

Comparative Analysis of Seismicity and Tectonics of the Territory of Armenia



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Abstract The Armenian Highland is one of the most active parts of the Alpine-Himalayan seismic zone, which is connected to the collision zone of the Arabian-Eurasian plate. In recent history, many strong earthquakes occurred in Armenia, destroying many buildings and leading to loss of many human lives. The last and most disastrous Spitak earthquake ($M_s = 7.0$) occurred in 1988. We analyze the distribution of earthquake epicenters in space and time and compare it with the tectonic environment of this territory, showing that all strong earthquakes are associated with active blocks and their junctions. We also calculate and analyze the focal mechanisms of these earthquakes. The analysis shows the presence of all types of fault on the territory of Armenia: strike-slip, reverse, thrust, normal fault with different components, and dominant strike fault. The detected combinations depend on the motions relative to the neighboring block.

Keywords Earthquake · Fault · Focal mechanism · Kinematic · Strike-slip · Normal · Reverse

1 Introduction

Armenian Highland is situated in one of the most active segments of the Alpine-Himalayan seismic belt, the collision zone between the Arabian and Eurasian plates. As a result of convergence of the Arabian and Eurasian plates, the Anatolian block is being ejected westward, and the Iranian block is forced eastward [1–7]. There are many potentially tectonically active faults accommodating plate convergence within the collision zone, collected in the Geological Datasets Layer [8, 9]. GPS surveying

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suggests that the steady northward convergence of the Arabian plate relative to the Eurasian plate occurs at a rate of 15–20 mm/year [10–12].

This collision is responsible for the complex deformation and is associated with an intense earthquake activity affecting this region, including active mountain building in the Caucasus in general and in the territory of Armenia in particular. Armenia experiences North–South shortening and East–West extension expressed by strong earthquakes and volcanic activity [1, 13, 14].

During the history of Armenia, numerous strong earthquakes occurred which destroyed many buildings and took many human lives. The last and most catastrophic one was the Spitak 1988 earthquake ($M_s = 7.0$) that caused the death toll of more than 25,000 and left about 500,000 homeless. The most active earthquake sources are located in North Armenia (Ani, Spitak, Noyemberyan), in Ararat Valley in the central part of Armenia (Ararat City, Paragar, Garni, Dvin) and in the South of Armenia (Vayots Dzor, Tatev) [2, 9, 15–19].

Thus, in view of its structural position, Armenia is characterized by significant tectonic and seismic activity, and the study of the latter has been [3, 8–10, 16, 19–24], and remains of great interest and importance for both fundamental and applied scientific research. This study aims to carry out a comparative analysis of seismicity and tectonics of the territory of Armenia. The distribution of earthquakes epicenters in space and time was studied, and the focal mechanisms of the earthquakes were calculated and analyzed. Based on these data, the compression (P) and expansion (T) maps of the principal stresses were constructed.

2 Seismotectonics and Faults Model

As already mentioned, the territory of the Republic of Armenia (RA) occupies a part of the Alpine-Himalayan range. It coincides with the Lesser Caucasus and forms the northern and north-eastern part of the Armenian Highlands. Having a modest area, RA has a variety of geographical, geological, and especially tectonic structures associated with its tectonic position (Fig. 1).

The Greater Caucasus and the Armenian Highlands, occupying the central part of the land collision, are distinguished by the density of active faults [8, 19, 25–27]. Fault tectonics is characterized by kinematic diversity: compressive (e.g., the 1988 Spitak earthquake fault), extensional (e.g., the Gavaraget fault) and lateral (the stress regime in the territory of Armenia is mainly lateral, with its transtensional and transpressional manifestations [8, 19, 27]) with the simultaneous presence of structures.

Armenia, eastern Turkey, and northwestern Iran lie in the central part of the collision zone, where numerous active strike-slip and reverse faults form north-curving structural arcs. Despite the length of each of these faults does not exceed 350–500 km and displacement rates vary from 4 to 0.5 mm/year, $M = 7.2–7.5$ earthquakes are associated with them [28, 29]. It should be noted that the internal deformation of the platforms mainly occurs along the fault systems, at about ≤ 2 mm/

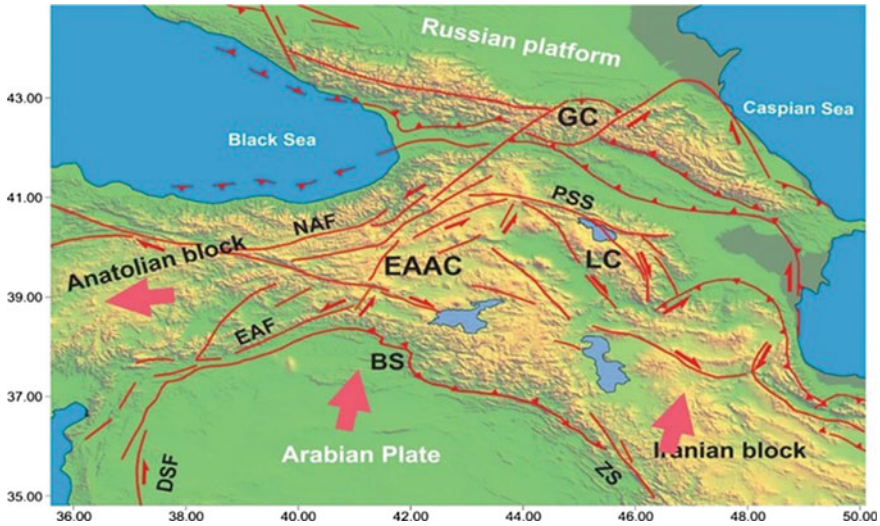


Fig. 1 Tectonic units and fault zones located around Armenia. North Anatolian Fault (NAF), East Anatolian Fault (EAF), Dead Sea Fault (DSF), Bitlis Gap (BS), Zagros Gap (ZS), Pambak-Sevan-Syunik Fault (PSS), Mets Kovacs (GC), Eastern Anatolian Complex (EAAC), Lesser Caucasus (LC) [8, 19, 25–27]

year rate [10, 17]. Most of the faults in the borders of Armenia, southern Georgia, eastern Turkey and northwestern Iran have strike-slip mechanism of displacement combined with reverse-fault or normal-fault component. Faults bounding the troughs of the Greater Caucasus, or those that developed within the ridge itself were produced mostly by thrust or reverse faulting with a small strike-slip component observed for the oblique structures.

The main (and most dangerous) faults in Armenia are Yerevan (YeF), Pambak-Sevan-Syunik (PSSF), Garni (GF), Javakhq (JaF), Gavaraget (GaF), Ghiratakh (GirF) and Debakli (DebF), which formed the basis for the assessment of the new seismic hazard in the territory of Armenia (Fig. 2). Of these, only the Pambak-Sevan-Syunik fault and Garni fault have reliably established fault slip rate estimates.

The Pambak-Sevan-Syunik fault is considered the most active fault in Armenia, and its seismic risk is the highest in the entire Caucasus [27, 30]. It consists of 9 segments, the length of each segment varying from about 50–135 km [11, 17, 27, 29]. Paleoseismological and archaeoseismological studies show that the maximum expected magnitude of the Pambak-Sevan-Syunik fault is estimated to be Mw 7.5 [30]. The fault corresponds to the eastern boundary of the North-Armenian Structural Arc [21, 27] and exhibits steady dextral displacement with some vertical displacement. The distribution of the fault segments generally follows the northwest–southeast orientation [31]. Evidence of right-striking, often vertical, prevailing reverse-fault, displacements, are recorded along the entire PSSF [24, 29, 30].

The Garni fault extends in the North–North–West direction from the village of Aznabyurd to the city of Spitak, where it joins the Pambak-Sevan-Syunik fault. The

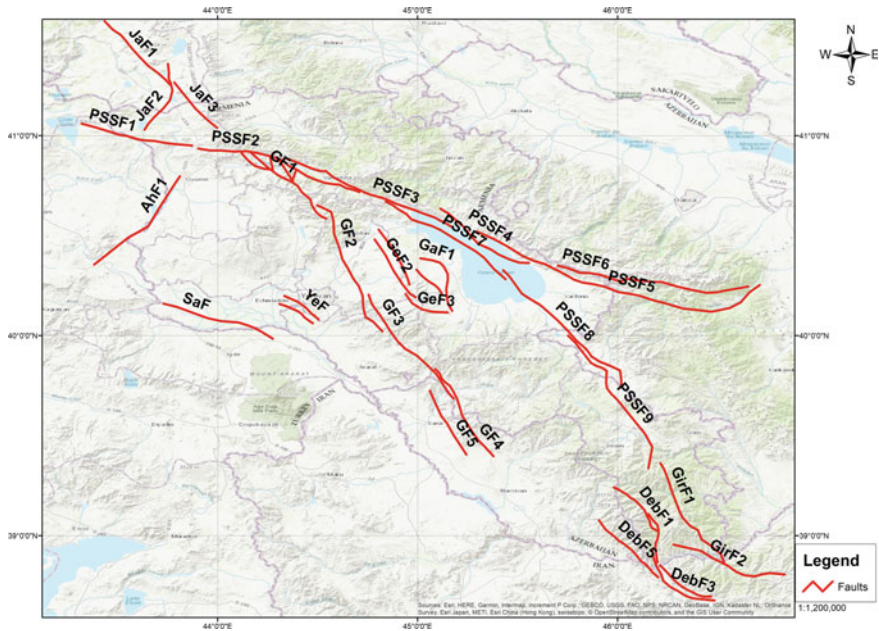


Fig. 2 Fault zones in Armenia. Yerevan (YeF), Pambak-Sevan-Syunik (PSSF), Garni (GF), Javakhq (JaF), Gavaraget (GaF), Ghiratakh (GirF) and Debakli (DebF) [9, 17, 21, 27, 30]

Spitak 1988 earthquake occurred on the northern flank of the Garni fault and formed a 37 km long surface seismogenic fault. The fault consists of five segments. The Garni fault has repeatedly caused high seismic activity. The consecutive series of earthquakes that occurred along the Garni fault zone from southeast to northwest included 906 ($M = 6.8$), 1679 ($M = 7.1$), 1827 ($M = 6.8$) and 1988 ($M_s = 7.0$) seismic events [27]. Along the length of the Garni fault, right-lateral strike-slips with amplitudes up to 200 m are recorded everywhere. In segments extending close to the parallel of the fault, right-lateral displacements are combined with reverse strike-slip, and in segments extending close to the meridian, with reverse strike-slip [24].

The Javakhq fault crosses the western part of the Javakhq and Samsar volcanic ranges. It consists of three segments, the longest of which is about 77 ± 20 km [21, 32]. The extension of the Javakhq fault is north–northwest. Separate segments of the fault are characterized by the kinematics of reverse and strike-slip motion. The following strong earthquakes are associated with the active fault of Javakhq: 1088 ($M = 6.4$), 1899 ($M = 6.4$), 1912 ($M = 6.4$) and 1925 ($M = 5.6$) [21, 33]. The southern segment of the Javakhq fault extends in the north–northwest direction and has two distinct scarps, 15–20 m high and 3 km long. The latter are connected to each other by a 1 km long upward fault, forming a triangular depression [30]. According to the model outlined in [7], the maximum expected magnitude due to the Javakhq fault is estimated at 7.3 [21].

The Gavaraget fault extends along the western side of Lake Sevan in the northwest to southeast direction, and consists of three large branches, which are combined with strike-slip displacements by normal kinematics [9]. The Gavaraget fault extends in the north–south direction from the city of Gavar to the village of Gegharkunik and is located 52 km east of Yerevan. The fault has a vertical displacement of 40–50 m, and the horizontal displacement is not revealed. Two historical earthquakes are associated with this fault: 1226 ($M = 6.2$) and 1322 ($M = 6.6$) [17]. The maximum amplitudes of the vertical displacements of the fault are found on the branch of the eastern Karmir village and are 200 m in the area of Sarukhan and Lanjaghbyur villages.

The zone of deep Yerevan Fault was identified and described already in 1955 [16, 22, 25, 34]. Later on, more detailed descriptions were given in [5, 9, 23, 26, 34–37]. The deep Yerevan fault is drawn along the strip stretching from the Tekor (Diegor) River mouth—Karmrashen Station—Aghavnatoun Village—Parakar Village—Tazagyugh (Ayntap) Village—Abovyan Village—Dvin Village—Dargalou Village—Arpa Village—Dagri Village (Nakhichevan)—Joulfa Town [34]. The fault is characterized by reverse motion kinematics. It is about 33 km long and extends in the north–west direction, with a dip angle of 60–70° N [2, 7, 18, 22]. However, authors [26], agreeing in general with this mapping of central and western part of the Yerevan Fault, have drawn its southeastern extension along the southern foots of the Ourts and Hayots-Dzor Ranges and considered this structure as the northern boundary of the Miocene molasse and salt-bearing suites in the Middle-Arax Depression. Many mineral springs existing in the region of Dvin, Kaghtsrashen, Nor-Oughi villages, Vedi and Ararat towns, as well as vast areas of travertine deposits were considered the main criteria supporting this assumption. Geophysical survey data revealed a swell-like uplift along the southern flanking of the Aragats-Tsaghkounyats block of the Paleozoic basement [36]. The uplift is 4–8 km wide and stretches from Maralik settlement in the northwest through Talin Town up to the Ayntap (Tazagyugh) village in the southeast (the Ayntap-Maralik swell). The Ayntap-Maralik swell itself consists of separated buried uplifts named Parakar-Norabats, Aghavnatoun, Talin and Maralik, which were identified mainly by geophysical evidence. In some works, only the central part of the Yerevan fault is singled, being referred to as the Parakar-Yenghidja Uplift [37].

The Giratagh fault extends in the northwest direction, its length is approximately 80 km. The fault is inverted, strike-slip, right-lateral normal and reverse, combined with strike-slip displacements. The dip angle is 70–80°, and the depth of the fault is approximately 45 km [9, 10, 17]. The Syunik (1407, $M = 6.5$, $I = 8–9$) earthquake is associated with this fault.

The Debakline fault is a major northwest-striking fault with traces of modern activity. It consists of five segments. The length of the fault is 80 km. The fault is of a reverse, left-lateral displacement nature combined with strike-slip displacements. The depth of the fault is approximately 15 km [9, 10, 17]. Zangezuri I (1931, $M = 6.3$, $I = 8–9$ points) and Zangezuri II (1968, $M = 4.9$, $I = 6–7$ points) earthquakes are associated with this fault.

3 Focal Mechanism

In the Armenian Highlands, and especially in the Caucasus, a number of studies aimed at determining the parameters of the focus of earthquakes and studying the mechanism of their occurrence, as well as evaluating dynamic and kinematic parameters have been conducted since the 1950s [12, 18, 23, 38–41]. We have carried out calculations of focal mechanisms of $M \geq 3.5$ earthquakes in RA and adjacent areas during the 2002–06.2022 period using the P wave first entry method [16, 42–44]. The calculation is based on the data provided by the International Seismological Center (ISC), the Euro-Mediterranean Seismological Center (EMSC), and the Regional Service of Seismic Protection (RSSP) of the Ministry of Emergency Situations of the Republic of Armenia. The calculation method is based on the approach that the polarization of the P wave from the hypocenter of the earthquake has different directions and, therefore, will be different for seismic stations with different installation dip azimuths. Indeed, the first entry of the wave arrival indicates the compression of the medium (the mass forming the medium moves towards the station) or expansion (the mass forming the medium moves away from the station). Usually, the calculation of focal mechanisms is carried out either only for the upper half-planes or only for the lower half-planes, so that they are calculated for the same half-plane. In our case, the calculation of focal mechanisms was carried out for the lower half-plane [45]. As a result, the main parameters of the two possible nodal planes characterizing the rupture dynamics in the epicenter for the aforementioned earthquakes were determined: Strike, Dip, Slip or Rake, as well as the values of the plunge angle and azimuth angles of the main stress axes.

In RA and adjacent areas, focal mechanisms of 371 earthquakes have been calculated using the computer programs AZMTAK and PMAN [46]. Diagrams of these mechanisms are shown in Fig. 3. In the studied area, various types of motions are observed including strike-slip, reverse, thrust, normal fault and combination thereof.

The observed epicenters in the RA territory are mostly located on the mapped faults or very close to them (Fig. 3). Accumulations of earthquakes are observed in the northern part of RA, at the intersection of the active fault zones of Javakhq, Pambak-Sevan-Syunik (PSSF1, 2) and Garni (GF1) (Fig. 2). Earthquakes with the epicenters adjacent to these faults are characterized by varied motion kinematics, mainly strike-slip, reverse/thrust and normal types of motion. In 10 of the total 37 earthquakes, reverse and normal kinematics are combined with slip motions. In the areas adjacent to the Javakhq fault, and to the first and second segment of the Pambak-Sevan-Syunik fault, earthquakes are mainly characterized by the reverse type of motion which corresponds to the kinematics of faults, while in the vicinity of the Javakhq volcanic range strike-slip and normal types are more common.

Another accumulation of earthquakes is observed in the intersection of the 3rd, 4th and 5th segments of the Pambak-Sevan-Syunik fault counting to a total of 5 earthquakes. The strongest of these earthquakes occurred on February 5, 2021 with a magnitude of 4.8. The earthquakes are mostly characterized by the strike-slip type of motion, only one (November 6, 2011) showing the normal type. In the areas adjacent

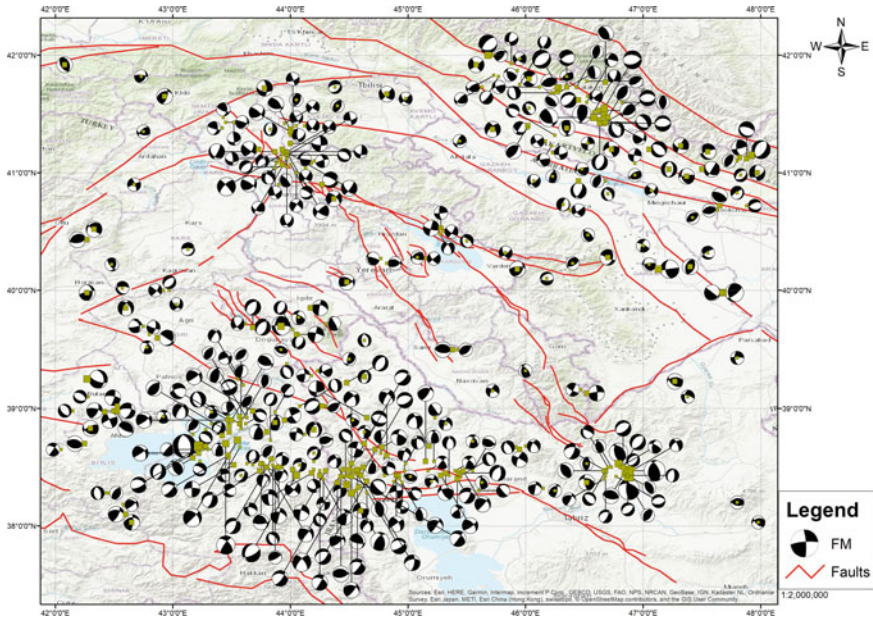


Fig. 3 A schematic map of epicenters and focal mechanisms of $M \geq 3.5$ earthquakes occurred between 2002 and 06.2022

to 5th and 6th segments of this fault, earthquakes are characterized by strike-slip (1), thrust (3) and normal (2) types. It should be noted that these motions also correspond to the kinematics of these segments.

In the Gavraget fault zone, earthquakes are mainly characterized by strike-slip and normal types of motion. The earthquakes occurred in 2nd, 3rd, 4th, and 5th segments of the Garni fault are mainly characterized by the reverse (thrust) motion type.

In the Yerevan fault, the single earthquake of magnitude $M \geq 3.5$ occurred between 2002 and 06.2022 (February 13, 2021, $M = 4.7$). Its kinematics is reverse which corresponds to the kinematics of the fault. Three earthquakes were recorded in Syunik Marz, in the southern part of the RA territory, two of which are adjacent to the Giratagh fault, and one to the Debakline fault. The earthquakes adjacent to the Giratagh fault are characterized by the strike-slip motion type, and the Debakline is characterized by the reverse type.

Comparing the above results with the kinematics of faults presented in Sect. 2, we conclude that the types of faults motion in the earthquakes foci recorded in the territory of RA correspond to the kinematics of faults. The analysis shows the presence of all types of faults in Armenia: strike-slip, reverse, thrust, normal fault with different components and dominant strike fault.

In order to study the stress field, the compression (P) and expansion (T) maps of the principal stresses were constructed (Fig. 4). The analysis shows that the near-horizontal direction of compressive stress prevails in the foci of earthquakes in the study area (see Fig. 3). For 202 out of 371 earthquakes, the direction of compressive stress with the horizontal forms an angle $\alpha < 30^\circ$, and for 99 it is $30^\circ \leq \alpha \leq 60^\circ$. The stress of 70 earthquakes has a near-vertical direction: $\alpha > 60^\circ$. The near-horizontal direction is also dominant in the direction of expansion stress but slightly less pronouncedly. Of all considered earthquakes, for 200 the expansion stress has an angle to the horizontal $\alpha < 30^\circ$, for 87 $30^\circ \leq \alpha \leq 60^\circ$, and for 68 $\alpha > 60^\circ$.

Separating the directions of propagation of the kinematic axes of compression and expansion for earthquakes that occurred in the territory of RA, it turns out that the area is subjected to the effects of compression from northeast to southwest and expansion from northwest to southeast. It can be assumed that near-horizontal direction of compressive stress is observed in near-latitudinal faults, and extensional stress in near-meridional faults.

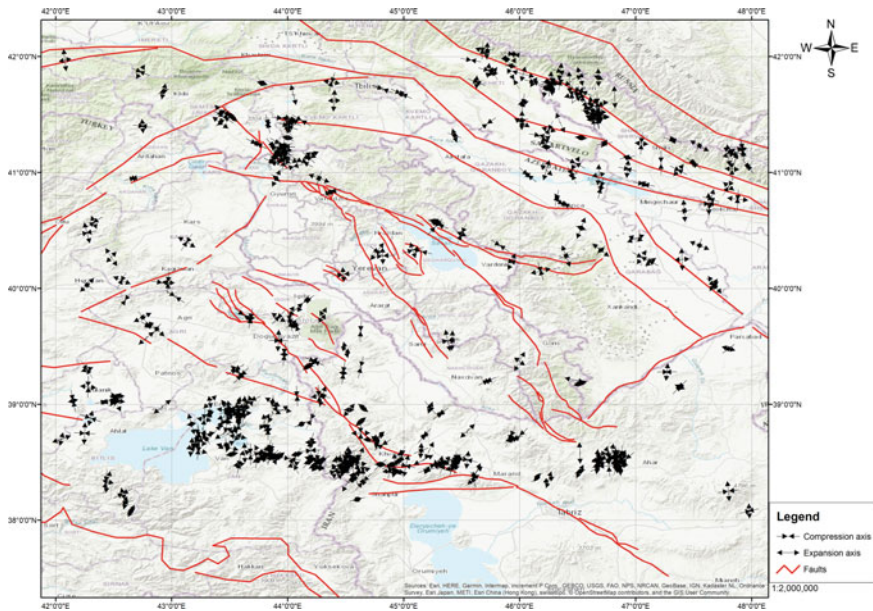


Fig. 4 Schematic map of main axes (P, T) in the center of $M \geq 3.5$ earthquakes that occurred in 2002–06.2022

4 Conclusions

The analysis shows the presence of all types of faults in Armenia: strike-slip, reverse, thrust, normal fault with different components and dominant strike fault. The types of fault motion in the foci of earthquakes recorded in the territory of RA correspond to the kinematics of the faults.

Analysis of the distribution directions of compression and expansion kinematic axes for earthquakes occurred in the territory of RA reveals that the area is subject to the effects of compression from northeast to southwest and expansion from northwest to southeast. It can be assumed that near-horizontal direction of compressive stress is observed in near-latitudinal faults, and extensional stress in near-meridional faults.

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