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Geology and zircon U-Pb geochronology of the Mtkvari pyroclastic flow and evaluation of destructive processes affecting Vardzia rock-cut city, Georgia

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ABSTRACT

Late Cenozoic subaerial volcanic highland crop out in Eastern Anatolia and the western part of the Lesser Caucasus, part of which, located in Georgia, is known as Samtskhe-Javakheti. The Samtskhe-Javakheti highland (~4500 km^2) is cut by the Mtkvari river canyon, where, into the thick pyroclastic flow in twelfth-century is hewn the unique city Vardzia. Despite this, characteristics of the pyroclastic flow, such as scale, source, type, genesis, isotopic age and evaluation of destructive geological processes of the Vardzia rock-cut city have not been well studied. Our research has shown that the Mtkvari pyroclastic flow is exposed at a distance of about 35 km from the Karzameti fortress to the Khertvisi fortress, it is inclined northward by 2-4°, and its thickness increases to the north from 40 m up to 80 m. These rocks represent welded, weakly welded and non-welded ignimbrites of the andesitic-dacitic composition. Isotopic parameters of these rocks (εNd varies between +3 and + 4, and $^{87}Sr/^{88}Sr$ between 0,70341 and 0.70450) indicate that they originated as a result of fractionation of mantle derived melts. As a result of field work, we interpret the Mtkvari ignimbrites as products of megacaldera collapse (modern Niala fields), which nowadays is filled by postcaldera domes of andesitic composition and Quaternary sediments. The result of zircon dating using the U-Pb method with LA-ICP-MS technology is 7.52 ± 0.21 Ma, which corresponds to the Late Miocene epoch. Geological research of the Vardzia rock-cut city has revealed that it is hewn into weakly welded ignimbrites and for which reason these rocks are under the intensive affecting of weathering and erosion processes. At the same time, the city is completely included in a tectonic block of 900 m length which is detached from the main body of rocks and is gradually subsiding towards the Mtkvari canyon. Nowadays Vardzia block is lowered by 30.6 m in comparison with bordering blocks. In addition, this block is split into several micro-blocks by a joint set, thus reducing its stability. The situation is worsened by the active deep fault running along the Vardzia rock-cut city, which represents a potential earthquake source.

1. Introduction

In Eastern Anatolia and the western part of the Lesser Caucasus, thick, subaerial Late Cenozoic volcanic rocks are exposed, which occupy more than 100, 000 km^2 of modern Georgia, Turkey, and Armenia. These formations contain invaluable information about the geological evolution of the region and therefore they have been objects of intensive study (Skhirtladze, 1958; Sengor et al., 2003; Tutberidze, 2004; Keskin, 2007; Sheth et al., 2015; Lin et al., 2017).

In medieval Georgia and the Byzantine Empire, both ritual and residential types of buildings have been carved out into fine-grained tuffs of these volcanic formations. Nowadays, their preserved parts represent important historical-cultural heritage. Because of the weak structure of the aforementioned rocks, buildings hewn into them are under the influence of natural destructive processes and present serious geotechnical problems (Yilmazer, 1995; Topal and Doyuran, 1997).

In Georgia, the rock-cut city Vardzia stands out among these types of buildings with its historical-cultural importance and size, hewn into thick ignimbrites on the left side of Mtkvari river canyon, between the villages of Vardzia and Chachkari (Fig. 1). The Vardzia rock-cut city was built by the King Giorgi III and his daughter Queen Tamar at the end of the 12th century and it comprised a city, religious buildings and defensive fortifications.

The complex consists of 13 floors with a total area of over 5000 m^2 and includes 542 dwellings, among them 28 special storage facilities for wine (Marani), 3 pharmacies, and 5 Christian churches. In 1283, after a strong earthquake, the cave complex was severely damaged, but it did not cease its operation. In 1553, the Persian army destroyed it, after

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Fig. 1. Front view of Vardzia rock-cut city, which is hewn into Mtkvari ignimbrites flow.

which the complex was abandoned. In 2007, Vardzia, together with Khertvisi fortress, was designated by UNESCO as a World Heritage Site.

In this paper we present study results about scale, origins, geometry, tectonics, petrography and zircon U-Pb dating of Mtkvari ignimbrites flow. This, we believe, will contribute to the research of Late Cenozoic volcanism of the region. Besides, as a result of conducted research, peculiarities of the geological structure of the Vardzia rock-cut city were unveiled, and the resulting hazards should be taken into account in order to design risk mitigation measures.

2. Methods and material

Field research was based on structural geology methods as well as physical volcanology approach. During the field work more than 270 samples were taken to conduct the petrographical, geochemical, and isotopic study. All the samples were located on a topographic map using GPS. To determine exact elevation and vertical displacement of the layers, a differential high accuracy DGPS – Leica Viva GS15 was used. Analysis of the samples was conducted in various laboratories in Georgia and Taiwan.

From the three parts of the Mtkvari pyroclastic flow, 15 samples have been taken, each weighing 3–4 kg, from which up to hundred zircon crystals were separated and 72 were dated. The zircons were dated using the U-Pb method at National Taiwan University, Taipei, Taiwan. After mounting the zircons on epoxy resin, cathodoluminescence (CL) images were taken to check the internal textures of the zircon grains and selecting the suitable positions for in-situ U-Pb analyses. Measurements of zircon U-Pb isotopes were performed using an Agilent 7500s ICP-MS coupled with a New Wave UP213 laser ablation system equipped at the Department of Geosciences, National Taiwan University following the analytical procedures by Chiu and others (Chiu et al., 2009).

3. Regional geology

The Caucasus represents a Phanerozoic collisional orogen formed along the southern Eurasian continental margin and stretches for about 1200 km from the Caspian to the Black Sea (Fig. 1). It is an expression of collision between the Arabian and Eurasian plates. Three major tectonic units are distinguished in the Caucasus region: The Greater and the Lesser Caucasian mobile belts and Inner Transcaucasus Massif. Exhumation processes in the Lesser Caucasus started at 11-10 Ma and 9-8 Ma both the Greater and the Lesser Caucasus were exposed, which were separated by marine sedimentary basin (Gamkrelidze, 1986).

Strong subaerial volcanic activity in Eastern Anatolia and the western Lesser Caucasus started from Middle Miocene, which lasted until Holocene. This volcanic activity shaped vast volcanic highlands, present in the Georgian, Turkish and Armenian neighboring territories. Part of the highland, located in Georgia, is known as the Samtskhe-Javakheti volcanic highland (~4500 km^2), which is cut by the Mtkvari river canyon, where thick ignimbrites resulting from pyroclastic density currents are exposed.

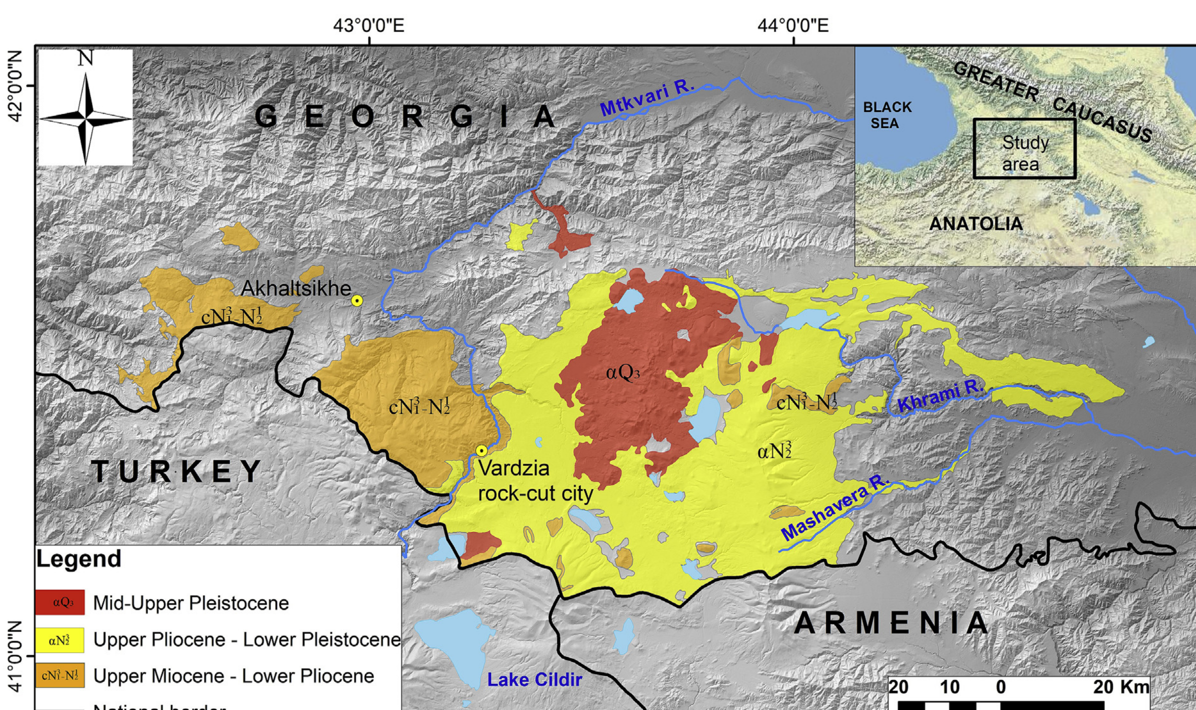

Fig. 2. Schematic geological map of the Samtskhe-Javakheti volcanic highland.

3.1. Samtskhe-Javakheti volcanic highland

The Samtskhe-Javakheti volcanic highland (Fig. 2) occupies more than 4500 km^2 in Georgia and discordantly covers Mid-Eocene tuff-breccias, sandstones and argillites. According to the tectonic zonation of Georgia, it is divided into two blocks: Erusheti and Javakheti (Gamkrelidze et al., 2002). The mean elevation of the highland is about 1500–2000 m above the sea level; individual volcanic edifices, however, reach up to 3000 m (Gumbati – 2996 m, Didi Abuli – 3305 m). The highland contains a complex geological structure and has been studied extensively (Skhirtladze, 1958; Ustiev and Jigauri, 1971; Tutberidze, 2004).

The genesis of this volcanic highland is a matter of debate. Some modern researchers believe that its formation was driven by slab break off followed by gradual subduction and melting in the mantle (Yilmaz et al., 1998). Some others think that the formation of this volcanic highland was the result of decompression melting of the asthenosphere (Keskin, 2007) or asthenospheric upwelling caused by the litospheric delamination (Neill et al., 2013; Lin et al., 2017). Other scholars argue that mantle plumes and the related mantle flow played an important role in its formation (Ershov and Nikishin, 2004).

Three main stages of magmatic activity have contributed to the formation of the highland: 1. Upper Miocene-Lower Pliocene, when huge, 700–1000 m thick dacite-andesitic volcanic tuffs and basaltic-andesitic lava flows were formed; 2. Upper Pliocene-Lower Pleistocene, when 120–270 m thick continental flood basalts were formed and 3. Mid-Upper Pleistocene, when the Abul-Samsari intraplate volcanic ridge was shaped (Okrostsvaridze et al., 2016c).

The ignimbrites of the Mtkvari river canyon are spatially and genetically related to the first aforementioned phase of magmatic activity. Volcanics of this phase in the geological literature is known as the Goderdzi formation (Skhirtladze, 1958). The Goderdzi formation (Fig. 3) in the Vardzia area, is divided into two parts: the lower part with a thickness of 200–250 m is made up of pyroclastic material, in which mainly dark, weakly cemented coarse-grained clasts of hypersthene and two-pyroxene-bearing andesitic and andesitic-dacitic composition dominate. At some parts of this coarse-grained tuff formation one can notice thin-layered basaltic-andesitic and pyroxene-bearing andesitic lava-flows. This part is overlain by a 40–80 m thick whitish layer of the andesitic-dacitic Mtkvari ignimbrites.

Mid-Upper Pleistocene: andesitic Abul-Samsari volcanic ridge; Upper Pliocene-Lower Pleistocene 100–280 m thick continental flood basalts and dacites of the Javakheti ridge; Upper Miocene-Lower Pliocene: andesitic pyroclastic rocks and basaltic-andesitic lava flows (700–1000 m).

On top of the Mtkvari ignimbrites, without any gaps, can be observed another thick layer of coarse-grained lithic breccia of two-pyroxene-bearing andesitic, pyroxene-hornblende-bearing andesitic-dacitic and hornblende-biotite-bearing dacitic composition. This part of the formation is 700 m and sizes of the individual pyroclastic fragments are bigger than in the lower part, diameters of which sometimes exceed 1 m. On the whole, the thickness of the Goderdzi formation reaches 900–1000 m (Skhirtladze, 1958).

SiO_2 content of the Goderdzi formation rocks changes from 58% to 65%, however, there is no Europium anomaly in rare earth element distribution patterns, which points to the lack feldspar of fractional crystallization in the magma chamber. Isotopic studies of this formation show that εNd values are positive and vary between +2 and + 4, and $^{87}Sr/^{88}Sr$ ratios vary between 0,7034 and 0.7045. Based on these data we assume that the rocks are the result of fractionation of mantle derived melts. U-Pb ages of zircons from the Goderdzi formation varies between 8 and 7 Ma (Lin et al., 2017).

Large amounts of eruptive material, rhythmic alternation of the different types of volcanics, noticeable sizes of lithic breccias (sometimes > 1 m), thick volcanic ash layers (up to 3 m), vast distribution of pyroclastic flow deposits and other factors make it apparent that the Goderdzi formation is the result of caldera-forming eruptions. One of those eruptions, we believe, was responsible for the formation of the Mtkvari ignimbrites (Okrostsvaridze and Popkhadze, 2016).

On the basis of field work, using physical volcanology techniques, we suppose that the magmatic center which produced the rocks of the Goderdzi formation was a megavolcano, located near the Georgia-Turkey border, in the districts of Akhaltsikhe and Ardahan. Modern Niala fields (12 × 18 km) are possibly the site of caldera subsidence, which could be the source of the Mtkvari pyroclastic flow. At present, it is injected by post-volcanic andesitic domes, such as Gumbati mountain (2996 m). The Niala fields are covered with Quaternary sediments and the eastern part of the caldera is eroded by the Mtkvari river canyon. Despite the fact, that this territory undergoes erosion for about 7–8 Ma, the identification of large caldera circular structures is still possible here. It should be noted that these are only preliminary results and future investigations must be carried out.

4. Mtkvari pyroclastic flow

The Mtkvari pyroclastic flow is well-observed in relief along Mtkvari river canyon because of its whitish color (see Fig. 3). The conducted field work shows that the Mtkvari pyroclastic flow is traced continuously from the Karzameti fortress to the Khertvisi fortress, more than 35 km in length. The thickness of the flow increases noticeably from the supposed volcanic center (40 m in average) to the periphery (80 m in average). Such thickness variability from the volcanic center to the periphery is characteristic for ignimbrite flows while the thickness of ash-fall tuffs decreases in the same direction (Branney and Kokelaar, 2002). The flow is inclined towards the north by the angle of 2-4°. Its surface is perfectly straight and the bottom is conformed to the relief, which points to its magmatic origins.

The width of the Mtkvari pyroclastic flow is a matter of discussion, because it is believed that it filled the Mtkvari river valley (Ustiev and Jigauri, 1971), though reliable evidence of existence of the valley during Miocene volcanic activities does not exist, while other geological facts indicate that the pyroclastic flow might have covered a much larger area. This issue will be covered in details later in the discussion section.

The upper boundary of the Mtkvari ignimbrites layer is a 25–35 cm thick, fine-grained white tuff layer (Fig. 4). As for the layers under ignimbrites, unfortunately, they are barely exposed as they are covered by colluvium. However, these rocks crop out straight under the central part of the Vardzia rock-cut city section of about 120 m length and present intensively broken and brecciated andesitic lava flow. In our opinion, this structure of the Vardzia foundation is a significant factor for preserving its stability. Apparently, the pyroclastic flow kept its relatively stable state at the Vardzia section due to this foundation.

Ignimbrite particles are not well graded which should be the result

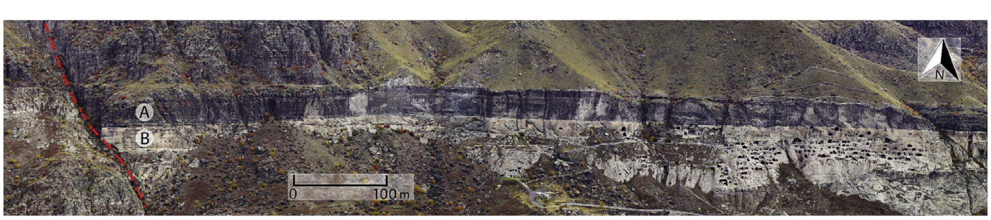

Fig. 3. Panoramic view of the Vardzia area. The dashed line indicates a detachment zone. In right -Vardzia rock-cut city. A- The Goderdzi formation, B - the Mtkvari pyroclastic flow.

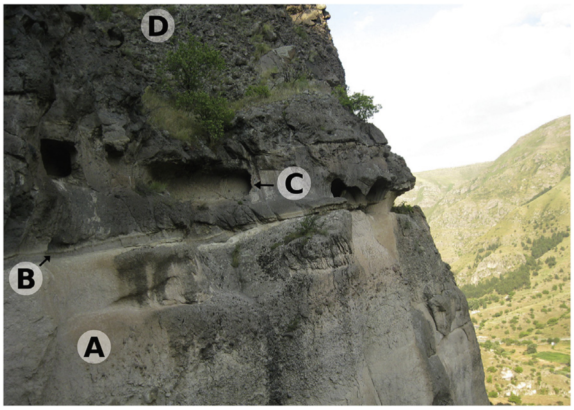

Fig. 4. A- Upper part of the Mtkvari pyroclastic flow to the south of Vardzia rock-cut city. B- Thin, white, fine-grained tuff layer – the upper boundary of ignimbrite layer. C- Volcanic ash-rich pyroclastic material and remains of the tunnel, dug out in it which was used for supplying Vardzia with water. D- Part of the upper section of the Goderdzi formation: lithic breccias with diameters sometimes reaching 1 m.

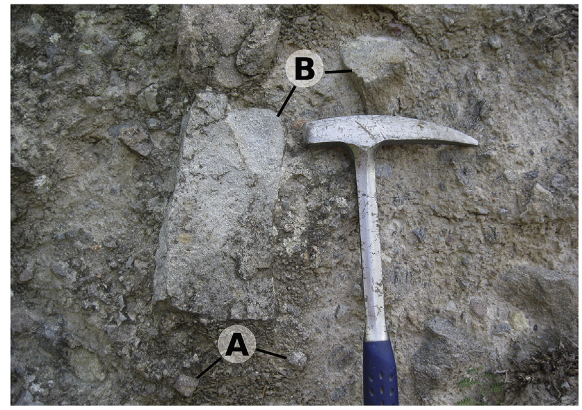

Fig. 5. Exposure of the Mtkvari pyroclastic flow on the right side of the Vardzia rock-cut city. Lithoclasts characterizing the horizon (0.2–3.5 cm). B- Rare rudaceous lithoclasts.

of the turbulence of pyroclastic density currents. We believe that these turbulent movements were responsible for mixing of ash and other pyroclastics. Nevertheless, exceptions can be noted, since at some places ignimbrites are represented only by ash or relatively small-size breccias (15–25 cm). We studied the distribution of ignimbrite material in the vicinity of the Vardzia rock-cut city. Consequently, we discovered relatively equal vertical distribution of constitutional material. For example, the lower part of the flow comprises 30% lithoclastic material and the middle and upper parts – 28% and 26%, respectively. The situation is different in case of volcanic ash, as its volume in the lower part of the ignimbrites is 41%, in the central part 48% and only 28% in the upper part. Even more unequal distribution is characteristic for pumice lapilli, which makes up 12%, 14% and 37% of the lower, central and upper parts of the ignimbrites, respectively. Despite such trend in material distribution, the Mtkvari ignimbrites should be considered as a massive, homogenous formation, which was deposited during turbulent movement.

4.1. Petrography of Mtkvari pyroclastic flow

The petrography of the Mtkvari pyroclastic flow is studied in detail (Ustiev and Jigauri, 1971) and this is why we describe it only briefly here. These tuffs can be divided into three parts: lithoclastic, porphyroclastic, and cementing materials. The lithoclastic material presents fragments of crystalline rock, which broke up in the debris of various sizes during the volcanic eruption. Typically, in the Mtkvari ignimbrites they are angular and their sizes in cross-section vary in the range of 0.1–3.5 cm, although sometimes lithoclasts of larger dimensions (5–15 cm) can be seen (Fig. 5). Lithoclasts are mainly hypersthene-hornblende andesite-dacites with rare biotite inclusions, in which average SiO_2 content is 58–61%. The porphyroclastic component in the Mtkvari pyroclastic flow is 40–50% of the entire mass and presents broken or euhedral plagioclase (0.5–1 mm). Hornblende, biotite, hypersthene and augite are seen in lesser quantity. Magnetite, apatite and zircon are observed as separate grains. Cementing material consists mainly of glass particles in fine-grained volcanic ash. Both walls gluing and gradual change of contours occur in the matrix, which is an obvious sign of welding process (Branney and Kokelaar, 2002).

The Mtkvari pyroclastic flow is petrographically andesitic-dacitic welded, weakly welded and non-welded ignimbrites, with SiO_2 content varying between 58% and 66% (Table 1). Its color changes with respect to the degrees of welding. In particular, southern parts of ignimbrites near the Karzameti fortress are highly welded and pink in color; to the north, near the Vardzia rock-cut city these ignimbrites are weakly welded and their color changes to whitish-pink, and even further to the north, near the Khertvisi fortress ignimbrites are white, non-welded, rocks. In general, these rocks can be easily excavated, for which reason in the Byzantine Empire and in medieval Georgia numerous ritual and residential types of buildings have been hewn into them.

5. Zircons U-Pb geochronology of the Mtkvari pyroclastic flow

At the isotopic laboratory of National Taiwan University, we dated zircons from the Mtkavri ignimbrites using the U-Pb method with an LA-ICP–MS. Samples were taken from three segments of the flow (Fig. 6): at the Khertvisi fortress (#13Ge-04); at the central part near the Vardzia rock-cut city (#13Ge-05) and at the beginning of the flow near the Karzameti fortress (#13Ge-0).

Near the Khertvisi fortress, the samples were taken at the bottom of the fortress, from where 51 samples were selected for zircon separation and the ages were determined for only 25 of them. At the central part, near the Vardzia complex, the samples were taken from two places: one from the exposed ignimbrite near the parking area (sp. 13Ge-05) and the second right at the entrance to the complex. From the 1st group, 50 samples were selected for zircon separation and only 14 of them were dated; from the 2nd group 46 samples were taken and 15 dated. At the starting point of the flow, samples were taken from the pink ignimbrite exposure near the Karzameti fortress. Among 48 samples only 22 were dated.

The zircons in all three groups of the samples from the Mtkvari pyroclastic flow have similar morphology, namely, similar prismatic forms; their lengths do not exceed 150 µm and the width is about 70–80 µm. Most zircons are euhedral with long prismatic pyramidal forms and show oscillatory zoning, indicating their magmatic origins. Zircons with separated core and rim are rarely observed with quite a simple zonality and only 2–3 zones are noted (Fig. 7). Some zircon grains are crumbled, presumably as a result of a powerful explosion of the magma chamber.

It should be noted that none of the zircon grains contain any fragments of old zircons, which means that these zircons are formed in the magma chamber, the source of the pyroclastic flow. Due to the limited volume of the paper and identical nature of the analyzed zircons, below we give only the sample #13Ge-04 CL pictures (Fig. 7), isotopic analyses (Table 2), U-Pb concordia plot (Fig. 8) and U-Pb weight mean (Fig. 9).

U concentration and Th/U ratio in zircons from sample #13Ge-04 vary within the range of 83–174 ppm and 0.68–1.59, respectively (Table 2); in sample #13Ge-05– within the range of 175–1474 ppm and 0.6–1.27, respectively; in sample #13Ge-06 – 130-669 ppm and 0.50–1.17 ppm, respectively. It should be noted that Th and U

Table 1
Major element geochemistry of the Mtkvari pyroclastic flow.

Sm. #	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O^-	H_2O^+	P_2O_5	Sum
5–14 MF	66.56	0.39	14.10	1.90	0.75	0.02	0.93	2.96	3.85	2.59	1.40	3.46	0.04	98.95
8–14 MF	66.32	0.73	15.30	2.19	1.13	0.13	1.72	3.64	4.87	3.43	0.26	0.32	–	100.04
10–14 MF	62.42	0.61	15.61	2.10	2.34	0.07	2.44	4.84	4.15	2.50	0.54	1.90	0.36	99.88
11–14 MF	61.51	0.88	15.15	0.21	3.60	0.14	4.00	6.13	3.08	2.40	0.46	2.12	0.23	99.91
14-14 MF	64.86	0.80	16.88	2.50	1.33	0.07	1.16	2.58	5.30	3.84	0.41	0.54	0.21	100.48
15-14 MF	65.32	0.73	16.30	2.19	1.13	0.13	1.72	3.64	4.87	3.43	0.26	0.32	–	100.04
17-14 MF	58.79	0.31	14.79	3.39	0.05	0.05	2.23	4.14	5.36	2.57	4.42	3.82	0.11	100.03
20-14 MF	62.54	0.58	16.30	3.55	0.53	0.05	1.27	3.52	3.54	2.79	2.39	2.75	–	99.81
21-14 MF	62.00	0.61	14.50	4.77	0.23	0.06	1.68	3.90	3.94	2.80	1.82	2.40	0.31	99.02
23-14 MF	66.16	0.39	14.30	1.93	0.72	0.02	0.93	3.16	3.85	2.57	1.42	3.46	0.04	98.95
25-14 MF	58.39	0.31	14.79	3.39	0.45	0.05	2.23	4.14	5.36	2.57	4.32	3.82	0.11	99.93
27-14 MF	64.86	0.88	16.30	2.80	1.33	0.07	1.16	2.58	5.50	3.84	0.50	0.38	0.21	100.41
28-14 MF	62.42	0.71	15.51	2.10	2.34	0.07	2.44	4.84	4.15	2.50	0.54	1.45	0.36	99.43
33-14 MF	64.86	0.88	16.30	2.80	1.33	0.07	1.16	2.58	5.50	3.84	0.50	0.34	0.21	100.37

Sampling sites: 5-4MIF - South of the Khertvisi fortress; 8-14MIF – At the Khertvisi fortress; 10-14MIF –At the village Saro; 14-14MIF –2 km north from the Vardzia river; 15-14MIF –1 km north from the Vardzia rock-cut city; 17-14MIF –Lowermost part of the Vardzia rock-cut city; 20-14MIF – The pathway of the Vardzia rock-cut city; 21-14MIF-Central part of the Vardzia rock-cut city; 23-14MIF- Upper part of the Vardzia rock-cut city; 25-14MIF - 1.5 km south from the Vardzia rock-cut city; 27-14MIF –4 km south from the Vardzia rock-cut city; 28-14MIF –8 km south from the Vardzia rock-cut city; 33-14MIF –At the Karzameti fortress – lower part of the unit.

concentrations in all zircons of the Mtkvari pyroclastic flow are proportional and Th/U index is always > 0.4, which manifests the typical magmatic formation of the zircons (Wu and Zheng, 2004).

With regard to the results of the zircons U-Pb geochronology, Fig. 8 shows the U-Pb concordia plot age of sample#13Ge-04, where the U/Pb curves are concentrated closely, which demonstrates that the U-Pb isotopic system was closed soon after crystallization. The weighted mean U-Pb age of this sample (Fig. 9) is 7.5 ± 0.4 Ma (MSWD = 0.74), which reflect its crystallization age. In general, in all three sections of the Mtkvari ignimbrites flow, the weighted mean U-Pb ages are practically identical and correspond to the Upper Miocene epoch, in particular: #13Ge-04 = 7.5 ± 0.4 Ma; #13Ge-05 = 7.5 ± 0.2 Ma and #13Ge-06 = 7.5 ± 0.2 Ma.

6. Evaluation of destructive processes affecting Vardzia rock-cut city

Weakly welded ignimbrites, where the Vardzia rock-cut city is excavated, have undergone significant destructive geological processes.

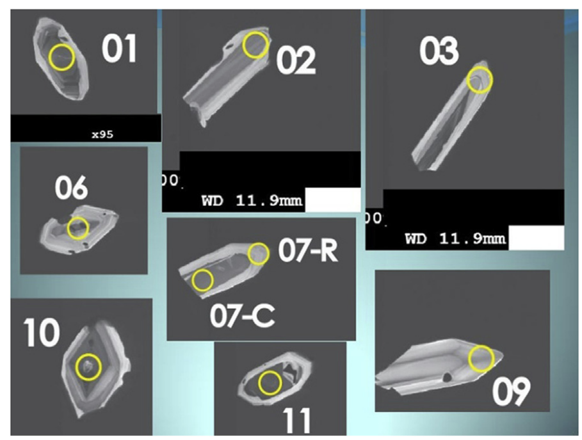

Fig. 7. Part of CL images of the zircon grains of the Mtkvari ignimbrites flow. Sample #13Ge-04.

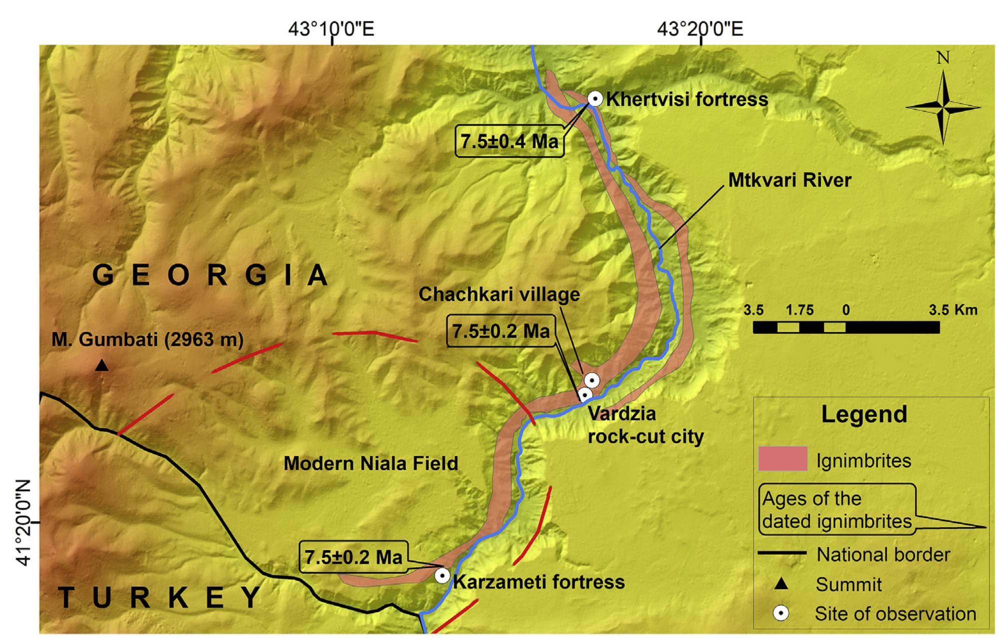

Fig. 6. Exposed part of the Mtkvari pyroclastic flow with zircon U-Pb ages and approximate contours of Georgian part of the caldera.

Table 2
U-Pb isotope data of the zircons from sample #13Ge-04 from Mtkvari pyroclastic flow.

Sample spot #	U (ppm)	Th/U	U-Pb ratios						Ages	
			$^{207}Pb/^{206}Pb$	±	$^{207}Pb/^{235}U$	±	$^{206}Pb/^{238}U$	±	$^{206}Pb/^{238}U$	± σ
1	157	1.50	0.10328	0.06204	0.01655	0.01157	0.00116	0.00013	7.5	0.8
3	83	0.68	0.04510	0.12707	0.00901	0.02705	0.00145	0.00030	9.0	2
4	132	1.08	0.04443	0.07670	0.00745	0.01368	0.00122	0.00015	7.9	1
5	83	0.74	0.04907	0.12368	0.00756	0.02038	0.00112	0.00022	7.0	1
6	115	0.67	0.04663	0.08098	0.00819	0.01525	0.00127	0.00020	8.0	1
7	118	0.89	0.04561	0.10426	0.00693	0.01691	0.00110	0.00019	7.0	1
8	119	0.61	0.04478	0.09766	0.00791	0.01841	0.00128	0.00021	8.0	1
11	86	0.76	0.04575	0.12554	0.00708	0.02067	0.00112	0.00022	7.0	1
12	138	0.77	0.03989	0.07526	0.00630	0.01262	0.00115	0.00015	7.4	1
13	187	1.29	0.04760	0.07657	0.00682	0.01179	0.00104	0.00014	6.7	0.9
14	104	0.73	0.04673	0.08420	0.00905	0.01746	0.00140	0.00020	9.0	1
15	166	0.86	0.04284	0.07602	0.00635	0.01201	0.00107	0.00014	6.9	0.9
17	113	0.76	0.03356	0.09622	0.00500	0.01504	0.00108	0.00017	7.0	1
18	174	1.59	0.04401	0.06227	0.00717	0.01085	0.00118	0.00013	7.6	0.8
19	84	0.75	0.04756	0.10157	0.00871	0.01983	0.00133	0.00021	9.0	1
20	140	0.92	0.04234	0.06783	0.00693	0.01183	0.00119	0.00014	7.7	0.9
21	119	0.78	0.04077	0.08749	0.00610	0.01384	0.00109	0.00015	7.0	1
23	124	0.72	0.04760	0.08817	0.00684	0.01355	0.00104	0.00015	6.7	1
24	149	0.84	0.07638	0.06863	0.01153	0.01158	0.00109	0.00013	7.0	0.8

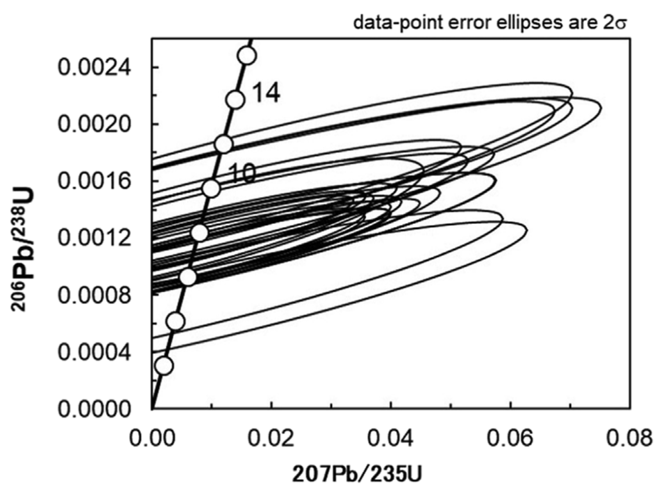

Fig. 8. Concordia plot U-Pb age of the Mtkvari ignimbrites flow zircons. Sample #13Ge-04.

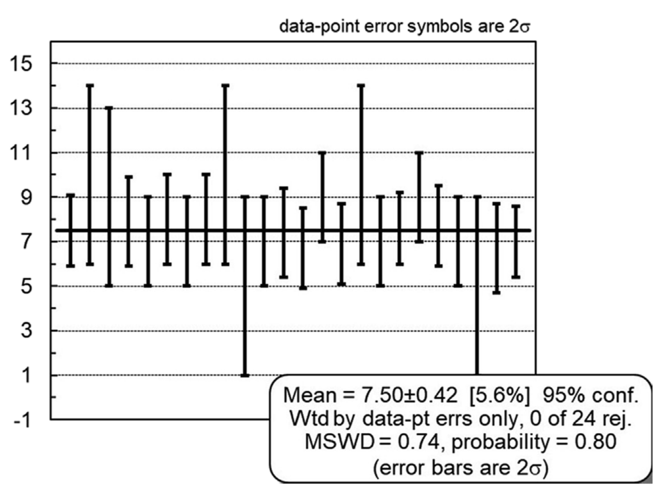

Fig. 9. Weight means U-Pb age of the sample #13Ge-04 from the Mtkvari pyroclastic flow.

Conducted research showed that in addition to destructive tectonic processes, these rocks are being eroded and weathered and their mineralogical composition also poses some ecological threat.

Due to severe climatic conditions (hot summer and cold winter), weakly welded ignimbrites easily undergo erosion and weathering. These processes are especially intense in tectonic stress zones and fracture systems, where carbonization and clay mineral formation can be observed. One of the clay constituents – montmorillonite is capable of increasing in volume when water is present. Therefore, montmorillonite is a noticeable damaging factor for the Vardzia complex.

Also, the geological structure of the Vardzia area is rather complex (Fig. 10). There are two types of faults distinguished: 1. faults provoked by regional geological processes and 2. Those conditioned by local gravitational phenomena. The basic tectonic feature of the area is a deep fault, which traces towards SW-NE and actually goes along the Mtkvari river canyon. Along the fault the Vardzia area is divided into two large blocks: the eastern Javakheti and the western Erusheti blocks. After the Mtkvari ignimbrites were formed (c. 7.5 Ma), a significant vertical displacement occurred along the fault.

As a result of field work it was discovered that the Mtkvari ignimbrites on the right side of Mtkvari river right across the Vardzia complex and further towards the upper reaches is submerged below the river level and covered by colluvial and alluvial deposits, although across the village Chachkari a small part of andesitic-dacitic tuffs of Mtkvari ignimbrites is exposed. The thorough analysis of this exposure showed that it is analogous to tuffs, constructing Mtkvari ignimbrites (Fig. 6). This exposure traces 60 m along Mtkvari River and then is covered by colluvial deposits. Although, at about 500 m towards the Tmogvi fortress, these rocks are exposed again in some places along the Khertvisi-Vardzia road; however, it has undergone intensive weathering and alteration. Up the river Mtkvari at its right bank, the Mtkvari pyroclastic flow gradually submerges and does not expose elsewhere (Okrostsvaridze et al., 2016a,b).

Where exposed, we measured exact elevations of the upper boundary of the Vardzia horizon, at both sides of the Mtkvari river using a high accuracy differential GPS. It was found that the upper border of the Mtkvari pyroclastic flow on the right riverside crops out at 1380 m above sea level, meaning, the Vardzia horizon, including the Vardzia rock-cut city, is 127 m higher than the pyroclastic flow located on the right side of the Mtkvari River. Taking the fact into consideration, that the Mtkvari ignimbrites on the right side of Mtkvari river are lowered by 127 m, one can suppose that the right side of the Mtkvari river – Javakheti block has subsided 127 m (Fig. 10).

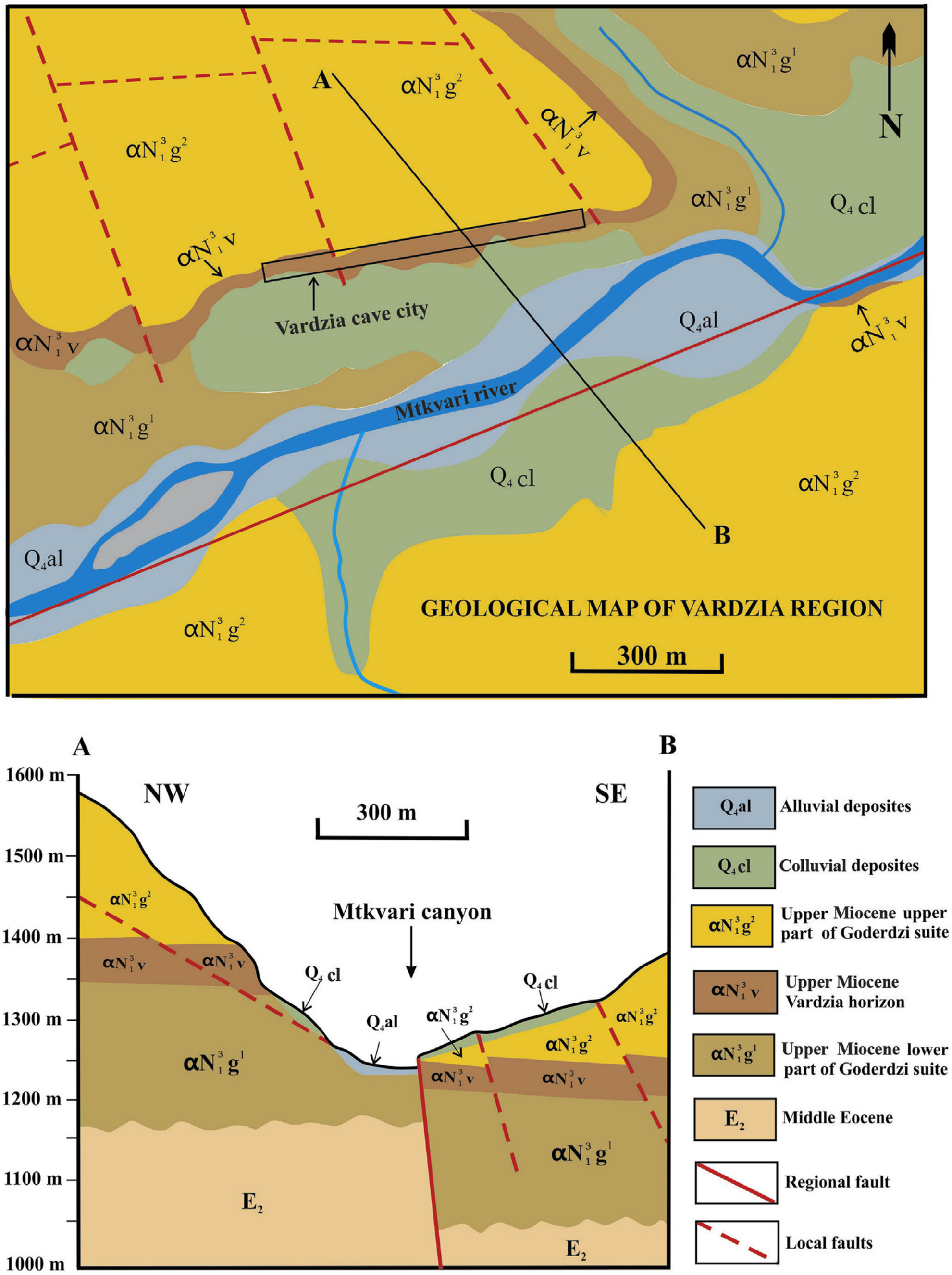

Fig. 10. The geological map of the Vardzia rock-cut city area with the cross section (A–B).

Besides the considered deep fault, several local faults are also observed in the Vardzia rock-cut city area, which plays an important role in shaping the local tectonic structure. As conducted work shows, the 900m-long block (Vardzia block) is detached from the main unit by local tectonic faults from the southern (Fig. 11) and northern sides. The faults themselves are the result of gravitational subsidence of the segment towards the Mtkvari riverbed provoked by the erosion of the river. Analogous segmentation of the horizon takes place in the entire longitudinal section of the horizon but with different intensities at different sections. These processes are observed in the Tmogvi area with particular intensity.

The drift of the Vardzia block is especially well-detected along the local tectonic fault existing to the south from it (see Fig. 11). There is a good geological picture of gravitational subsidence here. Moreover, a surface of rock gliding is well-observed, analysis of which shows that the block moved downstream with a slant of 32–35°. At the same time, because of the gliding surface is unchanged and not damaged, we believe this displacement is active. In addition, a thorough analysis of the fault helped to establish the scale of vertical displacement of the Vardzia block. In this cross-section the Vardzia horizon ends with a white, 25–35 cm thick, fine-grained layer (see Fig. 4).

We measured elevations of these layers on both sides of the fault with a high accuracy differential GPS. The lowered layer of the Vardzia block is located at 1393.6 m above sea level and that of the block bordered from the south at 1423.8 m. Taking into consideration these data, it turns out that the Vardzia block is located lower than the neighboring northern block by 30.2 m (Okrostsvaridze et al., 2016a,b).

The surface of the Mtkvari pyroclastic flow in the creeping block along the southern fault is not horizontal but is inclined towards the south-west, the opposite direction of the river bed with atilt of 2-3°. The

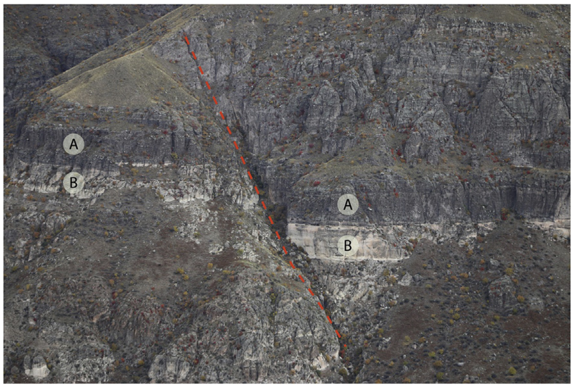

Fig. 11. A general view of the southern tectonic contact of Vardzia tectonic block. It is well seen a fault zone and Vardzia block drifted downwards. A - Upper part of the Goderdzi formation; B – Mtkvari ignimbrites flow; dashed line shows a local fault zone.

Fig. 12. Part of the Vardzia rock-cut city damaged by the AD 1283 earthquake.

figure shows remnants of the tunnel that used to supply the Vardzia rock-cut city with water. The plane of a rock fall divides the tunnel almost in half. This fact allows us to assume that water percolation caused the formation of the crack system (see Fig. 4), along which almost a third part of the Vardzia complex was destroyed by the disastrous earthquake of 1283 (Fig. 12).

The Northern Vardzia block is bordered by a fault system as well (see Fig. 3), but unlike the southern border, the tectonic disturbance is relatively intensive here. Rocks are mixed in the fault zone, and have undergone crushing and argillization, so it is difficult to determine the scale of block displacement, but certainly, it moves towards the canyon. The western border of the Vardzia block representing a detachment zone is placed on the eastern slopes of Erusheti ridge. It is not well expressed in the relief because it is mostly covered by colluvial depositions. Although prolonged depressions are nevertheless observed, which is geomorphologic expression of the tearing area.

The Mtkvari pyroclastic flow on the Vardzia rock-cut city segment is fragmented into small blocks by its parallel and perpendicular, vertical fractures. The distance between these fractures is 60–80 m, on average (see Fig. 3). The fracture system is also developed in the upper part of the Goderdzi formation, which significantly decreases the stability of the Vardzia rock-cut city rocks. At this stage of the research, their genesis is a matter of debate. If they are cooling joints, then they should not be extended to the upper part of the Goderdzi formation. Considering that, the fracture system might be of gravitational nature. It is worth noting that during an earthquake in AD 1283, the Vardzia rock-cut city collapsed along these fractures.

As for the foundation of the Mtkvari ignimbrites, unfortunately, they are barely exposed as they are covered by colluvium. However, these rocks crop out straight under the central part of the Vardzia complex at about 120 m section and represent intensively broken and brecciated gabbro-andesitic lava flow. The thickness of this outcrop cannot be measured. In our opinion, such structure of the Vardzia foundation is a significant factor for preserving its stability. Apparently, the volcanic flow kept its relatively stable state at the Vardzia section due to such foundation.

7. Discussion

As a result of our research, we believe that new important geological information has been obtained, though, there are still many issues we could not resolve this time.

It has been revealed that the Mtkvari pyroclastic flow consists of ignimbrite deposits with distinctive indications of turbulent movements. We determined its magmatic type, genesis, isotopic age, length and thickness, though its width is still uncertain. As noted above, it was assumed that the pyroclastic flow was developed in the Mtkvari river canyon (Ustiev and Jigauri, 1971); however, it is unknown whether this canyon existed about 7.5 million years ago.

In addition, geological evidence suggests that the flow covered a wide area. Specifically, in the Chachkari gorge, which cuts through the Mtkvari river canyon, the entire cross section of ignimbrites is exposed along the gorge for about 1.8 km with unvarying thickness (50 m in average). The analogous formation is also exposed in the Uraveli gorge where its thickness is about 40–50 m. Some ignimbrites are also detected in the upper part of the Goderdzi formation at the ridge between the rivers Uraveli and Mtkvari. These facts allow us to assume that pyroclastic flow could cover large area erupting to the north of caldera, and the pyroclastic flow was later dissected by river gorges, including Mtkvari river canyon, which was probably formed along the regional fault.

The genesis of intense vertical fracture net developed in the Mtkvari pyroclastic flow is a matter of discussion. If we consider these fractures as gravitational features, set 50–60 m apart from each other, the existence of fractures that are parallel to the pyroclastic flow should be adequately explained. However, it is possible that these fractures are also gravitational. Additionally, as it is known vertical cooling joint systems are characteristic for highly welded tuffs. As for moderately welded tuffs, joint systems are not well developed there and in non-welded tuffs cooling joints are practically nonexistent (Branney and Kokelaar, 2002).

As a final word, during intense zeolitization of the Mtkvari ignimbrites (Skhirtladze, 1991) among other zeolites the mineral mordenite is also formed (Okrostsvaridze and Gagnidze, 2013). Mordenite is classified as carcinogen mineral by the World Health Organization. According to this classification, mordenite is the most dangerous toxic mineral, 15–20 time more toxic than asbestos-chrysotile. Modern research shows that fibrous zeolites caused a regional epidemic of malignant neoplasm (bronchial carcinoma, malignant mesothelioma) (Baris and Grandjean, 2006). Presence of the carcinogen mineral is a serious threat to residents of local villages. This factor should be especially concerning to the Vardzia rock-cut city residents.

8. Conclusion

The conducted field work showed that the Mtkvari pyroclastic flow is exposed from the Karzameti fortress to the Khertvisi fortress on 35 km, it is inclined northward by 2–4 °and its thickness increases to the north (40–80 m). These rocks are weakly welded and non-welded andesitic-dacitic ignimbrites with following isotopic parameters: εNd values [+2 and + 4] and $^{87}Sr/^{88}Sr$ [0,7034 to 0.70450]. The isotopic parameters indicate their mantle origins. Based on field research it is supposed that the Mtkvari ignimbrites are products of a megacaldera collapse and the caldera nowadays is filled with andesitic domes and Quaternary sediments (modern Niala fields). Zircons, dated using the U-Pb method with LA-ICP-MS technology, are 7.5 Ma in average, which corresponds to the Late Miocene epoch.

Geological research of the Vardzia rock-cut city showed that the complex is hewn into weakly welded ignimbrites, for which reason these rocks are under the intensive affecting of weathering and erosion processes. At the same time, the city is completely included in a 900 m-long tectonic block, which is detached from the main body of the Goderdzi formation rocks and is gradually subsiding towards the Mtkvari River. Nowadays, the Vardzia block is lowered by 30.6 m in comparison with bordered blocks. Additionally, this block is split into several microblocks by a joint set and thereby its stability is lessened. The situation is worsened by the active deep fault running along the Vardzia rock-cut city, which represents a potential earthquake source. The only factor contributing to the relative stability of the Vardzia rock-cut city is the somewhat harder basaltic-andesitic brecciated stratum existing under it.

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