Chapter

Revelation of Potentially Seismic Dangerous Tectonic Structures in a View of Modern Geodynamics of the Eastern Caucasus (Azerbaijan)

Talat Kangarli, Tahir Mammadli, Fuad Aliyev, Rafig Safarov and Sabina Kazimova

Abstract

The stress state of the earth's crust in the Eastern Caucasus, located in the zone of collision junction of the North Caucasian, South Caucasian, and Central Iranian continental massifs, is a consequence of the inclusion of the Arabian indenter into the buffer structures of the southern framing of Eurasia at the continental stage of alpine tectogenesis. This evidenced from the results of geophysical observations of the structure and seismic-geodynamic activity of the region's crust. The latter, at the neotectonic stage, was presented as underthrust of the South Caucasian microplate under the southern structures of Eurasia. The analysis and correlation of historical and recent seismic events indicate the confinement of most earthquake foci to the nodes of intersection of active faults with various orientations or to the planes of deep tectonic ruptures and lateral displacements along unstable contacts of material complexes of various competencies. The focal mechanisms of seismic events reveal various rupture types, but in general, the earthquake foci are confined to the nodes of intersection of faults of the general Caucasian and anti-Caucasian directions. Based on the observed weak seismicity, active areas of deep faults were identified, which are accepted as potential source zones.

Keywords: earthquake, seismotectonics, focal mechanism, geodynamics, accretionary prism

1. Introduction

The territory of the Middle East, the northern periphery of which corresponds to the South Caucasus, is a collage of different-scale tectonic blocks—Anatolian-Taurus, Central Iranian, South Caucasian microplates, and smaller blocks (**Figure 1**), located between the Arabian continental plate (in the south) and the southern edge of the Eurasian continent (in the north). The latter at the neotectonic stage of tectogenesis (from the end of the Miocene) exist in the regime of collision convergence, which in turn causes exceptional tectonic activity in the region [2–15]. This feature is evidenced by often occurrence of strong and destructive earthquakes in Turkey, Iran, and the Caucasus Isthmus in the present time. The seismicity of these territories is explained by intensive restructuring of the structural plan with significant amplitudes of recent movements.

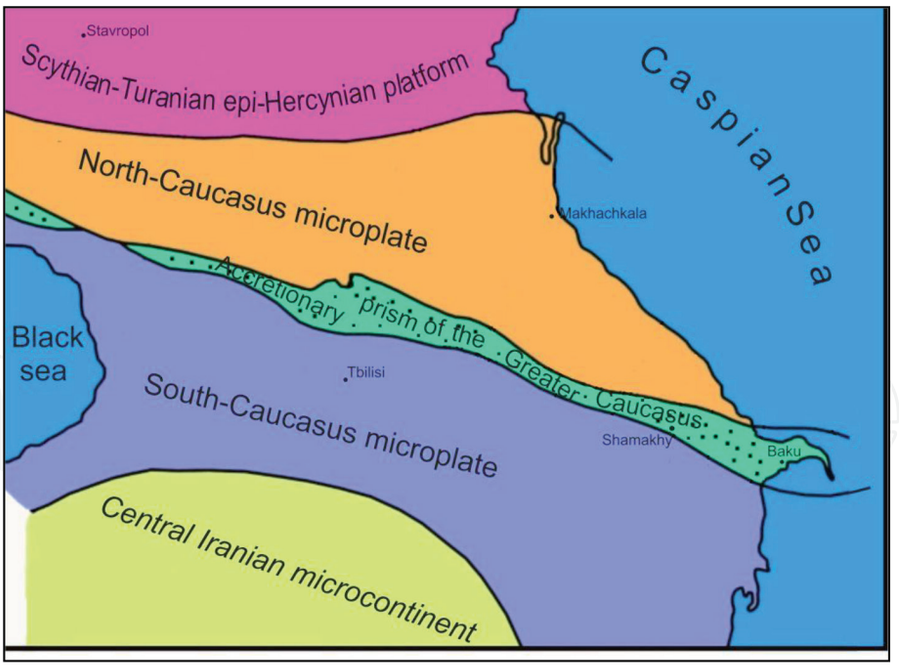

Figure 1.
Allocation of accretion prism within structure of the Greater Caucasus of the Caucasus isthmus (modified from [1]).

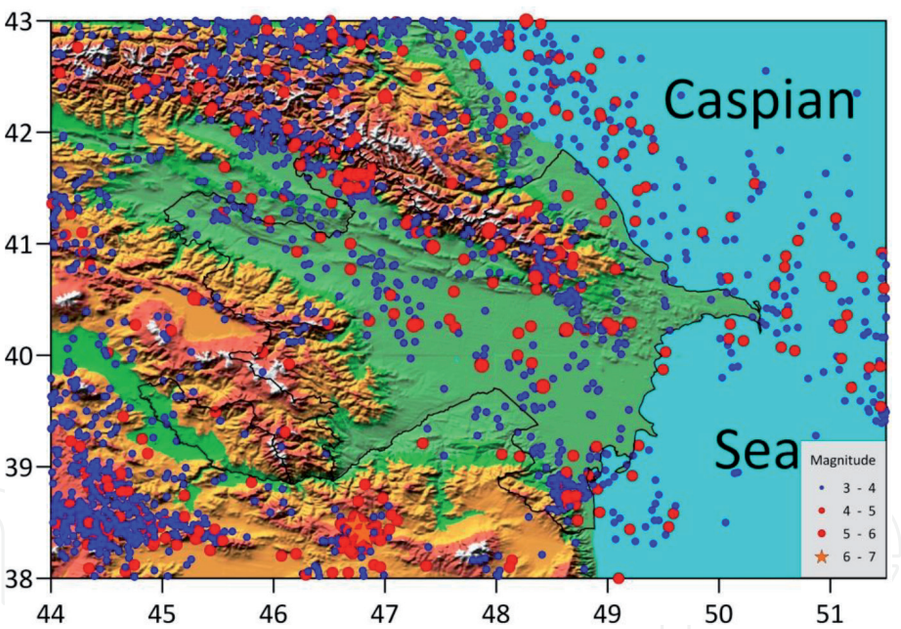

Figure 2.
Map of earthquakes epicenters $M \geq 3.0$ of the territory of Azerbaijan for the period 2004–2020.

In this regard, the eastern part of the South Caucasus, where Azerbaijan is located, characterized by highly seismic activity with periodic occurrence of seismic events with $M > 5$, is no exception (**Figure 2**).

The stress state of the earth's crust in the region located in the collision junction zone of the North Caucasian, South Caucasian, and Central Iranian continental massifs (tectonic microplates) is a consequence of the intrusion of the Arabian indenter into the buffer structures of the southern framing of Eurasia at the continental stage of alpine tectogenesis (from the end of the Miocene). This is evidenced by the results of geophysical observations of the structure and seismic-geodynamic activity of the region's earth crust. The latter, at the neotectonic stage,

was an underthrust (S-subduction—continental subduction or pseudosubduction) region of the South Caucasian microplate under the southern underbelly of Eurasia (Scythian-Turanian epigercynian platform) in the northern wing and active terrestrial volcanism with the formation of volcano-plutonic complexes. Namely, the process of lateral compression, which continues at the current stage of tectogenesis under the influence of the collision approach of the Arabian and Eurasian continents, determines the high level of seismic and geodynamic activity in the study area.

Seismological and paleoseismotectonic studies, and seismic and seismotectonic zoning works carried out in various seismic regions of the Caucasus (including territory of Azerbaijan) confirm the controllability of earthquake focal areas by a network of faults of general Caucasian and anti-Caucasian direction with various types of prolongation. However, in general, the reason of current seismic activity is the horizontal movements of different-scale tectonic blocks of the earth's crust, located in the zone of collision interaction of the Afro-Arabian and Eurasian continental plates.

We carried out the analysis and interpretation of seismological data, as well as the results from GPS monitoring of modern geodynamic activity with the identification of their correlations with the features of the deep structure. GPS monitoring data in the Eastern Caucasus indicate an intensive advancement of the South Caucasus block in the northern points. The analysis and correlation of historical and recent (2012–2020) seismic events indicate the confinement of earthquake sources mainly to the nodes of intersection of active faults of various strikes or to the planes of deep tectonic disruptions and lateral displacements along unstable contacts of material complexes of various competencies.

2. Recent geodynamic processes

The observed seismic activity is generally confined with the rates of horizontal movements that took place for the period of GPS monitoring of the modern geodynamics of the region since 1998 [6, 16–21]. In comparison with the data for 2004, the rates of horizontal movements for the absolute majority of observation points according to the data of 2020 increased by 2–8 mm/year (**Figure 3**). At the same time, transverse zoning is traced in the distribution of velocities, similar to the seismic one: to the west of Samur-Agdash velocity, disturbances are on average 8–10 mm/year, and to the east of it, they exceed 13 mm/year (13–15 mm/year).

At the same time, longitudinal zoning is observed in the distribution of the rates of horizontal movements, which correlates with the main Caucasian tectonic zoning of the territory.

Review of the distribution data of the velocity vectors of horizontal displacements of GPS geodetic points on the territory of Azerbaijan and the neighboring areas of Iran for the period 1998–2020 leads us to conclude about a significant (up to 15 mm/year) rate of movement in the north-north-east direction of the southwestern flank and the central strip of the South Caucasian microplate, including the territory of the south-eastern segment of the Lesser Caucasus, Kura depression, and Talysh. At the same time, within the northeastern flank of the microplate corresponding to the Vandam-Gobustan megazone of the Greater Caucasus, the velocity vectors are reduced to 6–13 mm/year, and even further north, in the hanging wing of the Kbaad-Zanginsky deep underthrust, that is, directly within the accretionary prism, completely decrease to 0–6 mm/year (data from 2010 to 2014). In general, the tangential contraction of the earth's crust in the region is estimated at 4–10 mm/year.

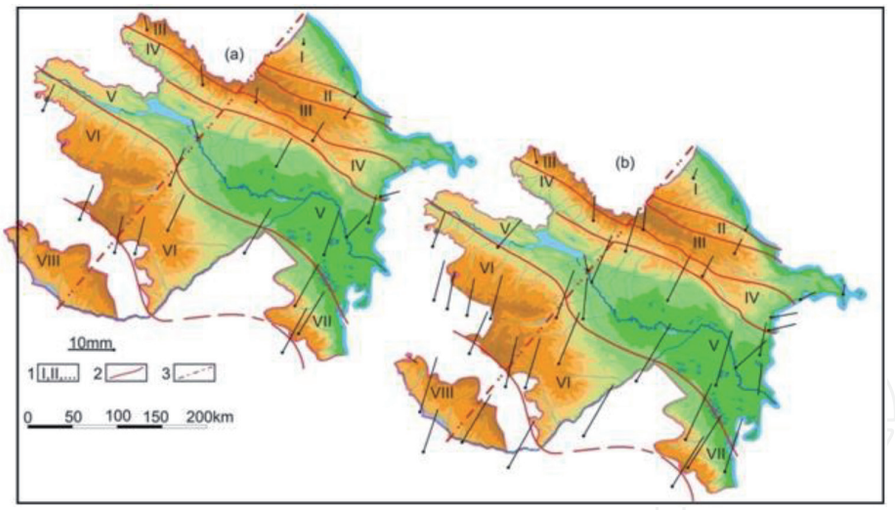

Figure 3.
GPS velocities of horizontal movements of the earth's surface in Azerbaijan and adjacent regions in 2004 (a) and 2020 (b). Compiled by R.T. Safarov. (1) main structural zones (longitudinal tectonic blocks): (I) Gusar-Davachinskaya, (II) the Lateral Ridge of the Greater Caucasus, (III) Southern slope of the Greater Caucasus, (IV) Kakheti-Vandam-Gobustan, (V) Kurinskaya, (VI) Artvin-Garabagh, (VII) Talysh, and (VIII) Araz; (2) deep faults at the boundaries of structural zones; and (3) Samur-Agdash fault.

This is confirmed by the observed directions and velocities of the earth's surface movement within territory of Azerbaijan and adjacent areas according to the results of measurements of GPS points in 2015–2020 (**Figure 4**). The velocity field clearly illustrates the movement of the earth's surface in the N-NE direction. At the same time, the plots clearly show a specific feature of the velocity field, namely a contrasting decrease in velocity at observation points located in the southern wing of the Zangin thrust fault, in comparison with the velocities recorded within the Kura and more southern zones (see **Figures 3** and **4**).

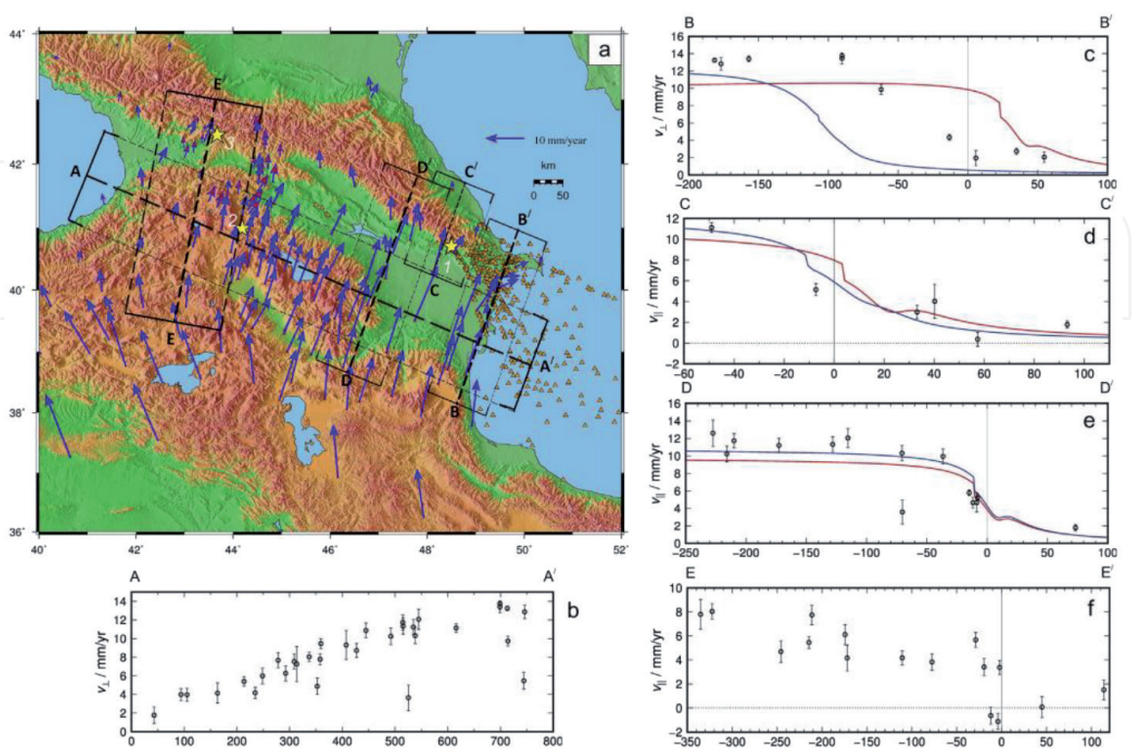

Figure 4.
GPS velocities of horizontal movements in Azerbaijan and adjacent regions (2020) and graphs of parallel and transverse components of GPS velocities along sections AA /, BB /, CC /, DD /, and EE / [5, 6, 16].

This phenomenon reflects the process of successive accumulation of elastic deformations in the pseudosubduction interaction zone of the northern flank structures of the South Caucasian microplate (Vandam-Gobustan megazone) with the accretionary prism of the Greater Caucasus.

Active faults: A well-pronounced indicator of the activity of faults (fault zones) is weak seismicity, so that, any even the smallest tectonic movements in disjunctive zones generate more or less strong seismic shakes.

The map of the earthquake epicenters that occurred on the territory of Azerbaijan over the past 20 years shows that focal zones are distributed very randomly here (**Figure 2**). At the same time, a similar peculiarity is observed within the most highly active regions, where the weaker earthquake foci clustering was observed in some areas.

One of the authors has developed a method for identifying real-time active segments of deep faults based on manifestations of weak seismicity in these zones [22]. This method is based on the idea of seismogenic structures (zones), which are known to be active faults that delimit geotectonic structures with different tectonic regimes and accumulate all strong and most of the weak and medium-strength earthquakes. According to the proposed method, the identification of seismogenic zones is carried out on the basis of the breakdown of the study area into equal areas and plotting of a map of weak seismicity. For each of these areas, within which the number of epicenters is not less than the specified threshold value, approximating lines of concentration of epicenters are constructed.

It is assumed that these lines correspond to active faults zones. These zones are actually potential source zones for strong earthquakes in specific territories. The method for determining active deep faults based on weak seismicity makes it possible to determine the location of potential source zones, as well as calculate their seismic potential and seismic effect that may occur on the earth's surface in the event of seismic activity. To assess the degree of their manifestation, the position of the sources of earthquakes and the parameters of the seismic regime are determined. At the same time, the catalogs of earthquakes are analyzed taking into account foreshock and aftershock activity, the stretch of pleistoseist zones, the character of the seismic effect decay depending on the distance, and other factors.

Coming from aforesaid, a map of potential seismic hazard for the territory of the Azerbaijan was compiled on the basis of a spatial analysis of weak seismicity (**Figure 5**), and active faults (fault zones) at the current stage of tectogenesis were identified. Based on the observed weak seismicity, active areas of these faults were identified, which are potential foci zones. At the same time, the relationship between the length of focal zones and the maximum possible magnitudes of earthquakes in them has been determined. It was found that the value of the maximum possible earthquake magnitudes (M_{MAX}) in the territory of Azerbaijan is approximately equal to 7 (M_{MAX} = 6.9 ÷ 7.3).

The features of the seismic activity manifestation on the territory of Azerbaijan are considered by us on the example of the southern slope of the Greater Caucasus, which at the current stage of tectogenesis is the most seismically active region of the country. Large seismic events periodically occur here, accompanied by the spontaneous release of large volumes of energy from the earth's interior. Seismic activity is associated with the ongoing intensive restructuring of the structural plan with significant amplitudes of the latest and modern movements: earthquake foci, as a rule, are confined to the boundaries of large geotectonic elements of the earth's crust and nodes of intersection of faults of various directions.

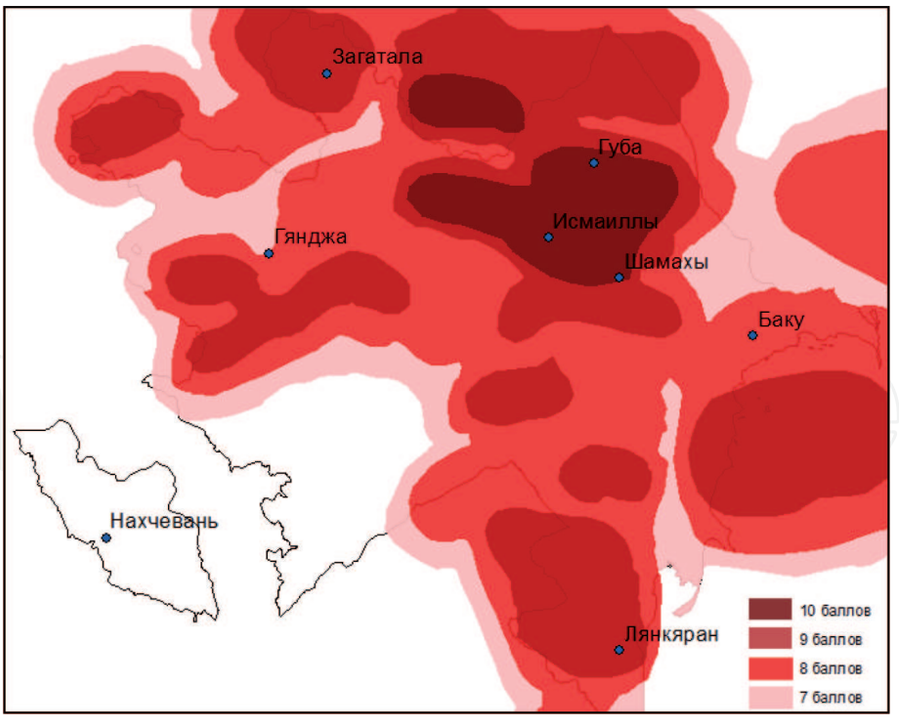

Figure 5.
Map of the potential seismic hazard of the territory of Azerbaijan. Compiled by T. Ya. Mammadli.

3. The dynamics of the manifestation of seismic activity

In-depth uneven distribution of earthquakes foci, in fact, proves ongoing pseudo-subduction interaction within southern slopes of the Greater Caucasus. The hypocentral levels exist in 2–6, 8–12, 17–22, and 25–45 km. The analysis of in-depth earthquake distribution evidences about existence of structural-dynamic interrelation between along with subvertical and subhorizontal contacts in the earth crust. Spatial and in-depth earthquake clustering can be explained from the point of view of block partibility and tectonic stratification of the earth crust (**Figures 6** and 7). Structurally, these clusters generally confine to the intersection junctions of fault zones with various directions or to the planes of tectonic ruptures and lateral displacements along weak contacts of multicomponent material complexes [21, 23–29].

Coming from temporal and spatial analysis of $M \geq 3$ earthquakes' foci distribution for the instrumental period of monitoring (1902–2020), we delineated dynamics of seismic activity in northern slope of the Greater Caucasus (**Figures 6** and 7). Using data of geophysical data reinterpretation, along with compiled tectonic and magmatic schemes of the study area, we divide this territory to four blocks (separated by various anti-Caucasian faults) with various levels of seismic activity [7, 29]. They are Zagatala, Sheki, Gabala-Shemakha, Gobustan zone. First, two clocks stand as eastern segments, whereas two others represent south-east segments of the Greater Caucasus. These segments are divided by Samur-Aghdash left-lateral strike-slip fault (**Figure 6**).

First, two blocks are distinguished for their lower seismic activity recorded throughout the entire period of observations (**Figure 7**):

- until 1980, 12 seismic events occurred within the Zagatala block's frontiers, confined to the consolidated crust's upper segment. Absolute majority of focuses (11) is located at depths of 12–30 km. Since 1980 until present, 66 events were recorded, with 9 events sourcing from the sedimentary cover, and 57—from 5 to 30 km depths of the consolidated crust;

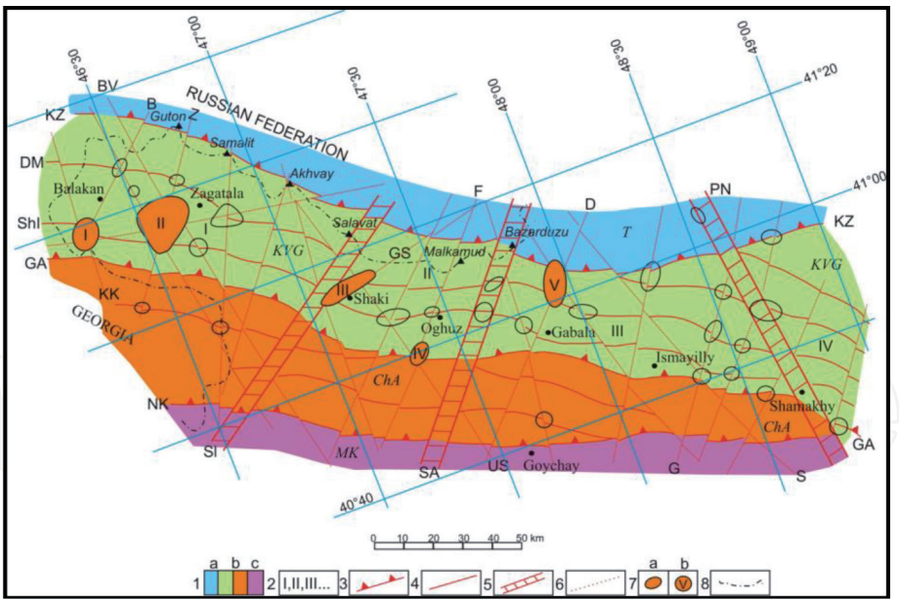

Figure 6.
Schematic map of fault tectonics and earthquakes foci zones distribution on the level of Pre-Jurassic basement—compiled by T.N. Kangarli, F.A. Aliyev and A.M. Aliyev [23]. (1) longitudinal blocks of the first order: (a) Tufan (T), (b) Kakheti-Vandam-Gobustan (KVG), (c) Chatma-Ajinohur (ChA), and (d) Middle Kur (MK); (2) transverse blocks of the first order: (I) Zagatala, (II) Shaki, (III) Gabala-Shamakhy, and (IV) Gobustan; (3) faults on borders of longitudinal blocks of the first range: KZ—Kbaad-Zangi, GA—Ganikh-Ayrichay-Alat, and NK—Northern Kur; (4) ruptures limiting the longitudinal blocks of the second order, including: DM—Dashaghil-Mudrisa and ShI—Shambul-Ismayilly; (5) faults on borders of transverse blocks of first level: Sl—Salavat, SA—Samur-Aghdash, and PN—Pirsaat-Neftchala; (6) other ruptures of anti-Caucasus direction, including: KK—Khimrikh-Khalatala, BV—Bulanligchay-Verkhiyan, B—Balakan, Z—Zagatala, GS—Gokhmug-Salyakhan, F—Fiy, US—Ujar-Saribash, D—Damiraparanchay, G—Girdimanchay, and S—Sighirly; and (7) earthquakes foci zones of 2012–2016 with $M \geq 3$: (a) given in a paper: (I) Balakan, (II) Zagatala, (III) Shaki, (IV) Oghuz, and (V) Gabala; and (b) other; and (8) state border.

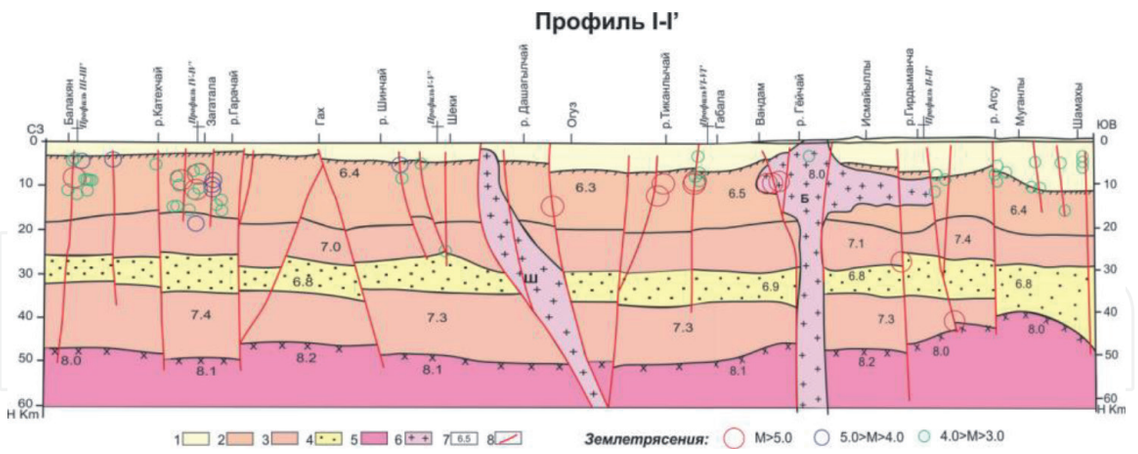

Figure 7.
Synthetic seismic profile of MOVZ along the longitudinal traverse of Balakian-Shamakhi. Compiled by T.N. Kangerli, A.M. Aliyev and F.A. Aliyev. 1–3 layers of the consolidated crust: (1) sedimentary; (2) "granite"; (3) "basalt"; (4) "waveguide"; (5) upper mantle; (6) intrusives (III—Sheki and B—Buinuz); (7) formation velocities of seismic waves; and (8) breaking violations.

First, two blocks differ by more pronounced seismic activity for the entire monitoring period (**Figure 7**). More detailed quantitative analysis gives us the following outcomes:

- Twelve seismic events took place within Zagatala block till 1980, which are confined to the upper part of earthquakes here. Nine of these events occurred in sedimentary layer, while 57 took place in consolidated crust within depth interval of 5–30 km;

- There occurred 14 seismic events within Shaki block till 1980. Three of these earthquakes took place in a depth of 3–5 km. which confines to alpine cover, while the rest part clustered in depths of 5–30 km, which confine with the consolidated crust. For the following period of 1981–2017, the number of earthquakes raised to 65, three of which occurred in the sedimentary layer, while 62 in consolidated crust (the distribution was 58 and 3 in the upper and lower segments respectively and 1 below Moho boundary).

Gabala-Shamakhy and Gobustan blocks have been more active throughout the entire period of observations, but there were also the leaps of seismic activity recorded in last quarter of XX century (**Figure 8**):

- until 1980, the total 29 seismic events have been registered within the block's structure, including the Alpine cover (14) and the consolidated crust's upper segment (14 events at depths of 5–30 km and 1 event below the Moho discontinuity). In the following period, the block's seismic activity increased to 219 events, 46 of which occurred in the sedimentary cover, 171—in the consolidated crust (141—5–30 km and 30—31–45 km), and 8—below the Moho discontinuity;

- Twenty-three seismic events have occurred in Gobustan block until 1980. Eight events were confined to the Alpine cover, 11—to the upper (5–30 km), and 4—to the lower segment (31–45 km) of the consolidated crust. During 1981–2017, the number of events increased to 196, 30 of which occurred in the sedimentary cover, 187—in the consolidated crust (139 in the upper and 48 in the lower segment), and 9—below the Moho discontinuity.

It can obviously be stated that the process of seismic activity was rising in the study area since 1980s of the last century. And this is despite the fact that the technical and methodological allowances for earthquake registration were not so qualitative as in the present (**Figure 9**). Within eastern segment of the study area, the upper part of the consolidated crust reveals as more seismic active, while in the south-eastern segment, earthquakes foci are scattered in the whole earth crust

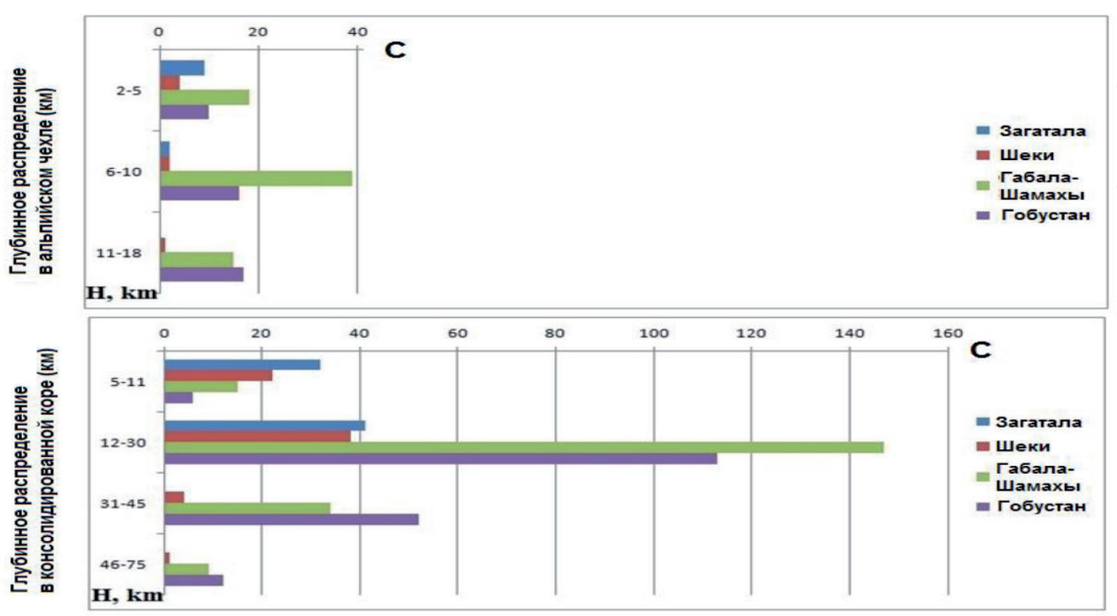

Figure 8.
Histogram of the vertical distribution of earthquake sources with M ≥ 3 over the blocks of the earth's crust on the southern slope of the Greater Caucasus within Azerbaijan (1902–2017). Compiled by F.A. Aliyev.

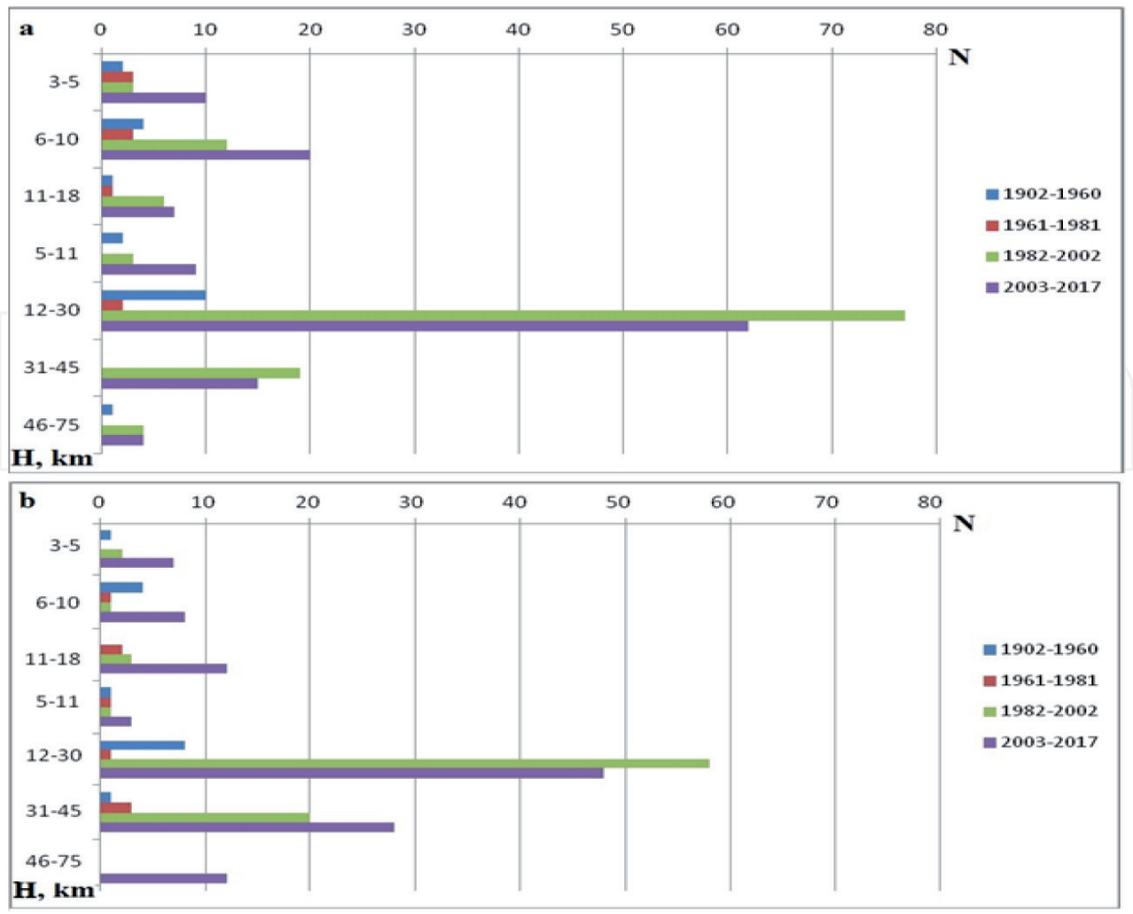

Figure 9.
Histogram reflecting changes in seismic activity (earthquakes with M ≥ 3) in the Azerbaijani part of the southern slope of the Greater Caucasus in space (in depth) and in time for the period 1902–2017: (a) Gabala-Shamakhi and Gobustan blocks; and (b) Zagatala and Sheki blocks. Compiled by F.A. Aliyev.

and also in the upper mantle. Most of deep seismic foci are located in a zone of the Western Caspian submeridianal fault. To the east of this fault zone, we can observe a stepped dipping the consolidated crust toward the Caspian hollow.

Spatial-temporal analysis of the distribution of strong seismic events in the Greater Caucasus region (within Azerbaijan borders) allows us to conclude that the northern flanks of Southern Caucasus microplate (these are structures that buried beneath accretionary wedge in the north, and the structures that revealed as a central segment or covered by a quaternary layer on the southern part of Kakheti-Vandam-Gobustan zone) are most active at the present stage of tectogenesis. These seismic active parts are divided into two zones:

- the zone controlled by the Ganykh-Airichay-Alat deep thrust of the all-Caucasian direction (or the border of Vandam-Gobustan and Sredne Kura tectonic zones) in the Ordubad-Balakyan-Mozdok strip of the anti-Caucasian seismotectonic zone in the west of the Azerbaijani part of the Greater Caucasus;

- complex tectonic node located in the east of described region within the boundaries of Talish-Samur-Makhachkala submeridional seismotectonic zone: corresponding to an intersection of two faulting zones: (1) northwest striking Western Caspian zone bordered by Pirsaat and Sighirly elementary deep strike slips from the northeast and southwest), and (2) northeast striking Girdimanchay-Shamakhy zone represented by Basgal-Khashi, Aghsu-Khaltan, and Jalair-Dibrar dislocations.

- a complex tectonic knot located within the Talysh-Samur-Makhachkala submeridional seismotectonic zone in the east of the described area, corresponding to the intersection of two fault zones: the northwestern direction West Caspian (bounded from the north-east by Pirsaat and south-west by Sygyrli by elementary right lateral strike-slip faults) and Girdymanchay-Gonagkend of northeastern strike (represented by Basgal-Khashyn, Agsu-Khaltan, Sagiyan-Dibrar, Goylyardag-Nabur, and other disturbances).

Under lateral compression environment, small-scale blocks that constitute the region's earth crust trigger the emergence of transpressive deformations, which combine the shear displacements along framing transverse deformations with the compression structures such as "general-Caucasus" ruptures. Such regime leads to an emergence of multiple concentration areas of the elastic deformations confined to the mentioned dislocations and their articulation knots. It is just the exceeded ultimate strength of the rocks that causes an energy discharge and brittle destructions (according to stick-slip mechanism) in such tectonically weakened regions of the southern slope of the Azerbaijani part of Greater Caucasus (**Figure 6**).

Due to lateral compression state of the small-size blocks, into which the crust of the region is fragmented into parts, the formation of a transpressive type of deformation combines shear displacements along transverse faults. These faults confine blocks with compression structures, which include faults of the general Caucasian direction. In this tectonic regime, elastic stress is being concentrated in several zones that confined to the indicated dislocations and their junction points. Due to excess of the possible strength ability of rocks, the accumulated elastic deformations leads to energy discharge by means of earthquakes (mostly stick-slip type) in these tectonically weaker zones of the southern slope of the Greater Caucasus (see **Figure 10**).

The existence of tangential stresses in the region in real time is also indicated by the focal mechanisms of earthquakes with $M \geq 3$ that occurred in the period

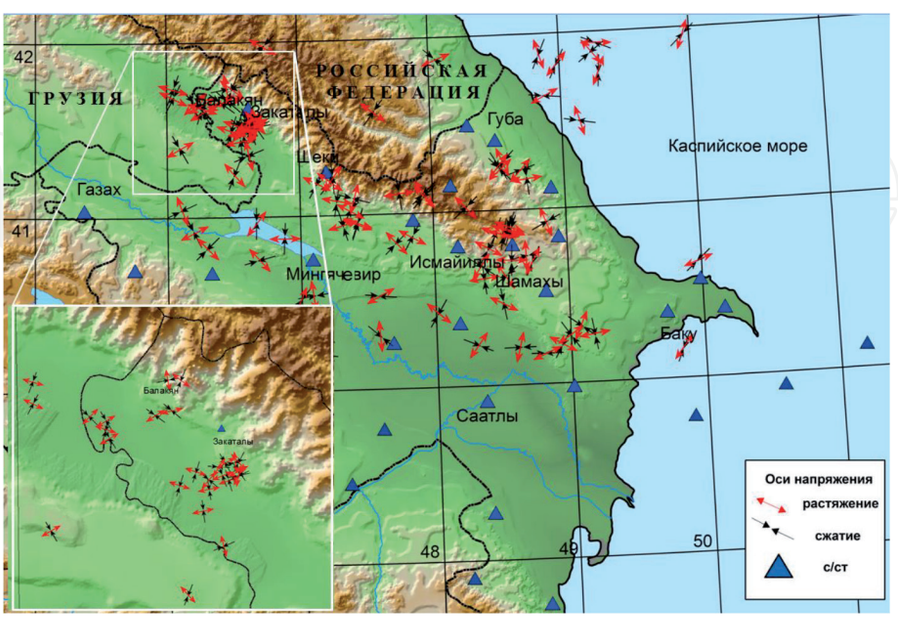

Figure 10.
Scheme of distribution of tectonic stresses from earthquake mechanisms with M ≥ 3 for 2003–2017—Compiled by S.E. Kazimova.

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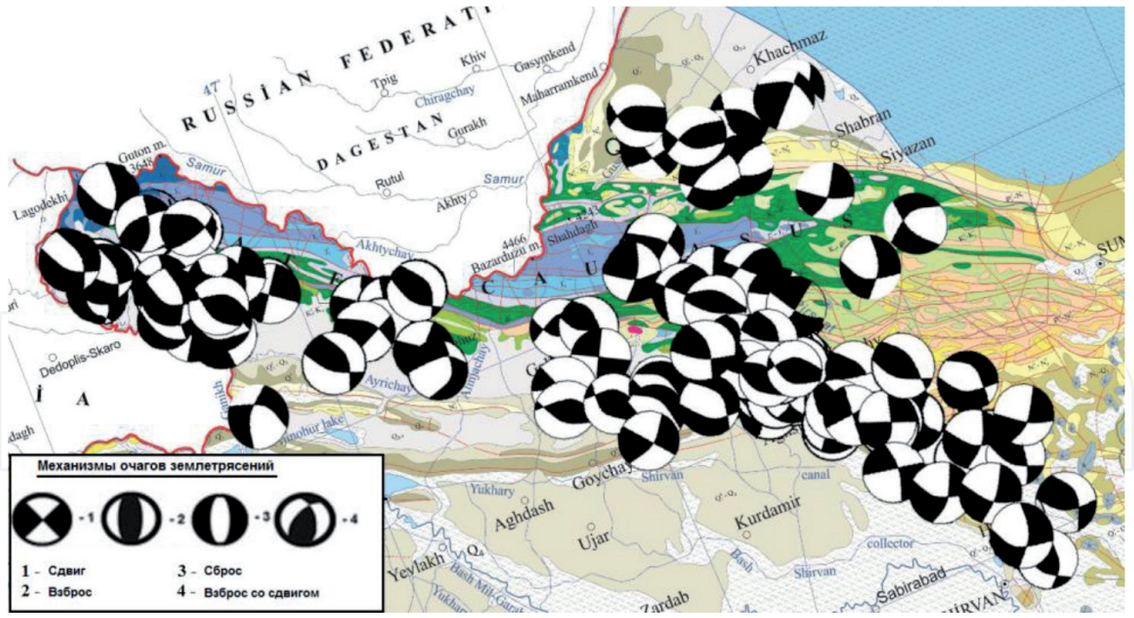

Figure 11.
Focal mechanisms of earthquakes with $M \geq 3$ for the period 2003–2017. Compiled by S.E. Kazimova.

2003–2017 (**Figure 11**). Analysis of the distribution of the axes of compression and expansion indicates the predominance of lateral compression oriented in the submeridional and NE-SW directions. The types of focal mechanisms generally correspond to the concepts of the geodynamics of convergent microplate boundaries, where the entire set of these mechanisms is noted (**Figure 11**)—from fault to reverse [23–25, 27, 28, 30, 31].

This is evidenced by the seismic events that took place in Northwestern Azerbaijan in the period from 2012 to the first half of 2018. As an example, the conditions and factors that determined the tangible seismic activity in the Zagatala, Balakan, and Sheki source zones are given.

One of most seismically active zones in 2012–2015 was Zagatala focal zone, where three earthquakes with M = 5.27–5.69 (07.05.2012) took place, along with one event with M = 5.02 (20.06.2012) and numerous aftershocks with M = 3.0–4.4. A huge number of earthquakes foci are located within depth of 5–20 km, which confines to the pre-Jurassic basement of Kakheti-Vandam-Gobustan zone's frontal part. Despite the mostly clustered focal zone, one aftershock occurred outside of this zone, within Alpine cover (07.05.2012, 05:40). This is located in vicinity of Kvemo-Kedi village (Georgia) and corresponds to a plane of Ganikh-Ayrichay-Alat thrust fault that plunges in the northern rhumbs at its intersection with northeast-oriented Zagatala trans-tensional fault.

Overall, this source zone is a complex disjunctive node located in the upper part of the pre-Jurassic basement, consisting of elementary knots of intersection of tectonic faults with various orientations, where earthquake foci confined (see **Figures 12** and **13**). The volume of the rock mass, where earthquake hypocenters along with aftershocks with $M \geq 3$ are concentrated, reaches approximately 3400 km^3.

These earthquake series are mainly associated with the activity of the Zagatala transverse fault, which in turn activated and related to the disturbances in the all-Caucasian and anti-Caucasian directions. Earthquake mechanisms here indicate the predominance of strike-slip and fault movements with the assistance of fault-strike-slip and reverse fault movements in the source zone.

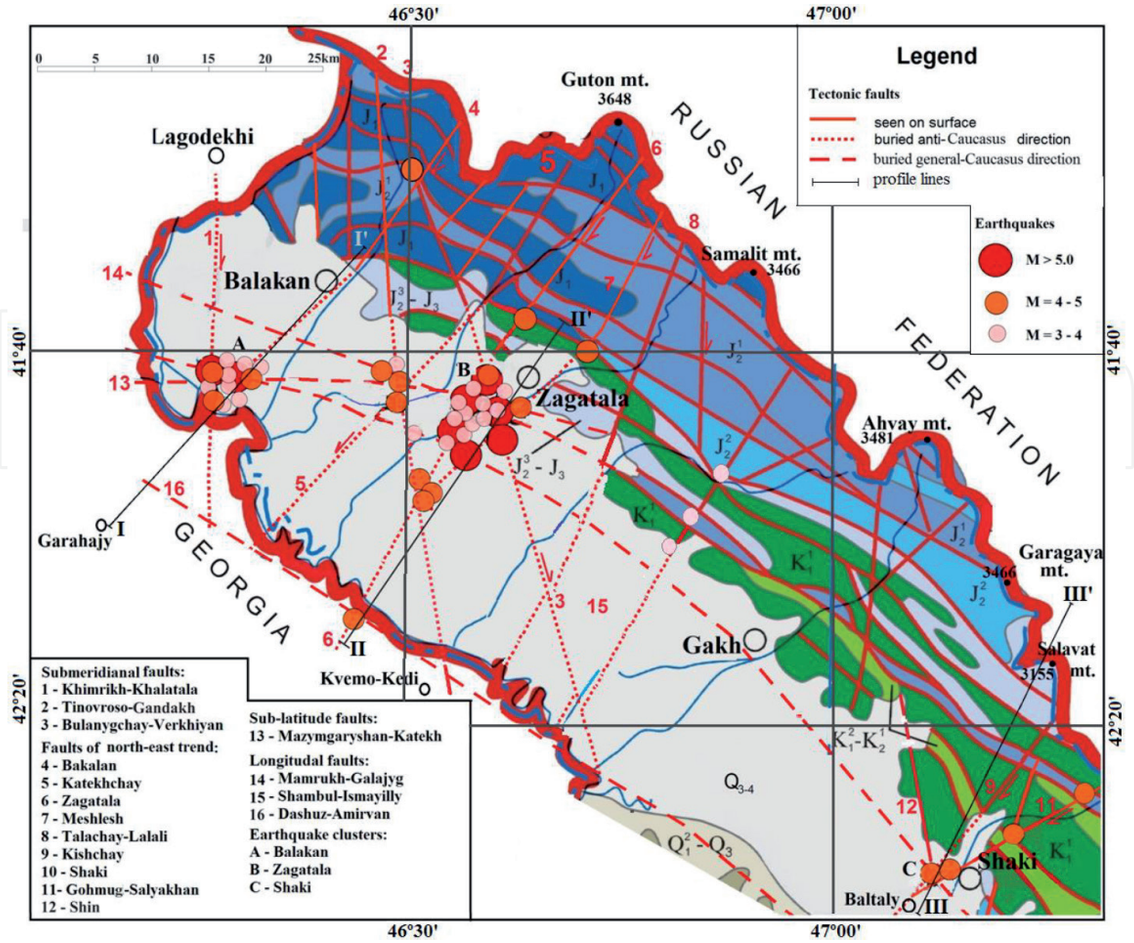

Figure 12.
The ratio of rupture dislocations and earthquake epicenters with M ≥ 3 for the period 2012–2014—By T.N. Kangarli, F.A. Aliyev, and A.M. Aliyev [23, 28].

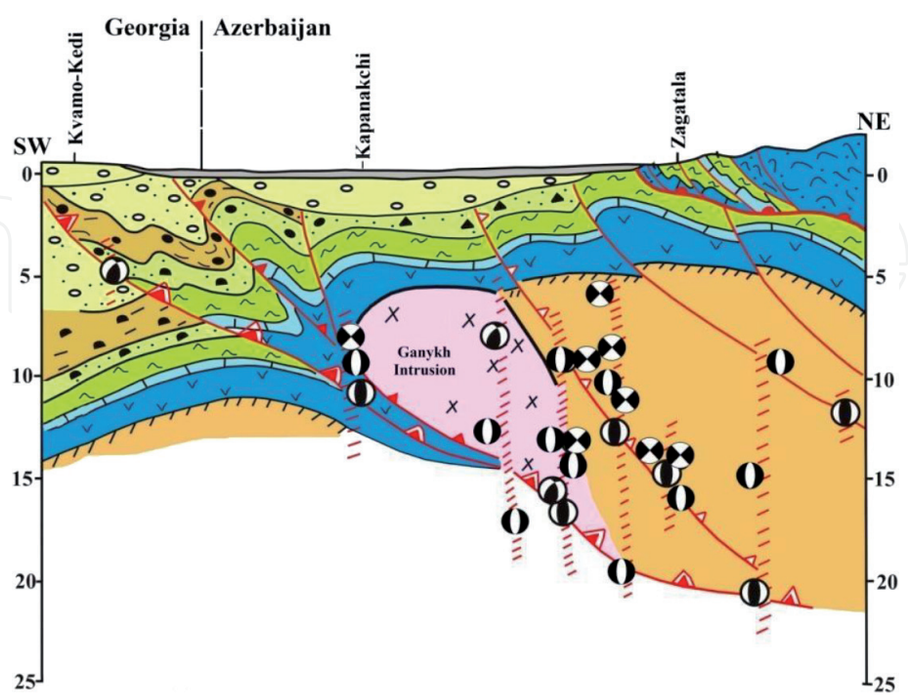

Figure 13.
Geological and geophysical section through Zagatala (III-III′ in Figure 8, 14), Balakan focal zones of earthquakes—By T.N. Kangarli, F.A. Aliyev, and A.M. Aliyev [23, 28].

4. Conclusions

Analysis was performed and correlation between tectonics and modern seismic activity of the studied region leads to the following conclusions:

- under the influence of the introduction of the Arabian indenter into the buffer structures of the southern framing of Eurasia, the territory of the South Caucasus at the present stage of alpine tectogenesis (from the end of the Miocene) is an underthrust area (S-subduction—continental subduction) of the South Caucasian microplate under the southern underbelly of Eurasia (Turanian epigercyn platform) in the northern wing and active ground volcanism with the formation of volcano-plutonic complexes in the southern wing;

- analysis of the manifestation and distribution of weak seismicity allow to determine the position of active faults (fault zones) at the current stage and to calculate their seismic potential;

- recent seismic activization is generally confined with the data of horizontal displacement rates for the period of GPS observations of the modern geodynamics of the region; GPS monitoring data indicate an intensive advancement of the South Caucasian block in the northern points;

- analysis and correlation of historical and recent (2012–2020) seismic events indicate the confinement of earthquake foci mainly to the nodes of intersection of active ruptures of various strikes or to the planes of deep tectonic disruptions and lateral displacements along unstable contacts of material complexes of various competencies;

- focal mechanisms of seismic events reveal various ones, mainly near-vertical, planes of faults and strike-slip faults, but in general, the earthquake foci are confined to the nodes of intersection of faults of the general Caucasian and anti-Caucasian directions.

Author details

Talat Kangarli[1*], Tahir Mammadli[2], Fuad Aliyev[1], Rafig Safarov[1] and Sabina Kazimova[2]

1 Institute of Geology and Geophysics, ANAS, Baku, Azerbaijan

2 Republican Seismology Survey Center, ANAS, Baku, Azerbaijan

*Address all correspondence to: tkangarli@gmail.com

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