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GEOCHEMISTRY

Chronology of Quaternary Volcanism of the Keli Highland, Greater Caucasus: Evidence from K–Ar Isotopic Dating

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The present paper is the continuation of systematic isotopic–geochronological study of recent volcanism in the Caucasus. We scrutinized volcanic rocks of the Keli Highland to determine the total duration and peak activity of volcanism in this region and correlate the distinguished phases of Quaternary magmatism with phases of other volcanic centers of the Greater and Lesser Caucasus.

The Keli Highland, located on the southern slope of the Main Caucasus Ridge west of the Krestovyi Pass, is one of the largest centers of recent volcanism within the Kazbek neovolcanic area of the Greater Caucasus. Unlike the adjacent Kazbek and Elbrus centers with large Quaternary polygenic stratovolcanoes, the Keli Highland (<150 km^2 in area) contains about 30 separate, mainly monogenic volcanic edifices represented by lava volcanoes, extrusive domes, and scoria cones. The development of large-scale volcanism makes the Keli Highland unique among other neovolcanic centers of the Greater Caucasus. Therefore, deciphering its evolution has a fundamental significance for constructing the time scale of Late Cenozoic magmatism in the entire Caucasus.

Volcanoes of the Keli Highland make up separate groups at the sources of the Ksani, Belaya Aragvi, Bol'shaya and Malaya Liakhvi rivers west of the Krestovyi Pass (Fig. 1). Lava flows smoothed the ancient relief and formed several mountainous plateaus (altitude 2000–3200 m) with volcanic cones rising above them from 100 to 600 m. The largest peak is Didi Nepiskalo Volcano (3694 m). The basement of the Keli Highland is composed of Middle–Late Jurassic and Early Cretaceous flysch deposits (sandstones and shales).

Geomorphologically, the Keli Highland is subdivided into several parts. The large Tsitelikhati Volcano rises in the southernmost part of the area. Its lava flows extend over several kilometers along the Ksani River valley. The Keli Plateau, composed of lavas of the Severnyi and Yuzhnyi Narvankhokh volcanoes and several extrusive domes, is located in the northern area near Lake Keli and upper reaches of the Aragvistavi River. The eastern part of the Keli Highland consists of the Patara Nepiskalo Caldera, as well as Didi Nepiskalo, Keli, Zapadnyi and Vostochnyi Khorisar, and other volcanoes. The N–S-trending Kai Don volcanic range (Fidarkhokh, Sharkhokh, Severnyi Shadilkhokh, Yuzhnyi Shadilkhokh, and other volcanoes) is located at the source of the Bol'shaya Liakhvi River in the western area. West of this range, one can see two large (Ermani–Akhubata in the south and Khodzhi in the north) lava flows extending along the riverine paleovalleys. The Knogo lava volcano and small, destroyed Knogo 2 extrusion are located side by side at the sources of the Malaya Liakhvi River [1].

The detailed study of volcanism of the Keli Highland was initiated by Skhirtladze [2], who described most volcanoes of the region and distinguished ancient (preglacial) and young (postglacial) lavas [2]. Based on geomorphological and petrochemical data, volcanic rocks of the Keli Highland were stratigraphically subdivided and detailed geological maps were compiled [3–5]. Practically all researchers indicated the very young (Quaternary) age of these volcanic rocks. In 1999, we published the first datings indicating the Late Quaternary age of volcanic rocks of the Keli Highland [6]. The bulk K–Ar data on the rocks from the Didi Nepiskalo, Vostochnyi Khorisar, Sharkhokh, and Yuzhnyi Shadilkhokh volcanoes are between 200 and 20 ka. As was shown in our work [7], the bulk K–Ar ages on Quaternary lavas can be overestimated owing to the presence of excess ^{40}Ar in phenocrysts. At the next stage of investigation, results of which are reported in the present communication, volcanic rocks of the Keli Highland were dated only based on groundmass separated from phenocrysts. We obtained 30 new K–Ar datings, which mainly characterize objects in the western part of the Keli Highland, as well as the large Tsitelikhati and Patara Nepiskalo volcanoes in the southern and eastern parts, respectively (Fig. 1).

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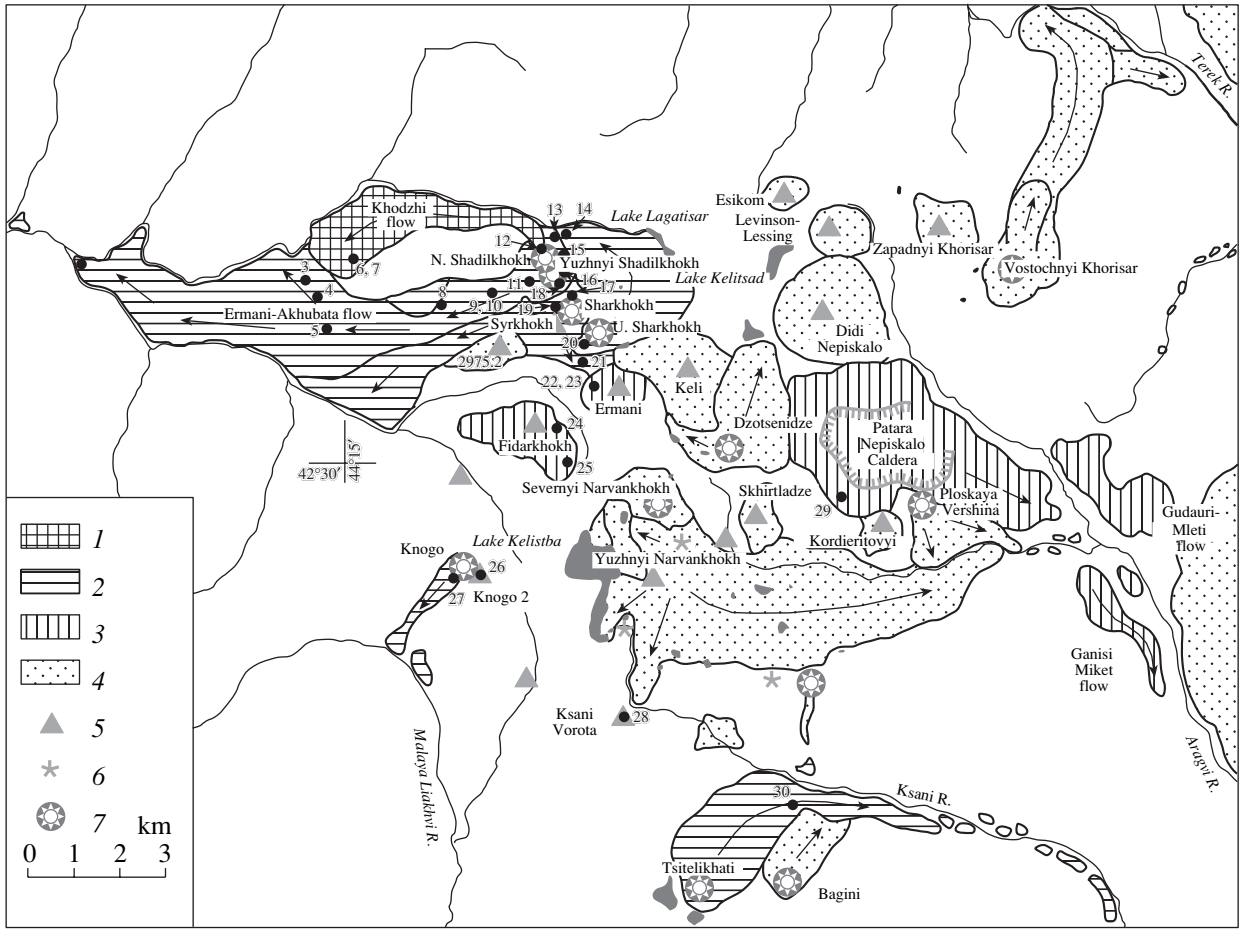

Fig. 1. Geological map of the Keli volcanic highland (compiled by author using data from [3–5]). (*1–4*) Quaternary lavas of corresponding activity phases: (*1*) III (Late Neopleistocene–Holocene), (*2*) II (Late Neopleistocene), (*3*) I (Middle Neopleistocene), (*4*) undated; (*5*) extrusions; (*6*) scoria cones; (*7*) lava volcanoes. Stratigraphic subdivision of volcanic rocks is based on the obtained geochronological data. Sample numbers: (1) YuO-19, (2) YuO-20, (3) YuO-14, (4) YuO-15, (5) YuO-16, (6) YuO-18, (7) YuO-17, (8) YuO-5, (9) YuO-3, (10) YuO-4, (11) YuO-13, (12) YuO-1, (13) YuO-6, (14) YuO-2, (15) YuO-8, (16) YuO-9, (17) YuO-11, (18) YuO-10, (19) YuO-12, (20) KE-17, (21) KE-16, (22) Ke-13, (23) KE-14, (24) KE-12, (25) KE-8, (26) KE-53, (27) KE-54, (28) KE-4, (29) KE-82, (30) KE-1.

As is evident from Fig. 2, all studied volcanic rocks of the Keli Highland chemically correspond to calc-alkaline dacites with the following composition (wt %): SiO_2 63.5–71.9, ($K_2O + Na_2O$) 5.2–6.4, K_2O (1.6–2.2). They have porphyric (more rarely, aphyric) texture with pilotaxitic or intersertal groundmass. Practically all dacites contain plagioclase (labrador–andesine) and orthopyroxene phenocrysts. Amphibole, subordinate biotite and quartz, and occasional clinopyroxene are also observed among phenocrysts. Microlites of the groundmass are represented by plagioclase (more often, andesine), orthopyroxene, rare amphibole, and opaque minerals (magnetite and ilmenite).

The applied modification of the K–Ar method was specially designed by the authors at the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (Moscow) for the study of recent magmatic rocks. The description and some results of the implication of this method are reported in [6, 7, and others].

Results of dating volcanic rocks of the Keli Highland are given in the table. Most of the studied volcanoes and lava flows are represented by several samples. Since K–Ar ages determined for individual samples overlap within analytical errors, the table presents weighed average values that more accurately characterize the age of individual volcanoes and flows than datings on individual flows.

Obtained K–Ar data fall within two age ranges (225–175 and 130–60 ka). In addition, the ^{40}Ar content in three samples (YuO-1, YuO-17, YuO-18) turned out to be lower than detection limit, indicating the very young age of these rocks and a lower (or maximum possible) age limit of 30 ka. These data suggest the following conclusions. First, volcanic activity in the Keli Highland occurred in two (Middle Neopleistocene and Late Neopleistocene) phases. Second, a later (Late

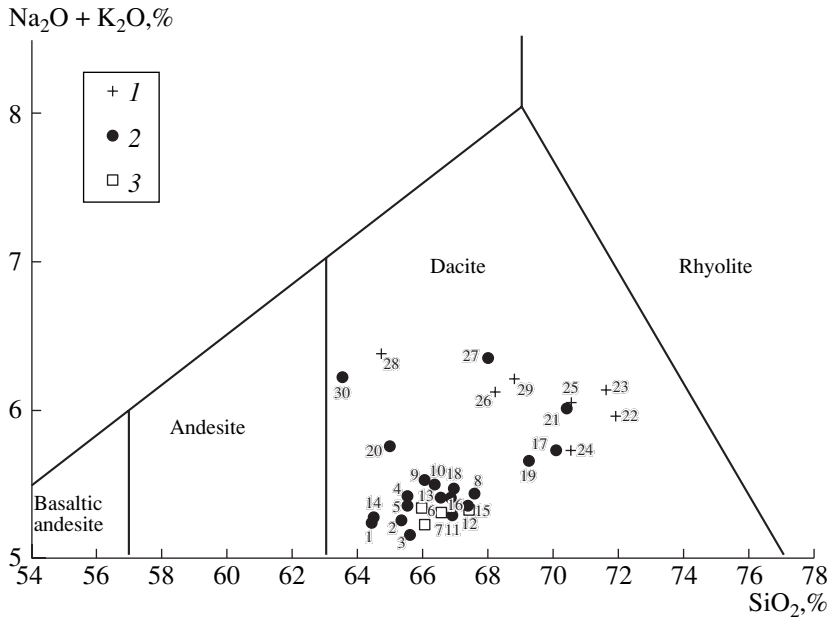

Fig. 2. The SiO_2–($Na_2O + K_2O$) plot for volcanic rocks of the Keli Highland. (1) Phase I; (2) Phase II; (3) Phase III. Sample numbers are as in Fig. 1.

Neopleistocene–Holocene) volcanic phase also existed in the study region. It should be noted that eruptions of this time are reliably marked by isotopic datings on the Kazbek and Elbrus volcanic centers [6–8]. Unfortunately, the three youngest samples mentioned above are strongly contaminated by atmospheric ^{40}Ar (up to 99.9 wt % of total ^{40}Ar), making it impossible to obtain more reliable K–Ar datings. Therefore, additional investigations are required to confirm the third, youngest phase of the volcanic activity at the Keli Highland. According to obtained isotopic data, the youngest magmatism in the region lasted ~200 ka.

Let us consider the results in detail. The first, Middle Pleistocene (225–175 ka) phase of volcanic activity produced the Fidarkhokh (225 ± 20 ka), Ermani (200 ± 75 ka), Knogo 2 (175 ± 50 ka), and Ksani Vorota (180 ± 40 Ka) extrusive centers. Extrusive volcanism is commonly represented by dacites, which are higher in SiO_2 and alkali contents than volcanic rocks of the second phase (Fig. 2). Magmatic melts, which produced the volcanic rocks of the first phase, were presumably very viscous, resulting in the formation of different-sized extrusive bodies rather than lava volcanoes. All dated extrusive domes bear traces of glacial reworking and are strongly disrupted. Obtained isotopic datings are well consistent with geomorphological data, which suggest the Middle Neopleistocene–initial Late Pleistocene age for extrusive volcanoes of the Keli Highland [3–5]. The eastward-facing Patara Nepiskalo Caldera (2–3 km across) also formed about 200 ka ago (195 ± 40 ka), probably owing to the activity of a large polygenic lava volcano, the flows of which extend down the valleys of the Aragvi (Ganisi–Miket flow) and Baidara rivers.

The second magmatic phase (130–60 ka ago) at the Keli Highland is marked by decrease of SiO_2 and alkali contents. Lava volcanoes of that time produced large flows, some of which (Ermani–Akhubata, and Tsitelikhati) are traced over more than 10 km. No extrusive volcanism occurred at that time. The beginning of Late Neopleistocene activity (about 130–100 ka ago) was primarily related to the activity of the Sharkhokh (130 ± 35 ka) and, possibly, Knogo (65 ± 65 ka) volcanoes, the eruption products of which have the most acid composition among volcanic rocks of this phase. Lava flows of Sharkhokh Volcano extended mainly westward along the paleovalley of the Ermani Don River and were subsequently overlain by the younger lavas (Fig. 1). We did not find basaltic andesites described by Skhirtladze [2] at the base of the volcanic sequence on the southern slope of the volcano. Our observations show that the lowermost horizon of volcanic sequence in the upper reaches of the Ermani Don River is represented by a horizon of aphyric platy dacitic lavas, which are clearly distinguished in the precipice on the right wall of the valley between the Ermani extrusion and unnamed extrusion located at an altitude of 2975.2 m. Measured ages (100 ± 35 ka) and chemical composition (Fig. 2) suggest that these rocks erupted from Sharkhokh Volcano. Thus, lavas of this volcano moved to both west and south in the Ermani Don River valley and enveloped the older extrusions. The Knogo Volcano, the products of which are chemically similar to rocks of the extrusive domes of the first phase (Fig. 2), produced a

Results of K–Ar isotopic dating of Quaternary volcanic rocks of the Keli Highland

Sample no.	Geological object	K, %, ±σ	$^{40}Ar_{rad}$, ng/g, ±σ	$^{40}Ar_{air}$, % in sample	Age, ka, ±2σ
KE-4	Ksani Vorota Volcano (3015.0 m)	1.76 ± 0.02	0.022 ± 0.002	91.2	180 ± 40
KE-8	Fidarkhokh Volcano	1.91 ± 0.02	0.027 ± 0.002	82.6	205 ± 30
KE-12	The same	1.77 ± 0.02	0.030 ± 0.002	85.3	245 ± 30
	Weighed average values (KE-8, KE-12)				**225 ± 20**
KE-13	Ermani Volcano (3304.2 m)	1.59 ± 0.02	0.022 ± 0.007	99.1	200 ± 120
KE-14	The same	1.60 ± 0.02	0.022 ± 0.006	99.1	200 ± 100
	Weighed average values (KE-13, KE-14)				**200 ± 75**
KE-53	Knogo 2 Volcano	1.52 ± 0.02	0.018 ± 0.002	94.7	175 ± 50
YuO-11	Sharkhokh Volcano	1.46 ± 0.02	0.010 ± 0.004	99.4	100 ± 80
YuO-12	The same	1.54 ± 0.02	0.015 ± 0.002	94.2	135 ± 40
	Weighed average (YuO-11, YuO-12)				**130 ± 35**
KE-16	Lavas of upper reaches of the Ermani Don River (Sharkhokh Volcano)	1.44 ± 0.02	0.010 ± 0.002	94.5	100 ± 35
KE-17	Vostochnyi Sharkhokh Volcano (3329.1 m)	1.79 ± 0.02	0.009 ± 0.0025	95.0	75 ± 40
YuO-2	Lava flow of the Vostochnyi Sharkhokh Volcano (2239.1 m)	1.80 ± 0.02	0.007 ± 0.002	98.3	60 ± 35
YuO-6	Yuzhnyi Shadilkhokh Volcano (3261.2 m)	1.94 ± 0.02	0.012 ± 0.006	99.5	90 ± 85
YuO-8	The same	1.70 ± 0.02	0.009 ± 0.003	96.1	80 ± 45
YuO-9	″	1.81 ± 0.02	0.012 ± 0.003	94.0	100 ± 45
YuO-10	″	1.84 ± 0.02	0.008 ± 0.002	98.8	65 ± 35
YuO-13	″	1.92 ± 0.02	0.009 ± 0.004	99.4	70 ± 55
	Weighed average values (YuO-6, YuO-8, YuO-9, YuO-10, YuO-13)				**80 ± 20**
YuO-3	Beginning of the Verkhnii Ermani–Akhubata flow	1.82 ± 0.02	0.009 ± 0.0015	89.9	70 ± 25
YuO-4	The same	1.85 ± 0.02	0.006 ± 0.002	97.5	50 ± 35
YuO-5	″	1.90 ± 0.02	0.008 ± 0.002	95.2	60 ± 35
	Weighed average values (YuO-3, YuO-4, YuO-5)				**60 ± 20**
YuO-14	Middle part of the Verkhnii Ermani–Akhubata flow	1.74 ± 0.02	0.010 ± 0.003	99.0	80 ± 45
YuO-15	The same	1.74 ± 0.02	0.011 ± 0.002	96.5	90 ± 35
YuO-16	″	1.76 ± 0.02	0.013 ± 0.003	93.4	105 ± 45
	Weighed average values (YuO-14, YuO-15, YuO-16)				**90 ± 25**
YuO-19	Termination of the Verkhnii Ermani–Akhubata flow	1.78 ± 0.02	0.007 ± 0.002	99.0	55 ± 30
YuO-20	The same	1.80 ± 0.02	0.010 ± 0.006	99.6	85 ± 85
	Weighed average values (YuO-19, YuO-20)				**60 ± 30**
KE-1	Tsitelikhati Volcano	1.80 ± 0.02	0.011 ± 0.003	94.8	90 ± 50
KE-54	Knogo Volcano	1.63 ± 0.02	0.007 ± 0.004	99.7	65 ± 65
KE-82	Patara Nepiskalo Caldera	1.50 ± 0.02	0.020 ± 0.002	88.4	195 ± 40
YuO-1	Severnyi Shadilkhokh Volcano	2.11 ± 0.02	Not detected	≥99.9	30
YuO-17	Khodzhi flow	1.84 ± 0.02	Not detected	≥99.9	30
YuO-18	The same	1.76 ± 0.02	0.003 ± 0.003	99.8	25 ± 25

relatively small (up to 5 km long) lava flow along the Malaya Liakhvi River valley.

Two lava volcanoes formed in the western part of the Keli Highland after cessation of the activity of Sharkhokh Volcano. A lava flow from the Vostochnyi Sharkhokh Volcano (Sample YuO-2, 60 ± 35 ka; Sample KE-17, 75 ± 40 ka) formed a small plateau near Lake Lagatisar. Products of this volcano are characterized by the lowest SiO_2 content among volcanic rocks in the western part of the Keli Highland (Fig. 2). A lava flow from the Yuzhnyi Shadilkhokh Volcano (80 ± 20 ka) buried the earlier lavas of Sharkhokh Volcano and descended westward (Ermani–Akhubata flow). Obtained datings range from 60 ± 30 ka (initial eastern part of the flow) to 90 ± 25 ka (middle part) and 60 ± 30 ka (terminal part). The western termination of this flow was found near the Settlement of Sgubiri 13 km from the effusion center. It is interesting that rocks of the Ermani–Akhubata flow in the initial eastern part are chemically similar to those of the Yuzhnyi Shadilkhokh effusion center and show a regular decrease in SiO_2 content with increasing distance from the effusion center.

Lava of the second phase, which produced the large Tsitelikhati Volcano (90 ± 50 ka), moved along the Ksani River paleovalley. This lava is presently preserved as individual remnants at the terraces along both banks of the river.

Thus, the Late Neopleistocene volcanic activity differed from Middle Neopleistocene one in character and scale. Composition of eruption products also varied with time.

The latest volcanic activity in the western Keli Highland is related to the Severnyi Shadilkhokh Volcano. This volcano postdated eruptions of Yuzhnyi Shadilkhokh Volcano on its northern slope, unambiguously indicating the younger age. The erupted lavas flowed down the Deskokhirdon River valley (Khodzhi flow). It was noted earlier that this flow consists of trachydacites [2]. However, our data indicate that volcanic rocks of the flow are typical moderately alkaline dacites. They contain a small amount of biotite phenocrysts, which are known only in lavas of the Didi Nepiskalo Volcano in the Keli Highland. Three K–Ar datings on rocks of the Severnyi Shadilkhokh and Khodzhi flows yielded a very young age. However, as mentioned above, we cannot reliably distinguish the activity of this volcano as an independent phase due to large error of isotope data.

Obtained geochronological data indicate that the Late Quaternary volcanic activity in the western Keli Highland migrated northward along the sublongitudinal Fidarkhokh–Sharkhokh–Yuzhnyi Shadilkhokh–Severnyi Shadilkhokh Range, which presumably marks a deep-seated fault. The migration was accompanied by a gradual decrease of SiO_2 content and alkalinity (mainly Na_2O) in the melts, thus indicating a higher contribution of mantle material to parental melts. The data suggest that the Severnyi Shadilkhokh Volcano region is the most hazardous area in terms of possible rejuvenation of volcanic activity in the western Keli Highland.

The magmatic phases of the Keli Highland based on the K–Ar data coincide with those of other large recent volcanic centers at the Greater Caucasus, such as Elbrus (225–170, 110–70, and 35–0 ka) [8] and Kazbek (450, 235–185, <50 ka) [6].

Thus, the Keli Highland is a large Late Quaternary volcanic center, which evolved for the last 200 ka. The initial phase of volcanic activity (225–175 ka ago) is recorded as extrusive bodies in different parts of the region. In Late Neopleistocene (130–60 ka ago), volcanic activity in the region reached a maximum with the eruption of mainly lava volcanoes that formed lava plateaus and valley flows. The Severnyi Shadilkhokh Volcano and related Khodzhi flow are the youngest edifices in the western Keli Highland. However, additional data are required to reliably support their Holocene age.

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