Seismic Situation's Probability Prediction in Greater Caucasus During the Period 2005-2025

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ABSTRACT

This paper presents probabilistic prediction of seismic situation along the structural-tectonic zones of the axial part and the southern slope of Great Caucasus. It is an important problem, because large earthquakes (M>6) occur frequently in this area. As usual, the calculated probabilities of occurrence of large earthquakes give more condensed information. As it was expected, conditional probabilities of a future earthquake is small immediately after previous shock and it increases with the time passed after the last earthquake. To solve this problem, the spatial distribution and frequency of occurrence of large earthquakes is studied. In particular, it was found that epicenters of earthquakes with M>6 are distant from each other in this zone on the average distance of 100km. On the basis of maximum seismic activity in these areas, the average periods of recurrence of large earthquakes have been identified. By using a time-dependent model of seismicity, some segments and subsegments of the structural-tectonic zones and conditional probabilities of occurrence of large earthquakes for the period 2005-2025 were calculated. Studies have shown that areas with a high probability of occurrence of large earthquakes deserve priority in controlling the seismic situation.

Keywords:
Greater Caucasus;
Seismic situation;
Structural-tectonic zone;
Conditional probability

1. Introduction

The main purpose of this study is the probabilistic prediction of large earthquakes in the area of the axial part and the southern slope of the Greater Caucasus, using a model with time-dependent seismicity, i.e. calculation of conditional probabilities of occurrence of large earthquakes.

The dynamic model of seismicity represents seismic processes in development which makes probability prediction of a seismic situation possible. Large earthquakes ($M > 6$) play a main role in seismicity. Thus, with respect to seismic process evolution, first of all separate phases of seismicity of individual large earthquakes and earthquake sequence regularities should be considered, and then the space-time relationships of the whole complex of seismic sources and their statistical and integral indices should be analyzed.

At present, description of continuous parameters of seismicity by individual source properties is not so well developed as earthquake totality relationships, from which the basic one is the Gutenberg-Richter's law of recurrence $log\, N = a^* - b\,(M - M^*)$, which defines for each earthquake totality: its seismic activity a^* (level of recurrence graph for fixed M^* value of M), graph slope b (graph of the logarithm of increase of number of seismic phenomena N when the magnitude decreases by one unit), and the upper bound M_{max} (recurrence graph's bound on its right, called maximum magnitude or seismic potential).

When describing seismic parameters by space-time relationships of earthquake totality, the idea of independency of individual seismic phenomena (Poisson processes) is presented openly or indirectly. In reality, earthquake sources occur hierarchically according to size (*G-R* law) as well as time (after-shock swarms, cyclic processes or periodic seismic activation and quiescence of earthquakes of definite magnitude level at "prevail" interepicenter distances). Thus, denial of a priori poissonity and study of inner structure of seismicity opens new possibilities to seismic investigations [1].

In the present work, we confined ourselves to consideration of space structure of seismicity using sequence of the large earthquakes ($M > 6$). Because of insufficient data about source depth, this problem is solved in two-dimensional approximation. Besides, for prediction of seismic situation, it was assumed that present state of the sequence of the large seismic phenomena is determined by the past and thus the future is somehow determined, and density of seismic flow within seismically active elongated linear zone serve as a ground for estimation of probability of the occurrence of a large earthquake in the given time period.

These propositions have been used for a structural-tectonic zone of the axial part and south slope of Greater Caucasus with a considerable linear length about 900*km* (90*km* width). This zone is marked for its very high seismic activity and historical data over a long period of time are available about the strongest earthquakes in this zone.

The most clearly defined tectonic features of the zone are largely determined by its position between the still converging Eurasian and Africa-Arabian lithosphere plates. During syn-collisional and post-collisional stages of the Late Alpine tectonic cycle as a result of continent-continent collision, the inversion of relief took place, which led to formation of fold-thrust belts of the Greater Caucasus. The complex network of faults determines the division of this area into a number of separate terrains. The boundary zones between these terrains represent the belts of maximum geodynamic activity with wide development of processes of tectonogenesis (folding, faulting), volcanism and seismicity [2-5]. The analysis of focal mechanism of strong earthquakes in the Caucasus shows that according to the dominant nearly *N-S* compression stress, this area is mainly represented by active faults of the following type: reverse faults and thrusts [6]. It is noteworthy that this area contains sites of the strongest ($M > 6$) Caucasian earthquakes -1100 Bzifi, 1350 Lechkhumi-Svaneti, 1742 Alaverdy, 1963 Chkhalta, 1991 Racha, 1992 Barisakho (Georgia); 1668, 1902 Shemakha, and 1948 Zakatala (Azerbaijan). Many earthquakes of this zone occurred in the upper part of the earth's crust and are shallow earthquakes.

2. Geological Background

The structure and geological evolution of the Caucasian segment of the Black Sea-Caspian Sea region is largely determined by its position between the still converging Eurasian and Africa-Arabian lithosphere plates, see Figure (1), within the wide zone of the continental collision. Problems of Late Proterozoic-Phanerozoic development of this area has been considered and discussed during the past decades in many publications. According to some previous studies [7-11], the region in the Late Proterozoic, Paleozoic, Mesozic, and Early Cenozoic belonged to the now-vanished Tethys Ocean (Prototethys, Paleotethys, Tethys) and its Eurasian and Gondwa-nian/Africa-Arabian margins, where a system of island arcs, intra-arc rifts, back-arc basins existed as characteristic of the pre-collisional stage of evolution of the region.

There are numerous publications regarding geodynamic evolution of the Caucasus. The region, along with other fragments that are now exposed at the Late Precambrian-Cambrian crystalline basement of the Alpine orogenic belt, was separated from western Gondwana during the Early Paleozoic as a result of back-arc rifting above a south-dipping subduction zone. Continued rifting and seafloor spreading produced the Paleotethys in the wake of northward migrating peri-Gondwanian terranes. The displacement of the Caucasian and other

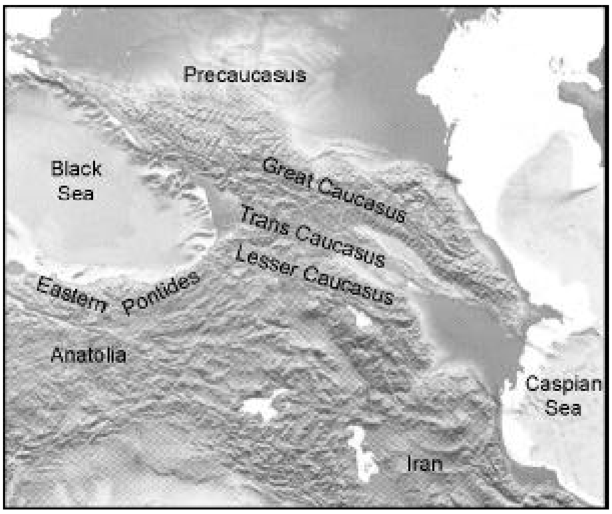

Figure 1. Physical map of the Caucasus and adjacent areas of the Black Sea-Caspian Sea region.

peri-Gondwanan terranes to the southern margin of Eurasia was completed by ~350*Ma*. Widespread emplacement of microcline granite plutons along the active continental margin of southern Eurasia during 330-280 Ma occurred above a north-dipping Paleotethyan subduction zone. However, Variscan and Old Cimmerian-Early Alpine events did not lead to complete closing of the Paleozoic Ocean. The Mesozoic Tethys in the Caucasus was inherited from the Paleotethys. In the Mesozoic and Early Cenozoic, the Greater Caucasus and Transcaucasus represented the Northtethyan realm - the southern active margin of the Euro-Asian lithosphere plate. The Oligocene-Neogene and Quaternary basins situated within the inter-mountain depression mark syn- and post-collisional evolution of the region; these basins represented a part of the Paratethys and accumulated sediments of closed and semi-closed basins. The final collision of the southern and northern plates and formation of the present-day intra-continental mountainous edifice of the Caucasus occurred in the Late Alpine. From the Late Miocene (~9-7*Ma*) to the end of the Pleistocene, in the central part of the region, volcanic eruptions in subaerial conditions occurred simultaneously with formation of molasse troughs.

The geometry of tectonic deformations in the Transcaucasus is largely determined by the wedge-shaped rigid Arabian block intensively indented into the Minor Asian-Caucasian region. All structural-morphological lines have a clearly expressed arcuate northward-convex configuration reflecting the contours of the Arabian block. However, farther north, the geometry of the fold-thrust belts is somewhat different - the Achara-Trialeti fold-thrust belt is, on the whole, *WE* trending; the Greater Caucasian fold-thrust belt extends in *WNW-ESE* direction.

3. Main Tectonic Units

The Caucasus is divided into several large tectonic units-terrains which differ one from another by their stability/lability degree. There are distinguished rigid (platform, sub-platform, quasiplatform) and fold-thrust units [12]. They are (from north to south): the Scythian (pre-Caucasus) young platform; the fold-thrust mountain belt of the Greater Caucasus including zones of the Northern Slope, Fore Range, Main Range and Southern Slope; the Transcaucasian intermountain depression superimposed mainly on the rigid platform zone (the Georgian Block); the Achara-Trialeti and Talysh fold-thrust mountain belts; the Artvin-Bolnisi rigid sub-platform zone; the Bayburt-Karabakh fold-thrust mountain belt; the North Anatolian-Lesser Caucasus ophiolitic suture; the Lesser Caucasian part of the Taurus-Anatolian-Iranian platform; and, at the extreme south of the Caucasus, the Aras inter-mountain depression. The youngest structural unit is composed of the Neogene-Quaternary continental volcanic formations of the Eastern Anatolian, Armenian, and South Georgian volcanic highlands and some centres of extinct volcanoes - Elbrus, Chegem, Keli, and Kazbegi (Greater Caucasus).

The territory of Georgia hosts only some of the mentioned zones: the Greater Caucasus and Achara-Trialeti fold-thrust mountain belts, the Rioni and Kura inter-mountain depressions, the North-transcaucasian (the Georgian Block), and South-transcaucasian (the Artvin-Bolnisi Block) terranes, the Javakheti and Keli-Kazbegi volcanic highlands, and extinct volcanoes.

It is commonly known that within the region there are sedimentary, magmatic and metamorphic rocks dating back throughout the Late Proterozoic-Phanerozoic. Their formation occurred under the various paleogeographic (facial) and geodynamic environments: oceanic and small oceanic basins, intercontinental areas, and active and passive continental margins-transitional zones from ocean to continents.

4. Input Data

Geologic-structural data for this work have been received mainly from three sources:

1) The map and the catalogue of active faults on the territory of Georgia, drawn on the basis of complex data [13];
2) The map of the seismoactive structures of the Caucasus [14];
3) The summary map of lineaments of the Caucasus and adjacent areas [15].

The following were considered as the sources of seismological data:

1) New catalogue of strong earthquakes in the *USSR* from Ancient Times through 1977 [16];
2) Catalogue of strongest ($M > 6$) earthquakes by macroseismic end instrumental data [17];

3) Catalogue of strong earthquakes (M > 4.5) of the Caucasus and adjacent areas, which also includes the whole historical period;
4) The map of seismic activity of the territory of the Caucasus for 1900 -1995 [18];
5) The data accumulated within the framework of the research project (*INTAS*-South Caucasus 9130) "Stress related Geohazards in South Caucasus" since 2007.

The last work (research project "Stress Related Geohazards in South Caucasus") reconsidered primary sources of historical earthquakes (of pre-instrumental period) in Georgia based on multi-disciplinary approach i.e. through the sharing of techniques and analysis of data of historical seismology, paleoseismology, archeoseismology, seismotec-tonics, geomorphology, etc. This work is continued in the research project - *EMME* which ultimately made it possible to identify, organize and use the necessary information to make a new unified parametric catalogue of historical earthquakes in Georgia. We studied 47 historical earthquakes and rated the intensity for each populated locality with a particular methodology. The final parametric catalogue for 44 historical earthquakes is presented by the information on the date and location of the epicenter, magnitude, depth of the focus and intensity in the epicenter. Three earthquakes had to be excluded from consideration because of the uncertain input data. This catalogue to some extent reduces the spatial and temporal heterogeneity of the material met in previous catalogues and improves the accuracy of determining the basic parameters of historical earthquakes.

After sorting, replenishing and revising the data on historical earthquakes of Georgia, we decided to present the results not only as a catalogue of key parameters (date, coordinates of epicenter, depth, magnitude, intensity at the epicenter) of historical earthquakes, but as a "descriptor" for each event introduced in the catalogue. The "descriptor" contains a description of the earthquake based on various sources and evaluation of the intensity by *MSK*, a short analysis of these data; and final earthquake parameters indicating the errors of their determination. It also contains a map of isoseismals, intensity points, seismodislocations, landslides and avalanches, earthquakes epicenters and tectonic faults.

Information on the errors of parameters of earthquakes is very important for the correct application of the catalogue for probability prediction of the earthquake and it depends on how we got these parameters-macroseismic or instrumental. Estimation errors of parameters is given for each earthquake depending on the type of data used. Something like this was done in [16-17].

In particular, for the historical part of the catalog, some mainly from macroseismic data, the real isoseismal center was adopted for the location of the earthquake epicenter, and in case of a small amount of data - the isoseismals models center. More specifically, the epicenter was taken as the weighted center of the first isoseismal with an error equal to its average radius.

For instrumental data, the epicenter was taken as the point corresponding to the minimum value of the discrepancy in source time on the basis of the data of individual stations, with an error equal to the major semiaxis of the ellipse of errors.

5. Spatial Structure of Seismicity and Regularities of Earthquake Recurrence

Investigations [19-21] of various regions (including the Caucasus) have confirmed that epicenters of earthquakes of the same magnitude level are separated from each other by the so-called "prevail" interepicentral distances. In other words, in large enough spatial-temporal areas there are distribution centers for any number of neighbor, couple of seismic phenomena with the given magnitude level (irrespective of their occurrence time) according to distances between these phenomena.

This hypothesis has been tested on the largest earthquakes of the discussed structural-tectonic zone. Because of somewhat scanty statistical data and certain errors in earthquake intensity determination, minimum distances have been calculated not between epicenters of earthquakes of separate magnitude range ($M = 6.1 - 6.5$; $M = 6.6 - 7.0$; $M = 7.1 - 7.5$) but among all epicenters of $M > 6$. It was found that the average distance between them was $\overline{R}_E = 100 \pm 30 km$, which coincides with the results of analogous investigations carried out for the whole Caucasus and which indicates at the causal-effective relationship between the sources of the large earthquakes in this structural-tectonic zone. In particular, the existence of such regularity can be explained as follows: In the area where the earthquake already occurred during a definite time, which is commensurable with the duration of seismic cycle here, an analogous phenomenon may occur at any place along earthquake occurrence zone, but not nearer than the definite distance which equals the length of source zone. In this case, a source zone is called the area from which an earthquake receives the most part of elastic energy (it is commensurable with spreading of corresponding aftershock zone) and its geometric size exceed three times the source size i.e energy release area, where rapid fault displacement takes place [20].

Figure (2) presents epicenters of all the latest (at the given place) large ($M > 6$) earthquakes in the discussed structural-tectonic zone. Spatial disposition of their corresponding sources coincides with large fault zones (*FZ*), such as: Main Thrust of the Greater Caucasus, Lagodekhi, Orkhevi *FZ* and Racha-Lechkhumi *FZ* (with its eastern prolongation).

The Main Thrust represents a complex system of faults located along the watershed range of the Greater Caucasus. On the map of seismoactive structures it is depicted as a single generalized line, whereas actually there exist a great number of subparallelen echelon or bifurcated faults trending from *WNW* to *ESE*. The Main Thrust has been identified on the grounds of geological data. Along this fault the basement rocks (metamorphites, migmatites, gneisses and various intrusive rocks of Late Proterozoic-Middle Paleozoic age) were exposed in the Main Range zone of the central segment of the Greater Caucasus fold-thrust mountain belt (*GCFTMB*), overthrust Lower Jurassic black slate formation and locally shallow-marine molasse sequences of Late Paleozoic [22-23].

The Main Thrust is well expressed topographically and is readily interpreted in the aerial and space images. In some places, the fault created well-expressed tectonic scarps and benches due to the different lithology and resistance to denudation of rocks composing its northern upthrown limb (crystallinicum) and downthrown southern one (shales).

To the west and east from the central segment of the Main Range zone, the crystalline core plunges beneath the sedimentary rocks and the system of faults forming the Main Thrust runs within the monotonous sedimentary Mesozoic and Cenozoic rocks. Here, the faults are reflected in the relief very vaguely and their attribution to the Main Thrust often becomes, to a considerable degree, uncertain. Both crystalline basement rocks and rocks of the sedimentary cover are strongly deformed into a system of linear folds of the Caucasian strike.

All the faults of the Main Thrust system are steeply inclined to the north conditioning the imbricate structure of the main range zone. The fault planes usually dip to *NNE*.

By their kinematics the faults belong to reverse faults that is unambiguously confirmed by geological and, locally, geophysical data. In particular, fault plane solutions are usually in good compliance with geological observation, indicating the reverse faulting with some right-lateral strike-slip component.

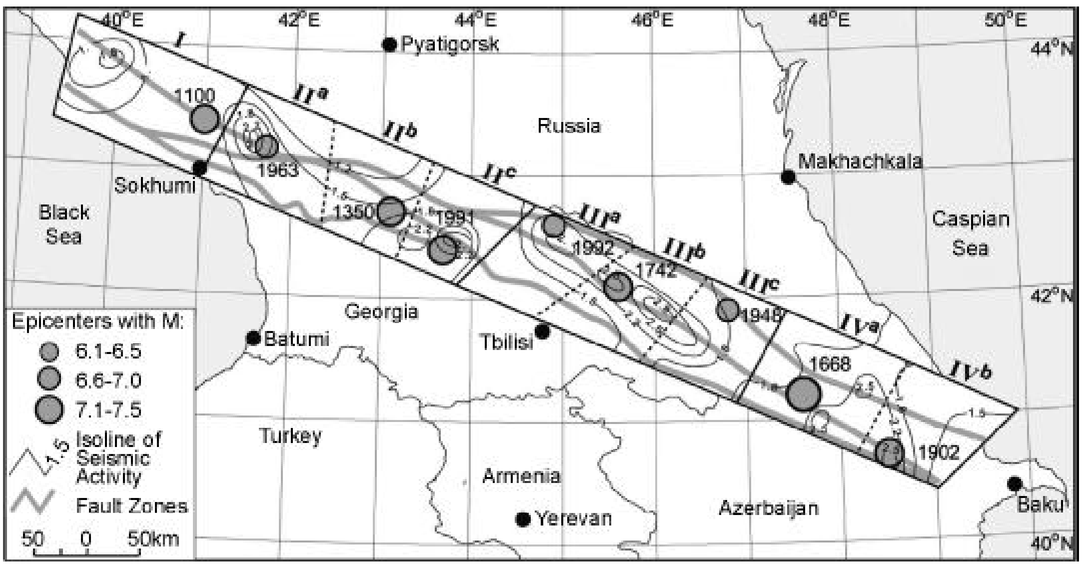

Figure 2. The large earthquakes ($M > 6$) sequence and segments and Sub-segments of seismic activity in a structural-tectonic zone of the axial part and south slope of Greater Caucasus.

The amplitude of horizontal displacement on the Main Thrust has not yet been defined. The vertical component of the displacement within its central segment is estimated, according to geological evidence, as several km for a few million years. Fission track data [24] indicate slip rates on the Main Thrust equal to 4-12*mm/yr*. To the west and east from the central segment uplift rates are gradually decreasing.

The Lagodekhi *FZ* of *N*100-1200 strike separates the Barisakho thrust sheet (Lower-Middle Jurassic black slate formation) from the southerly-located tectonic mega-slice built up of Middle Jurassic-Cretaceous carbonate turbidites of *GCFTMB*. Amplitude of the overthrust is about 1*km*. The most part of the thrust occurs within the Azerbaijanian part of Greater Caucasus. Thrusts plane is tilted in *NE* direction at an angle of 50^o-80^o.

The Orkhevi *FZ* represents a whole system of thrust- to- reverse faults developed along the southern frontal part of the eastern flysch megascale of the southern slope zone of *GCFTMB*. This fault system extends from *NW* to *SE*, in the Caucasian direction, at a distance of about 640*km*, from the Central Caucasus (Svaneti, Enguri river basin) to the town of Shemakha in Azerbaijan. In the eastern flysch basin of the Greater Caucasus, en echelon and bifurcated reverse faults, the Cretaceous turbidites, were observed subparallel. They overthrust from *N* to *S* various rocks of the southern slope zone (Central Caucasus) and Upper Neogene molasses of the Kura-Arax foreland. The faults, as a rule, expose at the day-surface and are studied fairly well. In eastern Georgia and Azerbaijan, they are often overlain by recent alluvial sediments and become blind faults. The Neogene rocks in the contact zones are strongly deformed. The amplitude of overlapping of foreland rocks by thrusts ranges from several km to first tens of *km* [25], which implies slip rate about 2*mm/y* (for the last 5*m/y*). The most portion of this motion took place, most likely, aseismically (by tectonic creep).

The Racha-Lechkhumi *FZ* represents a complex system of faults, predominantly *W-E*-trending, exposing on the day-surface within the central segment of the Racha ridge - the watershed between the Rioni and Kvirila rivers. On the map of seismoactive faults it is shown as a single line extending in *WNW-ESE* direction.

The Racha fault system, known in geological literature under the name of the Kakheti-Lechkhumi or Racha-Lechkhumi suture zone [22], serves as the boundary between two tectonic units of the Caucasus- the Georgian block to the south and the southern slope zone of the Greater Caucasus to the north. This geological boundary is quite distinct as it divides two markedly different geological terranes from each other. The suture zone is clearly expressed and coincides morphologically with the above-mentioned central segment of the Racha ridge and the *W-E*-trending part of the Rioni river gorge. Generally, the faults are steeply-dipping. In the northern part of the suture zone they dip to *NNE*, whereas in the southern part they are predominantly *SSW*-dipping, thus forming sublatitudinal graben-synclines and horst-anticlines. The youngest sediments that fill the graben-synclines are represented by shallow-marine and subaerial molasses of Upper Miocene, which are in tectonic contact with Jurassic and Cretaceous sequences. All the rocks, including Upper Miocene ones, are strongly deformed, creating series of linear sublatitudinal folds. To the east, the suture zone is obliquely tectonically overlapped by the flysch zone of the southern slope of the Greater Caucasus along the south frontal thrust of the eastern flysch basin (Lagodekhi *FZ*).

Both the geological evidence and focal mechanism solutions indicate that the system of Racha-Lechkhumi faults is dominated by compressional structures - reverse faults. At the same time, fault plane solutions also indicate the presence of right-lateral strike-slip component [26-29].

The above-mentioned regularity of interdisposition of these epicenters has been used in the process of dividing seismic activity of the mentioned structural-tectonic zone to segments and sub-segments, see Figure (2). Sub-segments' length is commensurable with average distance (100*km*) between epicenters and the borders coincide with zones of sharp changes in seismic activity and transversal lineaments of the Caucasus [15]. It is implied that each sub-segment has its own values of characteristics of seismic phenomena: flow density, velocity and seismic potential, or its own parameters of recurrence law. In reality, subsegments' differentiation is possible only (because of statistical lack of data) according to density of phenomena flow or seismic activity and seismic potential. The value of slope of earthquake recurrence graph for the entire structural-tectonic zone is considered to be the same, see Table (1).

Table 1. Calculated values of the parameters a^o_{max} and b of the relation (1) for the segments and sub-segments of a given structural-tectonic zone.

Segments and Subsegments	I	II^a	II^b	II^c	III^a	III^b	III^c	IV^a	IV^b	
a^o_{max}	1.8	2.5	1.8	2.5	2.5	2.8	2.5	2.5	2.5	$\sigma_a = 0.3$
b	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	$\sigma_b = 0.02$

By using maximum values of seismic activity observed during the last 100 years in each sub-segment, the average periods of recurrence of $M >$ 6.0, $M > 6.5$ and $M > 7.5$ earthquakes have been calculated by the formula:

$$LgT = bM - a^o_{max} \quad (1)$$

where a^o_{max} is the maximum values of seismic activity for $M = 0$.

The calculation results and occurrence year of the latest strongest earthquake in each subsegment are given in Table (2). The mean standard deviation of the parameters expressed by the formula (1) are $\sigma_a = 0.3$, $\sigma_b = 0.02$, $\sigma_M = 0.2$. Accordingly the error of calculated mean recurrence period is about 90%. These data are used when we calculate occurrence probabilities of the large earthquakes in the given structural-tectonic zone within the next 20 years (2005-2025).

6. Probability Estimation

Seismic situation prediction along axial part and south slope of Greater Caucasus is very important because the large earthquakes often occur here. During the last century six such events were recorded in the zone and three of them had surface effect (intensity) 9 in the epicenter.

There are several ways of solving this problem. The choice was determined by seismicity definition with respect to time. In fact it is time function, characterized by periodical activity and quiescence, which is characteristic of seismic cyclic processes. When defining probability of the large earthquake occurrence on the definite territory, it is very important to know on which stage of seismic cycle it is. This is assessed by the time passed after the last activity or occurrence of the large earthquake in the given area. In this case, conditional probability P of occurrence of an earthquake of a certain magnitude with the average recurrence period T during the nearest t interval in the given area (which is conditioned by time t passed from the last earthquake with the same magnitude level and in the same area), is calculated by formula:

$$P(t \le T < t + Dt / T > t) = \int_t^{t+Dt} h(t)dt \Big/ \int_t^{\infty} h(t)dt \quad (2)$$

If we assume that Gauss distribution is true for occurrence period's values, then:

$$h(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left[-\frac{1}{2}\left(\frac{t-T}{\sigma}\right)^2\right]} \quad (3)$$

where σ is the average square deviation of T values.

The probabilities of earthquake occurrence may also be defined on the basis of Poisson model of earthquake recurrence. Its important result is that the probability of earthquake occurrence does not depend on the time t passed from the previous

Table 2. Information on the probabilities of occurrence of large earthquake ($M > 6$) in different structural-tectonic zones of Greater Caucasus.

Segments and Subsegments	Mean Periods of Recurrence			The Latest Earthquake			Conditional Probability of Earthquake Occurrence (%) 2005 - 2025			Earthquake Occurrence Probability (Poisson Distribution, %) 2005 - 2025			Seismic Potential
No	$M>6$	$M>6.5$	$M>7$	$M>6$	$M>6.5$	$M>7$	$M>6$	$M>6.5$	$M>7$	$M>6$	$M>6.5$	$M>7$	M_{max}
I	670	1600	-	1100	1100	-	75	44	-	3	1	-	7
II^a	135	-	-	1963	-	-	35	-	-	14	-	-	7
II^b	670	1600	-	1350	1350	-	63	34	-	3	1	-	7
II^c	135	330	-	1991	1991	-	20	9	-	14	6	-	7
III^a	135	-	-	1992	-	-	19	-	-	14	-	-	7
III^b	65	160	-	1742	1742	-	99	82	-	27	13	-	7
III^c	135	-	-	1948	-	-	42	-	-	14	-	-	7
IV^a	135	330	770	1668	1668	1668	81	66	36	14	6	3	7.5
IV^b	135	330	-	1902	1902	-	60	30	-	14	6	-	7.5

earthquake and is the same before and after its occurrence. The probability is calculated by formula:

$$P = 1 - e^{\left(-\frac{Dt}{T}\right)} \quad (4)$$

Results obtained after calculations by this formula differ considerably from the results received by previous formulae but if in formula (4) we insert $t+\Delta t$ instead of Δt, then the results will be similar to these received by formula (2). Thus in case of insufficient data, conditional probability can be calculated by the following formula [30] instead of (2):

$$P = 1 - e^{\left(-\frac{t+Dt}{T}\right)} \quad (5)$$

In our case because of insufficient statistics it is difficult to estimate σ for earthquakes with various magnitude levels in separate subsegments; that is why formula (5) is used for calculation of conditional probabilities. Table (2) shows the results. In comparison, it also shows the probabilities received by Poisson distribution which differ considerably from conditional probabilities.

Figure (3) shows conditional probabilities of $M > 6.0$, $M > 6.5$, $M > 7.0$ earthquakes occurrence within the period 2005-2025 in every segment and subsegment of the given structural-tectonic zone. They are divided into three categories: subsegments which have high (>80%), mean (60%-80%), and low (<60%) values of conditional probability.

7. Discussion of Results

As it was expected, conditional probabilities of a future earthquake is small immediately after previous shock and it increases with the time passed after the last earthquake, see Table (2). The calculated probabilities of occurrence of large earthquakes give more condensed information than prolonged historical data. Practically for all segments and subsegments, probability of earthquake occurrence is defined for $M > 6$, partially $M > 6.5$ phenomena. That is why these results are used for discussion.

As noted above, this structural-tectonic zone selection of segments and subsegments was mainly based on areas of high seismic activity, see Figure (1). In addition, their northern borders coincide with the center part of the Greater Caucasus, and southern boundaries coincide with the interface between the southern slopes of the Greater Caucasus and the Caucasus intermountain depression. As for the western and eastern borders of the segments and subsegments, they coincide with the transverse lineament Caucasus allocated using the data of geology, seismometry, gravity and decryption of satellite photos.

In spite of considerable time passed from the latest large earthquake, the segment *I* of the considered structural-tectonic zone received only average probability. This is because maximum observed seismic activity is not high here: $a^{o}_{max} = 1.8$, which indicates a comparatively long period of large

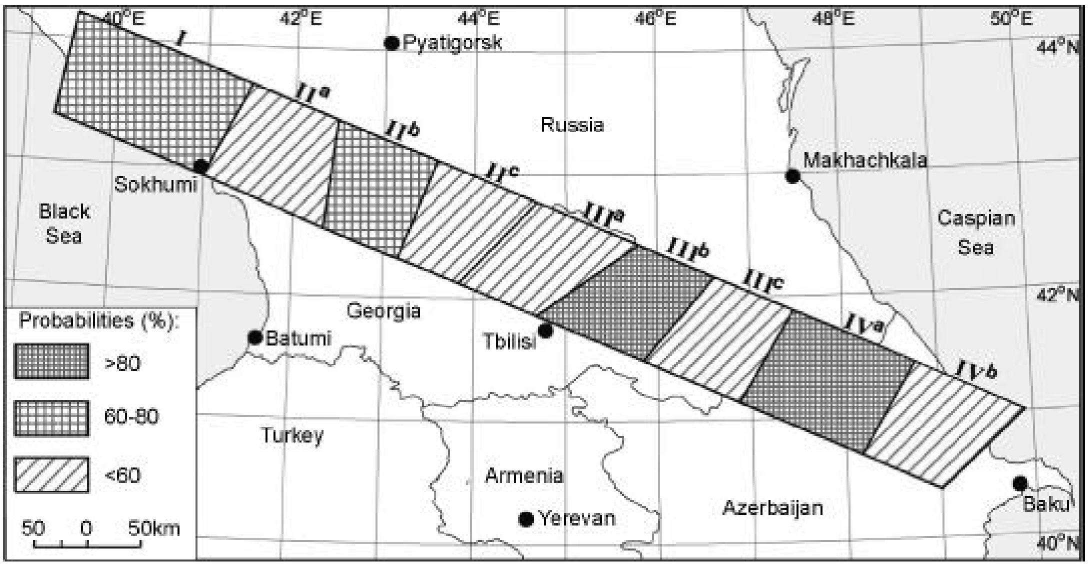

Figure 3. Probabilities of the large earthquakes ($M > 6$) occurrence in segments and subsegments of structural - tectonic zone of the axial part and south slope of Greater Caucasus in 2005-2025.

earthquakes recurrence. It must be also mentioned that the large seismic phenomenon is registered here after revealing seismodislocations. This fact decreases occurrence time accuracy considerably as the dating of seismodislocations is not accurate.

Western II^a subsegment of the *II* segment is characterized by high historical seismicity. Here are epicenters of four large earthquakes which have been established by paleoseismodislocations; besides 1905 earthquake with $M_S = 6.4$ which was occurred here, and finally in 1963 this was faulted by Chkhalta earthquake. That is why the probability of large earthquake occurrence is low here. Recently, in 1991, the eastern part (subsegment II^b) of this segment was broken by Racha earthquake ($M_S = 6.9$). As to subsegment II^b, here is the average probability of $M > 6$ earthquake occurrence because like in segment *I*, enough time has passed from the last historic earthquake as well, but at the same time the maximum seismic activity is low.

The *III* segment of the discussed structural-tectonic zone is distinguished by very high seismic activity and historical seismicity. In its eastern (III^c) and western (III^a) subsegments, large earthquakes occurred in 1948 and 1992 accordingly and III^b subsegment is well known by the strongest so called Alaverdi earthquake series. For the last time, it faulted in 1742 by $M_S = 6.7$ earthquake and that is why it has received high probabilities of $M > 6.0$ as well as of $M > 6.5$ earthquakes occurrence.

The *IV* segment belongs to Shemakha region, which is distinguished by its seismoactivity in the Caucasus. In spite of this it is possible here to differentiate earthquake occurrence probability too. In particular, the eastern part (subsegment IV^b) of this segment faulted in 1902. This is the reason that the present $M > 6$ earthquake occurrence has only an average probability. In the western part (subsegment IV^a), on the contrary, $M > 6$ as well as $M > 6.5$ seismic events probability is high. In spite of the experts' conclusions that seismic potential may reach $M_{max} = 7.5$ in this area, the probability of occurrence of such phenomenon is low.

8. Conclusions

For the probabilistic prediction of large earthquakes in the area of the axial part and the southern slope of Greater Caucasus, a calculation of conditional probabilities for the period 2005-2025 was made in the segments and subsegments of the zone. In this case, a model was used with time-dependent seismicity. In the process of research, it was found that the epicenters of large earthquakes in this zone are far apart on the average distance of 100*km*. For each beat, subsegments defined the maximum values of seismic activity, the average periods of recurrence of earthquakes $M > 6.0$, $M > 6.5$ $M >$ and 7.5, and time of the last large earthquake.

If we analyze the cycle of the last activity of the whole structural-tectonic zone, it can be concluded that the large earthquakes occurred here mainly in the centers of singled out segments and then the slits (subsegments) between them faulted. This process will of course affect probabilities of the large earthquake occurrence in the future.

It was also realized that as we have not enough data about recurrence of the large earthquakes ($M >$ 6) in sub-segments, the definition of average recurrence periods does not give a real picture only by maximum values of seismic activity; especially since singling out of some subsegments is not very reliable. But grounds for such analysis show that for adjacent segments (subsegments), it is more important to consider relative levels of probabilities than absolute levels in any separate segment and subsegment. The authors of this study believe that areas which received high probabilities of occurrence of large earthquakes deserve priority in control of seismic situation.

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