumes (Fig. 6). The calculated $^{147}Sm/^{144}Nd$ isotopic ratios (Table 1) of the rocks range from 0.105 to 0.137 and are much lower than the values assumed for the depleted (0.2148 ± 0.0024) [30] and primitive (0.1967 ± 0.0003) [31] mantle, as is typical of within-plate continental basalts. Note that similar values of this ratio were published for basic volcanics from the southern Baikal neovolcanic area, which was formed in the geodynamic environment of a mantle hotspot [1].

**Table 3.** Sr and Nd isotopic composition of subalkaline basalts from lava rivers of the Dzhavakheti Highland

| Sample | $^{87}Sr/^{86}Sr \pm 2\sigma$ | $^{143}Nd/^{144}Nd \pm 2\sigma$ | $\epsilon_{Nd}$ |
|---|---|---|---|
| *Khrami Flow* | | | |
| YUG-101 | 0.703967 ± 20 | 0.512877 ± 10 | +4.7 |
| YUG-103 | 0.703898 ± 20 | 0.512898 ± 10 | +5.1 |
| *Mashavera Flow* | | | |
| YUG-104 | 0.704165 ± 20 | 0.512810 ± 10 | +3.4 |
| YUG-111 | 0.704257 ± 20 | 0.512830 ± 10 | +3.7 |
| *Kura Flow* | | | |
| YUG-35 | 0.704091 ± 20 | 0.512840 ± 10 | +3.9 |
| YUG-42 | 0.704127 ± 20 | 0.512825 ± 10 | +3.6 |

Note: Rock names, sampling sites, and their position in the vertical sections of the lava rivers are listed in the note for Table 1. The analyzed material is rock groundmasses separated from phenocrysts.

Our results indicate that the compositions most closely approximating mantle magmas are the rocks of the Khrami Flow, which have the lowest $^{87}Sr/^{86}Sr$ and the highest $^{143}Nd/^{144}Nd$ ratios among all subalkaline basalts from the Dzhavakheti Highland (Table 3). These ratios show a linear correlation (Fig. 7) for all of our samples except only sample YUG-111 from the Mashavera Flow near Dmanisi.

In terms of the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios (Fig. 7, Table 3), the subalkaline basalts of the Kura and Mashavera Flows notably differ from the rocks of the Khrami Flow. Certain difference in Sr isotopic composition were also detected between individual basaltic samples of the lava rivers, although the scale of these differences is much smaller. For the Kura Flow, they are commensurable with the analytical errors. Note that there are no systematic differences in the $^{147}Sm/^{144}Nd$ ratios between the subalkaline basalts from various flows (Table 1).

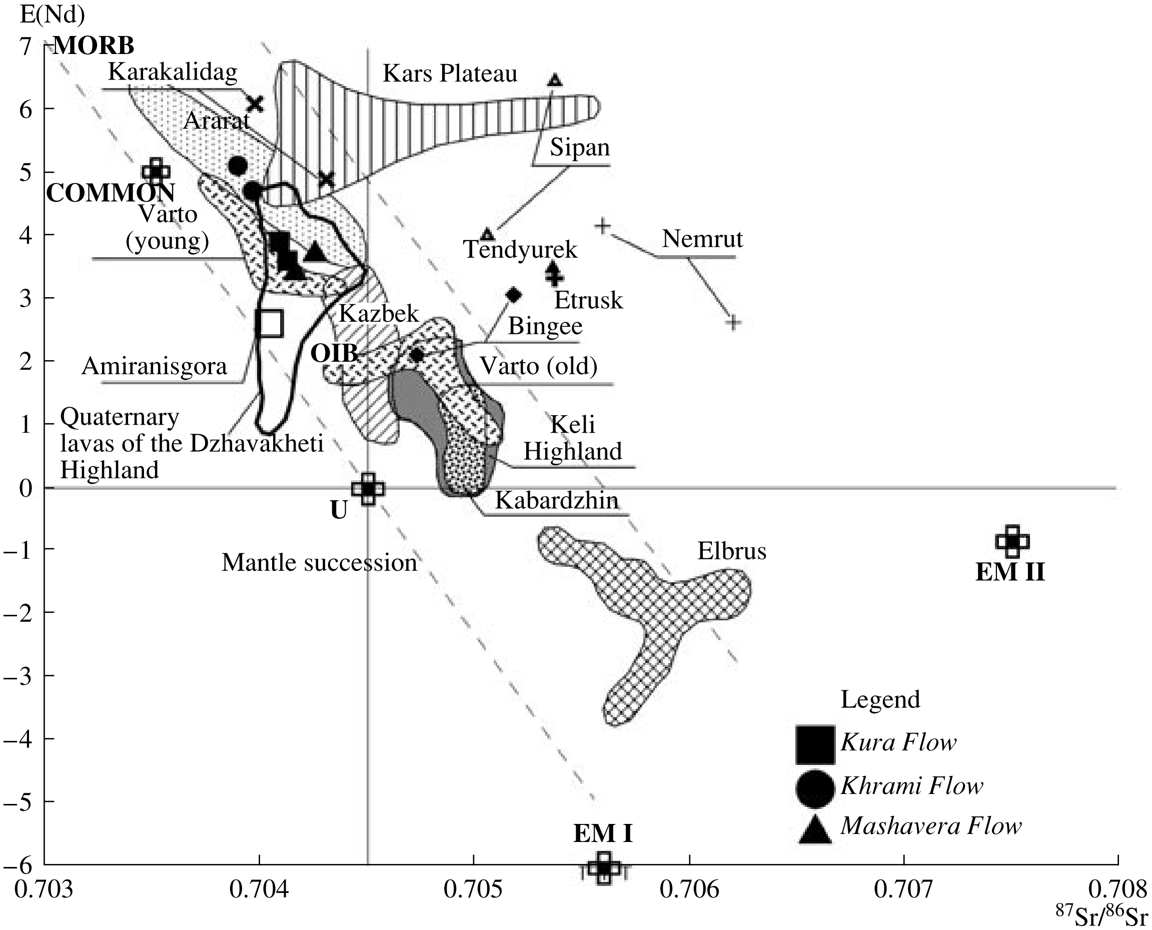

**Fig. 6.** Sr and Nd isotopic compositions of the examined basic lavas from the Dzhavakheti Highland and rocks from some young volcanic centers in the Greater Caucasus and eastern Anatolia. Data on volcanics from the Greater Caucasus are compiled from [8, 10] and those for eastern Anatolia are from [24, 32]. MORB—mid-oceanic ridge basalts; OIB—oceanic-island basalts; COMMON—depleted mantle of most plumes; EM1 and EM2—enriched mantle; U—primitive mantle.

The rocks have Sm, Nd, and Sr concentrations typical of continental basalts and low (10–25 ppm) Rb concentrations. The calculated $^{87}Rb/^{86}Sr$ isotopic ratios (Table 1) of the subalkaline basalts of the Khrami and Kura Flows are remarkably different (by a factor of two on average) from the analogous ratios for the rocks of the Mashavera Flow. This difference is caused by the higher Rb contents in the basalts of the latter flow.

The fact that the lowest $^{87}Sr/^{86}Sr$ and the highest $^{143}Nd/^{144}Nd$ isotopic ratios were identified in the basalts of the Khrami Flow is consistent with the aforementioned petrochemical characteristics of these rocks (their Mg# and Ni contents), which suggest that the rocks are closer to the compositions of the parental mantle magmas than the basalts of the other two lava rivers. Obviously, at the $^{147}Sm/^{144}Nd$ and $^{87}Rb/^{86}Sr$ ratios of the rocks, the older (by 1 Ma) age of the Khrami lava Flow than that of the Kura and Mashavera Flows could not cause the differences between their Sr and Nd isotopic compositions. Neither could these differences be brought about by the differentiation of the magma in a single chamber after the eruption of the Khrami Flow.

Theoretically, at least three principally different scenarios can be proposed for the derivation of the parental melts, all of them satisfactorily consistent with the results obtained on the Sr–Nd systematics of the subalkaline basalts and the variations in the Sr and Nd isotopic compositions in the lava rivers of the Dzhavakheti Highland: (i) the parental melts were derived from mantle sources with different Sr–Nd isotopic signatures; (ii) the parental mantle melts were contaminated and/or mixed with mantle material that was not in isotopic equilibrium with them as a consequence of the vertical heterogeneity of the mantle; and (iii) the parental mantle melts were contaminated with a crustal component, and/or the mantle melts mixed with partial crustal melts.

Available data argue that each of these mechanisms could participate in shaping the chemistries of the rocks or, what is more probable, these mechanisms were combined in a succession of stages. In the latter two situations, it is assumed that the initial mantle melts could already be partly crystalline and were contaminated (or mixed) with a compositionally contrasting material that also contained solid phases (perhaps, plagioclase and pyroxene with reference to our rocks). This can readily account for, for example, the differences in the Sr and Nd isotopic compositions between the phenocrysts and rocks as a whole and for the occurrence of unequilibrated phenocryst mineral assemblages in the compositionally contrasting (from andesite to rhyolite) rocks of other volcanic centers in the Caucasus [8 and others].

The "pollution" of the initial mantle melts with geochemically distinct material follows, first of all, from the Sr isotopic data. As can be seen from Fig. 7, there are statistically significant differences (which notably extend outside the analytical errors) between the Sr isotopic compositions of subalkaline basalts from the lower and upper parts of the Khrami and Mashavera lava rivers. The geochemical arguments in support of the contamination of the parental melts with crustal material include the fact that the "mantle" subalkaline basalts show typically "crustal" concentrations of Ni, Zr, Ga, and Ba and the Ba/Nb, Ba/Sr, Zr/Y, and other ratios. Some varieties of the subalkaline basalts exhibit petrographic evidence of their possible hybrid genesis, for example, olivine microphenocrysts armored by clinopyroxene rims (in the Mashavera Flow).

Note that some geological observations testify that the lava rivers and even individual flows could be erupted at the Dzhavakheti Highland from different volcanic edifices. This does not rule out the possibility of the existence of a single magma chamber but suggests that separate intermediate or near-surface chamber could exist with compositionally distinct host rocks. This idea finds support, for example, in the fairly broad range of the compositions and ages of the rocks composing the basement of the Dzhavakheti Highland, which is made up of Paleozoic granitoids, and metamorphic schists, Jurassic–Paleogene volcanic rocks, and Cretaceous limestone.

We do not rule out the possibility of the derivation of the parental melts from different mantle sources that they could be contaminated with mantle material that was not in equilibrium with them. At the same time, we believe that the Sr and Nd isotopic compositions of lava rivers in the Dzhavakheti Highland were controlled, first of all, by the contamination and/or mixing of the basaltic melts with crustal material that was not in geochemical equilibrium with them. With regard for the general similarities between the mineralogical and chemical compositions of the rocks of the basaltic rivers and very insignificant differences between their Sr–Nd isotopic characteristics, it should be admitted that this contamination should have been generally insignificant. One of the possible contaminants could be, for example, Cretaceous carbonate rocks, which are known to have low Sm, Nd, and Rb concentrations and elevated (by factors of 1.5–2) Sr concentrations (compared to those in continental basalts) at low $^{87}Sr/^{86}Sr$ isotopic ratios (no higher than 0.708–0.709).

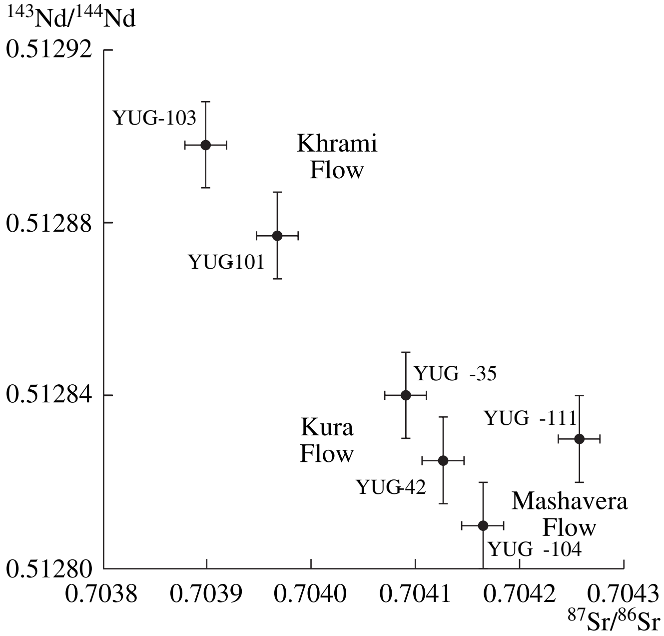

**Fig. 7.** Sr–Nd isotopic correlation diagram for basaltic lava rivers at the Dzhavakheti Highland.

Our isotopic characteristics obtained previously [10, 11] for rocks from the Amiranisgora Middle Pliocene extrusion ($^{87}Sr/^{86}Sr = 0.7040$, $\epsilon_{Nd} = +2.6$) and acid Quaternary lavas from the Samsari Range ($^{87}Sr/^{86}Sr =$ 0.7040–0.7044, $\epsilon_{Nd}$ from +1.0 to +4.6), which are, respectively, the earliest and the latest stages of young magmatism at the Dzhavakheti Highland, are generally close to the Sr and Nd isotopic characteristics of Pliocene basalts from the lava rivers (Fig. 6). However, the contamination of the acid lavas was more significant, particularly in terms of Nd isotopic composition.

As can be seen in Fig. 6, the Sr–Nd isotopic characteristics of volcanic rocks from the Dzhavakheti Highland are close to the analogous characteristics of effusive from Ararat and Varto volcanoes, eastern Anatolia, and to those of the youngest volcanic centers in the Kazbek area in the Greater Caucasus. The data points of rocks from these volcanic centers define, together with the points of volcanics from the Dzhavakheti Highland, a field in a Sr–Nd diagram that generally overlaps the mantle correlation field.

## CONCLUSIONS

Our isotopic–geochemical results obtained on three lava rivers at the Dzhavakheti Highland testify to at least two phases of Pliocene basaltic volcanism, which occurred in the area at 3.25–3.10 and 2.20–2.05 Ma. During the former phase, subalkaline basaltic lavas erupted from volcanic centers in the northern part of the Dzhavakheti Highland flowed down the ancient valley of the Khrami River. In the Late Pliocene, centers of basic volcanism were likely situated mostly in the Dzhavakheti Range and gave rise to the Mashavera and Kura lava rivers. Our K–Ar dates led us to ascribe the rocks composing lava rivers at the Dzhavakheti Highland to the Akhalkalaki Formation. With regard for our earlier isotopic data [10, 11], it can be concluded that volcanism at the Dzhavakheti Highland occurred in the Anthropozoic exclusively within the Samsari Range.

Our isotopic and petrological–geochemical data suggest that the leading role in the petrogenesis of the basic lavas of the Dzhavakheti Highland was played by the processes of fractional crystallization and contamination (and/or mixing) of the parental melts with geochemically distinct material, sometimes, of possible crustal nature. We believe that the "pollution" (most often, contamination) occurred during the differentiation of the melts [33]. The youngest subalkaline basalts and still younger Quaternary moderately acid volcanics were contaminated more strongly.

The comparison of the isotopic and geochemical data obtained for the volcanics of the Dzhavakheti Highland and analogous data on rocks from other centers of the youngest volcanism in the Caucasian sector of the Alpine Belt, information on the tectonic environments in which these rocks were produced, and the results of the seismic sounding of the regional mantle [34] indicate that the distinctive features of magmatism in the Caucasus in the Late Cenozoic can be adequately explained by a combination of collisional and initial rifting environments [7] or by a combination of a within-plate environment of a hot mantle filed and continent–continent collision [8].

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