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Original paper

Tectonics of source zones of strong earthquakes in the southeastern part of the Greater Caucasus

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Abstract: Relevance of the work: One of the main tasks of modern seismology is to determine the focal zones of strong earthquakes and their maximum magnitudes in these zones. This is necessary to assess the seismic hazard of territories. **Purpose of the study:** To study the features of the distribution of earthquake sources on the territory of Azerbaijan. **Research results:** It has been established that the sources of strong earthquakes are confined to zones of concentration of weak seismic tremors, inherent in active faults, characterized by contrasting tectonic movements. This shows that by identifying zones of concentration of sources of weak seismic shocks, it is possible to determine the focal zones of strong earthquakes. **Research methods:** Using the relationship between the length (L) of focal zones and the observed magnitudes (M) of earthquakes. The obtained result allows us to determine the maximum magnitude in the areas of potential sources of strong earthquakes.

Keywords: earthquakes, seismotectonics, tectonics of source zones, active faults, longitudinal and transverse structures, concentration of seismic shocks, potential source zones.

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GEOPHYSICS

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Оригинальная статья

Тектоника очаговых зон сильных землетрясений юго-восточной части Большого Кавказа

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Резюме: Актуальность работы: Одной из основных задач современной сейсмологии является определение очаговых зон сильных землетрясений и их максимальных магнитуд в этих зонах. Это необходимо для оценки сейсмической опасности территорий. **Цель исследования:** Изучить особенности распределения очагов землетрясений на территории Азербайджана. **Результаты исследования:** Установлено, что очаги сильных землетрясений приурочены к зонам концентрации слабых сейсмических толчков, присущим активным разломам, характеризующимся контрастностью тектонических движений. Это показывает, что путем выявления зон концентрации источников слабых сейсмических толчков можно определить очаговые зоны сильных землетрясений. **Методы исследования:** Использование связи между длиной (L) очаговых зон и наблюдаемыми магнитудами (M) землетрясений. Полученный результат позволяет определить максимальную магнитуду в зонах потенциальных очагов сильных землетрясений.

Ключевые слова: землетрясения, сейсмотектоника, тектоника очаговых зон, активные разломы, продольные и поперечные структуры, концентрация сейсмических толчков, потенциальные очаговые зоны.

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Introduction

Studies of the distribution of strong and destructive earthquakes in the world show that they are confined to deep fault zones [7, 10, 11, 22, 24, 2]. This allowed specialists to consider all large faults as zones of sources of strong earthquakes. Based on this, in 1950, I.E.Gubin proposed a seismotectonic method [11] for identifying earthquake source zones, according to which a narrow quasi-homogeneous seismic zone with a certain length is distinguished along each geological fault, and it is believed that these faults are active throughout their entire length. This method also assumes that at each point of a given fault, earthquakes with a magnitude (M) equal to the magnitude of the maximum observed (M_{max}) earthquake here can occur.

Thus, according to the seismotectonic method, all existing tectonic faults are active and seismostatistical data can be extrapolated along their entire length.

However, this method does not always justify itself. First, without any reason, he assumes that the faults are active along their entire length. Secondly, in fault zones where strong earthquakes have not been observed or are not available, the possibility of such earthquakes in the future is excluded.

Geological faults of Azerbaijan and seismicity of the territory

It is known that a geological fault means a discontinuity of rocks, without displacement (crack) or with displacement of rocks along the fracture surface. Earthquakes are the result of the rapid sliding of rocks along a fault line in zones of contrasting tectonic movement which is characteristic of active faults.

Studies show that faults are not always active along their entire length and earthquakes may not occur at all fault points [16,17, 18]. This can also be observed on the fault structures of the territory of Azerbaijan.

A number of zones of geological faults have been identified on the territory of Azerbaijan by various geological and geophysical methods [8 ,9]. These fault zones are clearly distinguished on the map of the deep structure of the Black Sea-South-Caspian region of regional subsidence, compiled under the editorship of K.M.Kerimov and A.Sh. Shikhalibeyli [19]. Figure 1 shows the Azerbaijani part of this map. It can be seen from the map that a number of longitudinal (all-Caucasian direction) and transverse (anti-Caucasian direction) faults are distinguished on the territory of the republic.

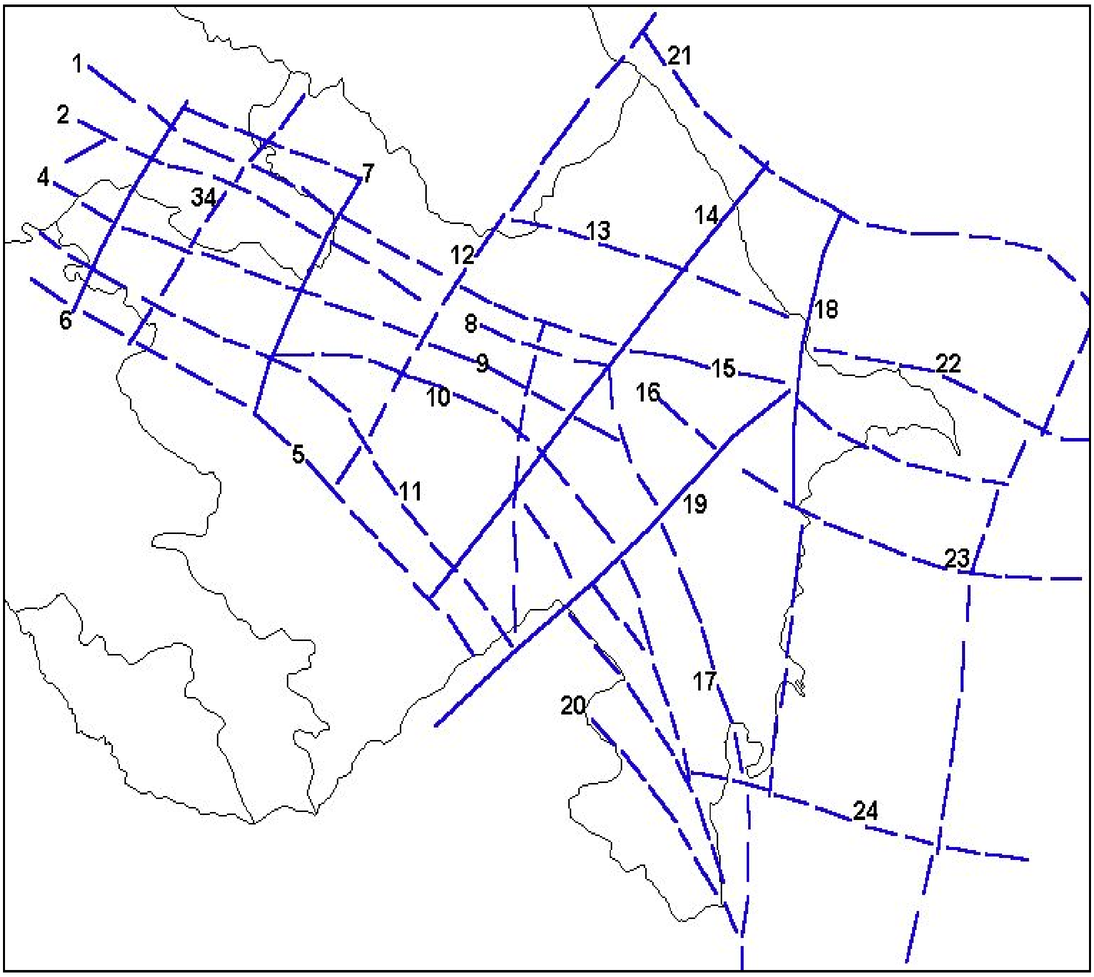

Fig. 1. Deep faults in the territory of Azerbaijan
(from the map "Deep structure of the Black Sea-South-Caspian region of regional subsidence" M.1:1000000/Editor-in-chief K.M.Kerimov, E.Sh.Shikhalibeyli, Baku, 1992)

Symbols:
1 – Vandam; 2 – Gagro-Dzhavsky; 3-4 – Tovuz-Aliabad; 5 – Front Lesser Caucasus; 6 – Gazakh-Signakh; 7 – Gandja-Alazan; 8 – North Adjinour; 9 – Geokchay; 10 – Mingachevir-Saatli; 11 – Kura; 12 – Arpa-Samur; 35 – Imishli-Gabala; 13 – Siyazan; 14 – Gyzylbogaz-Divichi (Shabran); 15 – Germian; 16 – Adzhichay-Alyat; 17 – West Caspian; 18 – Yashmin; 19 – Lower-Araz (Palmyr-Absheron); 20 – Talysh; 21 – Central Caspian; 22 – Absheron-Near Balkhan; 23 – Sangachal-Ogurchi; 24 – Mil

The seismotectonic method [11] assumes that these faults are active along their entire length and each point in them can become a source of seismic shocks.

On Figure 2 a map of the epicenters of strong earthquakes (with M≥5.0) in the territory of Azerbaijan for the period 427-2020 is given. This map shows that the number of such earthquakes in the republic is not so high; here strong earthquakes occurred rarely and not everywhere (or are not known everywhere). Therefore, data on strong earthquakes are not sufficient to judge the seismicity of individual areas, especially the activity of faults.

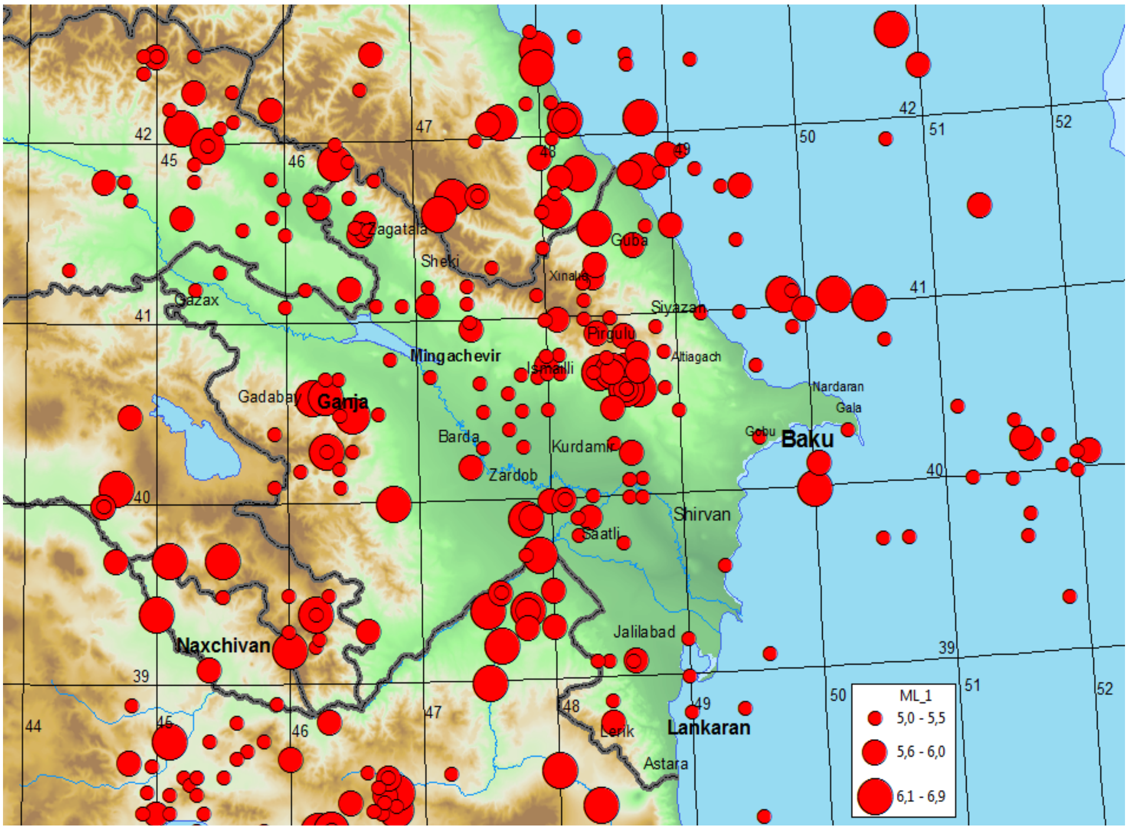

Fig. 2. Map of epicenters of earthquakes with M≥5.0 on the territory of Azerbaijan for the period 427-2020

Figure 3 shows a map of the epicenters of earthquakes with M≥3.0 on the territory of Azerbaijan for the period 1980-2020. The map shows that the earthquake sources are distributed extremely unevenly. They are mainly concentrated on the southern slope of the Greater Caucasus (from the Balakan region in the northwest of the republic to the Gobustan region in its southeast). It can also be seen on the map that uneven distribution is also observed within the most highly active regions. Condensation of earthquake epicenters in some places and their small number or even absence in others is noted. An increased accumulation of epicenters is observed in the area between the cities of Balakan and Zagatala, in the Oghuz district, to the east of the Gabala meridian, in the districts of Ismayilli and Shamakhi. To the east of the meridian 49°E, including on the Apsheron Peninsula, there are single epicenters of seismic shocks or are completely absent. Areas of increased seismicity also extend to the north and south. Within the Kura Depression, the southern continuation of the areas with an increased level of seismicity is clearly traced. However, a less dense accumulation of earthquake epicenters is observed here.

The above mentioned is another evidence that tectonic faults cannot be considered active along their entire length and, accordingly, strong earthquakes may not occur at all of their points.

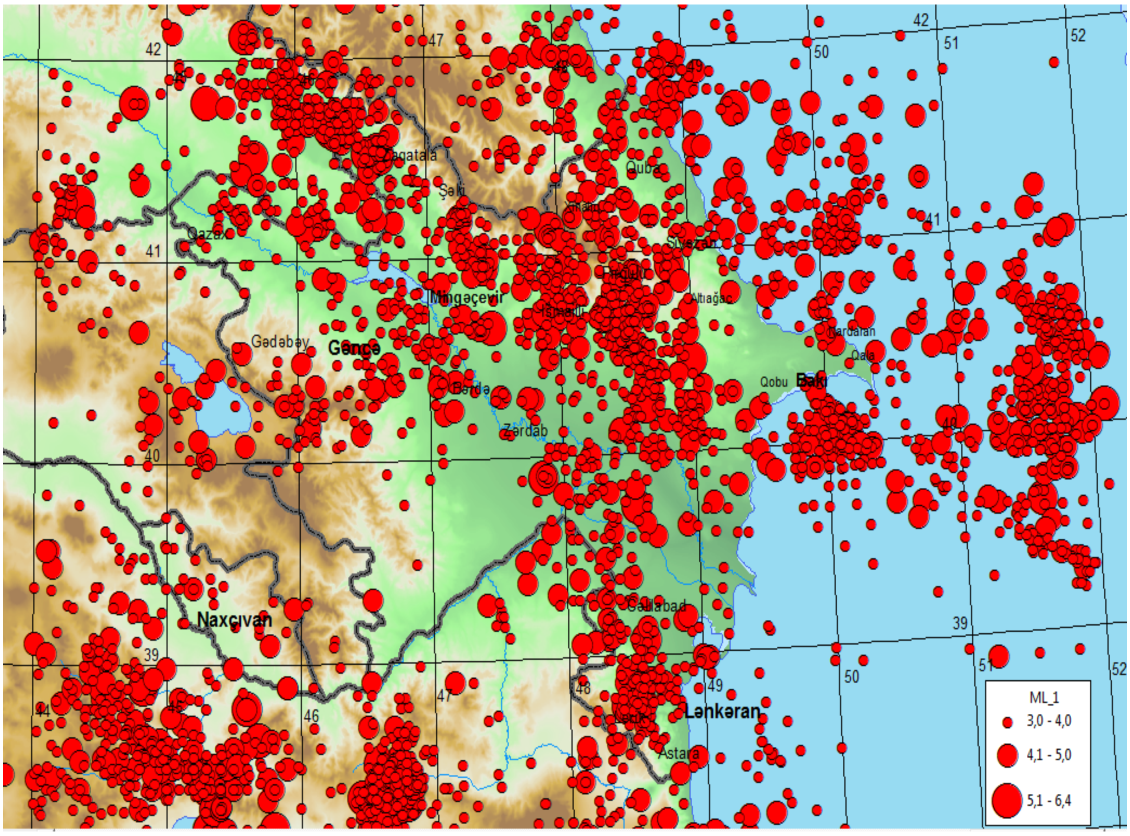

Fig. 3. Map of epicenters of earthquakes with M≥3.0 on the territory of Azerbaijan for the period 1980-2000

According to the currently widely used probabilistic seismic hazard assessment method, similarly to the seismotectonic method, each fault identified by geological and geophysical methods is considered active along its entire length without any reason, and each of its points is taken as a potential source zone. This method estimates the probability of occurrence of an earthquake and possible excess (usually 10%, 5%, 1%) of various magnitudes of earthquakes in the source zone within 50 years [3, 6, 15].

Source zones of strong earthquakes and their tectonic substantiation

T.Ya.Mammadli developed another method for determining seismogenic (active) zones of deep faults by weak seismicity, which allows more accurate determination of the spatial positions of real source zones of strong earthquakes [18]. This method is based on the concept of seismogenic structures, which are active faults that delimit tectonic structures with different tectonic development regimes and accumulate all strong and the bulk of weak and medium earthquakes. According to this technique, a lot of source (seismogenic) zones with different lengths and directions were identified in the study area (Fig. 4).

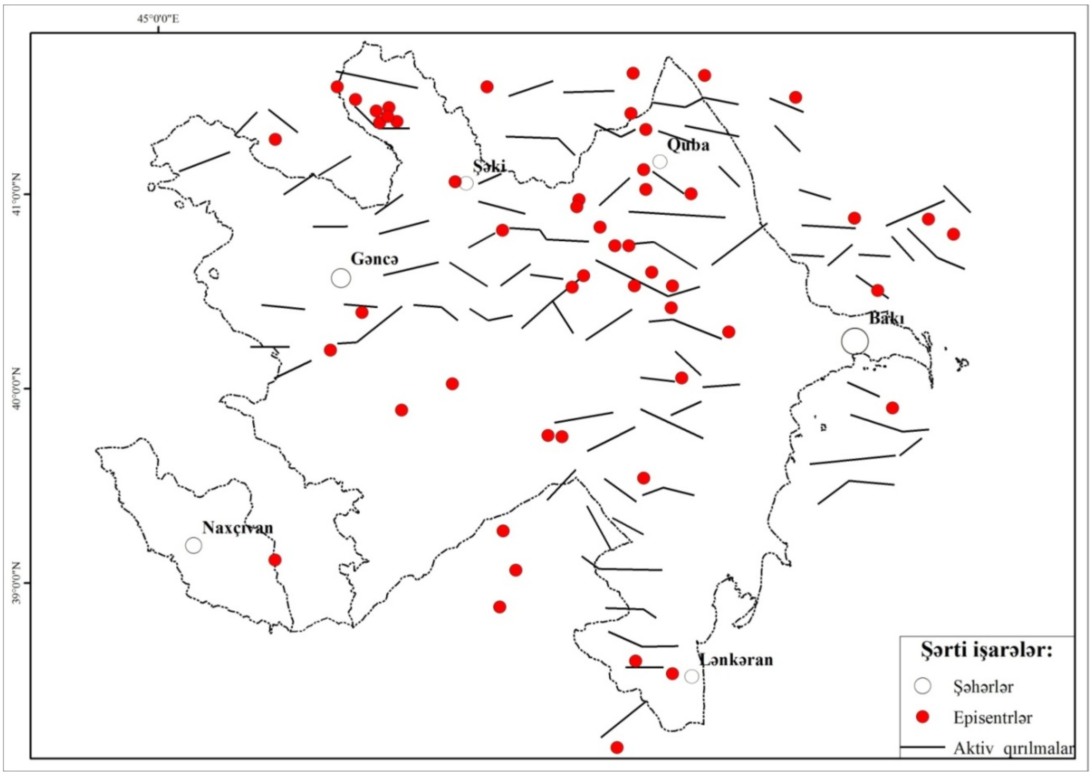

Fig. 4. Map-scheme of source (seismogenic) zones of the territory of Azerbaijan

The analysis showed that these source (seismogenic) zones correspond to individual segments of longitudinal (all-Caucasian direction) and transverse (anti-Caucasian direction) faults, previously identified by geological and geophysical methods [1, 4, 5].

The sizes of seismogenic lines indicate that active segments of faults in the territory of Azerbaijan are of small extent (up to 70 km).

Note that the seismogenic lines and epicenters of strong earthquakes that occurred here (M>5.0) have a high spatial coincidence (see Fig. 4.), which indicates the high accuracy of the method. The explanation for such a high spatial coincidence provides the results of the tectonic analysis of the region. It is known that an indispensable condition for the occurrence of strong earthquakes is contrasting tectonic movements, which are characteristic of fault zones that separate areas with different, and sometimes sharply changing, directions of tectonic movements. And the areas within the geological structures are characterized by a common tectonic regime (without contrasting movements) and, therefore, there are no conditions for the occurrence of strong earthquakes.

An analysis of the relationship between the structural plans of the longitudinal and transverse zones in the area of the junction of the southern slope of the Greater Caucasus with the Alazan-Agrichay imposed trough showed that here the tendency for the development of tectonic movements in the Quaternary is characterized by the growth of subsidence areas to the north (Reisner 1982). In areas where the longitudinal structural zones of the southern slope experience the greatest transverse deflection, the areas of subsidence penetrated the limits of the mountain-fold system most far. And in the areas of transverse uplifts, which manifest themselves within the longitudinal zones, the front of this process is delayed. Thus, certain segments of deep faults in the Quaternary time remain inside the areas of subsidence or uplift. No longer being the boundaries of structures (zones of contrasting movements) with different directions of tectonic movements, these parts of the faults do not show seismic activity. On the other hand, segments of deep faults separating zones with different directions of tectonic movements remain zones of contrasting movements and are characterized by high seismic activity.

Comparison of seismogenic (active) zones of the South-Eastern Caucasus (territory of Azerbaijan), identified by weak seismicity (see Fig. 3) with structural plans of longitudinal tectonic zones (see Fig. 1) shows that they correspond to segments of deep faults separating the zones with different directions of tectonic movements. Thus, the observed seismogenic (active) zones between the cities of Balakan and Zagatala, in the area of the city of Oghuz, between the cities of Gabala and Ismayilli, as well as between the village of Basghal and the city of Shamakhi, are connected by active segments of the Vandam fault, separating different parts of the anticlinorium of the same name from the Alazan-Agrichay trough.

A number of researchers [1,14,23] identified on the territory of the Greater Caucasus relatively elevated and lowered transverse structures. These transverse structures are separated by a chain of mud volcanoes and disturbing the linearity of the longitudinal structures by areas of folding flexural subsidence. An analysis of the distribution of sources of weak earthquakes shows that in some places of these areas, delimiting the transverse structures, there is a concentration of weak seismic shocks, which can be associated with differentiated vertical movements and can be identified as seismogenic zones of the anti-Caucasian direction. Thus, the seismogenic zone traced in the anti-Caucasian direction, in the area south of the city of Zagatala, is identified with the active segment of the Gazakh-Signakh transverse fault, which separates the Sheki uplifted transverse block, located east of Zagatala, and the western Balakan subsided block. The seismogenic zone, passing several kilometers east of the city of Sheki, can be identified as the active part of the Gandja – Alazan anti-Caucasian fault, separating the Sheki uplifted and Oghuz lowered transverse blocks. The seismogenic zone identified in the area east of the city of Gabala can be identified as the active parts of the Arpa-Samur transverse fault, which separates the Oghuz block from the Gabala – Ismayilli uplifted transverse block. To the east of the latter, there are not extended seismogenic zones, which can be identified by the active parts of the West Caspian transverse fault, separating the Gabala – Ismayilli uplifted transverse block and the lowered Baskal-Mayash block.

When approaching the West Caspian transverse fault, the hinge of the Vandam anticlinorium plunges sharply, to the east of it the southern Gandob uplift is completely covered by the Paleogene of the Shamakhi-Gobustan synclinorium. The northern Nialdagh uplift, affected by a transverse fault, east of Girdymanchay, retains the characteristic features of the structures of the southern slope. Deep faults of the all-Caucasian direction to the east of meridian 49^o are buried under the Paleogene deposits of the Shamakhi-Gobustan synclinorium and do not show activity. In this regard, single epicenters of seismic shocks are observed here or are completely absent.

An analysis of the data on the extent of seismogenic (source) zones (L) and the observed magnitudes of earthquakes in them allowed T.Ya.Mammadli to make the following equation [18]:

$$lgLkm=0.366M-0.883 \qquad (1)$$

The relationship between the length of the source (L) and the magnitude of earthquakes (M) was also identified by other researchers [10, 25, 27, 28]. However, the lengths of source zones were determined by them from macroseismic and aftershock data of strong earthquakes. Identified by T.Ya.Mammadli formula, when comparing these ratios, gives dependences of the source length L on the magnitude M that are quite close to real values [18].

Analysis of the obtained results

An analysis of the size (extension) of source zones in the territory of Azerbaijan shows that they have a small extent (mainly up to 50 km). Large destructive Gandja (427, 1139), Shamakhi (1559, 1872, 1902) earthquakes with M~7.0 repeatedly occurred in these sources in the past. According to formula (1), the extent of the Shamakhi earthquake of 1902 (M=6.9) can be estimated at 43-45 km.

However, in the Shamakhi-Ismayilli region, a seismogenic (source) zone is distinguished, the length of which reaches up to 70 km. According to formula (1), the maximum magnitude of the expected earthquake is M~7.4.

A.A.Nikonov [5, 21], having collected data from numerous historical manuscripts in an attempt to determine the magnitude and macroseismic area of earthquakes that occurred in the vicinity of the city of Shamakhi in 1667–69, came to the conclusion that in 1668 an earthquake with a force of 10 points occurred, the magnitude of which was M=8. In his opinion, the earthquake source was at a great depth (H=50–60 km), so the earthquake covered a very large area – the length of the 10-point zone was 80 km, the length of the 9-point zone was 270 km. Our calculations show that an earthquake with M>7.5 cannot occur in this zone. However, if we take into account that on the southern slope of the Greater Caucasus the depths of strong earthquakes do not exceed H=10-15 km [12] and, using the equations of the macroseismic field of N.V.Shebalin [26], we can confidently assume that in 1668 in Shamakhi a catastrophic 11-point (according to the MSK-64 scale) earthquake occurred in the area. The high macroseismic effect covered a fairly large area. The length of the 11-point zone was 100-120 km, the length of the 10-point zone was about 150 km, and the 9-point zone occupied even more area. According to historical data, this earthquake with its subsequent aftershocks led to great destruction, claimed 80,000 human lives [21]. The analysis shows that such an earthquake with a magnitude of M~7.5, a depth of H=10-15 km, and covering a wide area of high macroseismic effect (the length of high-point zones is 150-200 km) could lead to such numerous victims. It should be noted that an earthquake of approximately the same magnitude (M=7.7) occurred on February 06, 2023 in Turkey. The earthquake was one of the biggest disasters to hit the region in recent times. Tens of thousands (more than 50,000) of people died and were injured, there were changes in the relief. Thus, the length of the seismogenic (source) zone, the results of the analysis of numerous historical data and their comparison with macroseismic manifestations of a recent earthquake of approximately the same magnitude (M=7.7) allow us to confirm the existence of a potential large source in the Shamakhi-Ismayilli region.

Conclusions

1. In the South-Eastern Caucasus (territory of Azerbaijan), active deep faults of the all-Caucasian and anti-Caucasian directions are distinguished. Faults of the all-Caucasian direction correspond to zones separating longitudinal structures with different directions of tectonic movements. Faults of the anti-Caucasian direction are connected by differentiated vertical movements of relatively uplifted and lowered transverse structures.

2. The size (length) of most active faults (sources) in the territory of Azerbaijan is small (from 20 to 50 km) and they can generate strong earthquakes with a magnitude of M~6.0÷7.0. These earthquakes due to their small depths on the Earth's surface appear up to 7-9 points on the MSK-64 scale.

3. In the Shamakhi-Ismayilli region, a source zone has been identified, the length of which reaches 70 km. The maximum magnitude of the expected earthquake in this source is M~7.4. The macroseismic effect of such earthquakes can reach 11 points on the MSK-64 scale.

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