

Seismic Hazard Maps of the Northwest and Central Caucasus on a Detailed Scale

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Abstract—The paper presents the results of a new generalization of seismic hazard data for the northwestern and central sectors of the Greater Caucasus. A fundamentally new model of the seismotectonic basis for the seismic hazard map of the region has been prepared. The model is used to calculate seismic impact on a probabilistic basis. The work included three stages. At the first stage, seismotectonic studies were carried out, as a result of which a seismotectonic model was created and a map of zones of possible earthquake centers was compiled. At the second stage, the seismicity and seismic regime were studied in detail. The third stage calculated the frequency of seismic vibrations of various intensities in the study area based on the parameters of the macroseismic field equation, seismic activity patterns, zones of possible earthquake sources, and the slope of the earthquake frequency of the earthquakes. As a result, seismic hazard maps were compiled. The northwestern and central sectors of the Greater Caucasus look like a seismic hazardous area, where the level of seismic impacts reaches 8.5 on maps A and B. At the same time, compared to the data from the GSZ-97 and GSZ-2015 maps, the results appear more differentiated and generally significantly reduce the level of seismic hazard in the region. The study is important from the methodological aspect in light of seismic risk management of this densely populated and actively developed territory of Russia.

Keywords: earthquakes, seismic hazard assessment, Caucasus, seismotectonics, paleoseismogeology, seismic shaking, seismic regime

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INTRODUCTION

The study of destructive natural phenomena, primarily strong earthquakes, is the most important part of the more general and very urgent problem of ensuring environmental and public safety, especially in view of markedly increased damage from strong earthquakes and associated tsunamis, landslides, rockfalls, etc. This is particularly true for such tectonically active areas as the Caucasus.

The North Caucasus is characterized by a high population density, well-developed infrastructure, and mainly low quality of civil engineering. The latter circumstance was fully manifested in the moderate Kurchaloy earthquake of October 11, 2008 ($M_S = 5.8$) in the Chechen Republic and Republic of Dagestan, which involved human casualties and serious destruction (Rogozhin et al., 2014).

Seismic hazard assessment for the Caucasus region as a whole was most recently conducted during the GSHAP International Project in the mid-1990s (Bal-

asanian et al., 1999). Since then, no new generalizations for assessing seismic hazard for the region as a whole have been performed, although studies in this direction are carried out regularly.

With a case study of the Northwest and Central Caucasus, the paper considers the results of a new generalization of seismic hazard data for the region. The work is part of an integrated multidisciplinary basic research project of the Russian Foundation for Basic Research (project no. 18-00-00247 KOMFI “Seismic Hazard Assessment of the Northwest and Central Caucasus on a Detailed Scale Based on a New Methodological Approach” under the topic “Assessment of Economic and Social Damage from Hazardous Natural Processes for the Northwest and Central Caucasus Based on Development of New Detailed Seismic Zoning and Risk Maps”). This requires a new detailed seismic hazard map for the region.

Currently, a fundamentally new model of the seismotectonic basis for the seismic hazard map of the Northwest and Central Caucasus has been prepared. It

is used to calculate seismic impact on a probabilistic basis. The next planned phase of research is to assess economic and social damage from hazardous natural processes.

RESEARCH METHODOLOGY

The range of problems to be solved in developing the model of a new seismic hazard map of the North Caucasus can be divided into three blocks (Lutikov et al., 2008):

(1) The first block combines seismotectonic studies, during which cartographic works are carried out in the territory under consideration, using seismic geological, neotectonic, and geodetic data on seismically active tectonic structures, a seismotectonic model is created and the seismic potential is estimated. The result of these works is the mapping of possible earthquake source (PES) zones.

(2) The second block is a detailed study of the seismicity of the region, and here the scope of analysis is much wider than for seismotectonic studies, since it is necessary to take into account the possible contribution to the seismic impact from the high-magnetic zones of the PES remote from the object of study, previously identified at the general seismic zoning (GSZ) stage. In this case, it is advisable to use the most complete earthquake catalog compiled for an area whose borders are 150–200 km away from the framework of the seismic hazard map. The result of work at this stage is a map of the epicenters of strong and weak representative seismic events, sections of the depth distribution of seismicity, data on the slopes of the recurrence graphs and seismic activity patterns (matrices) calculated within each area for which a special recurrence graph.

(3) The third, final, block includes (i) establishment of the parameters of the macroseismic field equation (in most cases already known from the literature) and (ii) on its basis using seismic activity schemes and PES zones, with account for the slope of the recurrence graph, calculation of the recurrence of seismic shaking of various intensity in the territory where seismic hazard is being assessed. The result is mapping of the initial seismic score within the seismic hazard map with possible 50-year exceedance probabilities of 10% for objects of reduced and normal risk and 5% for construction objects of increased risk.

Moreover, in the first block, seismicity data obtained as a result of studies in the second block are used at the stage of seismic potential assessment.

Seismically active tectonic structures are distinguished on the basis of:

(1) collection, analysis, and generalization of stock materials on seismicity, geology, tectonics, neotectonics, Quaternary and modern activity of geological structures, deep structure using cartographic material on a scale of 1 : 1 000 000 or larger;

(2) identification and preliminary determination of the parameters of active tectonic structures based on remote sensing data (decryption of aerial and satellite images and digital terrain maps);

(3) detailed geological and geomorphological study of active tectonic structures, study of seismic deformations and paleoseismic dislocations in research areas (field works), sampling and timing of the history of movements along faults;

(4) generalization of all available material in the form of maps of paleoseismic dislocations, active faults, and PES zones.

Based on the analysis of available seismological databases, a unified, uniform in magnitude M_S , catalog of historical and instrumentally recorded earthquakes was compiled, which covers the entire territory of the Western Caucasus (Fig. 1).

REMOTE NEOTECTONIC STUDIES

The neotectonic studies were based on a structural-geomorphological analysis of the relief, aimed at identifying neotectonic dislocations.

Formation of the Regional Relief

The formation of structural forms in the relief on the Caucasus, i.e., coerosive stage, dates from the Late Sarmatian, namely, 10 Ma ago. Since that time, the active growth of the Caucasian Orogen begins. In the formation of the orogen, two stages are distinguished. The first is codenudation, corresponding to overall uplift at low rates, during which uplift is fully compensated by denudation processes, and thin molasse accumulates in submontane and intermontane depressions. The increase in the rate of tectonic movements causes a lag in denudation processes and leads to the morphological formation of an orogen in the relief. At this time, in the submontane and intermontane depressions, accumulation of coarse molasse occurs, which is an erosion product of the evolving orogen. The orogen leads to dissection of the rising uplift via denudation processes, mainly erosion, and this, second stage of development is distinguished as late orogenic–coerosive.

We performed, at a new methodological level, a structural and geomorphological interpretation of topographic maps with a scale of 1 : 1 000 000, as well as satellite and radar images, involving various geological and geophysical materials and data obtained by predecessors. In the decryption, GIS technologies were used, which made it possible to compare different types of materials, obtain the most reliable information on neotectonic dislocations, and correlate them with geological and seismic events and modern horizontal and vertical movements.

The deciphering features for identified neotectonic structures, which are the basis of structural and geomorphological studies, are presented in many works.

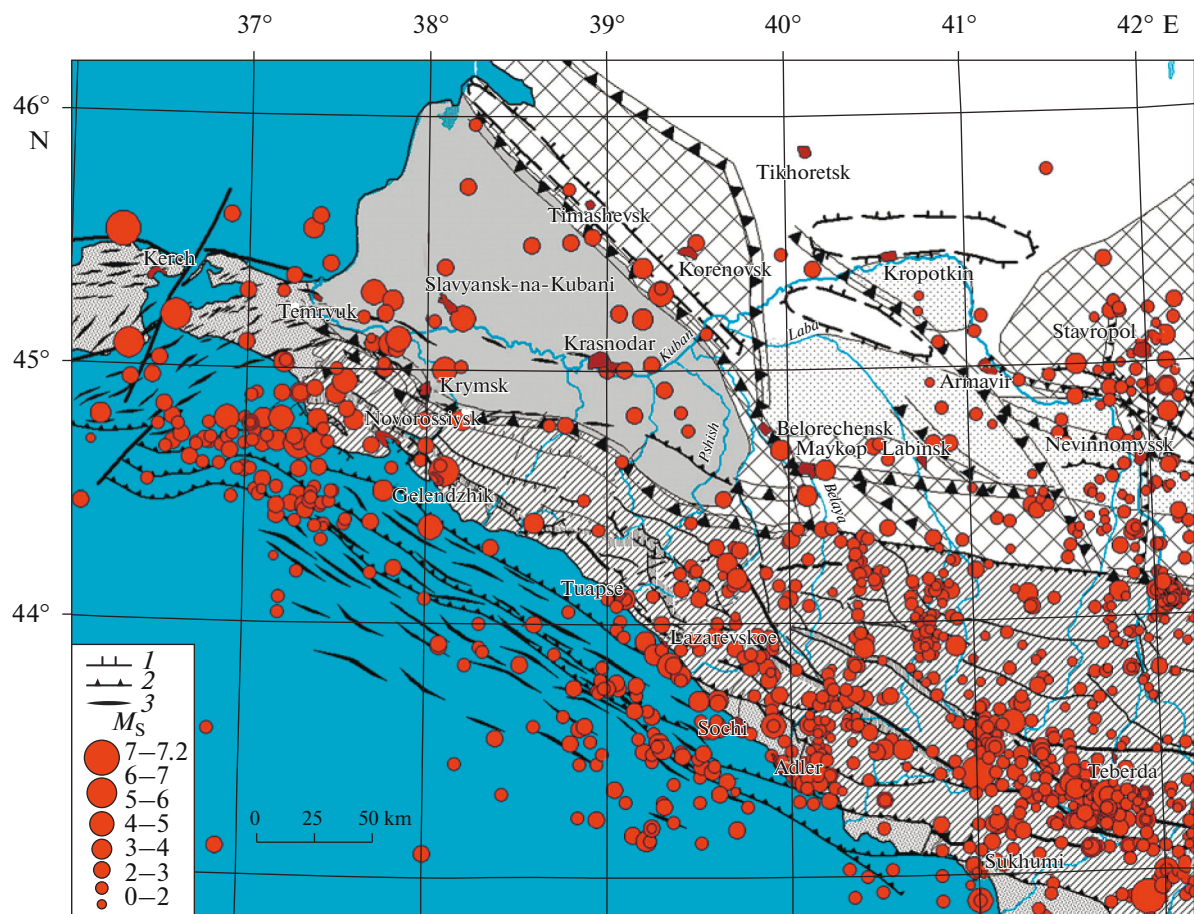


Fig. 1. Epicenters of earthquakes in Western Caucasus based on instrumental and historical data from ancient times to 2017. Main fault and block structures (see Fig. 2), as well as fold structures, are shown: (1) normal faults; (2) thrust faults; (3) axes of anticlinal folds in Neogene–Quaternary sediments.

The main deciphering features are the pattern of the hydraulic network and absolute elevation marks (among them, hydraulic network around the bases of slopes of growing uplifts, the formation of antecedent sections of valleys on their arches, and an increase in the cutdown depth of riverbeds). A radial pattern of the hydraulic network indicates the formation of the neotectonic plications. Divergence of the hydraulic network from the center along radii indicates a growing uplift, and convergence, an evolving basin. Linear river valleys and their segments are often confined to rupture, flexure, and increased fracture zones, etc., which are traditionally called zones of weakness (Kostenko, 1999). Recently, the term lineament has come in vogue, which has a broader interpretation. When using this term, we imbue the concept with a tectonic nature. In this sense, the terms zone of weakness and lineament are close. As a result of analysis of the relief, the main faults were identified and their kinematics determined, as well as systems of different ranks of blocks, uplifts, and depressions creating the neotectonic structure of the Caucasus.

The interpretation of cartographic materials was supplemented by construction and interpretation of geological and geomorphological profiles. Interpretation of the profiles makes it possible to determine the morphology of uplifts and depressions in longitudinal and transverse sections, to reveal structural features and deformations of coerosive surfaces, terraces in the relief, erosive cutdown, and to estimate the amplitudes of neotectonic dislocations and the degree of correspondence of tectonic dislocations to their modern expression in the relief, to classify them as ancient, the neotectonic newly formed and inherited, and determine their activity at the neotectonic stage.

By analyzing the amplitudes of the relief, it is possible to identify fold structures with different amplitudes: uplifts and depressions, as well as blocks of different rank and amplitude, bounded by zones of weakness or lineaments. A comparison of the latter with faults established by geological and geophysical methods allows us to speak with greater confidence about the tectonic nature of the identified dislocations and consider zones of weakness as evident or blind faults.

The neotectonic dislocations in the Northwest Caucasus and western part of the Central Caucasus identified in this way are a series of blocks broken by faults. The amplitudes of tectonic movements since the Late Miocene are indicated by us on maps in iso-bases taking into account E.E. Milanovskii's research (1968).

A study of the neotectonic structure of the Northwest and Central Caucasus showed that the onset of the orogen of the Greater Caucasus dates from the Late Miocene, when at the end of the Sarmatian and Meotian, an arched uplift began to form. A sharp increase in the uplift of the Greater Caucasus in the Late Sarmatian is recorded by significant coarsening of sediments. These are pebbles and coarse-grained sandstones, which now outcrop along the southern periphery of the frontal Ciscaucasian troughs. At this time, the troughs were involved in intense subsidence, accompanied by accumulation of thick Upper Sarmatian sequences. Their thickness (>1200 m) is several times greater than that of Lower and Middle Sarmatian deposits. A single Ciscaucasian trough, the beginning of which lies at the end of the Oligocene–Early Miocene, significantly decreased in size by the modern era; it was divided into a number of troughs (West Kuban, East Kuban, Terek–Caspian), and the structure became more complicated. These changes are caused by further development of the orogenic process in the Late Pliocene and Pleistocene (up to present day), characterized by the dominant growth of positive structural forms owing to adjacent negative forms. Along with vertical growth, the Caucasus uplifts continued to expand (Kostenko and Panina, 2001).

The orogen of the Greater Caucasus arose on alpine basins that developed from the end of the Paleozoic or Early Jurassic. In the modern relief, this is expressed as an arched-block uplift with amplitudes of 4.0–4.5 km and a steep southern and gentle northern slope, the amplitudes of which are 2.5–3 and 1–2.5 km, respectively, as well as a decrease toward the bounding uplift of submontane and intermontane depressions. The uplift of the Greater Caucasus subsides to the northwest and southeast and is divided into a series of transverse segments, terraces bounded by neotectonic fault zones. The western step is a slightly elevated mountain structure of the Northwest Caucasus, and the central step corresponds to the highest elevated structure of the Central Caucasus. The boundary between the steps is the transverse Pshekh–Adler fault zone, possibly with a dextral shear component. Individual ruptures in this zone are decoded sufficiently well in the relief, generally have a north-northwestern strike, intersect the orogen, and continue into the West Kuban submontane basin, where they are its eastern border.

Northwest Segment of the Greater Caucasus

In the present-day relief, the Northwest Caucasus is an asymmetric arched-block uplift with small (250–500 m) and moderate (1.5–2.0 km) heights. The arch of the uplift has a flattened shape, the southern slope is steep, and the northern slope is gentle. The slopes of the structure unite a system of fold–block uplifts, the amplitudes of which decrease toward the West Kuban and Black Sea basins, creating a stepped pattern in the relief. These steps are separated from each other by longitudinal (sublatitudinal) regional faults: reverse, thrust, and normal faults. The most extensive normal faults include those previously identified in (Nesmeyanov, 1992, 1999; Rogozhin and Ovsyuchenko, 2005). In certain areas, some of them coincide with normal fault dislocations indicated on our maps (Figs. 2, 3). Major normal faults: Gaiduisky, Babichevsky, Neberdzhaevsky, North Shizsky, and North Kotkshsky.

Reverse–thrust dislocations also occupy a significant place in the neotectonic structure of the Northwest Caucasus. A series of thrust faults expressed in the relief was established from drilling data (Popkov, 2007). The Akhtyr thrust fault is well expressed in the relief, along which the northern slope of the orogen is thrust over the West Kuban submontane basin. The thrust has a complex structure and, in turn, consists of a series of separate thrusts along which the structures of the Soberbash–Gunaisky synclinorium moved to the north, overlapping the southern slope of the West Kuban foothill basin. This relationship of orogens with foothill basins is typical and occurs quite often. In the modern relief, a step is clearly distinguished here, which has allowed some researchers to interpret the juncture zone as the Akhtyr flexural–slip zone (Nesmeyanov, 2001). Based on geophysical data, this boundary zone is interpreted as a vertical deep fault. Analysis of the tectonic deflection curves of the West Kuban Basin showed that beginning in the Late Miocene, the basin migrated to the north and west (Kostenko and Panina, 2001). This is also indicated by displacement of the Kuban River bed to the north. This likely indicates the reverse–thrust fault nature of the Akhtyr fault.

South of the Akhtyr fault, thrust faults with a northern and southern dip are clearly expressed in the relief, disrupting structures of the Psebai–Goyt anticlinorium. In the east (on the Tuapse–Sochi segment), the Main Caucasian thrust fault with a northern dip of the fault plane is traced in the neotectonic structure. To the south, from Sochi to the Pshekh–Adler fault zone, the Vorontsov thrust fault is also expressed in the relief, also with the fault plane dipping to the north.

Whereas on land, the Northwest Caucasus is a single arched–block uplift, in the Black Sea, a system of linear sublatitudinal folds is well expressed in the sub-sided part of the Tuapse Trough, complicated by

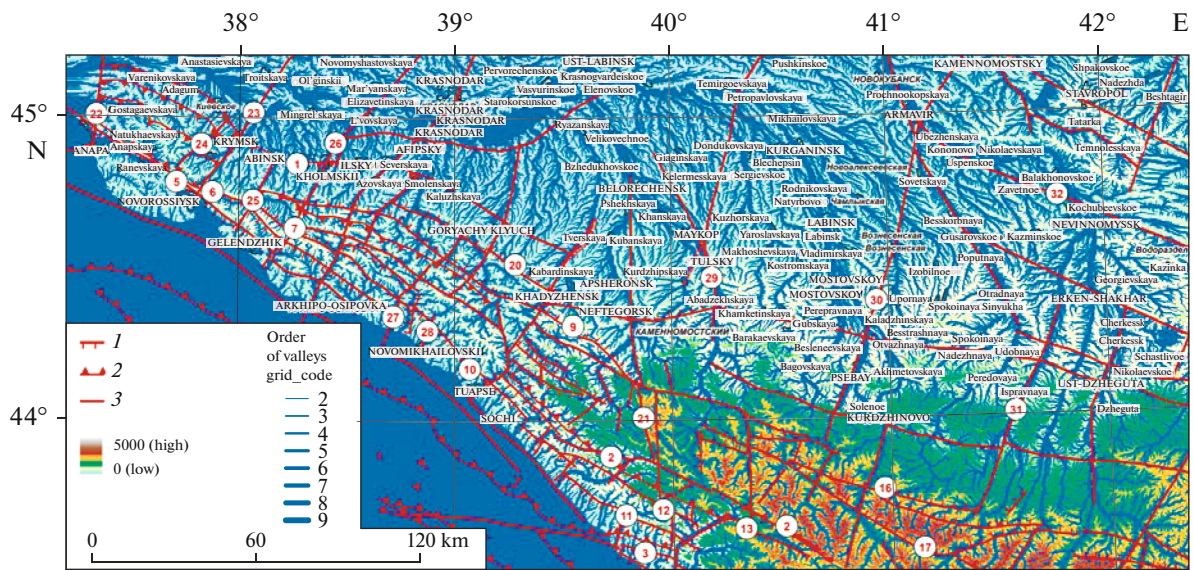


Fig. 2. Map of orders of river valleys and neotectonic faulting of Western Caucasus. (1) Normal faults; (2) thrust faults; (3) faults with uncertain kinematics. Numerals in circles are faults: thrust and reverse faults: 1, Akhtyr; 2, Main Caucasian; 3, Vorontsovskiy; 4, Black Sea system; normal faults: 5, Gaidukskiy; 6, Babichevskiy; 7, Neberdzhayevskiy; 8, North Shizskiy; 9, South Fanagoriskii; 10, Mzymta ; 11, Chvizhepsinskiy; 12, Kepshinskiy; 13, West Pseushkinskiy; 14, Goryacheche-Klyuchevskaya; 15, Nuzhskiy; 16, South Sibistinskiy; 17, Arkhyz; 18, North Svistunovskiy; 19, South Atsgara; 20, North Kotkhskiy; transverse fault zones: 21, Pshekhsk-Adler; submeridional fault zones: 22, Ust-Kuban; 23, Novorossiyskiy; 24, Divnomorskaya; 25, Abinskaya; 26, Krasnodar; 27, Dzhubginskaya; 28, Novomikhailovskaya; 29, Maykopskaya; 30, Armavirskaya; 31, Zelenchukskaya; sublatitudinal fracture zones: 32, Armaviro-Nevinnomyssk.

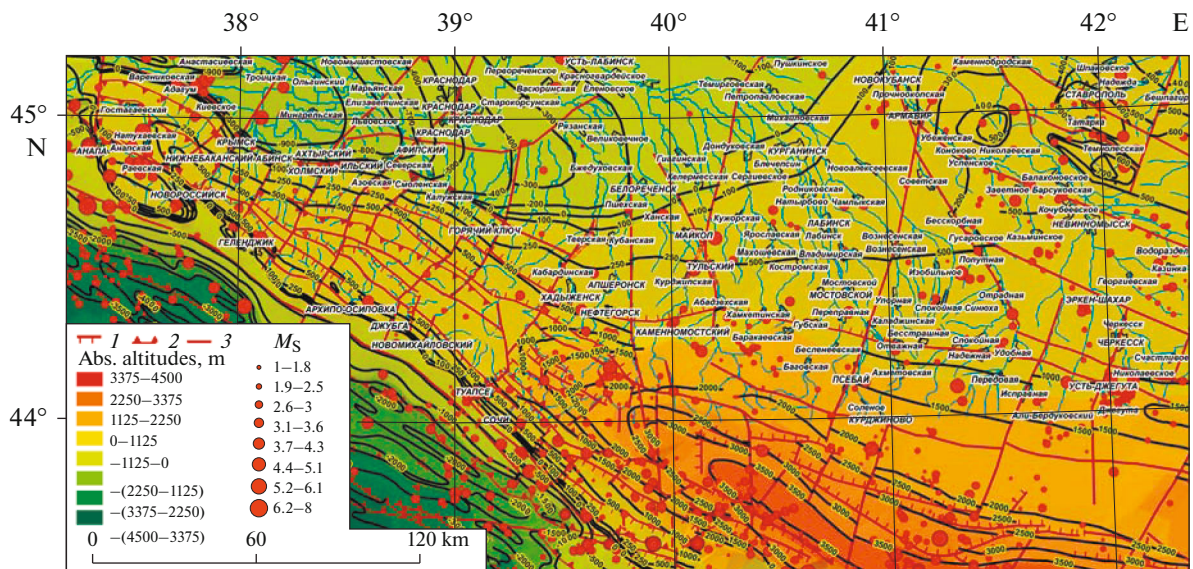


Fig. 3. Neotectonic map of Northwest and Central Caucasus: (1) normal faults; (2) thrust faults; 3, faults with uncertain kinematics

extended reverse and thrust faults. Since the Late Sarmatian, this region subsided 3–4 km, and up to now, folding has occurred in sediments in the Tuapse Trough. The axial surfaces of folds are tilted to the north, just like the reverse thrust faults along which structures of the Tuapse Trough thrust over the Shatsky Rise, where sediments are nearly horizontal.

In addition to sublatitudinal zoning, the Northwest Caucasus, just like the entire Greater Caucasus, is also characterized by transverse zoning, caused by a step-wise decrease in absolute elevation of blocks of the relief from the Pshekh–Adler transverse fault zone to the west from 2000 to 100 m (Taman Peninsula). Submeridional dislocations—normal faults often compli-

cated by a shear component—are, as a rule, tensile structures that arose during growth of uplifts in the submeridional compression field. These ruptures develop river valleys and displace ridges; along the strike of structures, they serve as the boundaries of blocks of different heights and are often marked by earthquake epicenters. Dislocation zones, as a rule, can be traced to the region of the West Kuban basin. These include (from west to east) the Ust-Kuban, Novorossiysk, Divnomorskaya, Krasnodar, Novomikhailovskaya, and Tuapse zones (see (Kostenko and Panina, 2001)). The Tuapse zone is interpreted as a zone of transverse crushing with grabenlike troughs (Nesmeyanov, 2001).

In the west, the arched-block uplift of the Northwest Caucasus borders on the more subsided Kerch–Taman region, which separates the Caucasus from the Crimean Mountains. The Taman neotectonic uplifts (anticlines) are elongated to the northeast, while the structures of the Northwest Caucasus have a sublatitudinal (west-northwest) strike. A sharp change in strike and absolute uplifts indicates the presence of a transverse fault zone here, passing through Anapa in the south and Temryuk in the north and previously called the Ust-Kuban zone. This zone separates the high (100–200 m) plain from the system of hills (200–500 m) located to the east of the Caucasus. To the north, it separates the shelf of the Sea of Azov and the low plain of the West Kuban Basin.

Central Segment of the Greater Caucasus

The central step of the Greater Caucasus is located east of the Pshekh–Adler fault and flexure zone. This article discusses its western part, bounded in the east by the Cherkessk meridian; in the south, its boundary runs along the city of Khost and south of Arkhiz, Upper Teberda, and Krasny Karachai. The absolute heights in the central uplift of the Caucasus is more than 3 km. The arch part of the uplift is contoured by the 3.5 km isobase. The orogen in this segment still possesses asymmetry (a steep southern and gentle northern slope), but it is becoming wider. This step has a complex structure and corresponds to the crystalline core of the Greater Caucasus, composed of Paleozoic metamorphic rocks and granite intrusions, which are expressed in the relief as the highest mountain peaks. In neotectonic structure, longitudinal and transverse tectonic zoning are also expressed here, in the form of blocks with different amplitudes in the relief.

The boundaries of the blocks are faults (normal, reverse, and strike-slip). The most extensive faults are shown on the map (see Fig. 2). Faults are expressed in the relief by scarps and are emphasized by fragments of river valleys. The steep southern slope is disrupted by the Main Caucasian thrust fault, and the northern slope is complicated by a series of sublatitudinal faults. The extended fault zones of the fault type of the northern slope include the sublatitudinal Arkhyz, which run

parallel to it and are located north of the South Atsgara and South Sibista faults. The Goryache-Klyuchevskoi normal fault separates the substantially degenerate East Kuban submontane depression, which is significantly involved in the uplift, from the northern slope of the Caucasian Orogen. In the modern relief, this depression corresponds to a high plain with absolute heights of 100–500 m.

The Stavropol uplift adjacent to the orogen from the north is also disrupted by a series of WNW-trending faults parallel to the structures of the Caucasus. The Armaviro–Nevinnomyssk zone, which continues in the east, passing through the Mineralnye Vody region and farther eastward, partially falls in the studied area. To the north, parallel to it, a fault zone is expressed in the relief, which passes through Stavropol and further east to the region of the Tersko-Caspian trough. Both fault zones are emphasized by seismicity.

In addition to sublatitudinal, transverse fault dislocations play a significant role in the recent structure of the Central segment of the Caucasus. These gaps have a NNE and NNW strike and are developed by fragments of the valleys of such rivers as the Belaya, Malaya and Bolshaya Laba, Bolshoi Zelenchuk, Teberda, Podkumka, etc. Beginning in the arched part of the orogen, faults are also traced in the vicinity of the Scythian Plate: East Kuban Basin and the Stavropol Uplift. Being the boundaries of blocks with different maximum height marks and, combined with the longitudinal faults with sub-Caucasian strike, they form the block structure of the Caucasus.

TECTONIC STUDIES

Thus, the neotectonic structure of the Northwest and Central segments of the Greater Caucasus is an asymmetric arched-block uplift with a gentle northern and steep southern slope. It is broken by sublatitudinal, submeridional, and diagonal faults. The main sublatitudinal (longitudinal) element of the Greater Caucasus is the central uplift, the arch of which in this territory is contoured by isobases with maximum values of 3.5 km in the Central segment and up to 250 m on the periphery of the Northwest Caucasus. From the north and south, the uplift is framed by internal and external systems of uplifts and depressions, forming its slopes, which border submontane depressions and uplifts of the Scythian Plate. The values of the isobases at the boundaries with structures of the frame of the Scythian Plate range from 500 m in the Central segment to zero at the boundary between the orogen and the Black Sea and West Kuban basins in the Northwestern segment.

At the neotectonic stage, the Greater Caucasus orogen is undergoing active growth and expansion towards the submontane depressions and water areas framing it. Thus, the West Kuban basin has significantly decreased in size and migrated to the north, and

the East Kuban depression, entrained in the uplift, is hardly expressed at all in the modern relief and merges with the western slope of the Stavropol Plateau. Such a structure has resulted from collision processes in the eastern sector of the Alpine belt. Plunging of the Transcaucasian (Lesser Caucasus) region under the Greater Caucasus orogen led to the formation of the thrust–fault system of its southern slope with a northern dip of the fault planes. Similar thrust faults have been recorded in the central part of the Northwest and Central Caucasus orogen. Against longitudinal zoning, transverse zoning is also clearly expressed in the contours of the relief and configuration of structural forms associated with the features of the internal geological structure. In particular, this applies to the Northwestern and Central segments, which differ sharply in internal structure. At the neotectonic stage, the more ancient longitudinal and transverse faults and shear zones were clearly rejuvenated (see Fig. 1). Along these faults, earthquake epicenters often build, which indicates their activation at the present stage of development.

Tectonic field studies showed that along the northeastern boundary of the West Caucasus orogen, a series of faults merged in the wide Akhtyr and Circassian flexure–fault zones. In the light of new geological and geophysical data (Rogozhin et al., 2014, 2015), these faults merged near the surface into a single structure, complicated by several gently sloping reverse faults and masking the real deep structure. At depth, the flexures are underlain by a steep reverse fault dipping to the south and embedded to the north in the section of the Ciscaucasian Trough in the form of a wedge at the level of contact between Lower Jurassic rocks and a complex of Permian–Triassic molasse and platform sequences (Zolotov et al., 2001).

In recent years, the microseismic sounding method has been used to construct deep sections along a series of profiles—Ossetian, Tuapse, two Elbrus, through the Anapa flexural–slip zone, Moldava and Akhtyr flexural–slip zones, across the strike of the Taman Peninsula and in the Kerch Strait (Rogozhin et al., 2014, 2015a, 2015b).

A feature of the neotectonic structure of the Northwestern Caucasus orogen is complication of the axial part by the narrow, several kilometers wide, suture–depression zones of near–fault grabens (Nesmeyanov, 1992). These depressions formed along the zones of the largest faults, accompanied by the maximum tensile deformations of the Alpine complex—the Main Caucasian thrust fault, Pshekish–Tyrnyauz, Krasnaya Polyana, Bekisheysky, and Semigorsky. The faults are confined to the boundaries of these local flexural structures, in the zones of which traces of Holocene seismotectonic displacements were found (Rogozhin et al., 2004; Rogozhin and Ovsyuchenko, 2005; Rogozhin et al., 2008, 2010, 2014). Earthquakes of the recent past are evidence of the modern activity of axial

depressions: the 1963 Chkhaltva earthquake with $M = 6.4$, which occurred in the Bzybko–Chkhaltva depression, and the 1905 Teberda earthquake with $M = 6.4$, which occurred in the Dombay depression.

The entire boundary of the Caucasus orogen and Black Sea Basin is a steep flexurelike bend complicated by numerous reverse and thrust faults (Meisner and Tugolesov, 1998). Such a number of them in the seafloor topography and their confinement to the arches of anticlines indicate that folds in the Tuapse Trough continue to grow to this day. Faults are also clearly pronounced in the relief, and in Quaternary sediments, vertical displacements with an amplitude of up to 1 km are observed. In seismic sections, the total amplitude of the vertical fault displacement of the foot of the Quaternary cover in the region of the continental slope reaches 2.2 km (Stroenie..., 1992). Thus, faults in the Black Sea zone reveal very well expressed signs of young activity. On land, the structures of the Tuapse trough are expressed in the the Sochi–Adler–Sukhumi depressions involved in the Pliocene–Quaternary uplift.

According to high-precision releveling, the central part of the orogen is rising at a rate of 2–7 mm/year, and the West Kuban basin is an zone of present-day subsidence at a rate of up to 1 mm/year. The junction zones of multidirectional vertical movements occur within the Akhtyr flexure–slip zone, which characterizes it as a modern tectonic stress concentration zone.

PALEOSEISMOLOGICAL STUDIES

Figure 4 reflects the level of paleoseismological study of the Western Caucasus. Targeted paleoseismological studies in the Caucasus began in the late 1960s. As a rule, the results made it possible to establish the existence of paleoseismic dislocations without localizing the source of ancient seismic events or determining their magnitude and age (Ostrovskii, 1970; Nesmeyanov et al., 1987; Belousov et al., 2000). They were used by us in compiling the map in Fig. 4. The exception is a study supervised by V.P. Solonenko (Khromovskikh et al., 1979), as a result of which the first estimates of the magnitude of paleoseismic dislocations were obtained and several focal zones were localized. In the studied region, these include the Bzyb focal zone (inverted reverse fault with $M = 7.2$), the Nenskra–Abakura zone (a series of inverted reverse and transtensional faults with $M = 7.1–7.2$), and the Quira zone (normal fault with $M = 6.7$).

Further detailed studies in this direction are continued in the present paper. On the southern slope and in the axial part of the Northwest Caucasus, potential focal zones with $M_{\max} = 6.5–6.8$ (Kotsekhurskaya and Kuznetsovskaya in Fig. 4) (Rogozhin and Ovsyuchenko, 2005; Rogozhin et al., 2014, 2015a); in the Sochi–Krasnaya Polyana zone, a source of the same name was established with $M_{\max} = 7.3$ (Rogo-

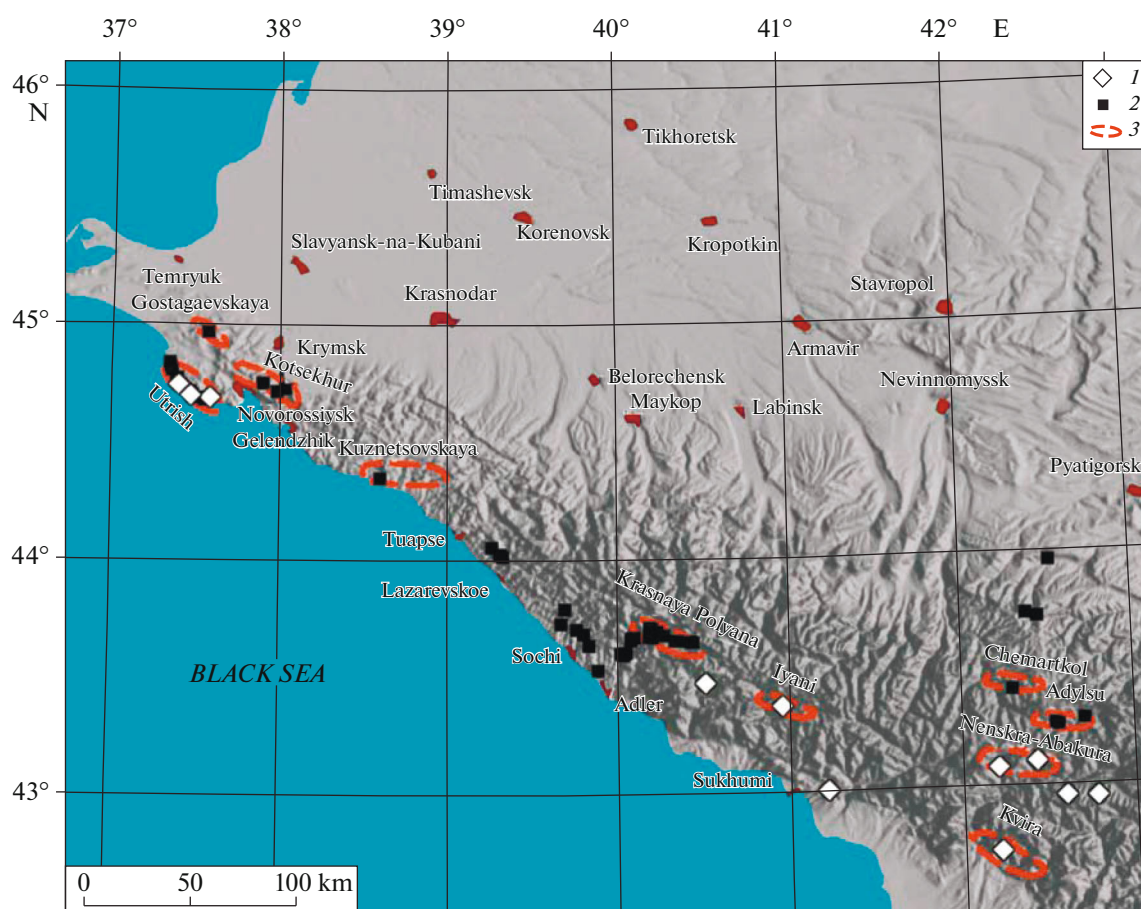


Fig. 4. Map of paleoseismogeological study of Western Caucasus. (1) Paleoseismic dislocation after (Khromovskikh et al., 1979); (2) seismogravitational structures according to field studies and literature data (Ostrovskii, 1970; Nesmeyanov et al., 1987; Belousov et al., 2000); (3) focal zones of paleoearthquakes for which detailed characteristics were obtained by authors of this article.

zhin et al., 2010); in the region of the volcanic Mt. Elbrus, two focal zones (Chemartkol and Adylsuyskaya) were studied with $M_{\max} = 6.5-7.0$ (Rogozhin et al., 2004; Rogozhin et al., 2008, 2018). For the vast majority of these sources, detailed characteristics of their structure and long-term seismic regime have been obtained, necessary for assessing seismic hazard. Recently, the Utrish and Gostagaevskaya ancient earthquake focal zones were also studied in detail on the western plunge of the Caucasus. The results of paleoseismological studies conducted in 2012–2018 in Gostagaevsky focal zone and Anapa and Akhtyr flexural–slip zones are indicative.

In the Gostagaevsky focal zone, traces of an ancient earthquake were identified in the area of the neotectonic Babichevsky fault identified earlier by S.A. Nesmeyanov (1992). In the relief, a fault is traced along the left side of the Gostagaevka River in the form of a polygenetic, primarily tectonic scarp with a total length of about 9 km. The surface structure of the fault zone was studied in a specially dug ditch (Fig. 5) A young rupture with normal-fault kinematics was found in a mine, clearly confined in the relief to the

foot of the scarp. A sharp change in the structure of the loose sediment cover is taking place over the fault, while in its footwall, coarse-grained (colluvial) sediments overlying the ancient soil layer (paleosol) occur. The thickness of the colluvial bodies reaches 40 cm. The accumulation of the colluvial wedge that buried the paleosol (a fragment of the paleosurface) in the footwall of the fault indicates a sharp rise of bedrock in the past to the surface in the form of a scarp, which supplied detrital material. Most likely, this was due to impulsive seismotectonic displacement to the surface along the fault as a result of rupture from a strong earthquake. The vertical amplitude of slip is comparable to the thickness of the colluvium near the fault, about 40 cm. The radiocarbon age of the paleosol in the footwall is 5630 ± 70 years (sample A-2, laboratory no. IGAN 4085). Thus, traces of very ancient movement that occurred around 5000–5500 years ago were discovered in the ditch.

The obtained magnitude of a singular seismotectonic displacement and length of the fault revealed in the neotectonic Babichevsky fault zone correspond to the forecast magnitude M_{\max} previously obtained for

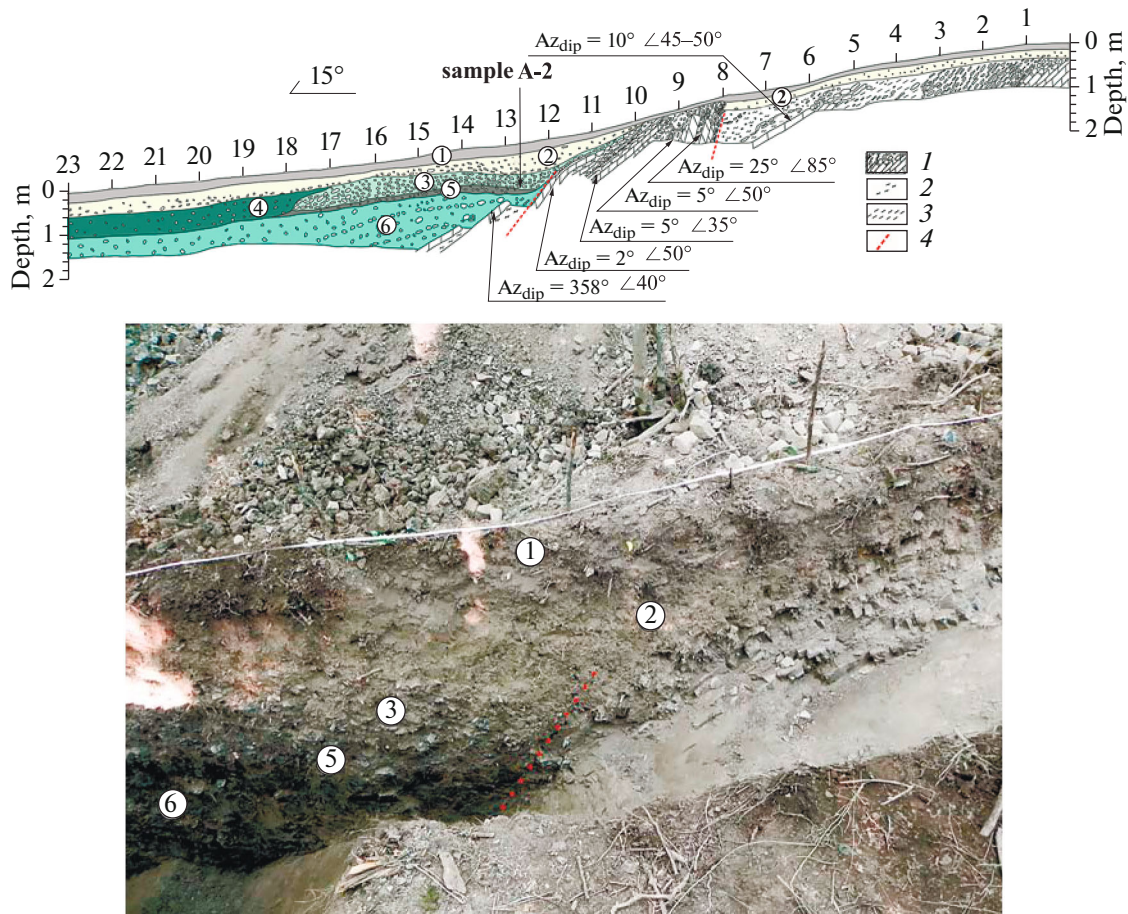


Fig. 5. Seismic fault structure in zone of Babichevsky fault in wall of ditch D-2. Sketch and photo of fragment of ditch at 10–14 m. (1) Bedrock (greenish gray aleuritic marls); (2) dark green, dense, heavy, plastic clay; (3) greenish gray dusty loam; 4, tectonic fault planes. Sample A-2, place of sampling for radiocarbon analysis. Numerals in circles: 1, humus horizon of modern soil; 2, light gray dusty loam with grus and gravel; (3) coarse-clastic formations (blocks, grus, marl grus) with greenish gray loamy fill; 4, redeposited dark green clay with fragments of greenish gray loam and paleosol; 5, paleosol; 6, dark green, heavy, plastic clay with fragments of marls (horizon of slope current).

the Mikhailovsky PES zone by the formalized extra-regional seismotectonic method (Rogozhin et al., 2001). Kinematics of forecast displacements: transtensional fault. Paleoseismological studies using the same methodology were performed for all the active main fault zones in the region: Akhtyr, Moldava, Neberdzhavskaya, Babichevskaya (northern branch), Supsekhsky, Martovsky, Utrishsky, Mikhailovsky suture–depression zones of near-fault grabens, Sochi–Krasnaya Polyana, Shaumyanovskaya, Gogopsinsky, Tugupsinsky, Bekkazheskaya, Vladislav, Bekisheyskaya, Kyukurtli, Krasnaya Polyana, Mzymtinskaya, Main Caucasian Fault, etc. (Rogozhin et al., 2014, 2015a, 2015b, 2018).

COMPILATION OF THE PES ZONE MAP

When constructing the PES zones map for the West Caucasus, the seismic potential (M_{\max}) was determined and regionally mapped by three comple-

mentary methods: paleoseismogeological, traditional, and formalized. The results of paleoseismogeological studies are described earlier in publications and are summarized in Fig. 4.

Based on multiannual research data by the traditional method, the following seismogenic structures were identified in the studied region: The Northern and Southern Crimean–Caucasian and Western Caucasian regional marginal flexural–slip zones, and the Mikhailovskaya, Pshekish–Tyrnyauz, and Mzymta suture–depression zones, extending along the axial part of the Caucasus (Nesmeyanov, 1992). Each seismogenic structure is taken as an axial element of the PES zone, the width of which corresponds to the size of the source of the maximum expected earthquake. The maximum magnitude estimate is 6.5 for the Southern Crimean–Caucasian zone (Gelendzhik segment). A magnitude of 6.0 was taken for the axial (Mikhailovskaya) and Northern Crimean–Caucasian (Akhtyr) zones. For the Pshekish–Tyrnyauz zone, 6.5.

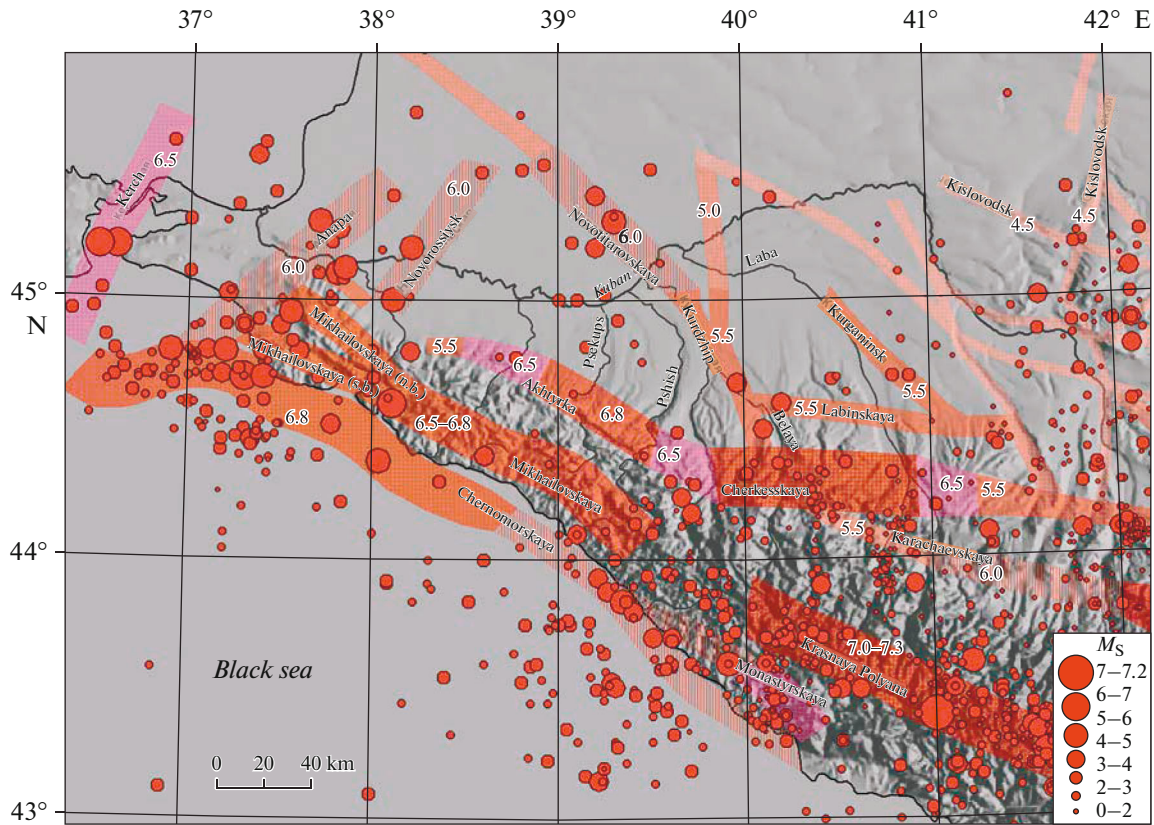


Fig. 6. Map of PES zones in Western Caucasus with earthquake epicenters based on instrumental and historical data. Numerals indicate M_{\max} of PES zones.

In the Sochi–Krasnaya Polyana area, the seismic hazard is determined by the Mzymta PES zone with $M_{\max} = 7.0$ and the Sochi segment of the South Crimean–Caucasian zone with $M_{\max} = 6.0$ (Nesmeyanov et al., 2004).

According to the methodology developed for creating the normative GSZ-97 maps, seismic hazard zoning is based on the LDF model, which contains three main structural elements—lineaments, domains, and potential foci of earthquakes of different magnitudes (Ulomov and Shumilina, 1999). This method of identifying seismic lineaments of a certain length, which control seismic manifestations with different energies, has successfully been used in studying the seismic hazard of large regions, such as the Greater Caucasus and Ciscaucasia as a whole (Balasanian et al., 1999).

As a result of studies using the formalized approach, seismic hazard assessment based on cluster analysis of a body of geological–geophysical and seismological data (Reisner and Ioganson, 1993; Rogozhin et al., 2001) showed that the seismotectonic zones of the northern slope of the Northwest Caucasus are characterized by a generally low or moderate level of seismic hazard: $M_{\max} = 3.7–5.1$. The territory of the West Ciscaucasia is generally characterized by $M_{\max} = 3.5–4.5$, which increases in some areas to

$M_{\max} = 5.5–6.0$. At the interfluvium of the Pshish and Psekups rivers, M_{\max} estimates for the northern slope of the Caucasus increase to $M_{\max} = 6.8$. The seismotectonic zones of the southern slope and the axial part of the West Caucasus are much more seismically active based on the calculated data. The seismic potential of the earthquakes expected here reaches $M_{\max} = 6.8$.

These M_{\max} estimates were verified during seismotectonic field studies in key areas. The most important results of these studies were published earlier. As a result, a map of PES zones for the West Caucasus was compiled (Fig. 6). This map differs fundamentally from the regional seismic lineament map (Ulomov and Shumilina, 1999; Balasanian et al., 1999) in its detail, higher fractionation of M_{\max} estimates, and confinement of PES zones to real tectonic faults of various ranks active at the neotectonic stage. The new detailed seismic hazard map for the Northwest and Central Caucasus is based precisely on the former map.

COMPILATION OF THE SEISMIC HAZARD MAP

Based on the PES zone map (see Fig. 6), detailed seismic hazard maps were compiled for the Northwest

Table 1. Seismic activity matrix $A_{3,3}$ in the geographical coordinate system for the Northwestern segment of the Caucasus, $b = 0.813$

North latitude, deg	East longitude, deg												
	35.75	36.00	36.25	36.50	36.75	37.00	37.25	37.50	37.75	38.00	38.25	38.50	38.75
43.17	0.005	0.003	0.003	0.001	0.002	0.002	0.001	0.001	0.001	0.002	0.005	0.003	0.005
43.33	0.003	0.005	0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003	0.019
43.50	0.003	0.003	0.002	0.002	0.003	0.003	0.001	0.001	0.001	0.001	0.003	0.006	0.029
43.67	0.001	0.001	0.002	0.002	0.003	0.003	0.001	0.001	0.001	0.001	0.003	0.006	0.043
43.83	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.017	0.02	0.006	0.043
44.00	0.001	0.001	0.001	0.001	0.001	0.014	0.014	0.001	0.001	0.02	0.025	0.01	0.031
44.17	0.001	0.001	0.001	0.001	0.001	0.014	0.029	0.017	0.005	0.005	0.006	0.005	0.019
44.33	0.001	0.003	0.003	0.001	0.012	0.017	0.078	0.092	0.022	0.003	0.003	0.003	0.014
44.50	0.003	0.006	0.006	0.006	0.041	0.071	0.124	0.107	0.03	0.026	0.015	0.003	0.012
44.67	0.003	0.005	0.007	0.039	0.107	0.186	0.171	0.063	0.023	0.035	0.015	0.012	0.014
44.83	0.001	0.002	0.009	0.041	0.083	0.145	0.127	0.04	0.015	0.01	0.004	0.012	0.014
45.00	0.001	0.001	0.005	0.01	0.01	0.033	0.032	0.011	0.031	0.024	0.001	0.001	0.001
45.16	0.001	0.001	0.001	0.002	0.017	0.034	0.019	0.015	0.043	0.04	0.013	0.001	0.001
45.33	0.001	0.001	0.002	0.002	0.012	0.015	0.008	0.018	0.017	0.016	0.012	0.003	0.005
45.50	0.012	0.001	0.002	0.002	0.002	0.002	0.009	0.009	0.001	0.001	0.001	0.003	0.008
45.66	0.012	0.001	0.001	0.001	0.002	0.002	0.004	0.004	0.001	0.003	0.003	0.001	0.006

Caucasus region in terms of and according to the methodology for constructing maps GSZ-97 A and B. Moreover, this was deemed valid to directly use the macroseismic field equation for the Caucasus region (*Seismicheskoe raionirovanie...*, 1980) in calculating seismic hazard using the normative MSK-64 macroseismic scale (currently, the new SHSI-2017 macroseismic scale is valid (see: GOST R 57546-2017 "Earthquakes. Seismic intensity scale"), which completely inherited the impact estimates from the MSK-64 scale).

Let us explain the general principles for compiling these maps. Detailed seismic hazard maps for the Northwest and Central segments of the Greater Caucasus were compiled based on calculation of seismic shaking (*Seysmicheskaya sotryasaemost'...*, 1979) on a detailed grid with cell size of $10'$ (0.165°) latitude \times $15'$ (0.25°) longitude. The matrix was used to calculate M_{\max} , which is a digital analog of the PES zone map, as well as the seismic activity matrix (Tables 1–4) for four overlapping segments of the Northwest and Central Caucasus, for which the seismic regimes were studied separately. Each of the considered segments of the Greater Caucasus had its own slope on the recurrence graph (parameter b), and the b values different somewhat from each other.

Seismic shaking at each given point (cell of the shaking matrix) is calculated by numerically integrating seismic impacts at this point from all seismic sources (cells of the M_{\max}) in the territory under consideration, taking into account the average recurrence

frequency of earthquakes with different magnitudes in them (cells of the seismic activity matrix) from the lowest completeness up to M_{\max} . Moreover, the average recurrence rate of earthquakes with magnitudes $M \leq M_{\max}$ is determined in each cell of the M_{\max} matrix based on a seismic activity $A_{3,3}$ in this cell and the slope of the recurrence graph (*Seismicheskaya sotryasaemost'...*, 1979).

In the calculations, the macroseismic field equation for the Caucasus was used:

$$I = 1.5M_S - 3.5 \log R + 3.0,$$

where R is the distance between the earthquake hypocenter and the observation point, i.e., $R = \sqrt{(\Delta^2 + h^2)}$ (here Δ and h are, respectively, the epicentral distance and focal depth in kilometers).

Seismic shaking (B_I) was calculated by a program for designed for this, which uses the M_{\max} matrix; seismic activity matrix $A_{3,3}$; recurrence slope b , and the average depth of the seismically active layer, selected in accordance with the regional depth distributions of hypocenters and from considerations of the maximum (smallest) focal depth for the corresponding magnitudes M_{\max} (Shebalin, 1969). Figures 7 and 8 show the obtained seismic hazard maps for the Northwest and Central segments of the Greater Caucasus.

Table 2. Seismic activity matrix $A_{3,3}$ in the geographical coordinate system for the South-Western segment of the Caucasus, $b = 0.85$

North latitude, deg	East longitude, deg												
	38.5	38.75	39	39.25	39.5	39.75	40	40.25	40.5	40.75	41	41.25	41.5
42.83	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.036	0.039	0.002	0.002	0.014	0.02
43.00	0.001	0.001	0.002	0.002	0.001	0.001	0.001	0.007	0.007	0.01	0.03	0.038	0.024
43.16	0.016	0.018	0.016	0.019	0.014	0.01	0.016	0.016	0.007	0.019	0.06	0.083	0.109
43.33	0.016	0.034	0.038	0.027	0.028	0.037	0.13	0.127	0.02	0.028	0.081	0.116	0.147
43.5	0.005	0.027	0.041	0.024	0.029	0.068	0.161	0.149	0.048	0.038	0.069	0.097	0.075
43.66	0.005	0.029	0.057	0.05	0.036	0.056	0.064	0.077	0.072	0.038	0.074	0.097	0.058
43.83	0.005	0.034	0.068	0.063	0.059	0.096	0.084	0.071	0.055	0.02	0.055	0.064	0.039
44.00	0.012	0.021	0.041	0.045	0.054	0.094	0.072	0.031	0.016	0.003	0.003	0.015	0.031
44.16	0.007	0.005	0.012	0.033	0.053	0.034	0.007	0.101	0.097	0.005	0.007	0.018	0.042
44.33	0.001	0.013	0.013	0.016	0.038	0.022	0.01	0.107	0.099	0.007	0.007	0.008	0.019
44.5	0.001	0.014	0.027	0.014	0.001	0.001	0.023	0.023	0.016	0.018	0.002	0.006	0.006
44.66	0.016	0.018	0.018	0.016	0.001	0.002	0.018	0.016	0.016	0.018	0.002	0.003	0.005
44.83	0.016	0.018	0.004	0.007	0.005	0.002	0.002	0.001	0.002	0.004	0.002	0.005	0.01
45.00	0.001	0.001	0.001	0.007	0.007	0.001	0.001	0.001	0.001	0.001	0.014	0.016	0.007
45.16	0.001	0.001	0.002	0.018	0.016	0.001	0.001	0.001	0.001	0.001	0.027	0.027	0.002
45.33	0.003	0.005	0.004	0.016	0.014	0.014	0.016	0.002	0.001	0.001	0.014	0.014	0.001

Table 3. Seismic activity matrix $A_{3,3}$ in geographical coordinate system for Central segment of Caucasus, $b = 0.907$

North latitude, deg	East longitude, deg													
	37.75	38.00	38.25	38.50	38.75	39.00	39.25	39.50	39.75	40.00	40.25	40.50	40.75	41.00
43.50	0.001	0.001	0.002	0.005	0.026	0.05	0.033	0.028	0.06	0.16	0.152	0.043	0.034	0.089
43.67	0.001	0.001	0.002	0.005	0.039	0.076	0.055	0.032	0.067	0.074	0.08	0.074	0.023	0.067
43.83	0.001	0.015	0.018	0.005	0.04	0.072	0.057	0.052	0.084	0.062	0.05	0.047	0.017	0.037
44.00	0.001	0.018	0.022	0.009	0.029	0.062	0.053	0.06	0.086	0.044	0.015	0.025	0.025	0.014
44.17	0.004	0.004	0.005	0.004	0.018	0.038	0.049	0.057	0.042	0.018	0.107	0.112	0.017	0.008
44.33	0.02	0.003	0.001	0.001	0.013	0.013	0.025	0.037	0.013	0.009	0.098	0.092	0.006	0.006
44.50	0.028	0.025	0.012	0.001	0.011	0.022	0.014	0.004	0.002	0.017	0.017	0.013	0.013	0.001
44.67	0.021	0.032	0.014	0.011	0.013	0.015	0.015	0.002	0.002	0.015	0.015	0.025	0.025	0.002
44.83	0.013	0.008	0.003	0.011	0.013	0.004	0.006	0.005	0.015	0.002	0.002	0.013	0.013	0.002
45.00	0.028	0.022	0.001	0.001	0.001	0.001	0.004	0.004	0.001	0.001	0.001	0.001	0.011	0.023
45.16	0.039	0.037	0.012	0.001	0.001	0.002	0.016	0.014	0.001	0.001	0.001	0.001	0.011	0.034
45.33	0.016	0.015	0.011	0.002	0.004	0.004	0.014	0.012	0.011	0.013	0.002	0.001	0.001	0.011
45.50	0.001	0.001	0.001	0.002	0.007	0.004	0.001	0.001	0.011	0.014	0.002	0.001	0.001	0.001
45.66	0.001	0.002	0.002	0.001	0.005	0.005	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
45.83	0.001	0.002	0.005	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
46.00	0.001	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

CONCLUSIONS

Based on detailed seismotectonic and paleoseismological studies and generalization of the available literature data, seismic hazard maps for the territories of the Northwest and Central Caucasus were com-

piled. On these maps, the Northwestern and Central segments of the Greater Caucasus appear as a seismic hazard area, where the level of seismic impacts is up to 8.5 on maps A and B (in terms of the GSZ-97 map). Recall that Map A was compiled to assess seis-

Table 4. Seismic activity matrix $A_{3,3}$ in geographical coordinate system for eastern part of Central segment of Caucasus, $b = 0.942$

North latitude, deg	East longitude, deg												
	40.5	40.75	41.00	41.25	41.50	41.75	42.00	42.25	42.50	42.75	43.00	43.25	43.50
43.68	0.07	0.017	0.05	0.08	0.051	0.018	0.002	0.011	0.009	0.024	0.107	0.119	0.069
43.85	0.039	0.005	0.01	0.029	0.031	0.011	0.011	0.022	0.025	0.046	0.171	0.16	0.036
44.01	0.018	0.012	0.003	0.011	0.022	0.02	0.076	0.069	0.073	0.087	0.103	0.094	0.012
44.18	0.082	0.015	0.008	0.013	0.029	0.029	0.073	0.089	0.091	0.073	0.037	0.032	0.028
44.34	0.066	0.006	0.006	0.008	0.015	0.013	0.019	0.065	0.08	0.069	0.039	0.004	0.031
44.51	0.011	0.011	0.001	0.006	0.006	0.002	0.019	0.048	0.046	0.052	0.037	0.004	0.008
44.67	0.02	0.02	0.002	0.002	0.006	0.017	0.02	0.024	0.024	0.007	0.001	0.002	0.002
44.84	0.011	0.011	0.002	0.004	0.012	0.03	0.032	0.022	0.018	0.005	0.001	0.002	0.004
45.00	0.001	0.009	0.019	0.011	0.006	0.013	0.017	0.012	0.006	0.013	0.011	0.002	0.004
45.17	0.001	0.009	0.028	0.019	0.001	0.001	0.011	0.021	0.011	0.013	0.011	0.001	0.001
45.33	0.001	0.001	0.009	0.009	0.001	0.002	0.013	0.021	0.009	0.001	0.001	0.001	0.001
45.50	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.001	0.001	0.009	0.009	0.001	0.001
45.66	0.001	0.001	0.001	0.009	0.009	0.001	0.001	0.001	0.001	0.009	0.009	0.001	0.001
45.83	0.001	0.001	0.001	0.009	0.009	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
46.00	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
46.17	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

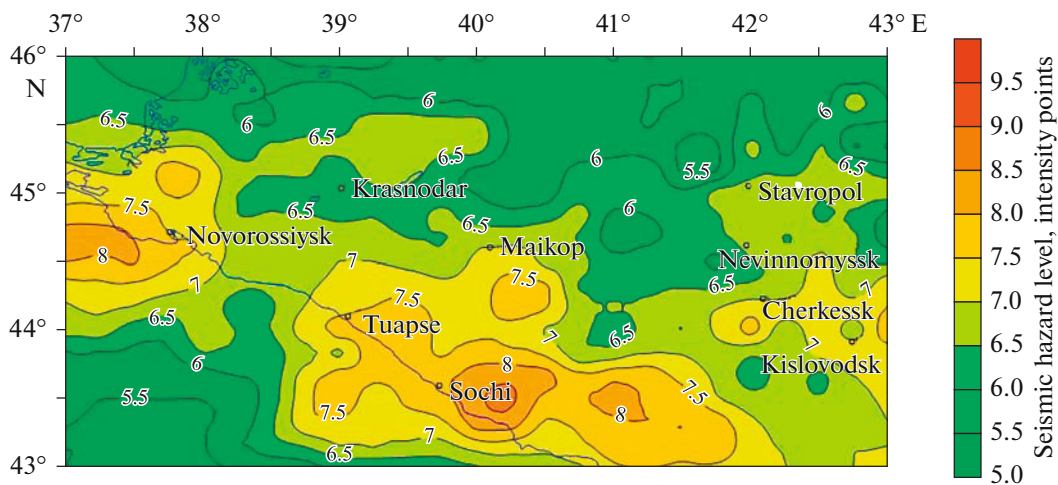


Fig. 7. DSR-A map of Northwest Caucasus with 50-year exceedance probability of 10%. Average recurrence period, 500 years.

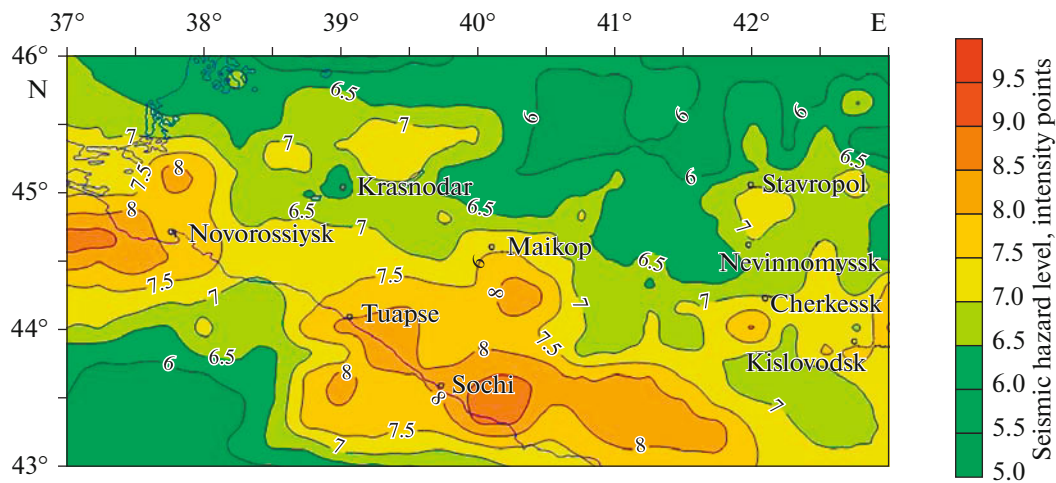


Fig. 8. DSR-V map of Northwest Caucasus with 50-year exceedance probability of 5%. Average recurrence period, 1000 years.

mic hazard for normal and low risk construction projects, and Map B, for high risk facilities. At the same time, in comparison with the corresponding fragments of the GSZ-97 map (Ulomov and Shumilina, 1999), the results obtained appear more differentiated and generally significantly lower the seismic hazard level in the region. This seems very significant compared to the active economic development of the territory in the design, construction, and operation of high-pressure pipeline systems.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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