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THE RECENT 2021 YEREVAN EARTHQUAKE (ML=4.9) IN THE SEISMOTECTONIC CONTEXT OF THE YEREVAN FAULT

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The earthquake of February 13, 2021 earthquake was the strongest earthquake ever reported in the vicinity of Armenia’s capital city of Yerevan in the modern instrumental time period. It was strongly felt throughout Yerevan and the surrounding areas. In this study, we analyze the source parameters and focal mechanism of this earthquake. Our calculated focal mechanism solution shows that this 2021 M4.9 earthquake is characterized by a thrust fault mechanism with a strike-slip component. We also discuss historical seismicity that has occurred over the course of a century in direct proximity to Yerevan, and demonstrate that the Yerevan Fault and Parakar sub-fault are seismically active systems. We also address the problem of possible NW and SE extensions of the Yerevan fault.

Key words: Earthquake, Yerevan fault, focal mechanism, thrust fault

Introduction

An Ml 4.9 earthquake (as reported by the seismic network of the Institute of Geological Sciences of Armenian National Academy of Sciences, IGS) occurred near Yerevan, the capital city of Armenia on 13/02/2021 at 11:29 UTC. This earthquake was widely felt across Yerevan and the surrounding areas (6-7 Intensity by MSK64 scale), and was followed by several M $\leq$ 3.5 aftershocks. No damage has been reported in association with this earthquake, which is the largest seismic event felt in the area since the instrumentally recorded MS 4.8 earthquake of 07/01/1937 (Karapetyan N., 1990).

Dvin, the ancient capital of Armenia, suffered severe damages from large earthquakes in 863 and 893 AD. These earthquakes are assumed to have been generated by the Yerean Fault (YF, Piruzyan, 1969).

The most catastrophic of the earthquakes known to have occurred in the Yerevan region happened on June 4, 1679. This event is known today as the Garni earthquake (Piruzyan, 1969), but in many historical sources it is also called the Yerevan earthquake. Since the beginning of the 20th century through today, only a few relatively strong earthquakes, the largest being magnitude

M=4, have been identified in this area. These are known as the "Yerevan earthquakes" (Karapetyan N., 1990).

As documented by Tovmasyan (2008), the focal mechanisms of the Yerevan earthquakes begin in 1973.

Tectonics and seismicity of the area

The Yerevan Fault (YF) is an active thrust fault that lies to the southwest of Yerevan, Armenia's capital city, which has a population of ~1 million (Fig. 1). The YF runs through the northeastern margin of the Ararat basin, and is inferred to have been tectonically relevant to the formation of Ararat basin, which is interpreted as a large valley complex pullapart structure (Karakhanyan et al., 2004, Dewey et al., 1986, Yilmaz et al., 1998) or volcano-tectonic structure. Southeast of Yerevan, at Dvin and Vedi, mineral springs and associated thick travertine deposits are present. These hot spring-related processes and materials are inferred to be associated with the activity of the YF (JICA, Report, 2012).

The YF and its nature were first discussed in scientific literature beginning in the 1950s (e.g. Aslanyan, 1954, 1958; Gabrielyan, 1959, 1981). The deeper portion of the Yerevan Fault was first identified and described by Aslanyan (1955). Later on, more detailed descriptions were published by Aslanyan (1958), Gabriyelyan (1959, 1981), Milanovsky (1968), Haroutyunian (1975), and other authors (Fig.1).

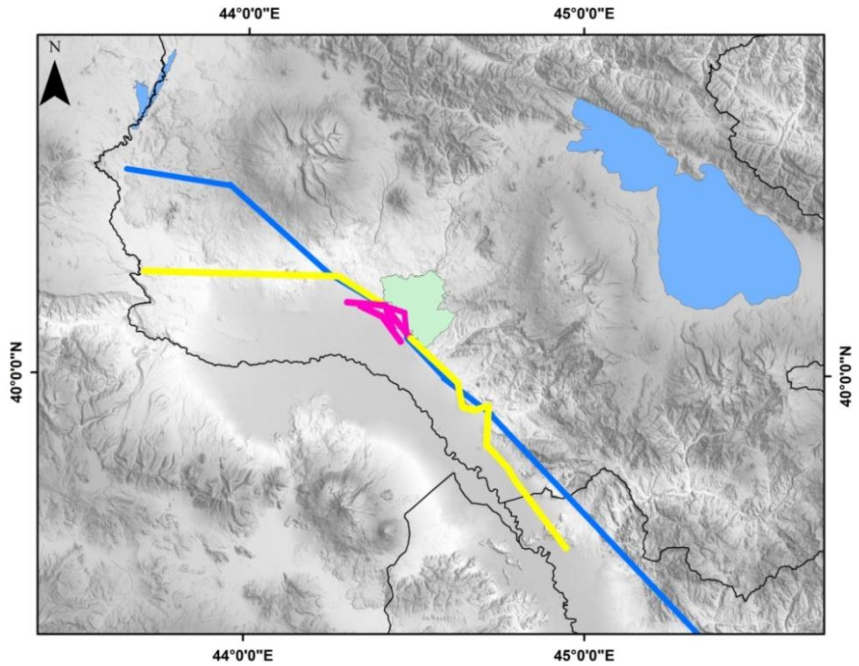


Fig.1. The location of the Yerevan Fault as mapped by Aslanyan (1955 and 1958, blue line), Gabrielyan (1959 and 1981, yellow line) and Milanovsky (1968, pink line). Yerevan, Armenia's capital city is marked by the green area.

Beyond that, the seismic activity of the YF is not well known. It was only much later after these initial mappings, in 2009, that the YF was first designated as an active fault highly important for seismic hazard assessment in Yerevan. However, the YF was not targeted for active fault mapping at this point, because it was thought to be a blind fault.

This assumption was based in part on the fact that the YF area is overlain by a thick cover of young deposits. As a result, the YF is expressed weakly at the surface (or, in some locations, not at all), which has shaped the interpretations of its position and geometry across many studies. If we superimpose the contours of the YF geometry proposed by these different studies, the central segment, the Parakar-Norabats uplift, appears to be the only one not characterized by controversial interpretations (fig.1). There has been considerable disagreement in the interpreted lengths and locations of the north-western and south-eastern segments of this fault system.

Aslanyan (1954, 1958) and Gabriyelyan (1959, 1981) performed gravity surveys around Yerevan and observed a NW-SE extending high gravity anomaly to the south of the city. They suggested active faults on the southwestern and northeastern edges of the high gravity anomaly, and named these faults the Parakar North fault and Parakar South fault (solid red lines at the center of fig.2). These faults represent the central segment of the YF system.

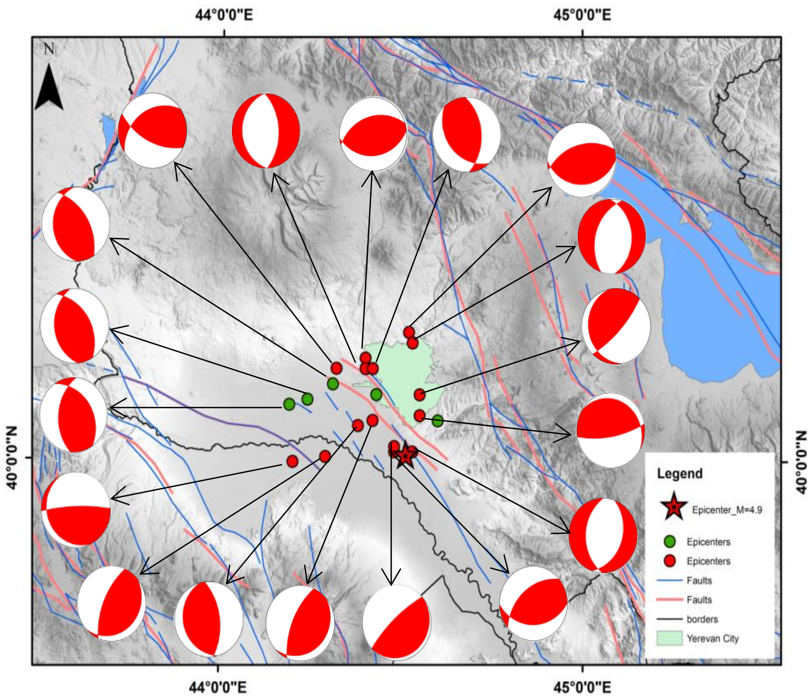


Fig.2. Map of active faults (solid blue lines) around the city of Yerevan (green area), based on 2011 GeoRisk report. The Yerevan Fault is inferred on both the northeastern and southwestern sides, as indicated by solid red lines. The locations of the Yerevan earthquakes (Tab.2) are shown as green dots (Karapetyan N., 1990). The locations of the 15 earthquakes studied by Tovmasyan (2008) are shown as red dots, some of which are summarized in Tab.3.

Tovmasyan (2008) studied the focal mechanisms of 15 small to moderately sized earthquakes ($1.9<ML<4.0$) that occurred within 30 km of Yerevan from 1973 to 2002, and found 11 events to have a reverse/thrust focal mechanism (fig.2). Earthquakes with E-W and NW-SE striking focal mechanisms had dips ranging from 55-72° to the north-northeast.

The uppermost boundary of the fault system is currently understood to be at 5 km depth, reflecting that the YF is blind near the city of Yerevan. The length of the YF is suggested to be 33 km at a maximum, based on the structure of the Ararat basin (Georisk report, 2011). Applying empirical relation from Wells and Coppersmith (1994), the maximum moment magnitude of an earthquake which could be generated by the YF is M_w6.8. However, it may be possible to rupture only a small portion of the YF, in which case an earthquake of lesser magnitude may occur (JICA report, 2013).

The largest earthquake that most recently occurred near Yerevan prior to this 2021 event was the M4.8 earthquake of January 7, 1937, near Parakar (fig.3). The fault lengths of these smaller earthquakes are estimated using the empirical relation of Wells & Coppersmith (1994), and the location of these fault lengths are set as the part of the fault model that represents maximum magnitude earthquake near Parakar.

Seismotectonic settings of the study area

Evidence on the recent tectonics of the Ararat Depression could be found in the studies of A. A. Gabriyelyan, A. T. Aslanyan, E. E. Milanovsky and other workers (Gabrielian A.A., 1958; Aslanyan A.T., 1958; Milanovski E.E., 1962).

The authors cited above have subdivided the Ararat depression into the following tectonic elements.

The Yerevan graben-synclinorium is bounded by the Hrazdan and Jrvezh-Manghyuz discontinuities on the west and on the east, respectively, and by the Paraqar-Yenghinjy horst uplift on the south. It is downthrown along the mentioned faults, and blocks bordering it are uplifted (fig.3) (G.Simonyan, 1963).

An analysis of the recent tectonics of this element is provided in the works of A. A. Gabriyelyan and S. K. Arzoumanyan, whose data indicate that the elevated areas of Elar, Mourad-Sar, P’teniss and Aramys, as well as the Yerablour Hills, represent salt domes.

The concealed **Paraqar-Yenghidgy horst** uplift is located in the central part of the Ararat depression and stretches in near-latitudinal direction along the line of Tazaghyugh-Yenghidja-Arbat-Paraqar-Aghavnatoun being bounded on the northeast and on the southwest by the Yerevan Fault and the Echmiatsin Fault, respectively (fig.3) (G.Simonyan, 1963).

As attested by borehole data in the region of the villages of Tazagyugh, Arbat, and Yenghidja, and at the Tairov Sovskhoz (Farm), the thickness of Quaternary sediments is in the range of 25-40м, and the drilled thickness of those units corresponds to 170 и 280m, respectively. Over the distance of more than 20km between the villages of Tazagyugh and Zvartnots, an Early-

Quaternary lake stratum is exposed on the surface; in the central part of the horst, it is overlain by the fourth terrace of the Arax River. This lake stratum was drilled by boreholes located to the south and to the north of the horst at depths ranging up to 45m. The gravimetry data suggest that in the northwestern direction the horst uplift was plunging and rising near the village of Aghavnatoun (G.Simonyan, 1963).

The Middle-Arax inter-mountain trough is the largest in Armenia. In the Quaternary, Lake Ararat stretched along the Arax River. In the recent relief, these two units are subdivided by a transverse bridge of the Mount Aragats massif located in between and composed of the Late Pliocene lava. The greatest thickness of fluvial-lacustrine deposits ranging to 450m was established by drilling in the central part of the trough within the Ararat depression, where the bottom of those deposits was located at the elevation of 350-400m. On the margins of the trough, the lake deposit thickness is decreased, and fragments of its remains have been preserved in places. In particular, the deposits are exposed in the southern part of the Yerevan city, near the Karmir Blour Fortress that is situated not far from the Paraqar Village, and in the central and northern parts of the city, at the elevations of 850, 950 and 1150-1200m, respectively (A. A. Gabrielian et al., 1993).

In the central part of Armenia, relief of the area is prevailingly of high-mountain type (ranging up to 3,000m and higher) and is represented by several range-uplifts elongating in near-latitudinal direction. Toward the south-west, the relief has moderately high elevations (up to 1,500-2,000m) and is likewise represented by systems of range-uplifts striking in the northeastern direction and becoming lower toward the Ararat depression. In addition, young Pliocene-Quaternary volcanic and fluvial-lacustrine formations are commonly developed in this region (G.P.Simonyan, 1999).

The longitudinal profile that is plotted southwestwards of the former one through the Aragats-Ghegham-Vardenis-Karabakh system of range-uplifts gives an idea about the neo-tectonic structure of the central part of Armenia. The Shirak Depression located on the western termination of the profile borders the low mountains of the Kars Plateau in the west, and the foot part of the giant volcanic massif of Mount Aragats in the east. According to geophysical evidence, lava thickness ranges up to 300-400m (G.P.Simonyan, 1999).

The latest significant volcanic activity on Ararat is most probably related to 1840. The disastrous M= 7.4 Ararat earthquake occurred on July 2, 1840 (Ambraseys and Melville, 1982). Many villages in the area around Ararat volcano and the towns of Dogubayazet, Maku, and Ordoubad were completely destroyed. The earthquake was accompanied by the formation of a 72-km-long seismogenic surface rupture and the failure of a landslide from the Ararat summit (Stepanian, 1964; Ambraseys and Melville, 1982).

After the 1840 earthquake, a fierce polemic started between the researchers who surveyed the earthquake ejects in 1840-1845 (Karakhanyan A., et al., 2002).

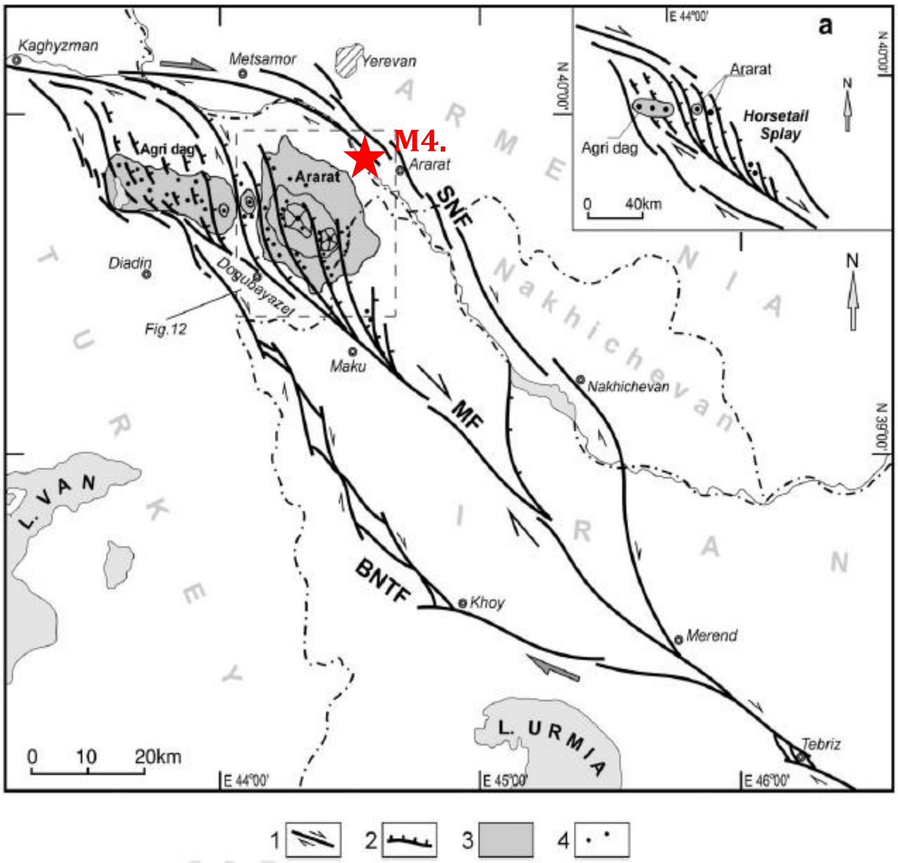


Fig.3. Ararat pull-apart basin. 1, Strike-slip faults; 2, normal faults; 3, Ararat and Agri-Dag volcanoes; 4, parasitic volcanoes. Active faults: SNF, Sardarapat-Nakhichevan fault; MF, Maku fault; BNTF, Balikghel-North-Tabriz fault. (a) Conceptual geodynamic model (Karakhanyan A., et al., 2002).

Davtyan (2006) processed the GPS data from the three sessions of measurements conducted in 1998, 2000 and 2003, and indicated that slip velocities were detected along the Pambak-Sevan Fault, Garni Fault, and Javakhq Fault, but were absent in the region of Aragats Volcano and in the Ararat Valley (fig.4, Davtyan, 2006). Motion velocities were not detected either along the Yerevan Fault, or Sardarapat structure, or any other faults (fig . 4).

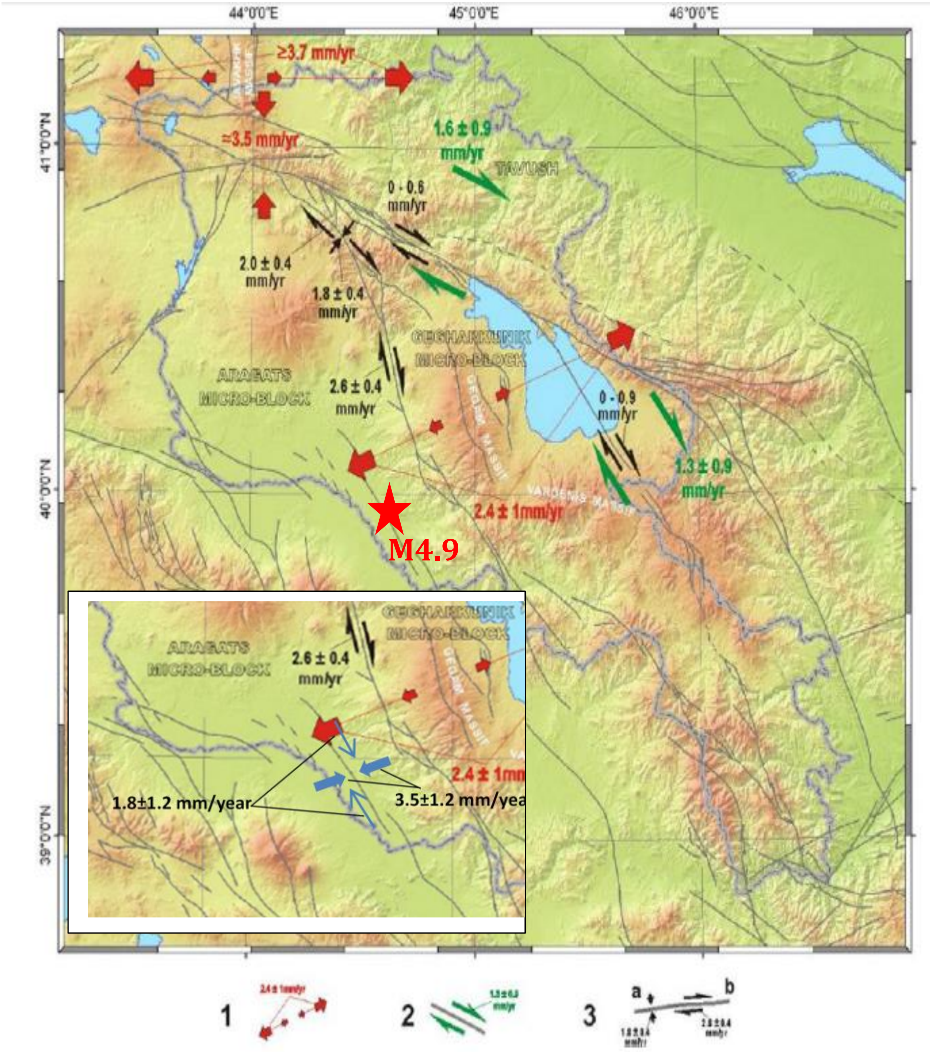


Fig. 4. Slip rates by the GPS data (Davtyan,, 2006).

1- Assessment of amount of deformation by the velocity analysis; 2 - Assessment of amount of deformation by the remote station data; 3 - Assessment of amount of deformation by the relation of Euler vectors

Seismicity of Yerevan Fault Area

Since the 20th century, only a few relatively strong earthquakes ($M_S \geq 4.0$) are known to have occurred within the proximity of Yerevan. These seismic events collectively came to be called the “Yerevan earthquakes” (tabl.1, fig.2; Karapetyan, 1990).

Table 1

Summary of Yerevan earthquakes

Date	Magnitude or intensity	Notes
Jan. 25, 1910	M_S 4.5, 6-7 MSK intensity	Felt in Yerevan
Jan. 7, 1937	M_S 4.8	Damage in both Yerevan and Parakar village
Jun. 16, 1973	M_S4.0, maximum MSK intensity 5-6	Recorded by several Caucasian seismic stations, Felt in Yerevan
Feb. 25, 1978	~5-6 MSK intensity	Felt in Yerevan
Aug. 2, 1984	~5-6 MSK intensity	Felt in Yerevan

Table 2

Summary of M<4 earthquakes studied by Tovmasyan (2008)

Date	Magnitude
Mar. 1, 1997	M_L3.9
July 29, 2005	M_L3
Apr. 11, 2007	M_L3
Nov. 4, 2008	M_L3.2

This historical seismicity, with nine moderately sized earthquakes occurring over the course of a century in direct proximity to Yerevan, demonstrates that the Yerevan Fault and Parakar sub-fault are a seismically active system (fig. 2).

Seismic data

The 2021 earthquake occurred in the close vicinity of several IGS seismic network stations (fig. 5). Digital waveform data for this event was extracted from the IGS and National Survey for Seismic Protection (NSSP) Armenian seismic network databases, as well as from the following stations of Turkey’s seismic network : TASB, 7602, 7603, 7604, DIGO, and IGDI.

These stations’ records provide high quality, unsaturated, broadband seismic data. These regional broadband records present an excellent opportunity to precisely analyze the source parameters and focal mechanism of this earthquake. This high data quality is demonstrated in an example seismometer recording of this earthquake, shown in fig. 4.

The 2021 earthquake in the context of the Yerevan Fault area

The 2021/02/13 M4.9 earthquake is the strongest event to have occurred in the Yerevan area since the M4.8 earthquake of 1937. All of the earthquakes discussed in this paper fall within the same region, and could have originated on the same fault (characterized by a reverse focal mechanism with a strike-slip component, as shown in Table 3 and fig. 5), although the uncertainties on epicentral locations do not allow this hypothesis to be confirmed.

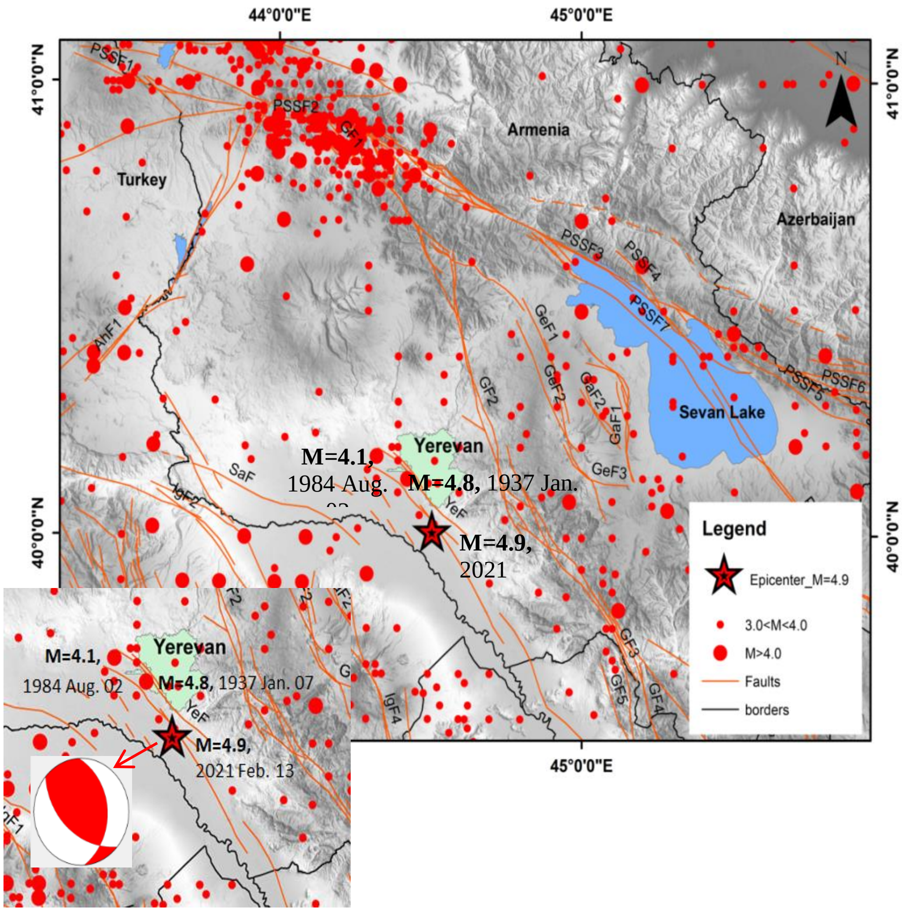
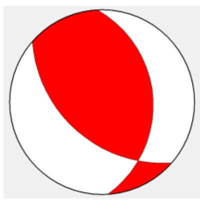


Fig.5: Regional seismicity and major active faults of the epicentral area of the 2021/02/13 earthquake. Inset: the focal mechanism of the 2021/02/13 earthquake.

Table 3

Epicenter coordinates and focal mechanism parameters of the 2021/02/13 earthquake.

EQ ____4.9 Magnitude
2021 February 13, 11:29:23.72 (UTC)
Latitude - 40.01556
Longitude – 44.51167
Depth – 13km
M=4.9



Strike1	Dip1	Rake1	Strike2	Dip2	Rake2
211.4	71.4	-27.6	310.9	64	-159.2

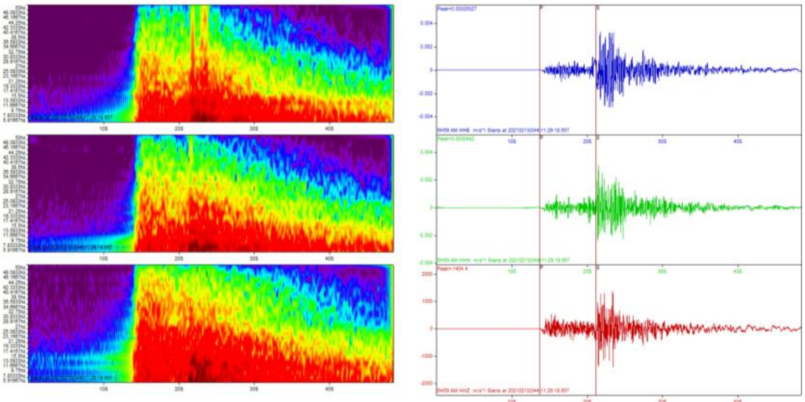


Fig.6: Seismic spectrum and waveforms of the 2021/02/13 earthquake recorded by the Arzakan station (ARZ in Fig. 5) of the Institute of Geological Sciences (IGS) Seismic Network.

We construct the focal mechanism solution for the 2021 earthquake. In addition to the waveform data extracted from the IGS, NSSP, and Turkish seismic networks, additional information from the surrounding regional stations was extracted as digital waveforms, or as first phase picks from the EMSC database (https://www.emsc.eu/Earthquake/) and the National Center of the Broadband Seismic Network of Iran (http://www.iiees.ac.ir/en/iranian-national-broadband-seismic-network/). P-wave phases from 37 seismic stations, which provide optimal azimuth coverage around the epicenter, were used in calculating the focal mechanism solution. The epicenter, main event focal mechanism, and aftershocks of the 2021/02/13 earthquake, and locations of seismic stations are shown in fig. 7.

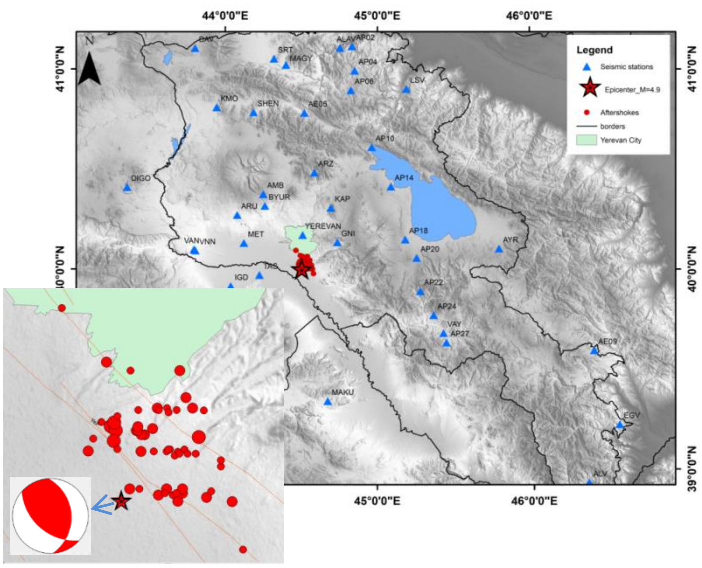


Fig.7. The epicenter and aftershocks locations, and main event focal mechanism, of the 2021/02/13 earthquake, and locations of seismic stations.

For determining fault plane geometry, the first motion polarity technique was applied to the earthquakes (Vvedenskaya A., et al., 1960). The FA2004 software package (Lander, 2004) was used to determine the focal mechanism. This software depends on the azimuth, angle of incidence, and polarities of P-phase. Any P-wave ray path leaving the source can be identified by two parameters: the azimuth from the source, φ, and the angle of incidence, i_0, which is a function of the distance, Δ, between the source and the recording station.

The earthquake's focal mechanism was determined geometrically, from the orientations of the P and T kinematic axes bisecting the angles between the fault plane and the auxiliary plane. They can also be determined from the orientation of one of the two nodal planes and the associated slip vector. From this, the focal mechanism solution with 2 nodal planes (strike, dip and rake parameters) was constructed.

Our calculated focal mechanism solution (tab.3) shows that this 2021 M4.9 earthquake is characterized by a reverse fault mechanism with a strike-slip component.

Discussion

The February 13, 2021 earthquake was the strongest earthquake ever reported in Yerevan city in the modern instrumental time period (1962 to present), and was strongly felt throughout Yerevan and the surrounding areas.

Accurately determining epicenter locations has been a long-term issue noted in various prior studies. Since the beginning of the instrumental period, the earthquakes that have occurred in the Yerevan area have been attributed to the blind Yerevan fault system.

The epicentral region of the M4.9 2021 earthquake (fig.3) may illuminate that the YF system is the same seismogenic source of the Ms4.8 earthquake of 1937.

Furthermore, the focal mechanism of this 2021 event demonstrates the same sort of active faulting mechanism as can be inferred from descriptions of the 1937 event.

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Սարգսյան Լ., Սահակյան Է., Լևոնյան Ա., Դեմիրճյան Հ., Թողրամաջյան Ն., Գևորգյան Մ., Բայրակթութան Ս.

Ամփոփում

Ժամանակակից գործիքային ժամանակաշրջանում՝ 2021թ փետրվարի 13-ի երկրաշարժը, ըստ հաղորդագրությունների, ամենաուժեղն էր Հայաստանի մայրաքաղաք Երևանում երբևիցե տեղի ունեցածներից: Այն ուժեղ զգացվում էր ամբողջ Երևանում և նրա շրջակայքում: Վերածվել է երկրաշարժի օջախի պարամետրերը և ֆոկալ մեխանիզմը: Մեր կողմից հաշվարկված ֆոկալ մեխանիզմը ցույց է տալիս, որ 2021թ M4.9 մագնիտուդով այդ երկրաշարժը բնութագրվում է կողաշարժի բաղադրիչ ունեցող վրաշարժի խզվածքի մեխանիզմով: Այդ, քննարկվել է Երևանի անմիջական մոտակայքում մեկ դարի ընթացքում տեղի ունեցած պատմական սեյսմիկությունը և ցույց է տրվել, որ Երևանյան խզվածքը և Փարաքարի ենթախզվածքը սեյսմիկորեն ակտիվ համակարգեր են: Անդրադարձ է կատարվել Երևանյան խզվածքի հնարավոր Հս.-Արմ. և Հվ.-Արլ. շարունակության խնդրին:

НЕДАВНЕЕ ЕРЕВАНСКОЕ ЗЕМЛЕТРЯСЕНИЕ 2021 ГОДА (ML=4.9) В СЕЙСМОТЕКТОНИЧЕСКОМ КОНТЕКСТЕ ЕРЕВАНСКОГО РАЗЛОМА

Саргсян Л., Саакян Э., Левонян А., Демирчян О., Тограмаджян Н., Геворгян М., Байрактутан С.

Резюме

По сообщениям за современный инструментальный период времени землетрясение 13 февраля 2021 года было самым сильным событием в окрестности столицы Армении – Еревана. Оно сильно ощущалось по всему Еревану и на окружающих территориях. В данном исследовании мы анализируем параметры очага и фокальный механизм этого землетрясения. Наш расчет фокального механизма показывает, что это зем-

летрясение 2021г. с магнитудой M4.9 характеризуется надвиговым механизмом с компонентой сдвига. Мы также обсуждаем историческую сейсмичность за столетие в непосредственной близости к Еревану и показываем, что Ереванский разлом и Паракарский суб-разлом являются сейсмически активными системами. Мы также рассматриваем проблему продолжения Ереванского разлома на СЗ и на ЮВ.