RUSSIAN JOURNAL OF EARTH SCIENCES, VOL. 6, NO. 4, PAGES 279–291, AUGUST 2004

Activity of Elbrus Volcano (North Caucasus)

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Abstract. This paper summarizes the results of the work done by Russian geoscientists in the area of Elbrus volcanic center from the end of the XX to the beginning of the XXI century. It is shown that the results of the geological and geophysical studies of the Elbrus Volcano, including the dating of its historic eruptions, the anomalous velocities of longitudinal waves, the regions of low resistivity, poor tectonic dislocations, the gravity and temperature anomalies, and the resonance specifics of the igneous rocks suggest that Elbrus is an active volcano underlain by molten igneous rocks. The geological characteristics obtained in this study for the geological structures in the Elbrus area can be used for the mathematical modeling of the wave processes induced in the layered rocks of this volcanic cone.

Introduction

At the end of the last century volcanologists began to pay more attention to the comprehensive study of the so-called "sleeping" volcanoes which may become active unexpectedly. As to the Russian territory, an example of these volcanoes is the Akademii Nauk Volcano (Kamchatka) located in the caldera of the same name, where volcanic activity had terminated 28±8 thousand years ago. However, simultaneous volcanic eruptions began unexpectedly on 02.01.1996 at the Karymskii volcano and in the Karymskii Lake filling the caldera of the Akademii Nauk Volcano [*Fedotov,* 1997]. As to the European part of Russia, Elbrus Volcano is believed to be potentially active [*Avdulov,* 1962; *Avdulov and Koronovskii,* 1993; *Garetovskaya et al.,* 1986; *Khitarov et al.,* 1984; *Krasnopevtseva,* 1984; *Masurenkov,* 1961, 1971].

Elbrus Volcano (5643 m), the highest peak of Europe, hangs over the densely populated North Caucasus areas and the adjacent southern areas of Russia (Figure 1). The inference of its potential reactivation calls for reliable information on the existence of a magma chamber in this region, including its size, the dynamic specifics of its heterogeneous rocks, and the time of its last eruptions. The results of theoretical studies and the data of high-accuracy gravity and other geophysical measurements available open up the prospects for predicting the time and places of volcanic events in this area [*Rogozhin et al.,* 2001].

The modern morphological classifications of volcanoes are usually based on the view that their shapes are controlled by the composition of magma and by the mechanisms of their volcanic eruptions. The commonly used data are morphological characteristics of the volcano, such as the absolute and relative heights of its cone, or the elevation of its basement. The study of quantitative relationships between these characteristics and the composition of the volcanic rocks are useful for analyzing the rising mechanism of magma and for estimating the depth of its origin. Proceeding from the laws of hydrostatics, the height of a stratovolcano, which had reached its limiting value, can be treated as a value controlled by the depth of the magma chamber. Hence, an important conclusion can be derived that the basic magma generated at a great depth must produce higher volcanoes [*Masurenkov,* 1972].

Paper number TJE04157.
ISSN: 1681–1208 (online)

The online version of this paper was published 28 September 2004.
URL: http://rjes.wdcb.ru/v06/tje04157/tje04157.htm

Figure 1. General view of Elbrus Volcano with the main dome of the Astrophysical Observatory of the Ukrainian Academy seen in front view (photo by L. Sobisevich).

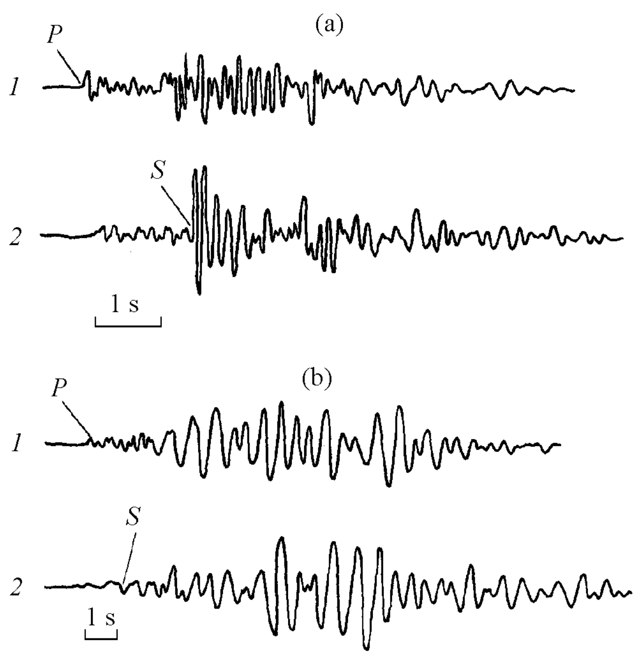

Figure 2. Seismic records of local earthquakes in the North Caucasus region: (1) Caucasus mineral water area, (2) Elbrus Cone area: (a) a vertical component, (b) a horizontal component [*Khitarov et al.,* 1984].

Elements of Tectonics and Lithosphere Structure

At the present time volcanoes are classified into two types. The first type includes active volcanoes of island arcs, most of which are not higher than 1500–2000 m. High volcanoes are not numerous there and can be ranked as basaltic or andesitic volcanoes (with SiO_2 contents of 49–59%) [*Fedotov et al.,* 1981]. The second type includes active volcanoes from young folded areas, which show the proved relationships between their heights and the compositions of the rocks composing them, yet display the general growth of their absolute heights and a great difference in the heights of the volcanoes differing in acidity. There are grounds to believe that the Elbrus Volcano also obeys the above regularity.

Our theoretical studies suggested two mechanisms for the seismoacoustic sounding of the magma chamber: (1) the analysis of a microseismic background in the source area, where the geoacoustic field may include radiation at some typical frequencies, and (2) the analysis of waves reflected from the wave source (some induced wave-type processes) during its active sounding. The use of both methods calls for the preliminary study of the microseismic background in the source region, for the creation of seismic recording channels suitable, in terms of their amplitude and frequency characteristics, to the problem at hand, for their optimum dislocation in place, and for the development of effective methods for seismic data processing and analysis.

The first experiments associated with the study of the seismic background in the region of the magma chamber and the magma source of the Elbrus Volcano were made at the end of the last century by a group of geoscientists from the Russian Academy of Science, including N. I. Khitarov, Yu. K. Shchukin, and A. V. Sizov [*Khitarov et al.,* 1984]. They measured the seismic background at the volcanic cone using a “Zemlya”-type analog equipment. During their 5-day measurements they recorded a number of seismic events which included a group of them which differed radically, in terms of the recording types, from the local earthquakes recorded in the adjacent areas of the North Caucasus (Figure 2). The most characteristic of the recorded events were their lower than normal frequencies, namely 1–2 Hz, compared to 5–6 Hz, usually recorded in the area of the Elbrus volcanic center. Besides, the Elbrus seismic records show small magnitudes of shear waves and indistinct first arrivals even in the absence of noise. These effects prove the presence of a magma chamber.

The authors of the paper cited above believe that the magma chamber resides at a small depth below the Elbrus volcanic cone, this fact being proved “by the presence of an intensive surface wave in all records.” They were unable to localize the source zone exactly. Nevertheless, they concluded that “even the data available suggest that with the low epicentral distance (10–15 km) the seismic velocity anomaly suggesting the existence of a zone of high seismic wave attenuation may exists under Elbrus at a depth of 0.5–2 km below the sea level.”

Seismic observations in the Elbrus area were resumed with the onset of the operations of a complex international geological and geophysical expedition which included geoscientists from the Institute of Physics of the Earth, the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, the Institute of Geosphere Dynamics, the Federal Caucasus Geological Survey, and a number of other organizations. In the course of this work the microseismic background was recorded in the area of the Elbrus volcanic edifice.

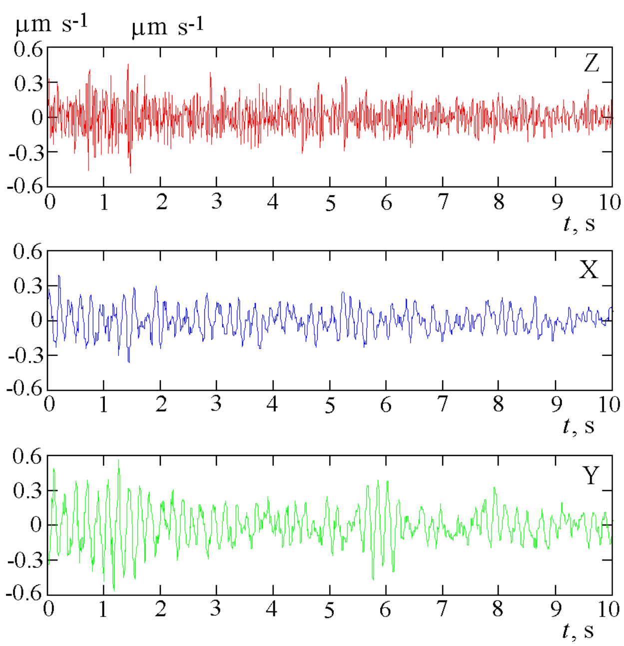

Figure 3. Velocigrams of the microseismic background recorded by the Astrophysical Observatory at 2 h, 00 min, September 04, 2000: (Z) vertical, (X) N-S horizontal, and (Y) W-E horizontal.

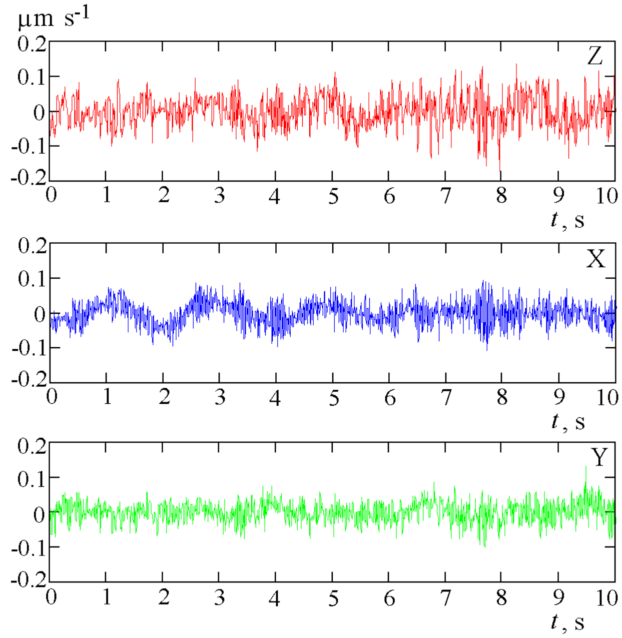

Figure 4. Velocigrams of microseismic background at 8 h, 50 min, September 02, 2000. Astrophysical Neutrino Observatory, (Z) vertical, (X) N-S horizontal, and (Y) W-E horizontal.

The first observation site was located in the Baksan R. ravine in the area of the Moscow University Geological Site located at the foot of the volcano. The absolute elevation of the site is 2300 m, its coordinates being 43°16′09″ N and 42°29′14″ E. The distance of this recording site from the Elbrus peak is 5.85 km.

The second observation site was located on the Terskol Peak, in the area of the Astrophysical Observatory of the Ukrainian Academy of Science. The coordinates of this site were 43°16′517″ N and 42°29′999″ E. The absolute height of the site was 3100 m. The distance from this recording site to the Elbrus Peak was 5.6 km. The choice of the second alternative background recording site was predetermined by the fact that the Azau Glade showed an extremely high microseismic background.

The third observation site, where seismic background was recorded, was located in the tunnel of the Neitrino Observatory with the coordinates of 43°16′338″ N and 42°40′878″ E, the altitude of the site being 1740 m, and its distance from the Elbrus Peak being 21.9 km. We begin the description of the study of the seismic environment in the Elbrus volcanic center with the results of recording the microseismic background.

Figures 3 and 4 show the characteristic velocity records of the microseismic noise (ten-second samples) in the Elbrus region [*Sobisevich et al.,* 2001]. The upper figure shows the vertical wave component, the intermediate, the horizontal component in the S-N direction, and the lower, the horizon-

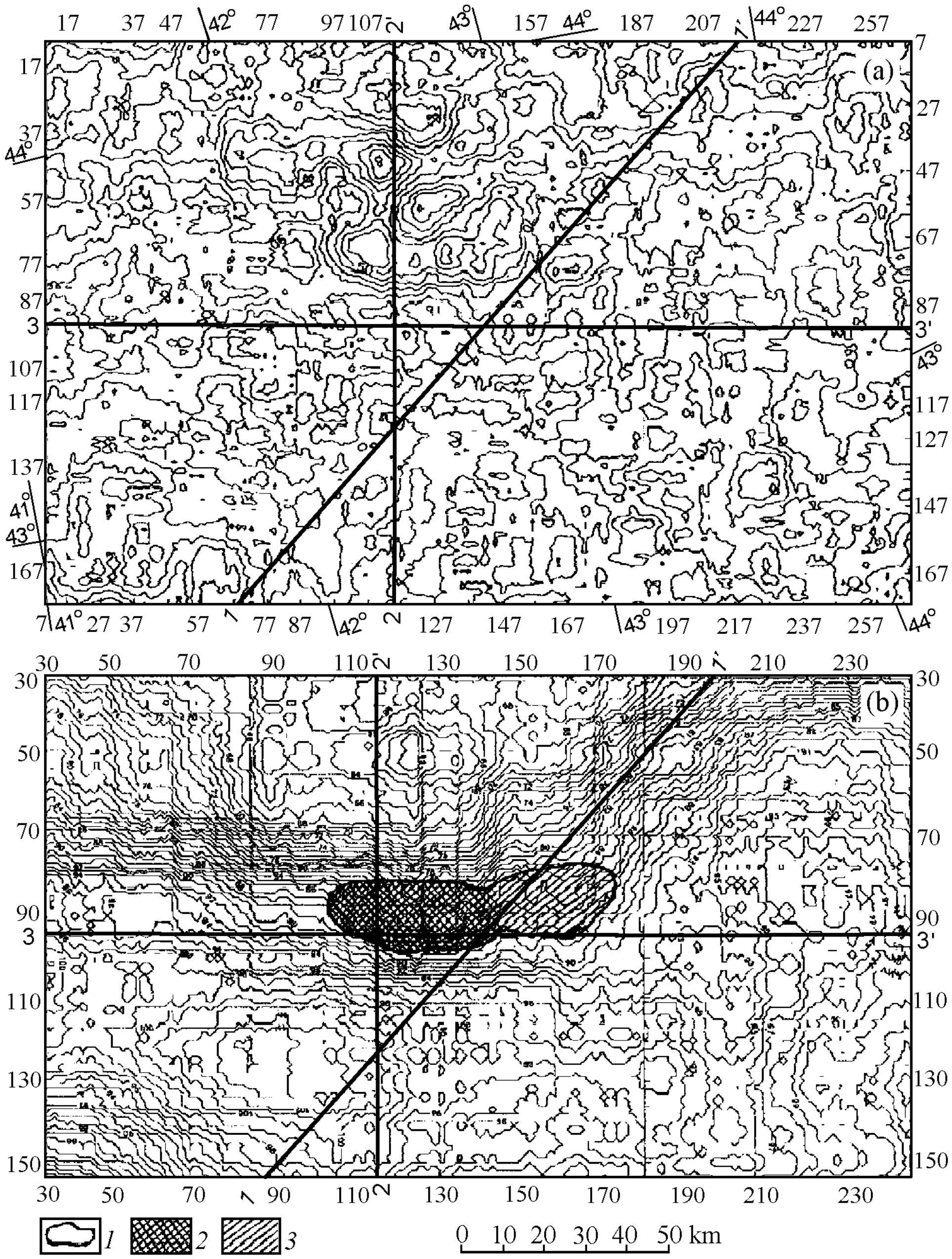

Figure 5. Tectonic breaking of the Central Caucasus lithosphere for the depth levels of about 7 km (a) and about 30 km (b). (1) Areas of local heterogeneities showing low values of the tectonic breaking field; (2, 3) areas of low tectonic breaking: (2) highly anomalous, (3) intermediate.

tal component in the W-E direction. Of particular interest is the observed low-frequency modulation of the seismic background.

Listed in Table 1 are the mean square values of velocity variations and displacements along all constituents, calculated using 10-minute data samples. The analysis of the resulting data suggests that all of the oscillation constituents are roughly equal (see the data shown in Figure 2 [*Khitarov et al.,* 1984]). This phenomenon is characteristic of the microseismic background at the outcrops of hard rocks.

As follows from Table 1, the microseismic oscillation level in the area of the neutrino measurement site is two orders of magnitude lower than that at the Azau Site and an order of magnitude lower than that at the Terskol Mt. peak. Characteristic of the spectra is the presence of individual peaks. Some peaks might be associated with the industrial noise from various mechanisms, the other seem to be associated with the presence of resonance features in the volcanic cone [*Sobisevich,* 2001]. The results of our numerous experiments, carried out in the period of time from 1999 to 2002, suggest that the use of modern geophysical instruments, especially, of deformation measurement instruments, allows one to record induced wave processes caused by igneous rock structures and other local heterogeneities [*Sobisevich et al.,* 2001, 2002a].

The fine structure of the local heterogeneities in the area of the Elbrus volcanic cone was studied using a technology developed at the United Institute of the Earth's Physics [*Nechaev,* 1999; *Nechaev and Sobisevich,* 2000]. In accordance with the technology offered in these papers, the field of the tectonic breaking of the Central Caucasus lithosphere was plotted using the results of processing the photographs of the ground surface, obtained from the "Resource" Satellite. The first result of this work was the map of a lineament network for a territory measuring 185×277 km with the Elbrus Volcano located in its central part. The subsequent processing of this map resulted in getting several maps varying from 1 to 50 km in depth, where the values of tectonic shattering were calculated using a network of 1×1 km.

Let us see the specific features of this field for the upper part of the Central Caucasus lithosphere, using a section map for the average statistical depths of about 7 km (Figure 5) [*Nechaev and Sobisevich,* 2000].

This horizontal section shows the slow growth of tectonic breaking from the southern termination of the epi-Hercynian Scythian Platform toward the region of the Central Caucasus horst-anticlinorium and its subsequent decrease toward the southern Greater Caucasus subsidence. The Laba-Malka zone of the highs is marked by the low values of this field (<80 arbitrary units), whereas its western area (gently monoclinal Mesozoic sediments) shows higher values (70–90 arbitrary units), as compared to its eastern margin (involved in the uplifting of the southern segment of the epi-Hercynian Scythian Platform). The protrusions of the Paleozoic basement show the high values of a tectonic breaking field (80–100 arbitrary units). The Tyrnyauz suture zone, composed of Paleozoic and Jurassic rocks, was mapped as a narrow transition zone of elevated horizontal gradients, its eastern segment (east of the Kuban River) being most distinct. The inversion anticlinorium of the Greater Caucasus core, composed of highly folded metamorphic rocks of the Liass-Dogger age (Central Caucasus Horst-Anticlinorium) is distinguished by the maximum values of this field (up to 120 and higher arbitrary units). They occur as individual blocks separated by the areas of lower values (<100 arbitrary units).

The more southern region of the synclinoria in the southern Greater Caucasus limb, filled with Malm and Cretaceous isoclinal folded flysch, is represented by the lower values of the field (less than 110 arbitrary units) in the form of individual local anomalies (<90 arbitrary units). The Abkhazia-Racha Step, located in the south of the territory concerned and represented by the anticlinoria and steps of the southern limb of the Greater Caucasus (moderately folded nonflysch Mesozoic rocks), showed somewhat lower values (<100 arbitrary units).

The lithospheric heterogeneities, potentially associated with the magma chamber of the Elbrus Volcano, were located by way of analyzing the vertical sections of the tectonic breaking field (Figure 6). Profile 3–3′ has a general Caucasus

Table 1. Mean-square velocity variation ranges, in μm s^{-1}

Oscillation component	Night time	Day time
	Azau Site	
Vertical	0.33	1.11
South-North	0.44	1.2
West-East	0.34	1.22
	Astrophysical Observatory	
Vertical	–	0.089
South-North	–	0.089
West-East	–	0.134
	Neutrino Site	
Vertical	0.015	0.016
South-North	0.009	0.010
West-East	0.010	0.012

strike and extends along the Tyrnyauz suture zone across the Elbrus Volcano. This profile shows that the Central Caucasus lithosphere consists of two structural stages (with a boundary between them being inferred at a depth of about 20 km); the lower stage is inferred to be a basaltic crust, its base being located at a depth of slightly greater than 50 km.

Considering the behavior of the nearly horizontal lithospheric interfaces in the vicinity of the Elbrus volcanic cone, worthy of mention is their regular rising, this fact suggesting that this volcanic cone is restricted to the region of the anomalous structure of the lithosphere. The upper part of the basaltic crust (about 20 km thick) in its central segment located under the Elbrus Volcano showed anomalous values of the tectonic breaking field. This suggests that:

(1) the Central Caucasus territory had been initially underlain by the basalt crust of the same type, which was close, in terms of its physical and mechanical properties, to its present-day remnants of the pre-Paleozoic basement (blocks and slabs) located west and east of the central anomalous region;

(2) the central block had moved northward and up the section along the nearly meridional crustal faults, and the Transcaucasus transverse uplift was formed during the next stage of the Central Caucasus evolution, when an anomalous region embracing the deep layers of the lithosphere began to form, as indicated by the rise of the Moho discontinuity;

(3) the almost ten-percent decline of the values of the tectonic disintegration in this anomalous region suggests that the physical and mechanical properties of the central block (slab) changed toward their lower values. This suggests the existence of an extension region in the Transcaucasus transverse uplift (in its western periphery) and implies that the local region of abnormally low tectonic fracturing can be interpreted as a potential magma source for the Elbrus Volcano.

The potential existence of a magma source chamber was used as a basis for locating the Elbrus magma chamber in the upper part of the crust. For this purpose an area, 30×30 km in size (with Elbrus Volcano standing in its middle), was

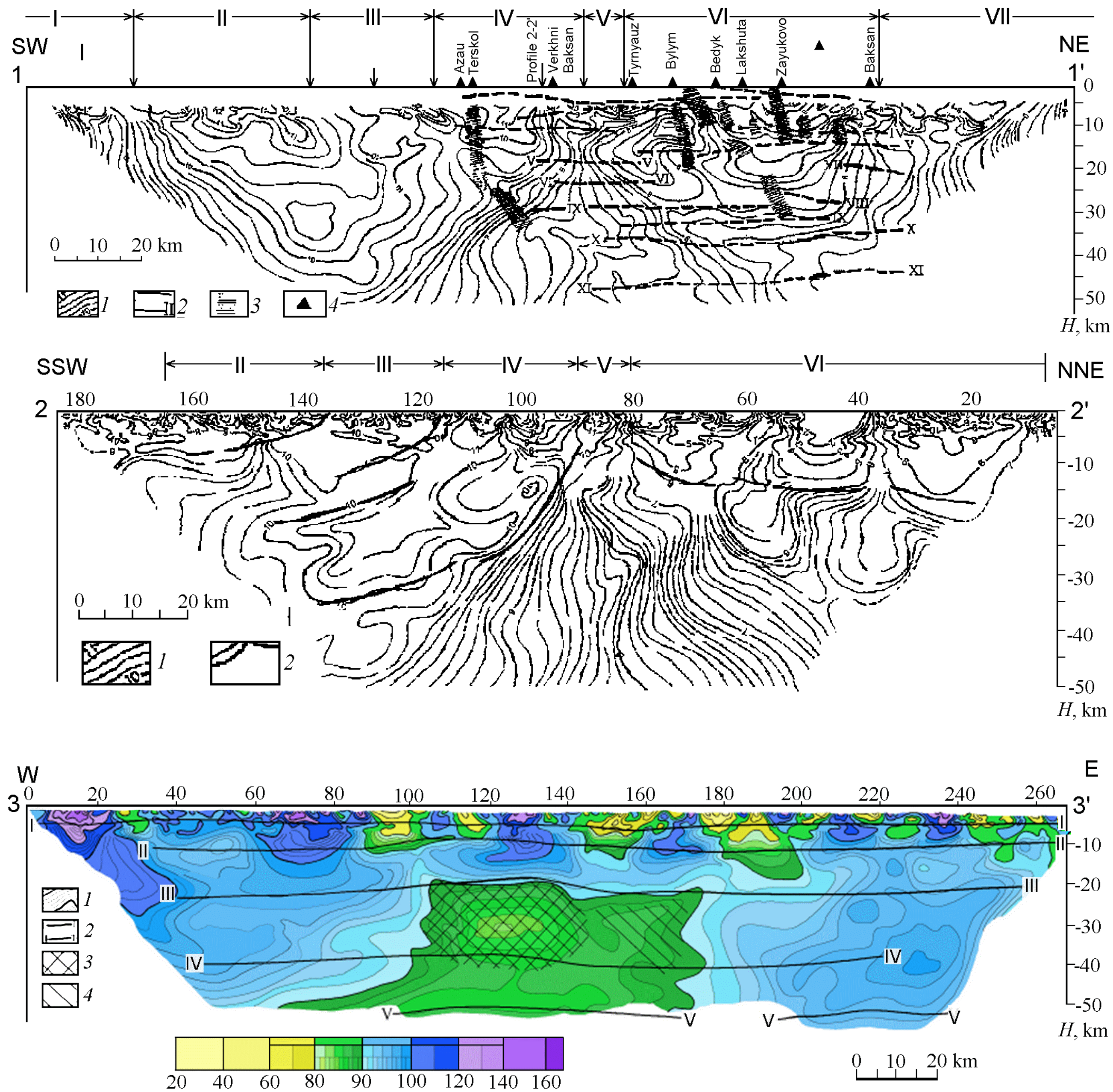

Figure 6. (a) Vertical section of the tectonic breaking (1–1′) plotted along the Azau-Baksan Profile. (1) Lithosphere tectonic breaking contour lines: thick lines are multiples of 10 arbitrary units, thin lines show intermediate values; (2, 3) results of interpreting the data recorded using the method of earthquake reflected waves (after S. A. Agamirzoev): (2) nearly horizontal boundaries inside the crust, (3) inclined fault zones; (4) observation site; (b) vertical (submeridional) section across the field of the tectonic breaking of the lithosphere (2–2′) plotted across the Caucasus strike and passing across the Elbrus peak; (5) inferred crustal interfaces; (c) vertical section of tectonic breaking (3–3′) plotted along the Caucasus strike and passing through the Elbrus peak (nearly latitudinal): (1) contour lines of the tectonic breaking of the lithosphere: thick lines show the values, multiple of 10 arbitrary units, thin lines show intermediate values; (6) nearly horizontal boundaries in the crust, identified on the basis of a specific tectonic disintegration pattern; (7, 8) regions of abnormally low values of the tectonic breaking field: (7) highly anomalous, (8) moderately anomalous.

chosen for processing space photographs in greater detail. As a result, fields of tectonic breaking were obtained for the horizontal sections corresponding to the average statistical depths of 4, 3, 2, and 1 km.

The position of the Elbrus Volcano in these maps was determined using the lowest values of the tectonic disintegration field in the projection area of the magma chamber.

The analysis of the maps for different depths showed that at a depth of about 4 km the Elbrus volcanic chamber had a roughly isometric form (measuring 10×15 km), elongated in the northern direction relative to the position of the crater. The horizontal section at a depth of about 3 km showed an insignificant branch of a ENE direction, which is most extensive in the higher section (2 km) and remains the same at the next level (1 km). It is of interest to note that the volcanic chamber of Elbrus is connected with its parental magma source in the vertical section of the tectonic shattering field extending along the strike of the Caucasus Range (Figure 7). The Elbrus magma chamber, outlined by a contour line of 90 arbitrary units, resides in the area of the volcanic cone and has the following dimensions: its lower limit is restricted to a depth of about 8 km, the western boundary of the chamber is roughly vertical, the eastern boundary is inclined eastward at an angle of about 40°; the magma chamber is as wide as 9 km at a depth of about 5 km and diminishes slowly in the direction toward the ground surface. According to our data, the size of the chamber diminishes greatly at a depth of about 2 km, where it is not larger than 5 km, its size being 2–2.5 km at a depth of 1 km.

The magma chamber of the Elbrus Volcano is restricted to the western periphery of the magma source residing at a distance of 10–12 km above it. It appears that magma flows from its source to the magma chamber along tectonically shattered zones.

The values of the tectonic shattering of the lithosphere confirm the presence of a weak zone of this kind (in the region of the western termination of the Trans-Caucasus transverse uplift). The latter is traceable in the depth interval of 45 to 12 km and is expressed by an abrupt change in the behavior of the field contour lines (growing more vertical) and in the almost invariable field values (90–92 arbitrary units). This field pattern allows one to trace the potential route of magma flow into the chamber (shaded region in Figure 8) [*Bogatikov et al.,* 2002].

The above-mentioned igneous rock structures of the Elbrus Volcano are specific formations in terms of geophysics. For instance, magma formation results in the abrupt decline of the viscosity of the rock material in the melting region and, usually, in the decline of its density, as well as in the changes of some other geophysical parameters. These changes, in turn, lead to the rearrangement of the internal structure of the region and to the formation of objects with clearly expressed resonance peculiarities which manifest themselves in the modes of lithospheric deformations and induced seismic fields.

We studied the spectra of the lithospheric deformation modes in the area of the Elbrus Volcano using the analytical results obtained by a group of researchers headed by V. K. Milyukov (Shternberg Institute of Astronomy, Moscow State University), who were engaged for many

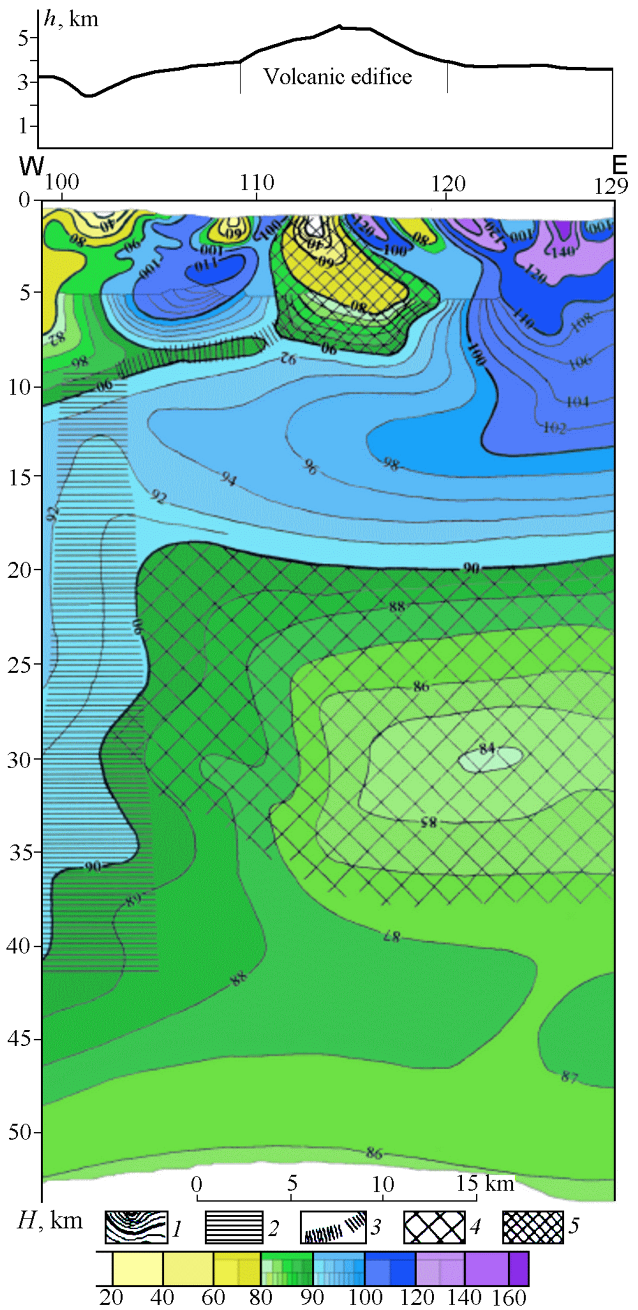

Figure 7. Vertical section of the tectonic breaking of the crust, passing across Elbrus Volcano and oriented along the Caucasus strike. (1) Contour lines showing the extent of the tectonic breaking of the crust: the thick lines are drawn with the interval of 10 arb. units, the thin ones show intermediate values with intervals of 2 or 1 arbitrary units; (2) the region (zone) of the highly broken lower crust; (3) nearly horizontal weak zones (potential flow of primary magma into the volcanic chamber); (4) region of abnormally low field values in the top of the basaltic crust, interpreted as a potential parental magma source which had supplied magmatic material to fill up the volcanic chambers; (5) region of abnormally low values in the upper crust, identified as a volcanic chamber [*Nechaev and Sobisevich,* 2000].

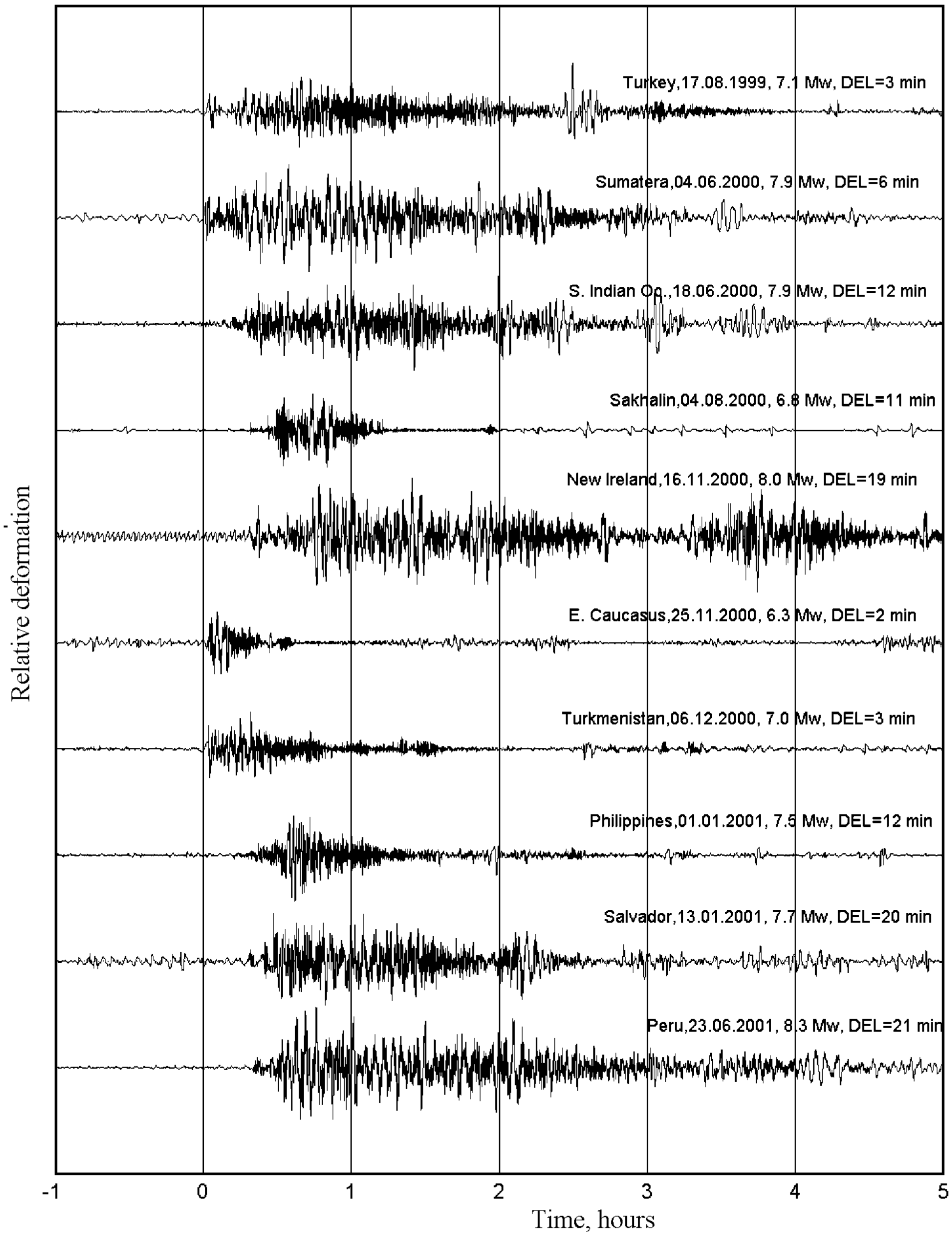

Figure 8. Observed deformations, plotted using the period of data discretization equal to 2 seconds [*Sobisevich et al.,* 2001, 2002a]

years in the systematic measurements using the Baksan laser interferometer-deformograph. The objects of these studies were the lithospheric deformations caused by high seismic events (earthquakes) of fairly large magnitudes (M_{max} ≥6.0–7.0 and higher) [*Sobisevich et al.,* 2001, 2002a]. Figure 8 presents a series of relative deformations observed for individual earthquakes.

We found that some modes in the region of extremely low frequencies could be identified with the high-frequency modes of the Earth's natural oscillations. This analysis allowed us to identify the characteristic modes induced during all earthquakes considered, unrelated to the Earth's natural oscillations. To be convinced in this fact the reader is referred to Table 2 which gives the parameters of the modes recorded during at least three of the earthquakes observed.

Similar data were obtained for 38 earthquakes (see the paper by *Sobisevich et al.* [2002b]). The interpretation of the experimental data in terms of the existing theoretical model of a magma source and of the magma chamber of the Elbrus Volcano, with due consideration of the real dynamic processes operating under the external and internal effects, allowed us to detect some characteristic resonances

Table 2. Duration of periods (in seconds) and Q factor of resonance modes, recorded during large earthquakes.

Mode	P, sec O	100 100	92 120	83 140	76 140	62 170	58 180	52 140	50 200
Period, s	1.	101.7 ±0.2	–	83.2 ±0.3	74.8 ±0.1	62.0 ±0.1	58.9 ±0.1	52.5 ±0.04	50.6 ±0.1
	2.	–	93.4 ±0.1	84.1 ±0.2	76.6 ±0.1	–	58.2 ±0.1	52.9 ±0.07	50.3 ±0.04
	3.	100.1 ±0.5	92.2 ±0.9	83.6 ±0.4	78.3 ±0.4	62.8 ±0.8	58.4 ±0.2	52.1 ±0.3	50.1 ±0.2
	4.	101.7 ±0.6	91.5 ±0.4	85.2 ±0.4	76.9 ±0.3	63.6 ±0.2	58.1 ±0.2	53.2 ±0.3	50.8 ±0.5
Q factor	1.	67	–	47	124	162	170	190	192
	2.	–	150	134	164	–	165	152	305
	3.	145	85	161	160	171	260	114	198
	4.	74	126	127	106	166	117	108	76

Note: Earthquakes: Turkey (1), Sumatra (2), Baku (3), Turkmenia (4) [*Sobisevich et al.,* 2001].

of the magmatic rocks of this type. As an example, Figure 9 presents the resulting spectrum of the intrinsic resonance modes of the Elbrus volcanic rocks.

These results were confirmed in 2002 after the geological and geophysical investigations along the Elbrus profile were completed, this work having been ordered by the Department of Natural Resources of Russia (Table 3). The work done in the framework of this project included the study of the structural features of the sedimentary cover and the Hercynian basement, the topography of deep crustal boundaries, the vertical and lateral heterogeneities in the crust and upper mantle, and the geophysical charateristics of crustal faults and fracture zones [*Arbuzkin et al.,* 2002]. This profile, 192 km long, crossed the territories of the Kabardino-Balkarian (~50 km) and Karachaevo-Cherkessian (~19 km) Republics and also the areas of the Predgornyi, Mineralnye Vody, and Aleksandrov regions of the Stavropol Territory (~123 km). This work provided new geological and geophysical data which were used to derive models along the profile line both for the upper part of the rock sequence and for the entire thickness of the Earth's crust (see Figures 10 and 11).

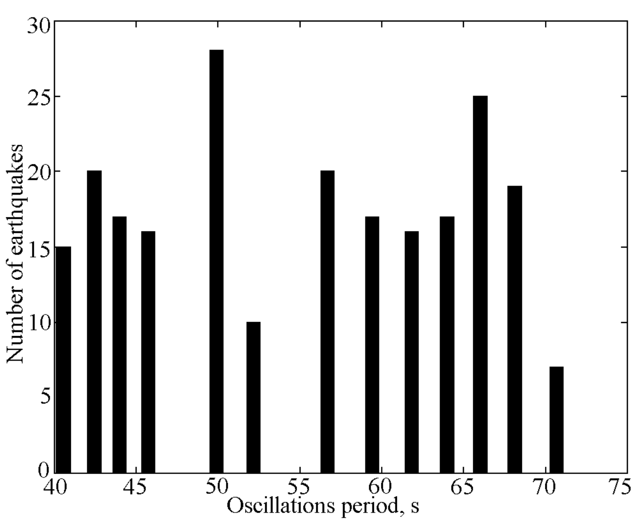

Figure 9. The spectrum of the resonance mode periods for the Elbrus volcanic rocks based on the data of deformation measurements. The bar width corresponds to the rms error of the respective period. Its height corresponds to the number of the earthquakes for which this mode has been determined [*Sobisevich et al.,* 2002b].

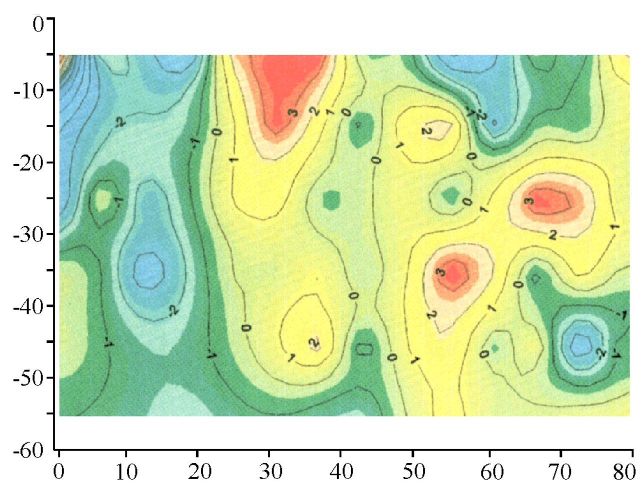

Figure 10. Seismic tomographic section along the line of the North Elbrus Profile, Scale 1:1000 000. The horizontal axis shows the profile distance in km (10 km is the coordinate of Elbrus Volcano), the vertical axis is depth in km. The left edge of the section is the south, the right edge is the north. The isolines map the relative slowness with an opposite sign in percent, the positive values corresponding to the high P wave velocities, the negative, to the low ones. This figure was plotted using the data reported by *Arbuzkin et al.* [2002].

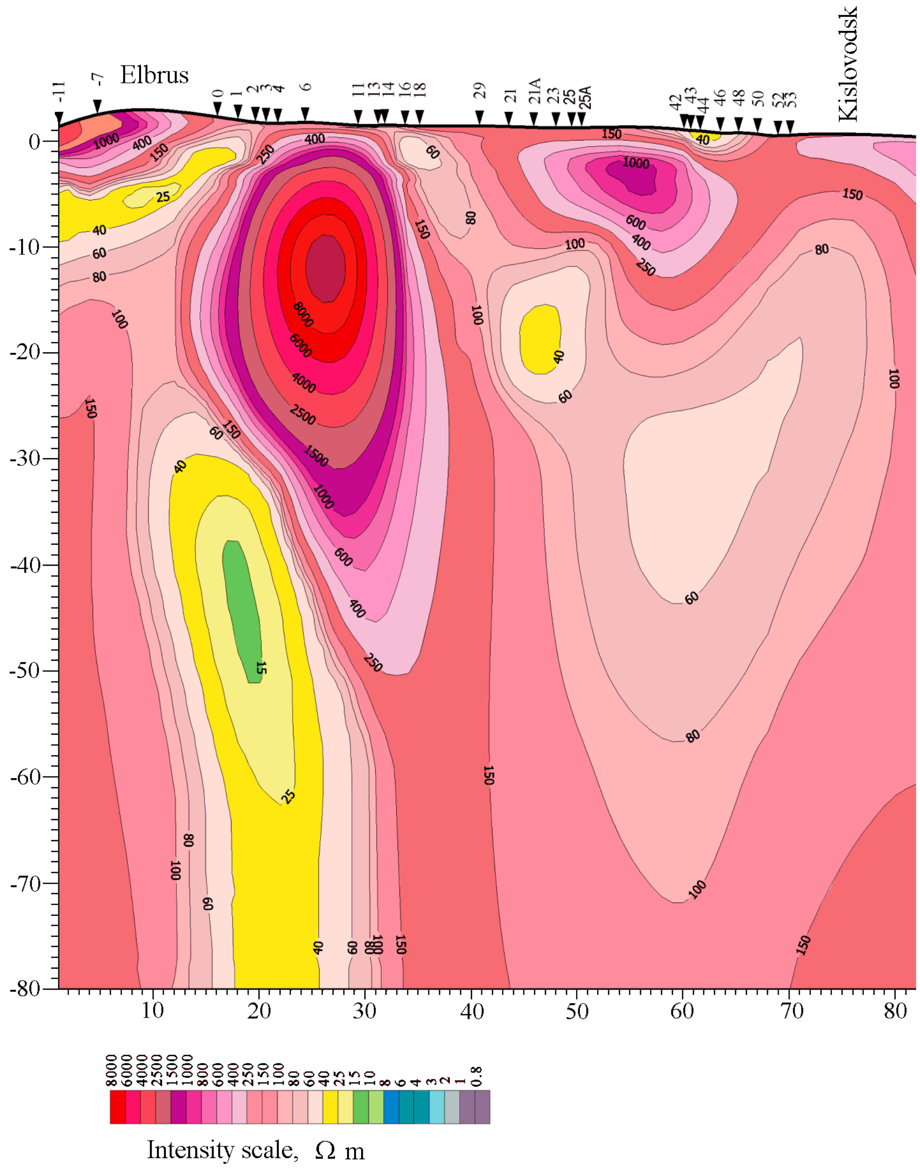

Figure 11. The resistivity section representing the interpretation of the data obtained by the magnetotelluric sounding performed along the North Elbrus profile. The horizontal axis is the distance along the profile in km, the vertical axis being the depth in km. The left edge of the section is the south, the right one being the north. The equal resistivity contour lines are plotted after [*Arbuzkin et al.,* 2002].

The experimental results obtained showed that the geoelectric properties of the upper part of the rock sequence were highly variable. The most conductive rocks were recorded under the northern half of the profile, namely, in the Scythian Plate, where the most conductive rocks are the Maikopian deposits. The numerous wells drilled there showed the resistivities of 1–2 and even 0.5–0.6 Ω m. The total conductivity of the Maikopian and overlying rocks was found to be as high as 1500 S in the Terek-Kuma Trough.

The results of the quantitative interpretation of the frequency sounding and induced polarization data showed that the deposits overlying the Maikopian rocks included 6 or 7 layers of different (mainly low) resistivity. In some areas their correlation was violated by the presence of subvertical shatter zones.

The sedimentary rocks of the mountainous areas are usually poorly conductive. In the south of the North Caucasus Monocline the sedimentary cover consists of Cretaceous terrigenous-carbonate deposits and Upper Jurassic–Early Cretaceous terrigenous rocks. Its total longitudinal conductivity is not higher than 10–15 S. As follows from the quantitative interpretation of the resistivity data, the thickness of the sediments there does not exceed 400–450 m, declining to 150 m in the Podkumok R. Valley. Southward,

Table 3. Resonance mode values of Elbrus magmatic rocks

Resonance mode period, s	70.7	68.1	66.0	64.0	61.8	59.4	56.7	52.2	49.9	45.7	44.0	42.4	40.6
Standard deviation, s	0.4	0.3	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.4	0.2	0.2
Number of earthquakes	7	19	25	17	16	17	20	10	28	16	17	20	15

in the Laba-Malka zone, the Lower Jurassic deposits (sandstone, siltstone, and argillite) are poorly conductive. They have a maximum thickness in the immediate vicinity of the Peredovoi Range in the Mara Basin (up to 500 m), which declines abruptly to 50–150 m in the area of the Malka Uplift, emphasizing the tectonic contact between these and other structural features of the Hercynian basement.

The sedimentary rocks of the Central Caucasus region are also characterized by shatter zones of varying intensity, which are most abundant in the Mineralnye Vody Protrusion. The results of gravity modeling admit the presence of the igneous rocks of the Mara volcanoplutonic rock complex at the base of the sedimentary cover at the northern flank of the Malka Rise. The Hercynian basement along the profile line is heterogeneous in resistivity, though shows less contrasting resistivity values as compared to the sedimentary rocks.

A more complex resistivity distribution pattern was found in the Central Caucasus tectonic block (to an absolute elevation of -5 km). It emphasizes the synclinal character of the Khasaut tectonically layered zone complicated by subvertical faults and grabens between them.

The southern fault corresponds to the Sredinnyi magmatically active fault which can be traced, outside of the profile, by the centers of the Mara Early to Middle Jurassic volcanoplutonic rocks.

Along the line of the profile this fault is accompanied by a vertical high-resistivity body which is interpreted as a diorite intrusion of Jurassic age.

Also clearly seen is the breaking of the pre-Jurassic basement in the Kislovodsk anticlinal zone, in the area where the sedimentary cover includes the rocks of the Mara Complex . Not less broken are the granitoids of the Malka igneous rock complex in the Bechasy anticlinal zone. The central part of the Malka Massif includes high-conductivity zones with resistivities which are not typical of igneous rocks.

The Shaukamnysyrt fold zone and the Peredovoi Range graben (synclinorium), both located more to the south, occur as a high-resistivity block residing roughly 1 km below the ground surface. The probability of the unity of these tectonic elements has been suggested earlier by G. I. Baranov and I. I. Grekov who inferred the rocks of the Shaukamnysyrt Series under the tectonic zone of the Peredovoi Range. This suggests the greater role of the faults restricting the high-resistivity block. The southern of these faults corresponds to the Pshekish-Tyrnyauz fault zone, the northern, to the not less significant Upper Malka fault. The so-called Northern fault does not continue into the continental crust and is ranked as a near-surface one.

The interpretation of the results of the magnetotelluric sounding, performed at the Elbrus slopes and in its close vicinity revealed the following structure of the consolidated crust. The volcanic rocks showed high resistivity values (>1000 Ω m). The exceptions are the sites located in the water-saturated lake deposits, which lowered the resistivity to 20–30 Ω m in the upper part of the rock sequence.

The crystalline basement of the Elbrus foundation is composed of the Proterozoic rocks of the Makera and Gondara complexes and Paleozoic granites which show rather high resistivities (hundreds to thousands Ω m). Resistivivity declines to 40 Ω m and less in a depth interval of 5–10 km.

This resistivity decline agrees with the universally known fact that as temperature grows to the values of 400°–1000° C, the resistivity of the rocks declines by a few orders of magnitude [*Lebedev and Shanets,* 1986]. This and the fact that the temperature difference between the walls and the centers of the peripheral sources of andesite-dacite magma of the Kamchatka stratovolcanoes with their radii measuring 3.0–3.5 km is about 1000° C [*Fedotov,* 1980], suggest that the low-resistivity body discovered at a depth of 5–10 km under the Elbrus Volcano is a magma chamber. The indirect evidence of a low-density body located at a depth of 5–10 km under Elbrus is provided by the interpretation of a negative gravity anomaly under Elbrus. Its magnitude and gradients can be estimated reliably by introducing a body with density of 2.37 g cm^{-3} with its upper edge at a depth of -5 km and a thickness of about 10 km. The rise of this low-resistivity body to the north explains the presence of the sources of the Neogene-Quaternary volcanism north of the Peredovoi Range (Tash-Tebe and other sources).

Another low-resistivity anomaly has been found at a greater depth of the crust (25 to 55 km) north of Elbrus. This anomaly, about 15 km wide, plunges steeply (up to 70°) to the north. Its contour coincides closely with the contour of a low-velocity region, located using the method of reflected earthquake waves, where the velocities of longitudinal waves are abnormally low, as follows from tomographic data. Taking into account that the upper conductivity anomaly is also accompanied by the anomaly of the low velocities of longitudinal waves, this anomalous region can be interpreted as a deep-seated magma source. The high conductivity and low velocity of this magma body suggest its high temperature.

Conclusions

The results of our geological and geophysical investigations, carried out in the Elbrus region, can be summarized as follows:

(1) Our interdisciplinary experiments proved the presence of a magma chamber in the Elbrus volcanic center. The results of the experimental measurements of the wave pro-

cesses in the vicinity of a magma chamber, evolving under the active external effects, are in good agreement with the theoretical data.

(2) The potential reactivation of the Elbrus Volcano, predicted by some investigators, calls for special investigations aimed to study the structure of the cone of this stratovolcano, including the exact location and monitoring of magma chambers in the Elbrus volcanic area.

(3) The final purpose of studying the Elbrus geological structure is to predict the areas of the potential lava flow by way of locating faults both on the open slopes and on the slopes covered by snow and ice. This can be done using a high-accuracy magnetic survey and magnetotelluric measurements with the subsequent geological study of the located heterogeneities of the physical fields.

(4) The existence of a direct relationship between the conductivity of the rocks and their temperature allows us to recommend the monitoring of the conductivity of the upper and lower conductors using magnetotelluric soundings twice a year at two to four sites (in the north and south of Elbrus) for the purpose of predicting the reactivation of these volcanic centers.

Acknowledgments. This work was supported by Program 13 of the Presidium of the Russian Academy of Sciences (Project 1.4), by the Russian Foundation for Basic Research (grant nos. 02-02-16100, 02-05-64939, 03-05-64215, 03-05-96744, and 03-05-64020), and by the CRD Foundation (Project RG1-2239).

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(Received 27 August 2004)