

The Elbrus Caldera in the Northern Caucasus: Geological structure and time of formation

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Abstract. Complex field work in combination with the detailed interpretation of aerial and satellite photographs allowed us to discover for the first time a large collapsed Elbrus Caldera (17×14 km along the edge of outer escarpment with a total area of ~230 km²). The Elbrus Volcano is located in its southern part. The mass ejecta of rhyodacitic and rhyolitic pyroclastics and the formation of the tuff and ignimbrite covers are related to the caldera formation. Time of the caldera origin, according U-Pb (SHRIMP) dating on zircon from fiamme of ignimbrites is between 689±30–722±15 Ka. Based on comprehensive investigation of the rocks of the Elbrus volcanic center, including K-Ar, ³⁹Ar/⁴⁰Ar and EPR dating of rock-forming quartz, we identified in its evolution precaldera, caldera and postcaldera cycles. Two last cycles were subdivided into early and late stages.

The geology and morphology of the Elbrus Volcano at the northern slope of the Main Caucasus Range (43°20' N and 42°27' E, altitude 5642.7 m) was studied beginning from the visit of H. Abich in 1853. The first information on the age of volcano and the petrography of rocks from some flows was published by A. P. Gerasimov and V. V. Dobyanskiy in 1910 and 1914. Results of the most important subsequent works were reported in [Gusev, 1948; Koronovskii and Rudakov, 1962; Masurenkov, 1961; Masurenkov and Panteleev, 1962; Milanovskii and Koronovskii, 1961; Molyavko and Ostafichuk, 1980, 1982; Popov and Koronovskii, 1987]. However, some topical problems, including those related to catastrophic events (existence or absence of caldera, lahars, etc.) remain open. Pleistocene calderas were not reliably known in the Northern Caucasus until recently. The Upper Chegem Caldera, which was outlined in 1991, is 2.8 Ma old [Lipman *et al.*, 1993].

Complex field work in combination with the detailed interpretation of aerial and satellite photographs, which was carried out in the Elbrus region in 1997, allowed us to answer at least one debatable question. For the first time, we have mapped a large collapsed caldera (17×14 km along the edge of outer escarpment with a total area of ~230 km²), which is proposed to be named the Elbrus Caldera (Figure 1). The Elbrus Volcano is located in its southern part. The mass ejects of rhyodacitic and rhyolitic pyroclastics and the formation of the tuff and ignimbrite covers are related to the caldera formation. Pre-caldera volcanics are not change to well known. We suggest that the dacitic lava flow in the Malka River valley may be a result of pre-caldera volcanic activity. Postcaldera dacitic lavas and tuffs form the eastern and western peaks of the Elbrus Volcano within the caldera. The sublatitudinal weakened tectonic zone, to which small volcanic edifices in the Kyrtyk River Valley are confined, extends across the eastern and western craters. It cannot be ruled out that this structure was a magma-controlling one.

The northern escarpment semiring (about 60% of the caldera perimeter) is expressed most clearly in topography. It extends from the upper reaches of the Biitik-Tebe River and the Palnbashi Pass on the west across the Tashly Syrt and Sirkh mountains on the north to the Kara-Kaya and Balyk Subashi mountains on the east. The foothills of the northern escarpment are traced for a substantial distance along the Kizil-Kol River Valley, which coincides with a segment of the inner fault. The height of the escarpment above the river channel reaches 700–850 m. The eastern escarpment has a similar height. The northern caldera escarpment in the Forerange is composed of the Devonian

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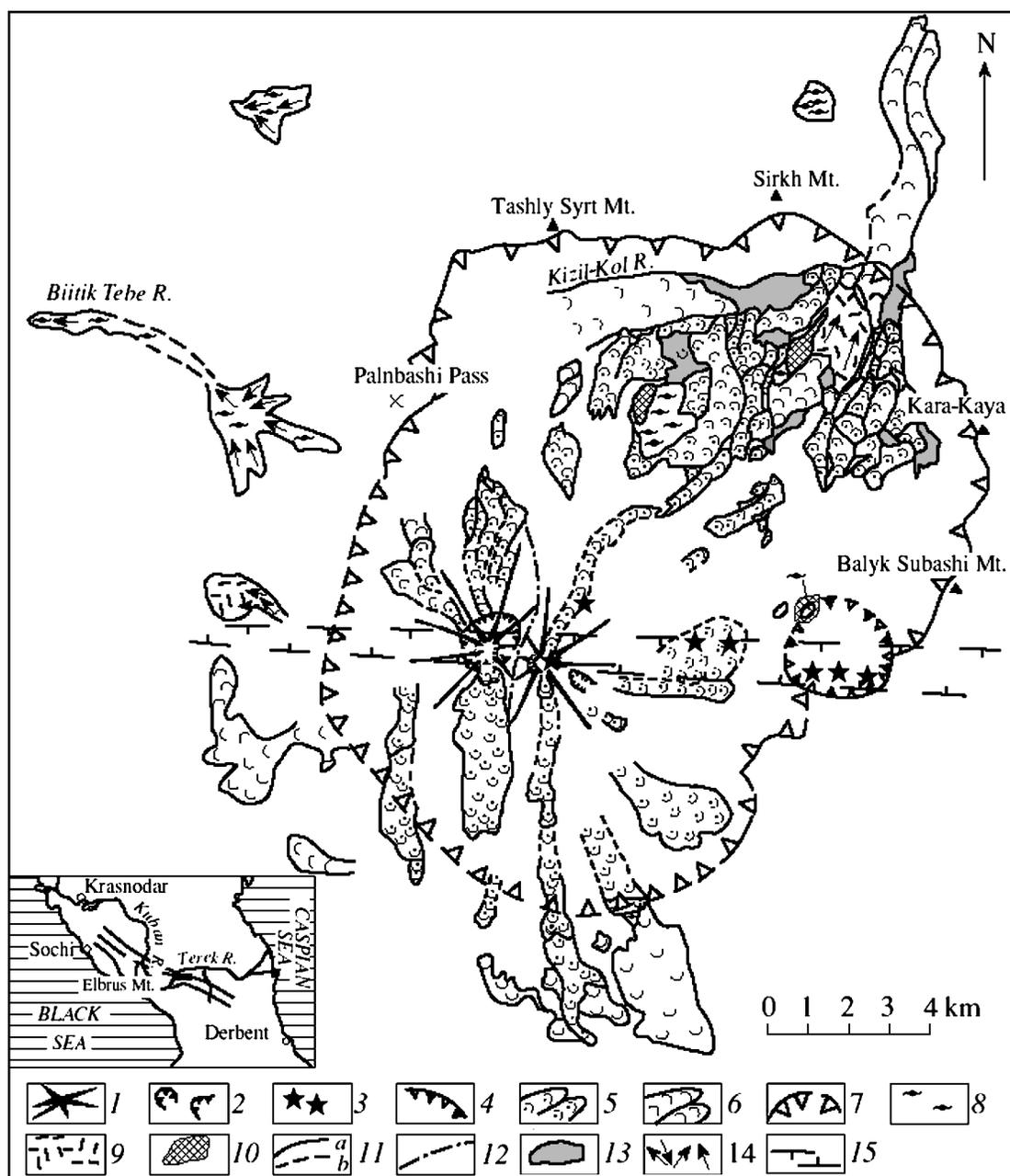


Figure 1. The sketch map of lava flows of the Elbrus Volcano and the Elbrus Caldera. (1) Volcanic edifices of the western and eastern cones (Q_4); (2) craters (Q_4); (3) small eruption centers (Q_4); (4) inferred crater or caldera in the Dzhikiukankez snow valley ($Q_3?$); lava flows: (5) Holocene, (6) Pleistocene; (7) escarpment of the Elbrus Caldera ($Q_2?$); (8) ignimbrites and tuffs of the caldera-forming eruption ($Q_2?$); (9) postcaldera pyroclastic flows (Q_3); (10) inliers of pre-caldera basement; (11) boundaries: (a) proved, (b) inferred; (12) boundaries of the western and eastern cones; (13) fragments of accumulative plains within lava fields; (14) direction of pyroclastic flows related to caldera-forming and post-caldera eruptions; (15) east-west magma-controlling weakened zone.

fractured and ferruginated gneissic tonalites, phyllites, limestones, and volcanic rocks, while central and southern parts of the escarpment in the Main Range mainly consist of altered Proterozoic mica schists, gneisses and Late Paleozoic

granites. The southern semiring of the caldera escarpment is not expressed in the relief, because it is overlapped by a thick pile of postcaldera volcanics from the intracaldera edifice of the Elbrus stratovolcano.

In the southeastern sector (Dzhikiukankez snow valley), the caldera is complicated by a specific (explosion or collapse explosion) crater or caldera, 2.5×2.0 km in size, almost entirely filled with ice.

The significant negative gravity anomaly below the Elbrus Volcano [Avdulov, 1962] may be regarded as geophysical evidence in favor of the Elbrus Caldera existence; such anomalies are among the most typical attributes of collapsed calderas [Zubin *et al.*, 1971]. Based on the morphology and geological structure, the Elbrus Caldera may be referred to as a resurgent structure (according to [Smith *et al.*, 1961]) with a domal uplift of the caldera floor after the eruption and collapse.

Inliers of Late Paleozoic granites overlapped by a thick (250–350 m) pyroclastic cover are typical of the caldera floor (see Figure 1). The lower part of the section consists of light gray welded tuffs of rhyolitic and rhyodacitic compositions with large crystals of pinkish quartz, feldspars, and biotite; the upper part is composed of gray and dark gray ignimbrites with numerous xenoliths of Late Paleozoic granites, Proterozoic mica schists and gneisses, Middle Paleozoic phyllites, volcanic rocks and limestones.

Beyond the caldera, the pyroclastic material of the caldera-forming eruption is preserved in small remnants having a rather great thickness (100–300 m) [Koronovskii, 1968; Kraevaya, 1985, *etc.*]. We also studied these remnants, which mainly consist of typical ignimbrites. A layer of loose light yellow ash and pumice materials begins at the base of the ignimbrites and covers almost everywhere, while a pumice-like rock with volcanic bombs of porous glass are typical of the uppermost part of the section. Fractured and fused plagioclase (An_{36–48}) and hypersthene crystals (up to 16–23 vol %), biotite flakes, rare quartz grains, and fiammes are incorporated into the groundmass, which consists of devitrified glass clasts and small crystallized glass lenses. The rock has a vitroclastic, tuff-like texture and pseudofluidal structure. Fiammes are composed of irregularly crystallized glassy lenses with microlithic and micropoikilitic textures and are commonly oriented parallel to the floor and roof of the volcanic pile.

The poor preservation of primary pyroclastic cover might be caused by two factors. First, the caldera was formed during a glacial epoch when almost the entire area could have been hidden under an ice cover similar to the present-day huge Vatnajökull glacier in Iceland. In this case, even a 1- to 10-m-thick, layer of hot pyroclastic material, gently tilted at the surface of the glacier, is rapidly frozen. As a result of the loss of heat, gaseous components, and the ability to move, the pyroclastic material is not accumulated as a thick pile. Most of the pyroclastic material could have been washed off during the ice thaw to be redeposited in piedmont depressions. Pyroclastic flows of a great thickness could have arisen only in most favorable sites where they could be transformed into ignimbrites and preserved until now. The second reason might be due to a high rate and intensity of denudation that affected the rapidly rising Main Caucasus Range, which at that time reached a considerable height.

The southwestern sector and related transcaldera zone are characterized by intense collapse processes. As a result of

the collapse of huge fragments of the ancient boundary escarpment, the intracaldera filling was exposed with a formation of the famous subvertical Kyukyurtly wall, more than 1000 m high. The base of the section is located here at an altitude of 3600–3700 m and represented by a thick (hundreds of meters) unit of compact lava breccia consisting of dacite and rhyodacite fragments, which are cemented by a material of the same composition. Large feldspar and quartz phenocrysts are typical of this rock, as well as ubiquitous native sulfur coatings [Koronovskii, 1968]. This rock is successively overlain by a dacitic tuff and brecciated lava layer (100 m) and a very thick pile of dacitic and rhyodacitic lavas intercalated with brecciated lava. At an altitude of about 5000 m, this section is overlapped by andesitic and dacitic lavas, which formed a specific “lava divide” for younger flows accumulated on the northern and southeastern sides of the Kyukyurtly wall [Koronovskii, 1968].

We suggest that age of the Elbrus Caldera has is much more younger than the Late Pliocene Upper Chegem Caldera (2.8 Ma), because the Elbrus Caldera still existed as a depression, whereas the Upper Chegem Caldera was transformed into an inverse positive form. The Middle or Late Pleistocene age seems to be most plausible. This inference is based on the fact that the rocks of the Elbrus volcanic center are absent in the Russ moraine in the Malka River Valley [Muratov and Gzovskii, 1948].

According scheme of the Elbrus Volcano evolution, which was developed by Koronovskii [1968], the two following complexes on the basis of geological and geomorphological data were distinguished: the lower (Late Pliocene–Early Pleistocene) and upper (Middle Pleistocene–Holocene). He assume, that age of ignimbrites, from which is beginning volcanic section, is corresponding to the lower complex – Late Pliocene – Lower Pleistocene.

Later Stankevich [1976] divided rocks of the Elbrus Volcano into three complexes, which were formed (according morphology, structural-tectonic position, K-Ar, I₀/²³⁴U, Pa/²³⁵U dating and paleomagnetic analysis) during the latest Pliocene, Pleistocene and Holocene. The First complex (most ancient) contained ignimbrites and associated with them tuffs rhyolite or rhyodacite composition (with a characteristic pink quartz); and agglomerate lavas, lava breccia of dacite and rhyodacite composition. K-Ar age of biotite from ignimbrite from effluent of the Irikchat river (eastern part of caldera structure) and biotite from rhyolite from effluent of the Ullu-Kam river (south part of caldera structure) are 6.0 Ma and 1.45 Ma, respectively. K-Ar age of plagioclase from the same rock and the same locality were 6.7 Ma and 0.6 Ma. All these K-Ar data, from his point of view, were overestimated (in unknown scale). On the basis of geological, radiological (ages of two others complexes) and paleomagnetic data E. K. Stankevich has come to the conclusion that more real formation of Elbrus Volcano started from the beginning of Late Pliocene (Late Apheron), and its activity lasted during the Pleistocene and was terminated in the Holocene, corresponding, as a whole, to the epoch of Brunhes straight change to normal magnetic polarity (0–0.7 Ma).

Currently new K-Ar data have been obtained by Chernyshev *et al.* [2001] on ignimbrites of Biitik-Tebe

River Valley, and several lava flows from the effluent of the Baksan, Malka, Bitik-Tebe river valleys. K-Ar dating of ignimbrites and associated with them tuffs of rhyolite composition (referred by the majority investigators to the early stage of the Elbrus Volcano evolution) were done on different rock-forming minerals, bulk-rocks and glass. A number of samples has appeared not suitable for K-Ar dating (a very high content of atmospheric radiogenic argon ^{40}Ar), and for low potassium minerals (plagioclase, pyroxene) in which excess ^{40}Ar was established, were obtained a very ancient and geologically senseless (15.7 Ma and 2.7 Ma) values. For the high potassium phases (biotite, bulk rock and glass) close values of K-Ar ages (from 740 up to 880 Ka) were obtained. Based on K-Ar dating *Chernyshev et al.* [2001] concluded that the formation of the early pyroclastic rocks (ignimbrites, tuffs and, from our point of view, time of caldera formation accordingly) occurred 800–900 Ka ago, while peaks of volcanic activity occurred within 160–225 Ka and less than 80 Ka ago.

Later *Bogatikov et al.* [2002] are carried out the new EPR dating (spectroscopy of electron paramagnetic resonance) of 31 rock forming quartz samples, which characterized the rocks of all stages and cycles of Elbrus volcanic centre evolution, except for the precaldera stage. The early stage of caldera cycle consisting of ignimbrites (intracaldera and outflow) and tuffs of rhyolite composition were formed according to EPR dating in the time interval 184–219 Ka. However, rhyolite ignimbrites, lavas and tuffs located in the basal section at the mouth of the Ullu-Kam and Kyukyurtly rivers shown age at 87–89 Ka. Geological data suggest that these age values are underestimated due to the thermal effect of the extrusion bodies of the late stage of caldera cycle and dacitic agglomerate lavas, lava flows which are overlapping of ignimbrites in basal section of the western part of Elbrus stratovolcano. Nevertheless, we understood that obtained EPR data it is necessary check by others reliable methods.

By this means we had a very discrepant data about time of ignimbrite, and accordingly caldera, formation. For the obtaining of more reliable data on time of Elbrus caldera formation we collected samples consist of fiamme only (weight of each samples was about 15–20 kg) from welded tuffs (ignimbrites) from outcrops at the effluent of the Kyukyurtly (into caldera) and Chuchkchur (outside caldera) river valleys and oldest porous lava flow of rhyolite composition (weight is about 20 kg) with pink quartz which occur on the upper part of welded tuff (ignimbrite) unit from the base of the Elbrus Volcano in the effluent of Kuban R. Valley. Then, for U-Pb age determination from all these samples zircon grains have been separated. We used the Stanford/USGS SHRIMP-RG. The ages represent ^{207}Pb -corrected $^{238}\text{U}/^{206}\text{Pb}$ ages, including an adjustment for initial disequilibrium between ^{230}Th and ^{238}U . U concentrations were high, common Pb concentrations were low, and all zircons were therefore close to concordia, so that the ^{207}Pb correction yields little error. The adjustment for initial disequilibrium adds between –50 and 100 Ka to the age of each spot analysis. Typically, we create a cumulative probability plot for the data and group those data that produce a clear peak at the young end of the data. We then calculate a weighted mean for those data. These are crystallization ages (not cooling ages) and should represent

the time that the zircon grew. It is always possible that the magma could erupt some time after the last crystals formed.

Below is shown U-Pb SHRIMP-RG data obtained on zircon samples.

Sample 541 (zircon from fiamme of welded tuff with a columnar jointing from the right side of the Kyukyurtly glacier). We analyzed 31 zircons from this sample. There was a single grain inherited from the Paleozoic basement (283 Ma). A great majority of the data formed a single young peak with an age of 722 ± 15 Ka. There are 8 grains with ages ranging from 1.0 to 1.5 Ma. Thus, again, there is evidence for this earlier period of magmatism that was assimilated by the later tuff. In general, the older ages come from zircons that are high in uranium and are found as cores in the middle of the zircon grains. We believe that such zircons high in uranium often crystallize from the late residual liquid in a crystallizing granite. Thus, there may be some 1.2 Ma granite beneath Elbrus.

Sample 544 (zircon from fiamme of welded tuff from the Chuchkchur River Valley (about 20 km to the NW outside from the Elbrus Volcano). We analyzed 25 zircons from this sample. There was a 72.9 Ma grain and another 393.7 Ma grain, presumably from the Paleozoic basement. Most zircons formed a single peak with an age of 720 ± 36 Ka. The probability that all zircons lie within that age is very low. A weighted mean of the 14 youngest grains is 689 ± 30 Ka, still with a relatively low probability. This rock is not distinguishable in age from either 541 or 542. Three grains had ages around 1.2 Ma and a single grain had an age of 2.1 Ma.

Sample 540 (oldest porous lava flow of rhyolite composition which overlapping directly the ignimbrite. Locality is the source of the Kuban River Valley). We analyzed 30 zircons from this sample. A great majority of the zircons had U-Pb ages between 600 and 800 Ka. The weighted mean of the primary young peak was 667 ± 16 Ka (2 sigma error). There were, also some older grains, showing an early crystallization event at –1.3 Ma. We would interpret these data as zircons from earlier intrusive events that have been assimilated by the magma that later rose through the crust and erupted as a lava.

The following conclusions may be stated from obtained on zircon by U-Pb SHRIMP-RG method:

- (1) None of these rocks were erupted less than 600 Ka (unless the crystallization long preceded eruption).
- (2) It appears that the ignimbrite in the Chuchkchur valley is the same as the ignimbrite at the base of the wall at Kyukyurtly. So, caldera have been formed between 722 ± 15 Ka and 720 ± 36 Ka, according to data obtained on zircon from fiamme of ignimbrite.
- (3) It appears that the Kuban lava is slightly younger than the ignimbrite but is largely related to it.

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