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RECENT SEISMIC ACTIVITY IN THE AREA OF THE GEGHAM VOLCANIC RIDGE (ARMENIA)

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The Gegham Volcanic Ridge (GVR) is located in the central part of the Neogene-Quaternary volcanic belt formed within the territory of the Armenian Highland. The duration of volcanism within the Gegham Ridge spans from the Late Miocene to the Holocene. The GVR is one of the densest clusters of individual monogenetic volcanoes in the world. The system of the Gegham Ridge faults consists of two components – faults of the axial part of the Gegham Ridge and the Gavaraget Fault. The Gavaraget Fault is the most active one in the Gegham fault system, and was associated with a few historical and recent earthquakes.

For investigation of current seismic activity of the study area and to follow possible seismic activity near the volcanic arcs, three more temporary seismic stations were installed in addition to the besides existing seismic network. The received data show that weak earthquakes occur in this area. The recalculation was carried out using the regional velocity model and registrations from all seismic stations covering this area in order to increase the accuracy of epicenter and hypocenter locations. The data show that this area is seismically active in case of small earthquakes (M<=3.4). In this study, source mechanisms of the set of earthquakes that occurred within 2022–2023 have been investigated with high reliability, using digital waveform data recorded by seismic stations of the Armenian seismic networks (including 3 temporary seismic stations mentioned above).

All data were relocated using local and regional seismic network data with the aim to reduce main parameter uncertainties in the catalogue, which is used in the current study.

Keywords: Gegham Volcanic Ridge (GVR), seismic activity, volcano-tectonic events, focal mechanisms of earthquakes, moment tensors

Introduction

Armenia, SE Turkey and NW Iran are located in the central part of the Arabian lithosphericcollisional zone, a region which experiences N–S shortening and E–W extension accompanied by intense faulting, strong earthquakes and active volcanism (Dewey et al., 1986; Taymaz, 1991).

GVR in central Armenia represents one of the densest clusters of individual monogenetic volcanoes globally. Within an oval-shaped area approximately 65 km long and 35km wide, spanning around 2100km² (fig.1), it contains 127 Quaternary volcanic vents. Volcanic activity in the GVR dates back to the Late Miocene (Baghdasaryan and Ghukasyan, 1985), persisting through the Holocene. The most recent evidence of volcanic activity dates to around 4500–4400 BP (Karakhanyan et al., 2003; Karakhanyan et al., 2002) or approximately 3450 BP (Avagyan et al., 2020). It's worth noting that during the late Miocene to Early Pliocene, a substantial caldera complex existed within the present boundaries of the GVR. This is evidenced by the presence of the Vokhchaberd volcanoclastic suite, reaching thicknesses of up to 500m in certain locations. Subsequently, during the Quaternary period, the GVR underwent a transition into a dense aggregation of spatially dispersed monogenetic vents, accompanied by extensive sequences of lava flows.

The study area, Gegham Volcanic Ridge, is situated between two major active faults in Armenia: the Pambak-Sevan-Syunik Fault (PSSF) and the Garni Fault (GF). Faulting within the ridge consists of two components – faults of the axial part of the Ridge and the Gavaraget Fault in the eastern part (fig.1).

The Gavaraget fault system, oriented NNW-SSE, comprises three major normal fault branches, each spanning 25–30km (fig.1), alongside horst and graben structures (Karakhanyan et al., 2016). Stretching from Gavar town in the north to Gegharkunik village in the south, the fault splits south of Gavar into two branches – the western Saroukhan-Lanjakhpiur branch and the eastern Karmirgiugh branch. South of Gegharkunik village, these branches converge, forming a meridian-elongated ramp-graben structure.

Fault motion primarily involves normal faulting with a slight strike-slip component, altering its orientation relative to the regional stress field (Karakhanyan et al., 2016; Avagyan, 2017). Maximum vertical displacements of up to 200m have been documented on the eastern branch. GPS monitoring in the area indicates extension rates of 2.75–3.4mm/yr in the central GVR cluster and 3.6mm/yr along the Garni Fault in the adjacent western cluster. This suggests a total recent extension rate for the Gegham pull-apart basin ranging from 6.35 to 7mm/yr, the highest recorded in Armenia. Geological estimates suggest vertical slip rates along the Karmirgiugh branch of the Gavaraget Fault range from 6–9mm/yr (Karakhanyan et al., 2013; Doerflinger et al., 1999; Davtyan, 2007).

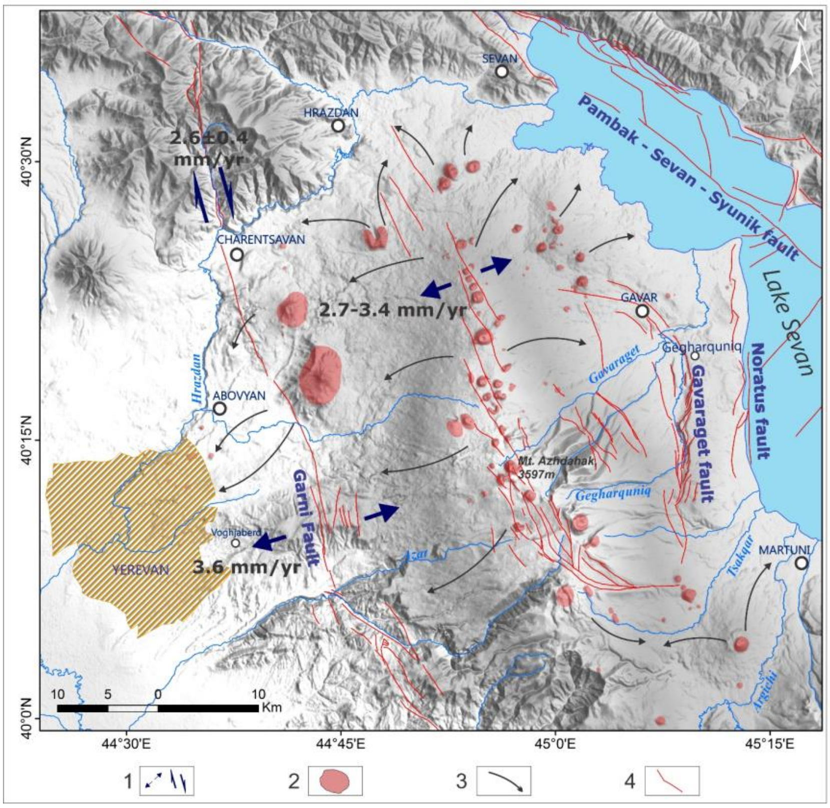


Fig.1. The volcano-tectonic setting of Gegham Volcanic Ridge (after Karakhanyan et al., 2003, Philip et al., 1989, Avagyan et al., 2010). 1. Strike-slip and GPS monitoring based extension rates; 2. Volcanoes; 3. Primary directions of basaltic-andesitic lava flows; 4. Active fault systems.

Two historical earthquakes are known in this area: the M6.2 Noratus earthquake of 1226/1227 AD and the M6.6 Vardenis earthquake of 1321/1322 AD, both likely associated with the Gavaraget fault system (Karakhanyan et al., 2011). Recent seismic events include the Gavar earthquakes of 1905 and 1909, measuring M3.8 and M4.7 respectively, documented through local historical records. The Gegham volcanic highland and its surroundings experience seismic activity primarily characterized by weak earthquakes.

Sinces 2014, in this area was recoreded several swarms of earthquakesoccuringevery year. Recent studies demonstrate that swarms of earthquake recorded in the study area and referred to as family earthquakes, have appeared to be of great interest for the volcano seismological studies. The analyses indicate shallow hypocenters of the earthquakes, and their magnitudes are rather low (Sargsyan et al., 2021).

Considering the volcano-tectonic processes ongoing in the area of the volcanic Gegham ridge as well as the continuous earthquake activity, we aim to study the effects by analyzing the parameters of earthquakes recorded in this area.

Data and Methods

During the last years, highly sensitive seismic stations have been installed and operated in the framework of a few international projects by the Institute of Geological Sciences of the Armenian National Academy of sciences (IGS), providing for good azimuth coverage to realize the studies.

For this study data from permanent network of IGS (Armenian-Taiwanese network), US-Armenian TRANSECT project of (CNET stations) and single stationsof “Seismic Protection Territorial Survey” of the Ministry of Internal Affairs of the Republic of Armenia) was used (fig.3). Aiming to increase the density of the azimuth coverage of the seismic stations and to improve the quality of seismological data, we additionally have installed three more temporary stations in the tudy area under the local project (21T-1E302 project by HESC MESCS) and International project (PEER 9-252). Information about the new temporary stations is provided in the table below (tab.1). The locations of seismic stations enclosing the entire studied area are shown on the map (fig.3).

Table 1

Seismic Station	LAT	LONG	ELEVATION (M)	SENSOR TYPE	DIGITIZER
Lernanist STN1	40.468841N	44.799537E	1964	Nanometrics TCH120-1 Trillium Compact Horizon Seismometer	Nanometrics CTR4-3S Centaur
Zovashen STN2	40.310088N	44.748253E	2012	Nanometrics TCH120-1 Trillium Compact Horizon Seismometer	Nanometrics CTR4-3S Centaur
Zar STN3	40.260288N	44.737357E	1694	Nanometrics TCH120-1 Trillium Compact Horizon Seismometer	Nanometrics CTR4-3S Centaur

The installation of three temporary seismic stations and field works are presented in fig.2.

Fig.2. The installationand service of three temporary seismic stations.

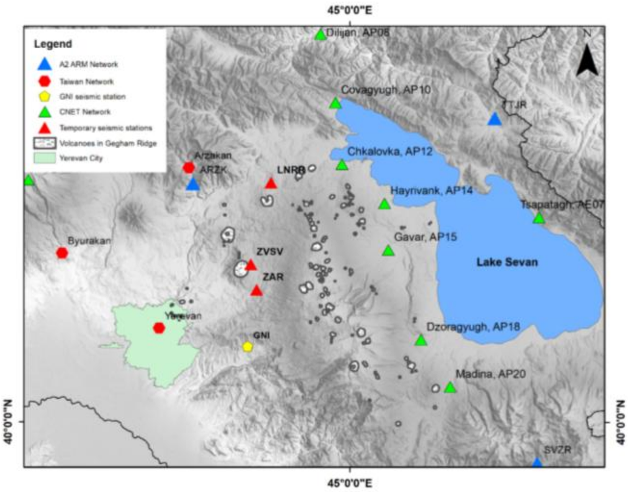


Fig.3. The distribution of seismic stations used in current study

The seismic events recorded during 6 months by the enclosure of stations contouring the volcanic highland of Gegham and the adjacent zone were analyzed; however, taking into account that minor earthquakes continuously recorded in the area had records taken at a few stations only, it was impossible to interpret some seismograms. Hence, not all of the seismic events recorded in the area could be processed and included in the earthquake catalogue. The prosseccing of seismogramss was done using DIMAS16 sofrware for phase picking maily. The solutions processed for the earthquakes were re-calculated using Hypo 71 software in an attempt to improve the accuracy of the main parameters and to minimize the RMSs.

As a result we have compilme the local catalogue for GVR area using all available infromation from above mentioned stations.

Results and Discussion

Seismic activity

Fig.4 demonstrates the distribution of earthquake epicenters for the events recorded in the study zone in the period from October 2022 to March 2023 when we have insalled the temprorary seismic station near volcanic range area.

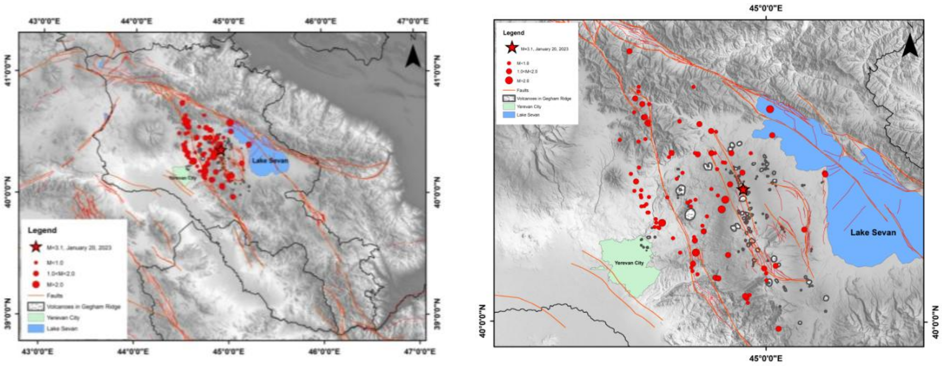


Fig.4. The distribution of earthquake epicenters for the events recorded in the study zone in the period from October 2022 to March 2023.

Overall, about 110 earthquakes were possible to locate in the area during the period of 6 months; the catalogue was compiled and analyses were conducted. The data demonstrate that just few earthquakes fell in the magnitude range of 2.0<M<3.0. About 100 of the recorded earthqaukes had the magnitude of M<2.0 which was also an evidence of weak earthquakes constantly recorded in the area (fig.5). The map of epicenter distribution indicates that the recorded earthquake epicenters distributed among the active faults and amoung the volcanic clusters as well. Anyway, the catalogue analysis indicates that earthquake swarms were not recorded in the study area during the considered period (6 months), and the epicenters were mainly distributed along the fault strike directions. Focal depths of the earthquakes are varying, ranging up to the depths of 20–25km.

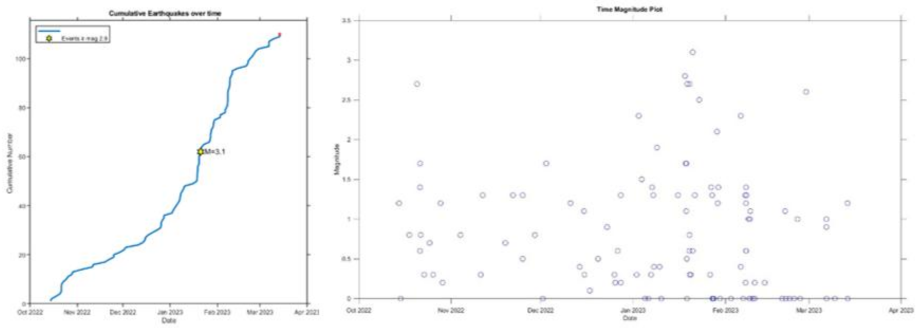


Fig.5. Cumulative number and time-magnitude distribution of earthquakes recorded in the Gegham Volcanic Ridge study area from Oct. 2022 – March 2023

Fault Plane Solutions

In this study, new focal mechanism solutions are constructed for 5 earthquakes (M > 2.0) that occurred between 2022 October – 2023 March in the Gegham Volcanic Ridge (fig.6). The digital waveform data for these events was extracted from the database of the Armenian seismic networks (mentioned above). Additional information from the GNI station was also extracted as digital waveforms from the database of Incorporated Research Institutions for Seismology (IRIS, Washington, http://ds.iris.edu/ds/).

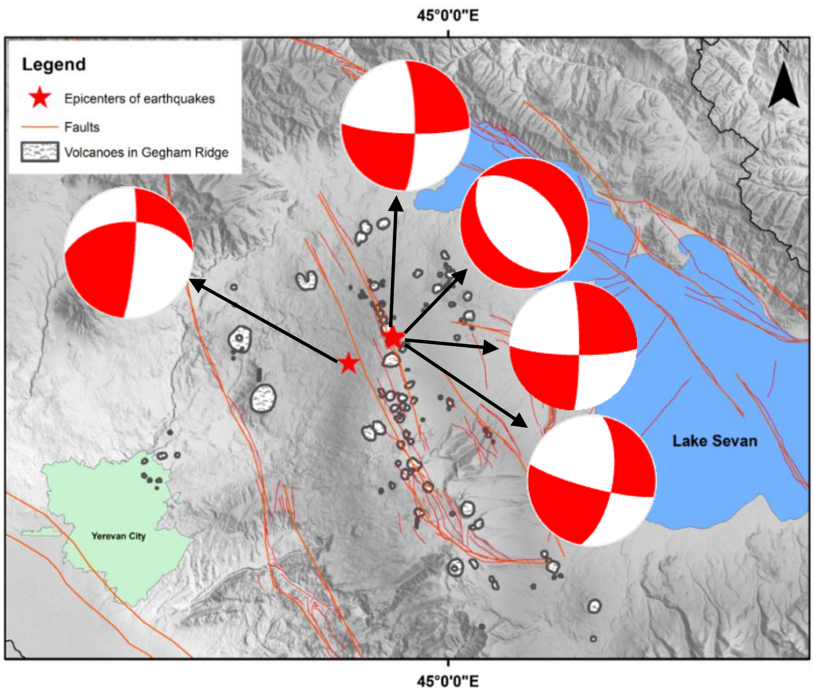


Fig.6. Fault plane solutions of the selected earthquakes that occurred in the study area

Using the program FPFIT (Reasenberg& Oppenheimer, 1985), we attempted to calculate double-couple FPS forlocal earthquakes with clear P-wave polarities recorded at aminimum of six stations (https://www.usgs.gov/software/fpfit-fpplot-and-fppage).

Events which fulfilled the following conditions were selected and the conditions are at least very clear P-wave phases, good azimuth coverage of stations and keeping only events with low RMS.

Earthquake focal mechanisms were 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 by the orientation of one of the two nodal planes and the associated slip vector. From this, focal mechanism solutions are constructed for selected earthquakes with 2 nodal planes (Strike, Dip, Rake parameters, Compressional (P) and Tension (T) kinematic axes).

The parameters of the earthquakes focal mechanism solutions are presented in the tab.2.

Focal-plane solutions for the indicated 5 earthquakes show that they are characterized mainly by the strike-slip fault mechanism (Strike Slip, SS), and just one with the magnitude of M2.1 displays the normal-fault mechanism (Normal Fault, NF).

Table 2

Composite fault plane solutions of the earthquakes using the program FPFIT

		STR1(°)	DIP1(°)	RAKE1(°)	STR2(°)	DIP2(°)	RAKE2(°)	P Az.(°)	P Pl. (°)	T Az.(°)	T Pl(°)
	2023 January 29, 03:51:31.08 Lat: 40.41996 N Long: 44.97307 E Depth: 9.277 km M2.1 **Normal Fault (NF)**	135	42	-90	315	48	-90	225	87	45	3
	2023 February 28 01:57:37.65 Lat: 40.41832 N Long: 44.97358 E Depth: 9.545 km M2.6 **Strike Slip (SS)**	10	63	-10	105	81	-153	330	25	235	12
	2022 October 20, 12:39:51.61 Lat: 40.34042 N Long: 44.8522 E Depth: 11.791 km M2.7 **Strike Slip (SS)**	5	83	40	269	50	171	131	21	235	33
	2023 January 19, 22:23:44.02 Lat: 40.4193 N Long: 44.97552 E Depth: 10.03 km M2.7 **Strike Slip (SS)**	0	83	-10	91	80	-173	315	12	46	2
	2023 January 20, 23:59:43.01 Lat: 40.41868 N Long: 44.97423 E Depth: 10.11 km M3.1 **Strike Slip (SS)**	0	78	-10	92	80	-168	316	15	226	2

Stress Tensor Inversion Method

Volcano-tectonic earthquakes, occurs on faults with favorable orientation according to the maximum and minimum compressional stress field. To determine the local stress field in Gegham Volcanic Ridge stress tensor inversion method was applied using earthquake focal mechanisms solutions.

In this study we apply the method by Delvaux and Speerner (2003), which allows us to determine the best-fit regional principal stress directions, $\sigma1$, $\sigma2$, and $\sigma3$, and the ratio $R= (\sigma2-\sigma1)/(\sigma3-\sigma1)$ with F (the average degree of misfit), as well as to estimate the associated uncertainty in the solution (Delvaux et al., 2003). Here $\sigma1$, $\sigma2$, and$\sigma3$ indicate maximum, intermediate and minimum principal compressive stresses, respectively (where $\sigma1\geq\sigma2\geq\sigma3$).

The ratio R is a measure of the value of the intermediate principal stress ($\sigma2$) relative to the maximum ($\sigma1$) and minimum ($\sigma3$) stresses, and it thus constrains the shape of the stress ellipsoid. The aforementioned method proposes a grid search method of inverting focal mechanisms to obtain the stress tensor (focal mechanisms stress inversion, WinTENSOR), in which stress field parameters are systematically tested against the focal mechanism orientations, and the calculated misfit depends on the orientations of fault planes and slip directions indicated by earthquake focal mechanisms. The system compares the values of the misfit function for each pair of focal planes in order to separate actual movement planes from the auxiliary plane. This function minimizes the deviation between the observed and theoretical slip directions on the plane, minimizes the normal stress, and maximizes the shear stress magnitude on the plane, in order to favor the slip on that plane.

The stress regime can be expressed numerically by the stress regime index (R'), defined in Delvaux et al. (1997b). The main stress regime is a function of the orientation of the principal stress axes and the shape of the stress ellipsoid: extensional, strike-slip and compressional. For each of these three regimes, the value of the stress ratio R fluctuates between 0 and 1.

Focal mechanisms of earthquakes are the primary data used for investigating the regional tectonic stress field. Therefore, to evaluate the orientation of the stress responsible for the earthquake events, a fault-slip data inversion was performed using nodal planes and slip vectors determined from the focal mechanism solutions.

In order to analyze the stress variations throughout the region, stress tensor calculation is performed for study area.

To plot stress tensor for the area of the volcanic Gheham Highland, focal mechanism solutions for 5 earthquakes were applied; distribution of their fault plane parameters (Strike, Dip, and Rake) is represented in the form of Rose Diagrams (fig.7).

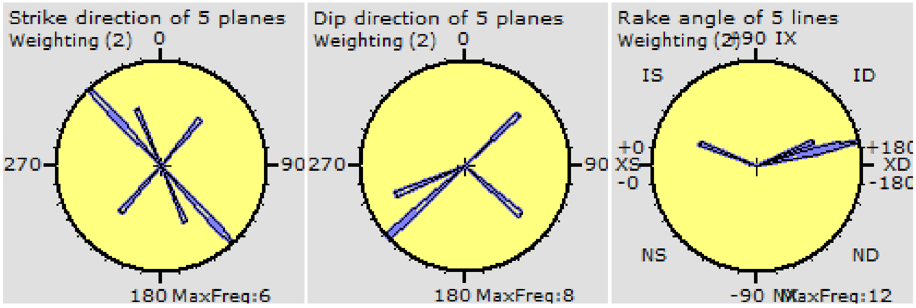
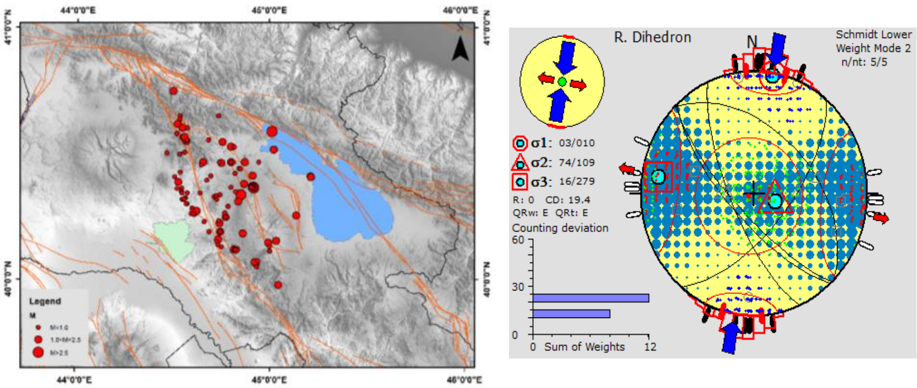
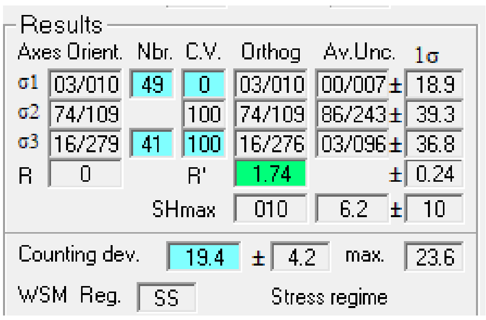


Fig.7. Rose diagrams for the distribution of fault plane parameters (Strike, Dip, Rake) of the earthquakes applied to plot stress tensor for the zone of the volcanic Gegham Highland





	Pl. (^{0})	Az. (^{0})
σ1	3	10
σ3	16	279
Stress Regime (SS)		

Fig.8. Stress Regimes determined for the study area.

The method of Rotational Optimization, and then the Dihedron technique, were used to produce the values of dipping (Pl.) and azimuth angles (Az.) for the principal compression axis, intermediate compression and extension axes of the stress tensor, as well as to estimate the values of stress ratio R and stress index R′. As a result, the stress tensor was plotted for the area of the volcanic Gegham Ridge (fig.1).

The stress regime computed for this group of earthquakes corresponds to strike-slip (SS) (fig.8).

- The sub-horizontal axis (pl.=3°) of compression stress σ1 is oriented NE to SW (Az.=10°).
- The sub-horizontal axis (pl.=16°) of the extension axis σ3 has NW to SE strike direction (Az.=279°) which implies an almost sub-latitudinal orientation (fig.8).

According to the stress tensor calculated for the highland area, NE-SW-oriented compression and NW-SE-oriented extension stress fields are active in the area (fig.8).

Conclusions

It is demonstrated, that weak seismic activity within Gegham volcanic ridgerecorded earthquake epicenters distributed among the active faults and amoung the volcanic clusters. This activity provides important evidence forvolcanic, thermal flow and tectonic activity and is of high interest from the standpoint of seismic investigation in terms of understanding the origin of the low-magnitude earthquakes that occur in the area.

The preliminary results of studies reported in this paper and conducted earlier demonstrate that earthquake swarms can be identified in the area and that they have been concentrated in the area of monogenetic volcanoes.

The stress regime calculated for this studied earthquakes indicates a strike-slip mechanism. The sub-horizontal compression axis is oriented NE-SW (Azimuth = 10°), while the sub-horizontal extension axis strikes NW-SE (Azimuth = 279°), suggesting a nearly sub-latitudinal orientation. These findings reveal that the NE-SW compression and NW-SE extension stress fields are actively influencing the highland region.

Actually, according to the data, there are not any clearly manifested earthquake swarms and the earthquake epicenters are distributed along active faults, because of the scarcity of data, we cannot conclude if the seismicity is volcanic or volcano-tectonic.

However, the Project is in progress and the seismic stations are still operational, hence, seismological data are accumulating and there is hope that in near future the pattern of the recorded earthquakes will be much clearer to enable an informed analysis.

To continue the studies, it is planned to expand the coverage of seismic stations in the Ridge area, and to install more stations, thereby supplementing the database as much as possible to support the analyses.

Acknowledgements

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ԺԱՄԱՆԱԿԱԿԻՑ ՍԵՅՍՄԻԿ ԱԿՏԻՎՈՒԹՅՈՒՆԸ ԳԵՂԱՄԻ ՀՐԱԲԽԱՅԻՆ ԼԵՌՆԱՇՂԹԱՅԻ ՏԱՐԱԾՔՈՒՄ (ՀԱՅԱՍՏԱՆ)

Սարգսյան Լիլիթ, Սահակյան Էլյա, Լևոնյան Արա, Դեմիրճյան Հովնաթան, Նավասարդյան Գևորգ, Գրիգորյան Էդմոնդ, Գևորգյան Միքայել, Մելիքսեթյան Խաչատուր

Ամփոփում

Գեղամի հրաբխային լեռնաշղթան (GVR) գտնվում է Հայկական լեռնաշխարհի տարածքում՝ նեոգեն-չորրորդական դարաշրջանում ձևավորված հրաբխային գոտու կենտրոնական մասում: Գեղամի լեռնաշղթայի սահմաններում հրաբխականությունը տևել է սկսած ուշ միոցենից մինչև հոլոցենը: GVR-ը հանդիսանում է առանձին մոնոգենային հրաբուխների՝ աշխարհի ամենախիտ խմբավորումներից (կլաստերներից) մեկը: Գեղամի լեռնաշղթայի խզվածքների համակարգը կազմված է երկու բաղադրիչներից, այն է՝ Գեղամի լեռնաշղթայի առանցքային մասի խզվածքներից և Գավառագետի խզվածքից: Գեղամի խզվածքների համակարգում Գավառագետի խզվածքը ամենաակտիվն է և կապակցվում էր մի քանի պատմական և ժամանակակից երկրաշարժերի հետ:

Ուսումնասիրվող տարածքի ընթացիկ սեյսմիկ ակտիվությունը հետազոտելու և հրաբխային աղեղների մոտակայքում հնարավոր սեյսմիկ ակտիվությանը հետևելու նպատակով, ի լրումն գոյություն ունեցող սեյսմիկ ցանցի, տեղադրվել են ևս երեք ժամանակավոր սեյսմիկ կայաններ: Ստացված տվյալները ցույց են տալիս որ այդ տարածքում տեղի են ունենում թույլ երկրաշարժեր: Վերահաշվարկը կատարվել է օգտագոր-

ծելով արագությունների տարածաշրջանային մոդելը և տվյալ տարածքը ընդգրկող բոլոր սեյսմիկ կայանների գրանցումները՝ նպատակ ունենալով էպիկենտրոնների և հիպոկենտրոնների որոշման ճշգրտումը: Տվյալները ցույց են տալիս, որ այս տարածքը սեյսմիկության առումով ակտիվ է փոքր երկրաշարժերի (M<=3.4) տեսքով: Այս հետազոտությունում բարձր հուսալիությամբ ուսումնասիրվել են 2022–2023թթ. տեղի ունեցած՝ մի խումբ երկրաշարժերի օջախի մեխանիզմները, կիրառելով Հայկական սեյսմիկ ցանցերի սեյսմիկ կայաններում գրանցված թվային ալիքային պատկերները (ներառյալ վերևում նշված 3 ժամանակավոր սեյսմիկ կայանները):

Այս ուսումնասիրությունում կիրառվող կատալոգի հիմնական պարամետրերի անորոշությունները նվազագույնի բերելու համար բոլոր տվյալները վերադիրքավորվել են, օգտագործելով տեղական և տարածաշրջանային սեյսմիկ ցանցերի տվյալները:

СОВРЕМЕННАЯ СЕЙСМИЧЕСКАЯ АКТИВНОСТЬ НА ТЕРРИТОРИИ ГЕГАМСКОГО ВУЛКАНИЧЕСКОГО ХРЕБТА (АРМЕНИЯ)

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Резюме

Гегамский вулканический хребет (GVR) находится в центральной части неоген-четвертичного вулканического пояса, сформировавшегося в пределах территории Армянского нагорья. Вулканизм на Гегамском хребте продолжался с позднего миоцена по голоцена. GVR представляет собой один из наиболее густых кластеров отдельных моногенетических вулканов мира. Система разломов Гегамского хребта включает в себе две компоненты – разломы осевой части Гегамского хребта и Гаварагетский разлом. В системе разломов Гегама Гаварагетский разлом является наиболее активным и ассоциировался с несколькими историческими и современными землетрясениями.

С целью изучения текущей сейсмической активности исследуемой территории и наблюдения за возможной сейсмической активностью вблизи вулканических дуг, в дополнение к существующей сейсмической сети, были установлены еще три временные сейсмические станции. Полученные данные показывают, что на данной территории происходят слабые землетрясения. Для увеличения точности определения эпицентров и гипоцентров проводился перерасчет с использованием региональной модели скоростей и

всех записей с сейсмических станций, охватывающих данную территорию. Данные показывают, что данная территория сейсмически активна в случае слабых землетрясений (M<=3.4). В данном исследовании с высокой степенью надежности исследовались механизмы очагов для набора землетрясений, случившихся в период 2022–2023гг., с применением данных цифровых волновых форм, зарегистрированных на сейсмических станциях сейсмических сетей Армении (включая 3 временные сейсмические станции, упомянутые выше).

Все данные были релокализованы с использованием данных с локальной и региональной сейсмических сетей с целью снижения погрешности основных параметров каталога, используемого в данном исследовании.