

FELSIC TUFFS FROM THE UPPER MIOCENE OF THE EASTERN PARATETHYS (GEORGIA, KAKHETI): COMPOSITION, SECONDARY ALTERATIONS, AND CORRELATION WITH VOLCANIC ERUPTIONS

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Abstract: This study presents new data on the secondary alterations and composition of felsic tuffs (65.38–66.12 wt.% SiO₂ for whole rocks and 75.94–79.98 wt.% SiO₂ for volcanic glasses) from Upper Sarmatian and Maeotian-Pontian continental sedimentary rocks of the Udabno Upper Miocene section (Kakheti, Eastern Georgia, Eastern Paratethys). These rocks show varying degrees of secondary alterations, characterized by the predominant development of smectites and zeolites (analcime and heulandite/clinoptilolite). Smectite was formed in the initial stages of secondary alterations, preceding intensive zeolitization. The Na-zeolites (analcime) are characteristic of Na-rich Upper Sarmatian pyroclastics, while the Ca-Na-zeolites (heulandite/clinoptilolite) are characteristic of Maeotian-Pontian pyroclastics with a high Ca content. Secondary alterations were accompanied by removal of K⁺ from volcanic material. Despite secondary alterations, the composition of the studied volcanic material to some extent reflects the characteristics of the initial pyroclastics. The source of Upper Sarmatian pyroclastics could be volcanic eruptions that occurred up to 7.65 Ma. The Maeotian-Pontian tuff is characterized by an association with phenocrysts of the minerals: clinopyroxene, orthopyroxene, amphibole, and plagioclase (Cpx-Opx-Amp-Pl). This pyroclastic material is most likely comparable to the volcanic rocks of the Goderdzi suite, reflecting episodes of eruptions in the Erusheti highland (southern Georgia) from ~7.5 to 7.0 Ma.

Keywords: felsic tuffs, secondary alterations, zeolitization, volcanic eruptions, Upper Miocene, Eastern Paratethys, Georgia

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1. Introduction

The study of volcanic tuffs allows us to determine the stages and characteristics of volcanic eruptions, facilitates regional correlations, enables radiometric dating of rocks (e.g., K-Ar, Ar-Ar, and U-Pb methods), and helps to identify the features of secondary alterations in pyroclastics.

Numerous layers of volcanic tuffs are present in the Upper Miocene sediments of Eastern Georgia (Eastern Paratethys) [Chumakov *et al.*, 1992]. A large part of Eastern Georgia is related to an intermontane depression of the Caucasian mobile belt, which is a central segment of the Mediterranean Alpine-Himalayan collisional orogenic system. In Georgia, extensive volcanic activity occurred from the Late Miocene to the Holocene (Figure 1) [Okrostsvaridze *et al.*, 2017; Tutberidze, 2012]. Volcanism was concentrated in five main regions: the South Georgian highland, the central part of the Lesser Caucasus folded system, Central Georgia, the Kazbegi and Keli highlands [Okrostsvaridze *et al.*, 2017; Tutberidze, 2012]. Late Miocene volcanic eruptions occurred on the South Georgian highland, part of the Samtskhe-Javakheti volcanic province, covering an area of more than

5000 km² [Okrostsvaridze et al., 2017]. These volcanic and volcano-sedimentary sequences correlate with the Goderdzi suite, which is widely developed in southern Georgia (Erusheti highland) [Chumakov et al., 1992; Lebedev et al., 2012; Okrostsvaridze et al., 2017; Tutberidze, 2012; Uznadze, 1965]. The eruption products are mainly represented by calc-alkaline andesites, dacites, rhyolitic dacites, and rhyolites [Lebedev et al., 2012; Tutberidze, 2012].

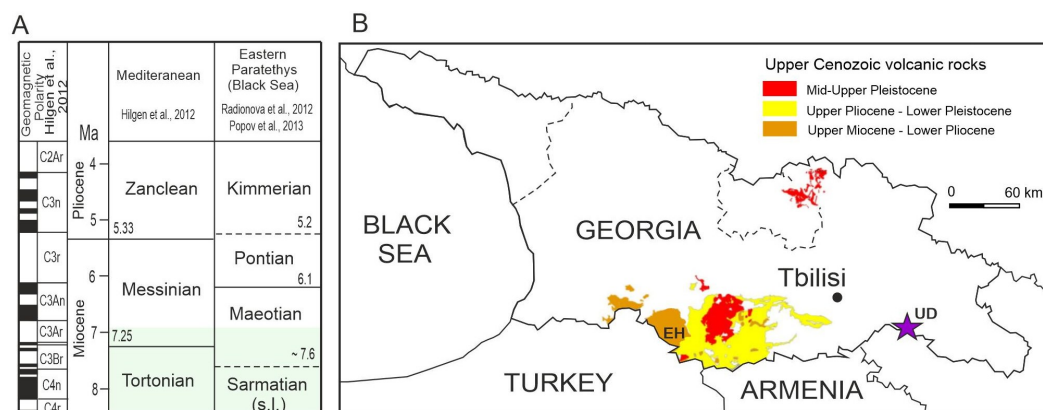


Figure 1. Studied stratigraphic interval (a) and Late Cenozoic volcanic formation of Georgia [adapted from Okrostsvaridze et al., 2017] (b). UD – location of Udabno section in Eastern Georgia (Kakheti), EH – Erusheti highland.

According to Aslanian et al. [1982], K-Ar dating of volcanic rocks (lavas and tuffs) from the lower and upper parts of the Goderdzi suite (Dzindzestkali, Uraveli, and Kura (Mtkvari) sections) ranges from 9.8 to 7.4 Ma. More recent K-Ar dating obtained for the effusive rocks of the entire Goderdzi Formation (Kura (Mtkvari) section) ranges from 7.8 to 7.0 Ma, with an average age of 7.5 Ma [Lebedev et al., 2012]. U-Pb dating of zircons from ignimbrites of the lower part of the Goderdzi Formation (Kura (Mtkvari) section) indicates an average age of around 7.5 Ma [Okrostsvaridze et al., 2017, 2024]. In areas adjacent to southern Georgia, Upper Miocene sediments contain tuff interlayers in the upper Middle Sarmatian, Upper Sarmatian, Maeotian, and, presumably, Pontian stages [Chumakov et al., 1992].

The purpose of this study was to examine the secondary alterations and chemical composition of tuffs from an Upper Miocene sedimentary sequence in eastern Georgia (Udabno section, Kakheti) and consider the possibility of using these data for regional correlations, rock dating, and for magmatic source identification.

2. Materials and Methods

2.1. Description of the Udabno Section

The Upper Miocene sediments of the Udabno section contain several tuff layers. The Udabno section is located in the southwestern part of Eastern Georgia (starting point: 41°26'35.12" N, 45°22'40.00" E; ending point: 41°28'17.10" N, 45°22'10.54" E, Kakheti) and comprises well-exposed Middle and Upper Sarmatian as well as Maeotian-Pontian and Upper Pliocene sediments of the Eastern Paratethys (Figure 2). The Middle Sarmatian sediments are represented by sandstones and clay-sandy rocks containing marine fauna such as *Macra vitaliana* d'Orb., *Cardium fittoni* (d'Orb), *Cerastoderma obsoletum ingratum* (Koles.) and others (identified by L. V. Muskhelishvili) [Vangengeim et al., 1989]. These sediments have an exposed thickness of at least 381 m [Buleishvili, 1960]. The Upper Sarmatian belongs to the thick series of continental sediments known as the Eldarian suite, which has a thickness of about 420 m [Vangengeim et al., 1989]. These sediments consist of interbedded colorful clays with interlayers of sandstones and conglomerates. Hipparion-dominated fauna was found in three horizons, at 120, 90, and 40–50 m below the upper boundary of the Eldarian suite [Vangengeim et al., 1989]. The first and last horizons with Hipparion fauna are known as the Udabno I and Udabno II complexes, respectively

[Buleishvili, 1960; Vangengeim et al., 1989]. Freshwater *Anodonta* fauna occurs in this Upper Sarmatian succession (oral report by M. A. Pevzner, 1985). The Upper Sarmatian rocks are overlain by continental Maeotian-Pontian sediments, belonging to the Shirakian suite, with a thickness of about 600 m [Vangengeim et al., 1989]. The Shirakian suite is represented by grey sandstones with rare interlayers of grey clay, and vertebrate bones are found in these sediments. The Upper Pliocene sediments, which transgressively overlie the Maeotian-Pontian succession, contain clay-sandy rocks with Akchagilian mollusc fauna and a conglomerate layer at their base.

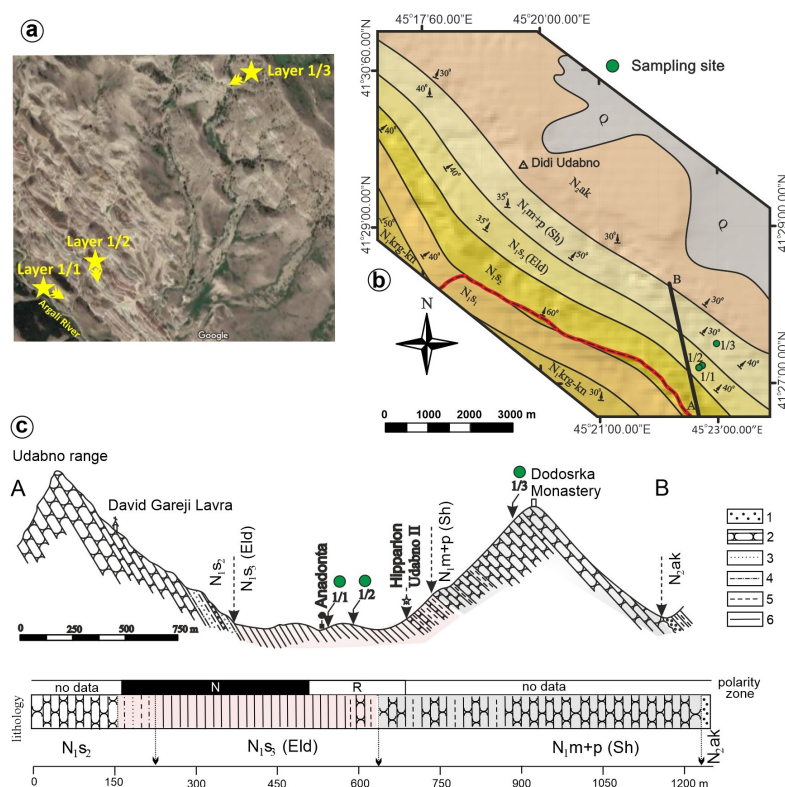


Figure 2. The Udabno section of Eastern Georgia (Kakheti). (a) Panoramic view of studied Upper Miocene sediments; (b) geological map of studied area: Q – Quaternary sediments, N₂ak – the Upper Pliocene (Akchagilian), N₁m+p (Sh) – the Maeotian-Pontian (Shirakian suite), N₁s₃ – the Upper Sarmatian (Eldarian suite), N₁s₂ – the Middle Sarmatian, N₁s₁ – the Lower Sarmatian, N₁kr-g-kn – the Karaganian-Konkian; (c) lithology of studied Upper Miocene sediments: 1 – conglomerate, 2 – sandstone, 3 – sand, 4 – siltstone, 5 – silty clay and clay, 6 – clays with sandstones and siltstones. 1/1, 1/2, 1/3 – location of the studied Upper Miocene layers.

The clay-sandy rocks of the Middle Sarmatian, as well as the sediments of the Eldarian suite and the lower part (50 m) of the Shirakian suite, have been studied using the paleomagnetic method [Vangengeim et al., 1989]. The studied Middle Sarmatian sediments and the lower part (300 m, up to the Udabno I horizon) of the Eldarian suite are characterized by normal polarity. The upper part (120 m) of the Eldarian suite and the lower part of the Shirakian suite yielded reversed polarity.

During the Middle Sarmatian, a shallow, brackish basin existed in the southwestern part of Eastern Georgia [Koiava, 2006; Paramonova et al., 2004; Shatilova et al., 2009, 2012]. By the end of the Sarmatian, continental environments had formed in the studied region as a result of orogenic movements. Isolated or weakly connected shallow lakes existed at this time [Koiava, 2006]. Continental settings were also present during the Maeotian-Pontian.

According to new data, the Sarmatian/Maeotian boundary is within chron C4n at ~7.65 Ma [Palcu et al., 2019; Popov et al., 2013; Radionova et al., 2012; Raffi et al., 2020; Rybkina et al., 2015].

The relative age of the studied tuff layers and their correlation with volcanism on the Erusheti highland of South Georgia will be interpreted based on the available geological (paleontological, magnetostratigraphic, and radiometric) data.

2.2. Sampling

In the Udabno section of Eastern Georgia (Kakheti), three tuff layers have been studied. Samples were collected from two tuff layers in the Upper Sarmatian (Eldarian suite) and one tuff layer from the Maeotian-Pontian (Shirakian suite). The first tuff layer from the Upper Sarmatian (41°27'12.41" N, 45°22'41.55" E, Layer 1/1) is a grey lenticular bed up to 0.3 m thick and approximately 12 m long, located between clay layers. The second tuff layer from the Upper Sarmatian (41°27'14.25" N, 45°22'44.67" E, Layer 1/2) is a green-grey bed 0.2–0.3 m thick, overlain by sandstone. The studied tuff layer from the Maeotian-Pontian (41°27'30.93" N, 45°22'59.51" E, Layer 1/3) is a grey rock with sand-sized granular material and up to 1.5 m thick.

2.3. Methods

Rock samples were examined in thin section using an optical microscope (Carl Zeiss Axio Scope 40). The materials were also analyzed using a Bruker D8 Advance X-ray diffractometer (Bragg-Brentano geometry, Cu K $\alpha_{1,2}$ radiation, $\lambda = 1.54184$ Å, LYNXEYE XE detector). Samples were scanned with high resolution for 5 h with a 2 s exposure time, 9000 steps, and a slot width of 0.5 mm. The mineral compositions and ratios were determined by comparing the intensities of the corresponding reflections using the program DIFFRAC.EVA V7. In addition, the XRD analysis results were refined using the Rietveld method and refinement was done using the GSAS-II program. These studies were carried out at the Skoltech Center for Energy Science and Technology (Moscow).

Scanning electron microscopy (SEM) was used to examine samples using a JSM IT-500 (JEOL, Japan) fitted with an Oxford Instruments X-MAX 50 mm² SDD for energy-dispersive spectroscopy (EDS) using INCA (v21) software. The EDS analysis standards that were used are presented in Table 1. Polished thin sections were coated with 25 nm of conductive carbon before SEM examination. These SEM studies were carried out at the Laboratory of Local Methods for the Study of Materials (Department of Petrology, Geological Faculty, Moscow State University).

Table 1. Standards used for EDS analysis (standards from “Jeol” catalog (Japan) (*), [Jarosewich *et al.*, 1980] (**), and stoichiometric compounds (***))

Element	Standard
Si	Hypersthene USNM-746**
Ti	Rutile 6001-54998 (O18)*
Al	Jadeite 7801-12245 (M3)*
Fe	Hypersthene USNM-746**
Mn	Pyrophanite 7801-12300 (M9)*
Mg	Diopside USNM-117733**
Ca	Augite USNM-164905**
Na	Anorthoclase USNM-133868**
K	Potassium feldspar USNM-143966**
P	GaP synthetic***

Major and trace elements in studied rock samples were analyzed by X-ray fluorescence spectrometry (XRF), using an ARL PERFORM'X 4200 spectrometer (Thermo Fisher Scientific (Ecublens) SARL, Switzerland), at the Aprelevsky branch of All-Russian Research Geological Oil Institute (Moscow). The ARL PERFORM'X spectrometer was a 4200-Watt system. This system has 6 primary beam filters, 4 collimators, up to nine crystals, two

detectors, helium purge and 5GN+ Rh X-ray tube for performance from ultra-light to heavy elements as it is equipped with a 50 μm Be window.

For comparison, we added to our database information on twelve volcanic rock samples of the Goderdzi Formation (Kura (Mtkvari) section), given in *Lebedev et al.* [2012], which is reflected in the classification diagrams. Classification diagrams were used to analyze the composition of the volcanic material, considering the presence of secondary alterations. Volcanic ash zircons were not detected in the studied rocks.

3. Results

3.1. Layer 1/1

The samples from Layer 1/1 are solid, fine-grained rock. According to X-ray diffraction analysis, this rock contains analcime, Mg-Na smectite (montmorillonite), quartz, and plagioclase (Figure 3). The groundmass is dominated by analcime (sodium-rich zeolite), characterized by an unevenly-grained (mainly fine-grained) texture (Figure 4a). The composition of the analcime is as follows (wt.%): SiO_2 57.99–59.54%, Al_2O_3 18.97–19.82%, and Na_2O 9.35–10.55% (Table 2). There are isolated angular grains of quartz, feldspar, apatite, and biotite, sized 0.01–0.03 mm (occasionally up to 0.08 mm), within the zeolite matrix. Relics of volcanic glass fragments with cusped walls and strong secondary alterations were identified in thin section (Figure 4b). The chemical composition of the whole rock sample from Layer 1/1 is provided in Table 3.

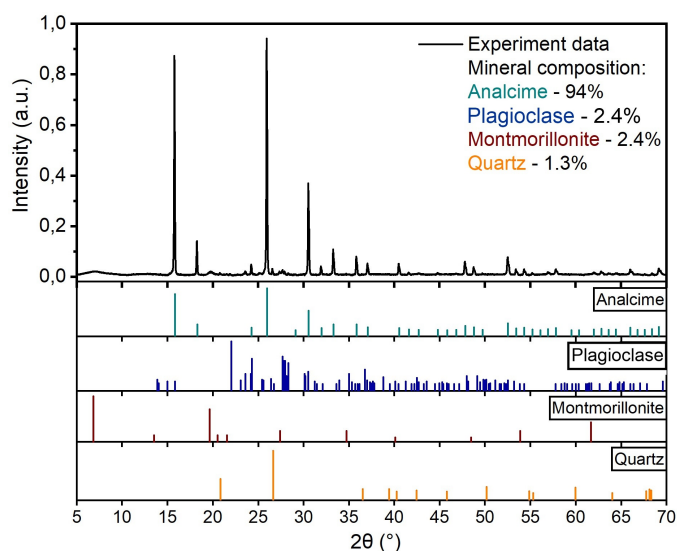


Figure 3. X-ray diffraction patterns of whole rock sample from Layer 1/1.

Table 2. Major elements (wt.%) of minerals in the studied rocks (Layer 1/1: analcime, Layer 1/2: smectite, Layer 1/3: Ca-Na zeolite). Analyses by SEM

Major Elements	Sample of Layer 1/1			Sample of Layer 1/2		Sample of Layer 1/3		
	Analcime	Analcime	Analcime	Smectite	Smectite	Ca-Na Zeolite	Ca-Na Zeolite	Ca-Na Zeolite
Major Elements (wt.%)								
SiO_2	57.99	59.01	59.54	45.52	47.94	64.38	64.67	66.48
TiO_2	–	–	–	0.16	0.23	–	–	–
Al_2O_3	18.97	19.68	19.82	11.99	12.83	14.49	13.87	14.61
FeO_{tot}	–	–	–	3.73	3.91	–	–	–
MgO	–	–	–	3.70	3.78	0.13	0.11	0.16
CaO	–	–	–	1.52	1.55	4.65	4.22	4.43
Na_2O	10.43	10.55	9.35	0.09	0.18	2.96	2.40	2.87
K_2O	–	–	–	0.09	0.09	0.45	0.46	0.52
Σ	87.39	89.24	88.71	66.80	70.51	87.06	85.73	89.07

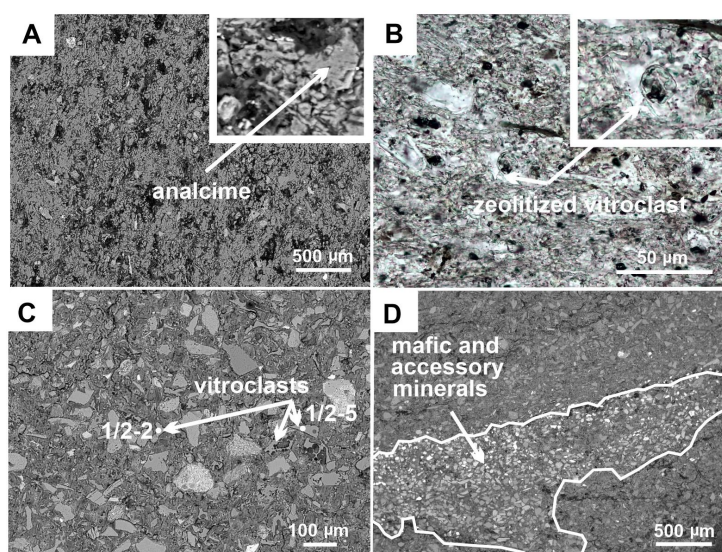


Figure 4. Upper Sarmatian tuffs of the Udabno section (Kakheti, Eastern Georgia). (a) Analcime-rich groundmass of rock (Layer 1/1), SEM image; (b) optical photomicrograph of volcanic glass relics (Layer 1/1); (c) fragments of volcanic glasses (Layer 1/2, 1/2-2 and 1/2-5 – microprobes on volcanic glasses), SEM image; (d) smectite-rich groundmass of rock containing the lenticular concentration of mafic and accessory minerals (Layer 1/2), SEM image.

Table 3. Chemical composition of the studied rocks. Analyses by X-ray fluorescence spectrometry (XRF). Alk – Na₂O + K₂O

Sample from Layer	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	MnO	CaO	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	Cr ₂ O ₃	SO ₃
	wt. %											
Layer 1/1	62.72	21.42	0.53	2.28	0.01	0.71	1.13	10.27	0.62	0.11	–	0.01
Layer 1/2	65.38	16.59	0.45	4.75	0.08	4.77	3.31	3.64	0.57	0.24	–	0.08
Layer 1/3	66.12	16.49	0.60	4.09	0.07	5.46	1.65	3.74	1.35	0.24	0.01	0.02
Sample from Layer	Ba	Cu	Zn	Pb	Ni	Co	Rb	Sr	W	V	Zr	Ce
	ppm											
Layer 1/1	–	32	78	45	–	–	–	125	–	63	632	176
Layer 1/2	157	20	54	–	11	–	14	311	–	42	220	40
Layer 1/3	–	22	59	–	27	14	25	707	–	79	157	–
Sample from Layer	Nd	Nb	Re	Y	Ga	Gd	As	Er	Th	Zr/Ti	Nb/Y	Alk
	ppm											
Layer 1/1	60	46	–	33	12	–	–	–	76	0.19	1.39	10.89
Layer 1/2	–	22	–	14	15	–	–	–	–	0.08	1.57	4.20
Layer 1/3	19	26	21	12	10	23	–	37	–	0.04	2.16	5.09

3.2. Layer 1/2

Tuff of Layer 1/2 is solid rock with a grain size up to 0.125 mm (typically 0.02–0.08 mm). This tuff is dominated by volcanic glass fragments, with crystal clasts and individual lithoclasts also present (Figure 4c). Crystalloclasts are commonly present as plagioclases (more rarely, potassium feldspar), quartz, and biotite flakes.

The Mg-Na smectite (montmorillonite), quartz, plagioclase, calcite, and an amorphous phase were detected in the composition of tuff by X-ray diffraction method (Figure 5). The smectite is in matrix between grained particles. The smectite composition is as follows (wt.%): SiO₂ 45.52–47.94%, Al₂O₃ 11.99–12.83%, TiO₂ 0.16–0.23%, FeO_{tot} 3.73–3.91%, CaO 1.52–1.55%, MgO 3.70–3.78%, Na₂O 0.09–0.18%, and K₂O 0.09% (Table 2). This tuff contains single grains replaced by Na-zeolite (analcime). In groundmass, the

lenticular concentrations of mafic and accessory minerals were revealed (Figure 4d). These minerals are represented by hornblende, pyroxene (ortho- and clinopyroxene), apatite, and titanomagnetite.

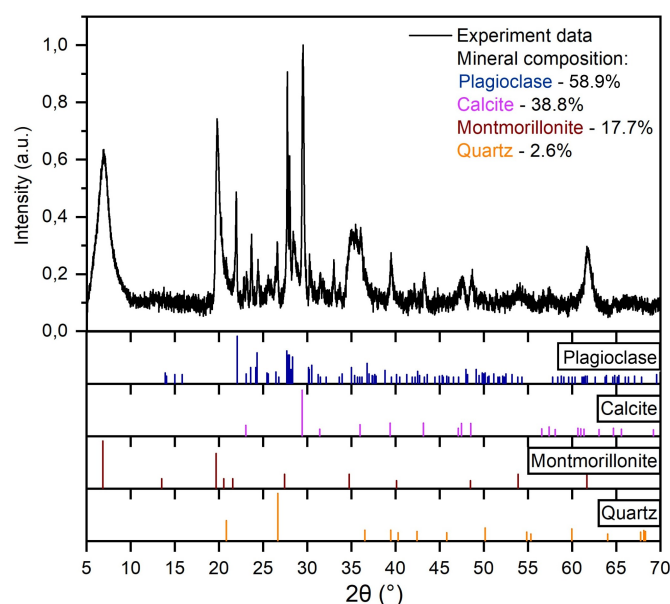


Figure 5. X-ray diffraction patterns of whole rock sample from Layer 1/2.

The volcanic glass fragments have the following composition (wt.%): SiO_2 75.94–79.98%, Al_2O_3 13.17–14.97%, and alkaline components 4.26–6.55% for major elements normalized to 100% (Table 4). Based on the silica content, the volcanic glasses have a dacite and rhyolite composition (Figure 6a). These volcanic glasses mainly belong to subalkaline petrochemical types of volcanics, with sodium predominating over potassium. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio ranges from 2.26 to 5.38, and the CaO content is 0.45–1.91%. Considering the presence of smectite and calcite as secondary minerals, the major element composition of the volcanic glass, including Na_2O , K_2O , and CaO, may not fully represent the primary composition of the pyroclastic material. The volcanic glass fragments are mainly represented by colorless cusped bubble-wall type shards.

Plagioclases have oligoclase and andesine compositions (An_{29} , An_{36}) (Table 5). Hornblende shows an $\text{Mg}/(\text{Mg} + \text{Fe}_{\text{tot}})$ ratio of 0.37 and the moderate Al content ($\text{Al}_2\text{O}_3 = 9.21$ wt.%). Based on the results of study, this rock can be considered as volcanic ash.

The chemical composition of the whole rock sample from Layer 1/2 is given in Table 3.

3.3. Layer 1/3

The samples of Layer 1/3 are solid rock with the grains sizes up to 1.5 mm (typically 0.15–0.25 mm) (Figure 7a). The rock is dominated by lithoclasts and crystalloclasts, with volcanic glass fragments present to a lesser extent (Figure 7b). Lithoclasts are fragments of similar volcanic rocks containing conspicuous crystals (phenocrysts), surrounded by a matrix of finer-grained minerals or glass (Figure 7c). Feldspars (mainly plagioclases) predominate among the crystalloclasts. Quartz, pyroxenes (ortho- and clinopyroxene), apatite, magnetite, and biotite are also present.

According to X-ray diffraction analysis, this rock contains zeolite (heulandite/clinoptilolite series), illite, Na-Mg smectite (montmorillonite), quartz, plagioclase, hornblende, and calcite (Figure 8). It is known that the zeolite frameworks of the heulandite and clinoptilolite species are identical [Bish and Boak, 2001; Coombs et al., 1998]. Typically, the two species cannot be easily and accurately distinguished by appearance alone based on X-ray diffraction data. These zeolite mineral species can be distinguished on the basis of the framework Si:Al ratio [Bish and Boak, 2001; Coombs et al., 1998]. Heulandite is defined

Table 4. Major elements (wt.%) of volcanic glasses in Upper Sarmatian (Eldarian suite, Layer 1/2: microprobes on individual grains 1/2-1 – 1/2-8) of the Udabno section (Kakheti, Eastern Georgia). Analyses by SEM

Major Elements	Sample of Layer 1/2							
	1/2-1	1/2-2	1/2-3	1/2-4	1/2-5	1/2-6	1/2-7	1/2-8
	Major Elements (wt.%)							
SiO ₂	67.96	68.85	71.83	72.21	72.88	73.46	74.27	74.31
TiO ₂	0.24	0.31	0.17	–	–	–	0.20	–
Al ₂ O ₃	12.97	13.53	13.12	12.79	12.52	12.41	12.40	12.31
FeO _{tot}	1.44	1.70	0.63	0.92	0.94	0.71	0.80	0.59
MnO	–	–	–	–	–	–	–	–
MgO	0.30	0.41	0.07	–	–	–	0.10	–
CaO	1.38	1.73	1.13	1.09	0.94	0.81	0.42	0.71
Na ₂ O	4.39	2.78	4.80	2.75	3.29	3.42	4.55	3.83
K ₂ O	0.81	1.07	1.29	1.12	0.96	1.04	1.04	1.69
P ₂ O ₅	–	–	–	–	–	–	–	–
Σ	89.49	90.38	93.04	90.88	91.53	91.85	93.78	93.44
Na ₂ O + K ₂ O	5.20	3.85	6.09	3.87	4.25	4.46	5.59	5.52
Na ₂ O/K ₂ O	5.42	2.60	3.72	2.46	3.43	3.29	4.37	2.27
Major Elements (wt.%) Normalized to 100%								
SiO ₂	75.94	76.18	77.20	79.46	79.62	79.98	79.20	79.53
TiO ₂	0.27	0.34	0.18	–	–	–	0.21	–
Al ₂ O ₃	14.49	14.97	14.10	14.07	13.68	13.51	13.22	13.17
FeO _{tot}	1.61	1.88	0.68	1.01	1.03	0.78	0.85	0.63
MnO	–	–	–	–	–	–	–	–
MgO	0.34	0.45	0.08	–	–	–	0.11	–
CaO	1.54	1.92	1.21	1.20	1.03	0.88	0.45	0.76
Na ₂ O	4.90	3.08	5.16	3.03	3.59	3.72	4.85	4.10
K ₂ O	0.91	1.18	1.39	1.23	1.05	1.13	1.11	1.81
P ₂ O ₅	–	–	–	–	–	–	–	–
Na ₂ O + K ₂ O	5.81	4.26	6.55	4.26	4.64	4.85	5.96	5.91
Na ₂ O/K ₂ O	5.38	2.61	3.71	2.46	3.42	3.29	4.37	2.26

Table 5. Major elements (wt.%) of minerals in Upper Sarmatian (Layer 1/2: An₂₉-Hbl) and Maeotian-Pontian tuffs (Layer 1/3: An₃₅-Bi) of the Udabno section (Kakheti, Eastern Georgia). Analyses by SEM

Major Elements	Samples of Layer 1/2			Samples of Layer 1/3				
	An ₂₉	An ₃₆	Hbl	An ₃₅	An ₄₂	Cpx	Opx	Bi
	Major Elements (wt.%)							
SiO ₂	61.01	60.66	44.67	58.51	57.38	49.74	51.82	38.07
TiO ₂	0.09	–	1.34	–	–	0.62	0.15	4.71
Al ₂ O ₃	23.29	26.19	9.21	24.93	25.98	3.98	0.78	12.82
FeO _{tot}	0.42	0.26	13.87	0.20	0.41	6.40	18.01	12.45
MnO	–	–	0.45	–	–	0.17	0.71	0.15
MgO	–	–	13.28	–	–	14.82	24.22	15.32
CaO	5.37	7.26	11.16	6.81	8.16	22.31	1.46	0.20
Na ₂ O	7.33	7.09	1.47	7.01	6.16	0.22	0.11	0.48
K ₂ O	0.89	0.56	0.81	0.48	0.63	–	–	8.14
P ₂ O ₅	–	–	–	–	–	–	–	–
Σ	98.40	102.02	96.26	97.94	98.72	98.26	97.26	92.34

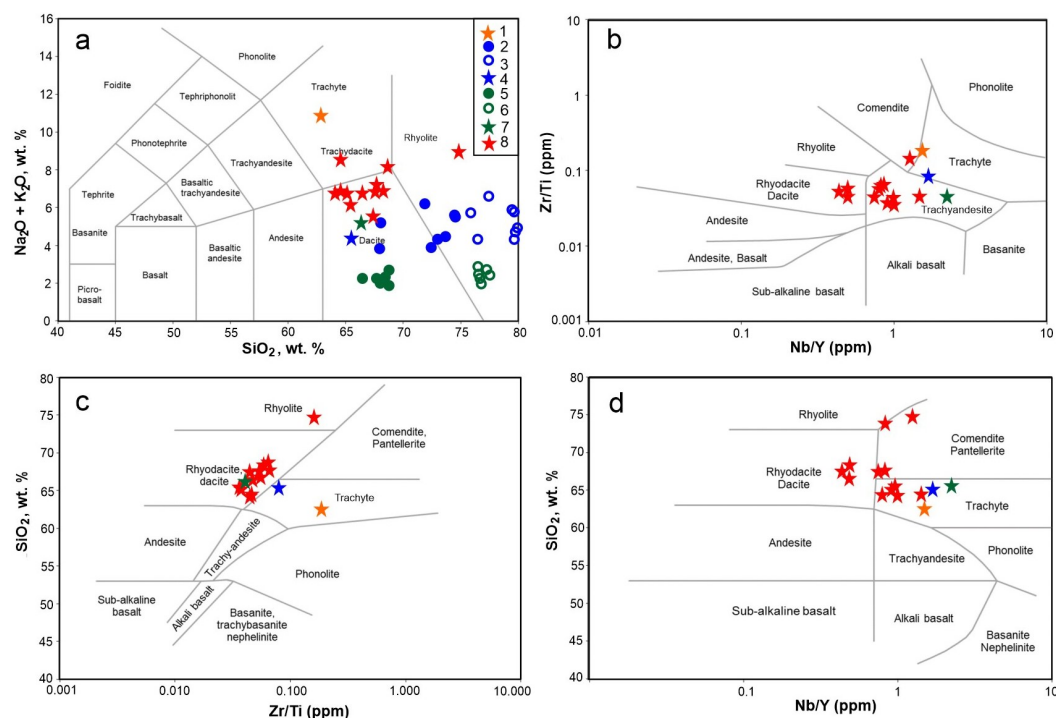


Figure 6. Classification diagrams for effusive from the Goderdzi suite (Kura (Mtkvari) section) and studied rocks. (a) Total alkalis versus silica (TAS) diagram after *Le Bas et al.* [1986]; (b–d) Diagrams after *Winchester and Floyd* [1977]: Zr/Ti versus Nb/Y plot (b), SiO_2 versus Zr/Ti plot (c), SiO_2 versus Nb/Y plot (d). 1 – composition of whole rock from Layer 1/1 (XRF), 2–4 – composition of rock from Layer 1/2: the volcanic glasses without (2) and with major elements normalized to 100% (3) (SEM) (Table 4), the whole rock (4) (XRF); 5–7 – composition of rock from Layer 1/3: the volcanic glasses without (5) and with major elements oxides normalized to 100% (6) (SEM) (Table 6), the whole rock (7) (XRF); 8 – composition of whole rock from the Goderdzi Formation (Kura (Mtkvari) section) with rock-forming oxides normalized to 100%, given in *Lebedev et al.* [2012] (XRF).

as the zeolite mineral series having the distinctive framework topology of the heulandite and the ratio $\text{Si} : \text{Al} < 4.0$. Clinoptilolite is defined as the series with the same framework topology and $\text{Si} : \text{Al} \geq 4.0$. The zeolite in the Layer 1/3 samples most likely belongs to the heulandite/c clinoptilolite series, since this mineral has the same framework topology as heulandite, and the $\text{Si}:\text{Al}$ ratio is close to 4.0 (from 3.77 to 3.96). The composition of this zeolite is as follows (wt.%): SiO_2 64.38–66.48%, Al_2O_3 13.87–14.61%, CaO 4.22–4.65%, Na_2O 2.40–2.96%, K_2O 0.45–0.52%, MgO 0.11–0.16% (Table 2).

Smectite is found as a completely pore-filling and partial crustification cement. Eu-hedral zeolite crystals occur in pores containing crustification smectite rims (Figure 7d). These zeolite crystals have formed after the crustification smectite cement. There is a grain-replacing zeolite, predominantly developing on volcanic glass. Illite, smectite, zeolite, and calcite are secondary alterations of pyroclastics. Illite and calcite are found sporadically, while smectite and zeolite occur more frequently.

The volcanic glass composition is as follows (wt.%): SiO_2 76.38–77.36%, Al_2O_3 15.05–15.46%, and alkaline components 1.99–2.82% for major elements normalized to 100% (Table 6). These volcanic glasses of felsic composition are characterized by the content of alkaline components, with sodium predominating over potassium, and a very low potassium content (Figure 6a). The low potassium content, as one of the most mobile components, is most likely related to the development of secondary alteration. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio varies from 4.49 to 8.35. The CaO content is 4.89–5.49%. Vitroclastics generally occur as isometric, highly vesiculated, cellular, and porphyric glass fragments.

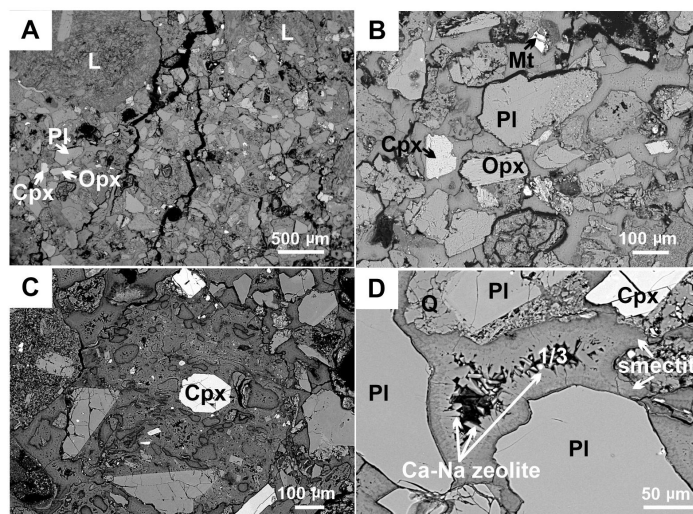


Figure 7. Scanning electron microscope images of Maeotian-Pontian tuff (Sample 1/3) from the Udabno section (Kakheti, Eastern Georgia). (a) Groundmass of rock containing grains size up to 1.5 mm; (b) fragments of pyroxenes, plagioclase, and magnetite in groundmass of rock; (c) clinopyroxene in lithoclast of volcanic rock; (d) euhedral Ca-Na zeolite crystals occur in pores containing crustification smectite rims (1/3 – microprobe on zeolite, see Table 2). Q – quartz; Pl – plagioclase; Cpx – clinopyroxene; Opx – orthopyroxene; Mt – magnetite; L – lithoclast.

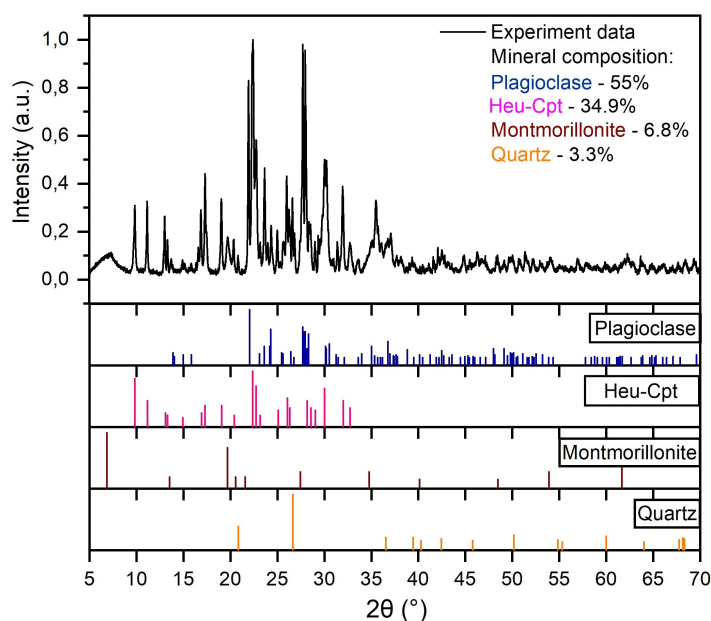


Figure 8. X-ray diffraction patterns of whole rock sample from Layer 1/3 with major minerals normalized to 100% (Heu – heulandite, Cpt – clinoptilolite).

The plagioclases have intermediate compositions ($An_{35,42}$) (Table 5). Biotite has the following composition (wt.%): SiO_2 38.07%, Al_2O_3 12.82%, iron (FeO_{tot}) 12.45%, and titanium oxide 4.71% (Table 5). Orthopyroxene shows an $Mg/(Mg + Fe_{tot})$ ratio of 0.70, which suggests it is most likely hypersthene (Table 5). Clinopyroxene is represented by augite (Table 5). Given the presence of a mineral association including intermediate plagioclases, hypersthene, augite, hornblende, and biotite, the felsic volcanic rock can be classified mainly as dacitic tuff. This tuff can be considered a product of volcanic ashfall.

The chemical composition of the whole rock sample from Layer 1/3 is given in Table 3.

Table 6. Major elements (wt.%) of volcanic glasses in Maeotian-Pontian (Shirakian suite, Layer 1/3: microprobes on individual grains 1/3-1 – 1/3-6) of the Udabno section (Kakheti, Eastern Georgia). Analyses by SEM

Major Elements	Sample of Layer 1/3					
	1/3-1	1/3-2	1/3-3	1/3-4	1/3-5	1/3-6
Major Elements (wt.%)						
SiO ₂	66.36	67.51	67.94	68.26	68.52	68.54
TiO ₂	–	–	–	–	–	–
Al ₂ O ₃	13.33	13.14	13.65	13.39	13.82	13.78
FeO _{tot}	–	–	–	–	–	–
MnO	–	–	–	–	–	–
MgO	0.35	–	0.44	0.30	0.41	0.39
CaO	4.62	4.50	4.88	4.33	4.88	4.50
Na ₂ O	1.75	1.89	1.56	1.91	1.49	2.15
K ₂ O	0.39	0.23	0.34	0.41	0.29	0.38
P ₂ O ₅	–	–	–	–	–	–
Σ	86.80	87.27	88.81	88.60	89.41	89.74
Na ₂ O + K ₂ O	2.14	2.12	1.90	2.32	1.78	2.53
Na ₂ O/K ₂ O	4.49	8.22	4.59	4.66	5.14	5.66
Major Elements (wt.%) Normalized to 100%						
SiO ₂	76.45	77.36	76.50	77.04	76.64	76.38
TiO ₂	–	–	–	–	–	–
Al ₂ O ₃	15.36	15.05	15.37	15.11	15.46	15.36
FeO _{tot}	–	–	–	–	–	–
MnO	–	–	–	–	–	–
MgO	0.40	–	0.50	0.34	0.46	0.43
CaO	5.32	5.16	5.49	4.89	5.45	5.01
Na ₂ O	2.02	2.17	1.76	2.16	1.67	2.40
K ₂ O	0.45	0.26	0.38	0.46	0.32	0.42
P ₂ O ₅	–	–	–	–	–	–
Na ₂ O + K ₂ O	2.47	2.43	2.14	2.62	1.99	2.82
Na ₂ O/K ₂ O	4.49	8.35	4.63	4.69	5.22	5.71

4. Discussion

4.1. Upper Sarmatian Tuffs: Type of Secondary Alterations, Composition, and Source of Pyroclastics

One of the studied layers of the Upper Sarmatian (Layer 1/1) is a rock almost completely replaced by analcime. Analcime is a Na-rich aluminosilicate mineral widely distributed in sedimentary rocks. This mineral can be formed by (1) replacement of volcanic material [Kossovskaya, 1975; Remy and Ferrell, 1989], (2) replacement of siliceous non-volcanic material [Do Campo et al., 2007; English, 2001; Karakaya et al., 2013; Savage et al., 2007], (3) hydrothermal mineralization [Jiao et al., 2018; Kelley et al., 2001], and (4) precipitated from an alkaline lake and pore water [Gall and Hyde, 1989; Houten, 1965]. Depending on the mechanism of formation, analcime with different characteristics is produced. Analcime formed by the replacement of the initial rock components (volcanic material, leucite, nepheline, feldspar, and other zeolite group minerals) usually is characterized by an unevenly grained texture [Ferguson and Edgar, 1978; Luhr and Carmichael, 1981; Wang et al., 2022]. The type of analcime can be determined by the Si:Al ratio [Coombs and Whetten, 1967; Richard, 1966; Teruggi, 1964]. The analcime derived from volcanic glass has a high silica content and a Si:Al ratio of more than 2.52. Layer 1/1 contains a pore-filling and

grain-replacing analcime, characterized by an irregularly grained texture and a Si:Al ratio of 2.59–2.60. Taking these data into account, as well as the presence of volcanic glass relics in the rock, the studied analcime can be interpreted as secondary alterations of volcanic material. This volcanic material is most likely fine-grained pyroclastics with a high content of volcanic glass fragments. Pyroclastic material can be transformed into precursor minerals (such as clay minerals and alkaline zeolites), which are further replaced by analcime. The Mg-Na smectite present in the rock may belong to these precursor minerals. Analcime formed by secondary alteration of volcanic material is found in sedimentary lake basins. The influence of saline-alkaline lake water has a positive effect on the formation of analcime, which agrees well with the fact that the Upper Sarmatian sediments accumulated in continental environment, including lacustrine basins. The fine-grained size of the pyroclastics supported a more intense formation of analcime.

The chemical composition of the whole rock sample from Layer 1/1 corresponds to trachyte in the classification diagrams, differing in lower SiO₂ content and higher concentrations of Na, Zr, Nb and Y from the other studied rocks (Figure 6). Formation of analcime was apparently accompanied by partial dissolution of silica and more noticeable enrichment of Zr. This rock was probably enriched in Zr by leaching of this element from primary crystals of pyroxene and amphibole, which agrees well with the data of *Rubin et al.* [1993], who studied altered volcanic rocks of the Trans-Pecos magmatic province (Texas).

The second Upper Sarmatian tuff (Layer 1/2) relates to volcanic ash containing mainly fragments of volcanic glass and crystalloclasts. This rock contains secondary alterations, among which smectite predominates; analcime as a replacement mineral occurs only in some grains. Based on the presence (even insignificant) of analcime, the next stage in the secondary alterations of this volcanic material can be the further formation of Na-zeolite. Volcanic glasses with existing secondary changes are characterized by the high content of SiO₂ and the predominance of Na₂O over K₂O and CaO. The K content is most likely reduced due to the high mobility of K⁺ under secondary transformations. Based on the content of SiO₂, these volcanic glasses belong to rhyodacite or rhyolite. The enrichment of volcanic glasses in sodium is probably the reason for the formation of the Na-rich variety of zeolite as a secondary mineral. The similarity of the development of secondary alterations, namely the formation of Na-zeolites (analcime), suggests the similarity of the chemical composition of the pyroclastic material of the studied Upper Sarmatian tuffs. Volcanic glasses of this tuff are characterized by a lower degree of secondary alteration.

The chemical composition of the whole rock sample from Layer 1/2 corresponds to dacite and trachyte in the classification diagrams and is characterized by lower SiO₂ content compared to the SiO₂ content found in the volcanic glasses present in this tuff (Figure 6). In the diagrams of Winchester and Floyd [Winchester and Floyd, 1977], the composition of this tuff is located between the compositions of the rocks of Layers 1/1 and 1/3.

The studied pyroclastics of the Upper Sarmatian occur in sediments characterized by normal polarity [Vangengeim et al., 1989]. The top of the Sarmatian (about 120 m) and the lower part of the Maeotian-Pontian sediments yielded reversed polarity. According to new data, the Sarmatian/Maeotian boundary is in chron C4n at ~7.65 Ma [Palcu et al., 2019; Popov et al., 2013; Radionova et al., 2012; Raffi et al., 2020; Rybkina et al., 2015]. The dates of about 7.65 Ma (C4n.1r) for base of the Maeotian were determined for the deepest part of the depression of the Dacian Basin and for the Panagia section of the Taman Peninsula [Popov et al., 2022]. Considering the age and polarity of the chrons in the magnetostratigraphic timescale, the studied Upper Sarmatian tuffs must be older than 7.65 Ma. Given the new K-Ar and U-Pb data [Lebedev et al., 2012; Okrostsvavidze et al., 2017], the formation of the Goderdzi suite (both lower pyroclastic and upper lava parts) started at ~7.5 Ma. In this case, the studied Upper Sarmatian tuffs are older than volcanic rocks of the Goderdzi suite, which occur in the northern part of the Lesser Caucasus within the Erusheti highland (Southern Georgia).

These Upper Sarmatian tuffs probably originated from other volcanic centers of the Caucasus or from nearby igneous provinces (e.g., Central and Eastern Anatolia, Turkey), given the fine grain size of the vitroclastic material.

4.2. Maeotian-Pontian Tuff: Type of Secondary Alterations, Composition, and Source of Pyroclastics

The Maeotian-Pontian tuff (Layer 1/3) contains mainly fragments of volcanic rocks (lithoclasts), crystalloclasts and to a lesser extent, volcanic glasses. Secondary alterations are characterized by widespread Ca-Na zeolite (heulandite/clinoptilolite) and Na-Mg smectite. In the pores the growth of euhedral zeolite crystals occurred later than the formation of smectite, which formed in earlier stages of secondary alteration. Volcanic glasses have a partial zeolitization.

Volcanic glasses have a high but lower silica content compared to Sarmatian tuffs. Based on the content of SiO_2 , these volcanic glasses belong to dacites or rhyolites. The CaO content is higher than the Na_2O and K_2O concentrations. Potassium content is extremely low (0.26–0.46 wt.%), most likely due to secondary changes and removal of K^+ . Secondary Ca-Na zeolites from this rock have a K^+ content of about 0.45–0.52%. The enrichment of pyroclastics in CaO is probably the reason for the formation of the Ca-Na zeolite as a secondary mineral.

The chemical composition of the whole rock sample from Layer 1/3 corresponds to dacite, rhyodacite, trachyte and trachyandesite in the classification diagrams (Figure 6). The composition of the whole rock is characterized by a higher content of alkaline components compared to their content in the volcanic glasses present in this tuff, which is due to the removal of potassium from them. The plot of SiO_2 versus Zr/Ti (after Winchester and Floyd [Winchester and Floyd, 1977]) shows that the composition of this tuff is similar to the volcanic rocks of the Goderdzi suite.

According to Lebedev *et al.* [2012], the volcanic rocks of the Goderdzi suite are characterized by the presence of mineral associations of phenocrysts: amphibole (Amp)-plagioclase (Pl), clinopyroxene (Cpx)-Amp-Pl, and Cpx-Pl. In some dacites, the hypersthene occurs together with clinopyroxene. The volcanic rocks of the Goderdzi suite are related to the calc-alkaline petrochemical series. These characteristics of volcanic rocks are much the same as those published by Tutberidze [Tutberidze, 2012].

Similar mineral association including Cpx-Opx-Amp-Pl was found in the studied Maeotian-Pontian tuff, characterized as part of the rocks of the Goderdzi suite by a high content of CaO. The Maeotian-Pontian tuff contains some coarse-grain material (particles about 1.5 mm), which most likely indicates the proximity of the eruption center supplying this pyroclastic material. Based on the composition (mineral association and content of major elements) and grain size as well as location, the Maeotian-Pontian tuff can be associated to one of the volcanic eruptions that formed the rocks of the Goderdzi suite. Considering new K-Ar and U-Pb data [Lebedev *et al.*, 2012; Okrostsvadze *et al.*, 2017], the formation of the Goderdzi suite began in the Maeotian time about 7.5 Ma. According to Lebedev *et al.* [2012], the duration of the Late Miocene impulse of volcanism within the Erusheti highland during formation of the Goderdzi suite was probably ~0.5 Ma. Given this data, the age of Maeotian-Pontian tuff can be about 7.5–7.0 Ma.

5. Conclusions

The study has obtained new data on felsic tuffs from the Upper Miocene of Eastern Georgia (Kakheti, section Udabno). These tuffs are intermediate to highly felsic in composition with SiO_2 content of 65.38–66.12 wt.% in whole-rock samples and 75.94–79.98 wt.% for volcanic glasses (for major elements normalized to 100%). The studied rocks have different degrees of secondary alteration and contain pyroclastic material reflecting episodes of Late Miocene volcanic eruptions.

Secondary alterations are dominated by the formation of smectite and zeolites (Figure 9) [Rostovtseva *et al.*, 2025]. Smectite characterizes the initial stages of secondary

changes preceding more intense zeolitization. Smectite forms the matrix between grained particles or crustification cement in the pores. Analcime and heulandite/clinoptilolite (Na- and Ca-Na zeolites, respectively) are present as secondary minerals in the studied rocks. The analcime is found in the Na-rich volcanic glasses of the Upper Sarmatian, while the heulandite/clinoptilolite is found in the Maeotian-Pontian tuff containing volcanic glasses with high content of Ca.

Age	Grain size and type of components	Some major elements (composition of volcanic glasses)	Type of secondary alterations	
from 7.5 to 7.0 Ma	Maeotian-Pontian Layer 1/3	grain size: 0.15-0.25 (up to 1.5) mm L > CR, G (?)	SiO ₂ 76.38-77.36% CaO 4.89-5.49% Na ₂ O 1.67-2.40% K ₂ O 0.26-0.46%	Na-Mg smectite + Ca-Na-zeolite (heulandite)
	Upper Sarmatian Layer 1/2	grain size: 0.02-0.08 mm G > CR, L (?)	SiO ₂ 75.94-79.88% CaO 0.45-1.92% Na₂O 3.03-5.16% K ₂ O 0.91-1.81%	Mg-Na smectite + analcime in minor amounts
up to 7.65 Ma	Upper Sarmatian Layer 1/1	grain size: 0.01-0.03 mm G > CR, L (?)	volcanic glasses are replaced by secondary minerals	Na-zeolite (analcime) + Mg-Na smectite

Figure 9. Features of secondary alterations the Upper Sarmatian and Maeotian-Pontian tuffs from the Udabno section (Kakheti, Eastern Georgia). Type of components: L – fragments of volcanic rocks (lithoclasts), CR – crystalloclasts, G – fragments of volcanic glasses, L(?) or G(?) – absence or limited number of components of this type.

In Maeotian-Pontian tuffs, the development of idiomorphic heulandite/clinoptilolite crystals in the central parts of pores after the formation of smectite was revealed. Secondary alterations were accompanied by the removal of K⁺ from volcanic glasses, the presence of which was found in authigenic Ca-Na zeolites (heulandite/clinoptilolite).

It is assumed that climate aridization and the presence of lake water contributed to the replacement of felsic volcanic glasses by smectites and zeolites in continental conditions. In the western half of Eurasia, at mid-latitudes, progressive drying was observed during the Middle and Late Miocene, accompanied by the development of mammal fauna adapted to open, savannah-like habitats [Fortelius *et al.*, 2014]. These data are supported by the presence of horizons with Hipparion fauna in the studied Upper Sarmatian deposits, characteristic of open landscapes in regions with a relatively arid climate. Despite secondary alterations, the composition of the studied pyroclastics to some extent reflects the features of initial volcanic material.

The studied Upper Sarmatian rocks most likely correspond to the felsic pyroclastics (75.94–79.98 wt.% SiO₂ for volcanic glasses) with a predominance of Na over Ca. Considering the age of the Sarmatian-Maeotian boundary and magnetostratigraphic data, the studied Upper Sarmatian tuffs have to be older than 7.65 Ma. In this case, the studied Upper Sarmatian tuffs are older than volcanic rocks of the Goderdzi suite, the formation of which started at ~7.5 Ma [Lebedev *et al.*, 2012; Okrostsvaridze *et al.*, 2017]. The source of this pyroclastic material could be the eruption centers of the Central and Eastern Anatolia adjacent to Caucasus, as well as other volcanic provinces.

The studied Maeotian-Pontian rock most likely belongs to the felsic pyroclastics (76.38–77.36 wt.% SiO₂ for volcanic glasses) with a predominance of Ca over Na. This pyroclastic is most likely comparable to the volcanic rocks of the Goderdzi suite, thus reflecting episodes of eruptions in the Erusheti highland (southern Georgia) from ~7.5 to 7.0 Ma.

In contrast to the Upper Miocene volcanic ashes of the Kerch-Taman region [Rostovtseva and Parfenova, 2006], the radiometric dating of the studied Upper Sarmatian and Maeotian-Pontian tuffs of the Udabno section using volcanic glass is problematic due to their secondary alterations.

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References

- Aslanian A., Bagdasarian G., Gabunia L., et al. The Georgian SSR, Armenian SSR and a part of Nakhichevan ASSR Neogene volcanic formations radiometric ages // *Izvestiya AN Armyanskoy SSR. Nauki o Zemle*. — 1982. — Vol. XXXV. — P. 3–24. — (In Russian).
- Bish D. L. and Boak J. M. 5. Clinoptilolite-Heulandite Nomenclature // *Natural Zeolites*. — De Gruyter, 2001. — P. 207–216. — <https://doi.org/10.1515/9781501509117-007>
- Buleishvili D. A. Geology and oil and gas potential of the intermountain basin of Eastern Georgia. — Leningrad : Gostoptekhizdat, 1960. — 236 p. — (In Russian).
- Chumakov I. S., Byzova S. L. and Ganzei S. S. Late Cenozoic geochronology and correlation of the Paratethys. — Moscow : Nauka, 1992. — 96 p. — (In Russian).
- Coombs D., Alberti A., Armbruster T., et al. Recommended nomenclature for zeolite minerals: report of the subcommittee on zeolites of the International Mineralogical Association, Commission on New Minerals and Mineral Names // *Mineralogical Magazine*. — 1998. — Aug. — Vol. 62, no. 4. — P. 1571–1606. — <https://doi.org/10.1180/002646198547800>
- Coombs D. S. and Whetten T. Composition of Analcime from Sedimentary and Burial Metamorphic Rocks // *Geological Society of America Bulletin*. — 1967. — Vol. 78, no. 2. — P. 269–282. — [https://doi.org/10.1130/0016-7606\(1967\)78\[269:coafsa\]2.0.co;2](https://doi.org/10.1130/0016-7606(1967)78[269:coafsa]2.0.co;2)
- Do Campo M., Papa C. del, Jiménez-Millán J., et al. Clay mineral assemblages and analcime formation in a Palaeogene fluvial-lacustrine sequence (Maíz Gordo Formation Palaeogen) from northwestern Argentina // *Sedimentary Geology*. — 2007. — Vol. 201, no. 1/2. — P. 56–74. — <https://doi.org/10.1016/j.sedgeo.2007.04.007>
- English P. M. Formation of analcime and moganite at Lake Lewis, central Australia: significance of groundwater evolution in diagenesis // *Sedimentary Geology*. — 2001. — Vol. 143, no. 3/4. — P. 219–244. — [https://doi.org/10.1016/s0037-0738\(01\)00063-x](https://doi.org/10.1016/s0037-0738(01)00063-x)
- Ferguson L. J. and Edgar A. D. The petrogenesis and origin of the analcime in the volcanic rocks of the Crowsnest Formation, Alberta // *Canadian Journal of Earth Sciences*. — 1978. — Vol. 15, no. 1. — P. 69–77. — <https://doi.org/10.1139/e78-006>
- Fortelius M., Eronen J. T., Kaya F., et al. Evolution of Neogene Mammals in Eurasia: Environmental Forcing and Biotic Interactions // *Annual Review of Earth and Planetary Sciences*. — 2014. — Vol. 42, no. 1. — P. 579–604. — <https://doi.org/10.1146/annurev-earth-050212-124030>
- Gall Q. and Hyde R. Analcime in lake and lake-margin sediments of the Carboniferous Rocky Brook Formation, Western Newfoundland, Canada // *Sedimentology*. — 1989. — Vol. 36, no. 5. — P. 875–887. — <https://doi.org/10.1111/j.1365-3091.1989.tb01751.x>
- Houten F. Crystal casts in Upper Triassic Lockatong and Brunswick Formation // *Sedimentology*. — 1965. — Vol. 4, no. 4. — P. 301–313. — <https://doi.org/10.1111/j.1365-3091.1965.tb01553.x>
- Jarosewich E., Nelen J. A. and Norberg J. A. Reference samples for electron microprobe analysis // *Geostandards Newsletter*. — 1980. — Vol. 4, no. 1. — P. 43–47. — <https://doi.org/10.1111/j.1751-908x.1980.tb00273.x>

- Jiao X., Liu Y., Yang W., et al. A magmatic-hydrothermal lacustrine exhalite from the Permian Lucaogou Formation, Santanghu Basin, NW China – The volcanogenic origin of fine-grained clastic sedimentary rocks // *Journal of Asian Earth Sciences*. — 2018. — Vol. 156. — P. 11–25. — <https://doi.org/10.1016/j.jseaes.2018.01.011>
- Karakaya N., Karakaya M. Ç. and Temel A. Mineralogical and Chemical Properties and the Origin of Two Types of Analcime in SW Ankara, Turkey // *Clays and Clay Minerals*. — 2013. — Vol. 61, no. 3. — P. 231–257. — <https://doi.org/10.1346/ccmn.2013.0610306>
- Kelley D. S., Karson J. A., Blackman D. K., et al. An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30° N // *Nature*. — 2001. — Vol. 412, no. 6843. — P. 145–149. — <https://doi.org/10.1038/35084000>
- Koiava K. P. The Biostratigraphy of Sarmatian deposits of Eastern Georgia based on foraminifera : Candidate thesis / Koiava K. P. — Tbilisi, 2006. — <https://doi.org/10.13140/RG.2.2.23185.12644> — (In Russian).
- Kossovskaia A. G. Genetic types of zeolites of stratified formations // *Litologiya i Poleznye Iskopaemye*. — 1975. — Vol. 2. — P. 23–44. — (In Russian).
- Le Bas M. J., Le Maitre R. W., Streckeisen A., et al. A Chemical Classification of Volcanic Rocks Based on the Total Alkali-Silica Diagram // *Journal of Petrology*. — 1986. — Vol. 27, no. 3. — P. 745–750. — <https://doi.org/10.1093/petrology/27.3.745>
- Lebedev V. A., Chernyshev I. V., Vashakidze G. T., et al. Geochronology of miocene volcanism in the northern part of the Lesser Caucasus (Erusheti Highland, Georgia) // *Doklady Earth Sciences*. — 2012. — Vol. 444, no. 1. — P. 585–590. — <https://doi.org/10.1134/s1028334x12050042>
- Luhr J. F. and Carmichael I. S. E. The Colima volcanic complex, Mexico: Part II. Late-quaternary cinder cones // *Contributions to Mineralogy and Petrology*. — 1981. — Vol. 76, no. 2. — P. 127–147. — <https://doi.org/10.1007/BF00371954>
- Okrostsvaridze A., Gagnidze N., Bobrova I., et al. Late Miocene volcanic ash layers of the intermountain depression of the eastern Caucasus: The product of a megacaldera explosion? // Joint meeting of IGCP 610 and INQUA POCAS Focus Group, Palermo, Italy, 1–9 October 2017. — Palermo, Italy, 2017.
- Okrostsvaridze A., Gamkrelidze I., Lee Y. H., et al. U–Pb geochronology and geochemistry of volcanic ash layers in the Eastern Caucasus intermountain Neogene basin: implications for their sources // *Arabian Journal of Geosciences*. — 2024. — Vol. 17, no. 4. — <https://doi.org/10.1007/s12517-024-11914-7>
- Palcu D. V., Vasiliev I., Stoica M., et al. The end of the Great Khersonian Drying of Eurasia: Magnetostratigraphic dating of the Maeotian transgression in the Eastern Paratethys // *Basin Research*. — 2019. — Vol. 31, no. 1. — P. 33–58. — <https://doi.org/10.1111/bre.12307>
- Paramonova N. P., Shcherba I. G., Khondkarian S. O., et al. Map 7: Late Middle Miocene (Late Serravallian, Sarmation s.s., Middle Sarmation s.1) 12–11 Ma // *Lithological-paleogeographic maps of Paratethys*. 10 Maps. Late Eocene to Pliocene / ed. by S. V. Popov, F. Rögl, A. Y. Rozanov, et al. — Stuttgart : Courier Forschungsinstitut Senckenberg, 2004. — P. 27–31.
- Popov S. V., Akhmetiev M. A., Golovina L. A., et al. Neogene regiestage stratigraphic scale of the South Russia: current state and perspectives // *General Stratigraphic Scale of Russia: current state and ways of perfection*. AllRussian meeting. May 23–25, 2013, Geological Institute of RAS, Moscow. Collector of articles / ed. by M. A. Fedonkin. — Moscow : GIN RAS, 2013. — P. 356–359. — (In Russian).
- Popov S. V., Golovina L. A., Palcu D. V., et al. Neogene Regional Scale of the Eastern Paratethys, Stratigraphy and Paleontological Basis // *Paleontological Journal*. — 2022. — Vol. 56, no. 12. — P. 1557–1720. — <https://doi.org/10.1134/s0031030122120024>
- Radionova E. P., Golovina L. A., Filippova N. Y., et al. Middle-Upper Miocene stratigraphy of the Taman Peninsula, Eastern Paratethys // *Open Geosciences*. — 2012. — Vol. 4, no. 1. — P. 188–204. — <https://doi.org/10.2478/s13533-011-0065-8>
- Raffi I., Wade B. S., Pälke H., et al. The Neogene Period // *Geologic Time Scale 2020*. — Netherlands : Elsevier, 2020. — P. 1141–1215. — <https://doi.org/10.1016/b978-0-12-824360-2.00029-2>
- Remy R. R. and Ferrell R. E. Distribution and origin of analcime in marginal lacustrine mudstones of the Green River Formation, South-Central Uinta basin, Utah // *Clays and Clay Minerals*. — 1989. — Vol. 37, no. 5. — P. 419–432. — <https://doi.org/10.1346/ccmn.1989.0370505>
- Richard L. H. Zeolites and Zeolitic Reactions in Sedimentary Rocks. — New York, USA : Geological Society of America, 1966. — 130 p. — <https://doi.org/10.1130/SPE85-p1>
- Rostovtseva Y., Koiava K., Odintsova A., et al. Secondary Alterations in Upper Miocene Tuffs of Eastern Georgia // *Recent Research on Sedimentology, Stratigraphy, Paleontology, Tectonics, Geochemistry, Volcanology and Petroleum*

- Geology. — Cham : Springer Nature Switzerland, 2025. — P. 129–132. — https://doi.org/10.1007/978-3-031-87558-8_26
- Rostovtseva Yu. V. and Parfenova O. V. Middle-upper Miocene volcanic ashes of the Kerch-Taman region // *Lithology and Mineral Resources*. — 2006. — Vol. 41, no. 5. — P. 440–449. — <https://doi.org/10.1134/s0024490206050051>
- Rubin J. N., Henry C. D. and Price J. G. The mobility of zirconium and other "immobile" elements during hydrothermal alteration // *Chemical Geology*. — 1993. — Vol. 110, no. 1–3. — P. 29–47. — [https://doi.org/10.1016/0009-2541\(93\)90246-f](https://doi.org/10.1016/0009-2541(93)90246-f)
- Rybikina A. I., Kern A. N. and Rostovtseva Yu. V. New evidence of the age of the lower Maeotian substage of the Eastern Paratethys based on astronomical cycles // *Sedimentary Geology*. — 2015. — Vol. 330. — P. 122–131. — <https://doi.org/10.1016/j.sedgeo.2015.10.003>
- Savage D., Walker C., Arthur R., et al. Alteration of bentonite by hyperalkaline fluids: A review of the role of secondary minerals // *Physics and Chemistry of the Earth, Parts A/B/C*. — 2007. — Vol. 32, no. 1–7. — P. 287–297. — <https://doi.org/10.1016/j.pce.2005.08.048>
- Shatilova I., Maissuradze L., Koiava K., et al. Bioevents on the territory of Georgia during the Late Cenozoic as evidenced by foraminifers and palynomorphs // *Proceedings of the Georgian Academy of Sciences. Biological series B*. — 2009. — Vol. 7. — P. 90–109.
- Shatilova I., Maissuradze L., Kokolashvili I., et al. The comparison of the results of palynological and microfaunistical investigations of the Sarmatian deposits of Eastern Georgia // *Bulletin of the Georgian National Academy of Sciences*. — 2012. — Vol. 6, no. 2. — P. 138–144.
- Teruggi M. E. A new and important occurrence of sedimentary analcime // *Journal of Sedimentary Research*. — 1964. — Vol. 34, no. 4. — P. 761–767. — <https://doi.org/10.1306/74d71186-2b21-11d7-8648000102c1865d>
- Tutberidze B. Cenozoic volcanism of the Caucasian Mobile Belt in Georgia, its geological-petrological peculiarities and geodynamic conditions // *Turkish Journal of Earth Sciences*. — 2012. — Vol. 21, no. 5. — P. 799–815. — <https://doi.org/10.3906/yer-1006-12>
- Uznadze M. D. Neogene flora of Georgia. — Tbilisi : Metsniereba, 1965. — 191 p. — (In Russian).
- Vangengeim E. A., Gabunia L. K., Pevzner M. A., et al. Stratigraphic position of the Transcaucasian hipparion localities on magnetostratigraphic data // *Izvestiya Akademii nauk SSSR. Seriya geologicheskaya*. — 1989. — No. 8. — P. 70–77. — (In Russian).
- Wang J., Liang C., Cao Y., et al. Occurrence, Genesis, and Significance of Analcime in Fine-Grained Sedimentary Rocks // *Geofluids*. — 2022. — Vol. 2022. — P. 3633047. — <https://doi.org/10.1155/2022/3633047>
- Winchester J. A. and Floyd P. A. Geochemical discrimination of different magma series and their differentiation products using immobile elements // *Chemical Geology*. — 1977. — Vol. 20. — P. 325–343. — [https://doi.org/10.1016/0009-2541\(77\)90057-2](https://doi.org/10.1016/0009-2541(77)90057-2)