FOCAL PARAMETERS OF THE OGUZ EARTHQUAKE SEPTEMBER 4, 2015 with ml = 5.9

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Studying the conditions for the formation of the earthquake source is of great importance for understanding the essence of seismic phenomena and developing methods for predicting seismic hazard. In this case, the main parameters of the study are seismic waves. At the present stage, a dense network of highly sensitive digital seismic stations, which allows recording all seismic events with a magnitude of ml> 0.1 within Azerbaijan, as well as extensive factual materials obtained from this network, have made it possible to develop many new methodological issues and outline new ways of predicting earthquakes. The purpose of this article was to determine the dynamic parameters of the source of a strong Oguz earthquake, as well as the solution of its mechanism.

On September 4, 2015, an earthquake with an observed intensity at the epicenter of I_0 = 7 points and I_0 = 7-3 points in nearby areas occurred near Oguz district. In accordance with the map of epicenters of seismic events for 1900-2003 in the region of the earthquake that occurred, a number of strong earthquakes were noted, with intensity at the epicenter of 6 or more points (Fig.1). The most significant of them are the earthquakes of 1953, 1968 with I_0 = 6-7 points, 1980, 1986, 1991 with I_0 = 5-6 points, March 5, 2000 I_0 = 5 points. The last tangible seismic event in this area was an earthquake on June 1, 2003 with I_0 = 6 points in the epicenter and 3-4 points in the regions of Mingachevir and Kurdamir (table 1) [1, 2].

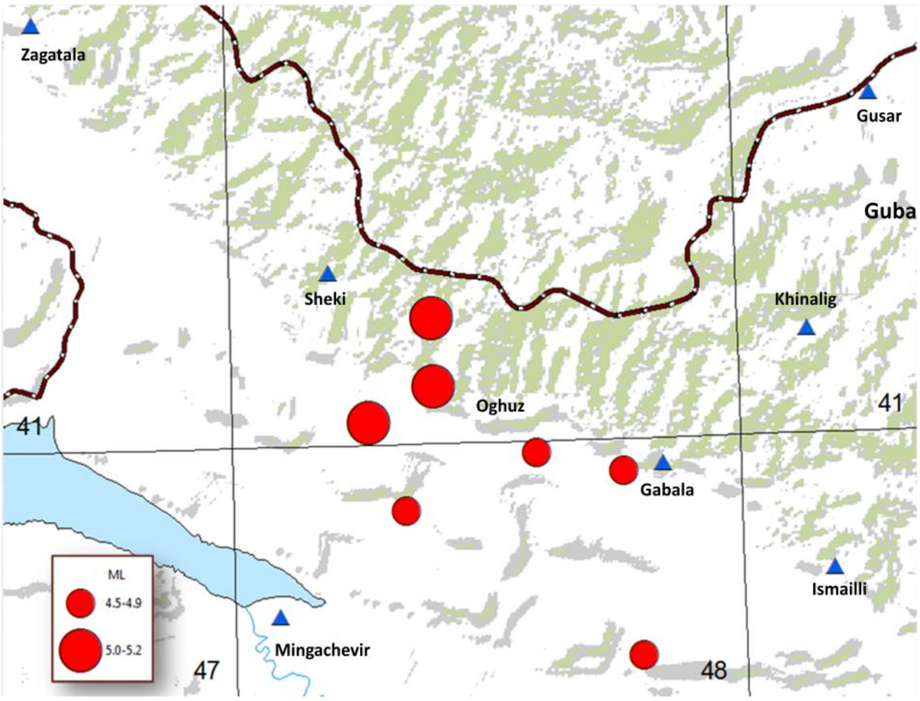


Figure 1. M ap of the epicenters of strong earthquakes in the study area for the period 1900-2003.

[1] Republican Seismic Survey Center of Azerbaijan National Academy of Sciences

Table 1. Strong earthquakes in Oguz and surrounding areas with an intensity at the epicenter of 5 or more points [1]

Date			Time			Coordinates		Depth	MI	Io points
year	month	day	hour	min	sec	northern latitude degrees	eastern longitude degrees	km		
1953	9	2	00	36	01	41.10	47.40	5	5.1	7
1953	9	16	11	15	29	41.20	47.40	28	5.0	6
1968	5	11	11	29	40	41.00	47.60	15	4.7	6
1980	4	1	07	33	41	40.70	47.80	20	4.7	6
1986	6	02	15	16	13	40.97	47.77	22	4.6	5
1991	10	21	11	58	23	40.92	47.34	16	4.5	5
2003	06	01	06	09	42	41.05	47.27	22	5.0	6

Instrumental data

Seismic vibrations from the September 4, 2015 earthquake were recorded by 18 world agencies and nearly 400 seismic stations in a wide azimuthal environment at distances from 300 to 13,407 km from the epicenter. The main parameters of the earthquake obtained by the Republican Seismic Survey Center of Azerbaijan are represented in Table 1. Based on macroseismic studies, it was revealed that the earthquake was felt most intensely in the Oguz and Sheki regions. Here, the intensity of the earthquake according to MSK-64 scale was estimated at 7 points. The earthquake was accompanied by more than 80 aftershocks with magnitudes from 0.5 to 4, 33 of which occurred on the first day [3,4]. The aftershock cloud spread up to 23 km in the direction of the south-west and 9 km in the direction of the west-east, however, the area of the main mass of the earthquake accumulation was 88 km^2. Despite the fact that the main source is located at a depth of 16 km in the granite layer, the depth of aftershocks varies between 11-34 km. As seen in Fig.2 the earthquake epicenter is confined to the zone of intersection of the longitudinal Dashgil-Mudrese and transverse Arpa-Samur faults [5]. It should be noted that the Arpa-Samur deep fault of the ancient formation at all times from the Paleozoic to the present day is a zone of active manifestation of tectonic movements, a conductor of magmatic melts, ore-bearing solutions and seismicity. According to Shikhalibeyli E.Sh. [6] the Arpa-Samur trans-Caucasian seismic-metal-bearing fault zone combines the Mrovdag-Zodsky, Terter and Khachinsky deep faults.

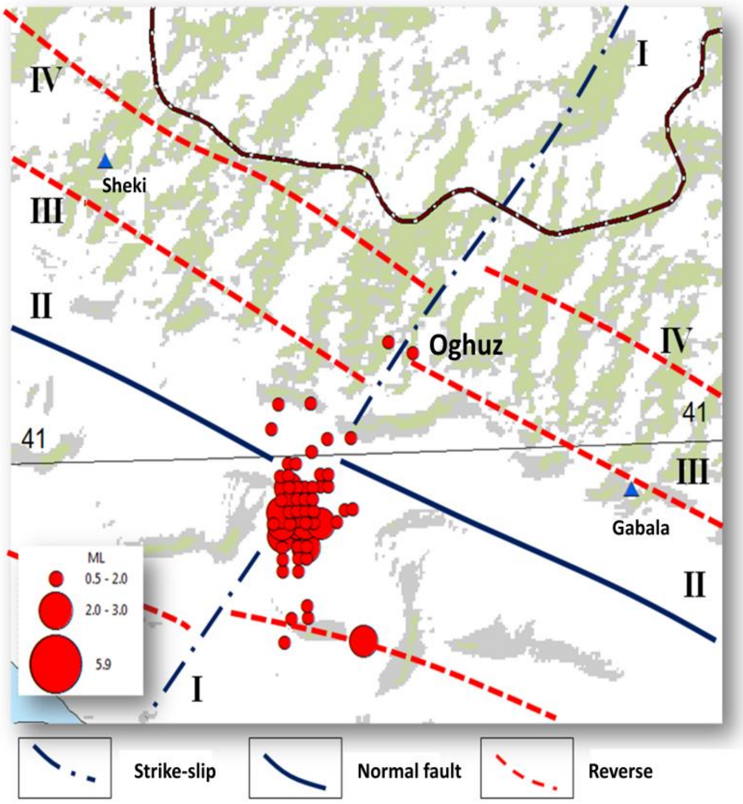


Figure 2. Aftershock field of the strong Oguz earthquake on September 4, 2015 with ml = 5.9
Faults: I - Arpa-Samur, II - North Adzhinour, III - Vandam, IV - Dashgil-Mudrese [4]

The solution of the source mechanism

The focal mechanism solution was obtained by the method of waveform inversion - Time-Domain Moment Tensor INVerseCode (TDMT INVC), developed by Doug Draeger from the University of California, Berkeley [7]. This package is used to calculate both the seismic moment tensor and Mw. In this method, the seismic moment tensor is determined on the basis of the inversion of the low-frequency part of the broadband 3-component waveform and then decomposed into the scalar seismic moment Mo and the orientation parameters of the strike, slip and rake forces. The moment magnitude Mw of interest to us is determined from the scalar seismic moment according to Kanamori [8]:

$$Mw = [\log 10 (Mo) - 16.1] / 1.5$$

The main source of RSSC ANAS seismograms. There is also information about the hypocenter and time at the source of the earthquake. Seismograms are downloaded in SEED format and converted to SAC format (Fig. 3). Broadband seismograms are selected subject to a distance limit (50-350 km). They should have a sufficient duration (the interval from P-waves to the initial part of S-waves is included) and quality (sufficiently high signal-to-noise ratio, lack of clipping). Preparation of seismograms for inversion includes: removal of the entry of the P-wave; deconvolution (restoration of true soil displacements); determination of epicenter distance, direct and reverse azimuths; calculation of radial and transverse components; filtering. Deconvolution takes place in the time domain [8]. For bandpass filtering, a 4-order Butterworth filter is used. If necessary, decimation is carried out in order to make the sampling frequency equal to 1 count per second. That is, lead to the same time step that the influence functions have: 1 second. In addition, the time interval that is used to solve the problem is determined.

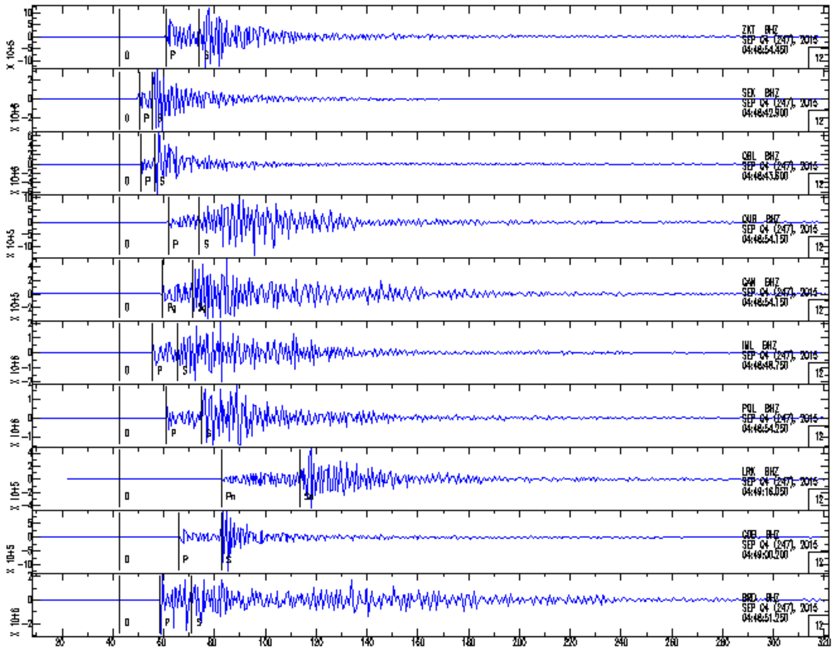


Figure 3. Wave recording of the Oguz earthquake in SAC format

Thus, the mechanisms of two earthquakes were constructed and analyzed: September 4, 2015 with ml = 5.9 (main shock) and October 13, 2015 with ml = 4.0. An analysis of the mechanisms of the sources of these earthquakes showed the predominance of two types of movements. The earthquakes that occurred in the Oguz region on September 4 at 04^h 49^m and October 13 at 00^h 13^m occurred under the action of tensile and compressive stresses of similar magnitude. Table 2 shows that the first nodal plane of the gap extends in the SE direction (153º) with a fall to the south-west at an angle of 86-90º, the second nodal plane has a NE strike (63º) with a fall to the south-east at an angle of 83-90º. In this case, the compressive stresses in the earthquake source were oriented in the north-east direction (azimuth 18) and acted near horizontally (angle with the horizon 0-7), and tensile forces were directed in the west-south-west direction (287-288) at an angle of 0-2 to the horizon. The type of movement of these earthquakes is a shift with a left-side horizontal component.

Table 2. Parameters of the mechanisms of the Oguz earthquake's sources in 2016 with ml = 5.9-4.0

№	Date, d m y	t_0, h min sec	h, km	Magnitudes			Axis of principal stress						Nodal planes					
							T		N		P		NP1			NP2		
				ml	mb	mw	PL	AZM	PL	AZM	PL	AZM	STK	DP	SLIP	STK	DP	SLIP
1	20150904	04:49:36	16	5.9	5.4	5.5	0	288	90	171	0	18	153	90	-180	63	90	0
2	20151013	00:13:31	16	4.0	-	-	2	287	82	180	7	18	153	86	-172	63	83	-4

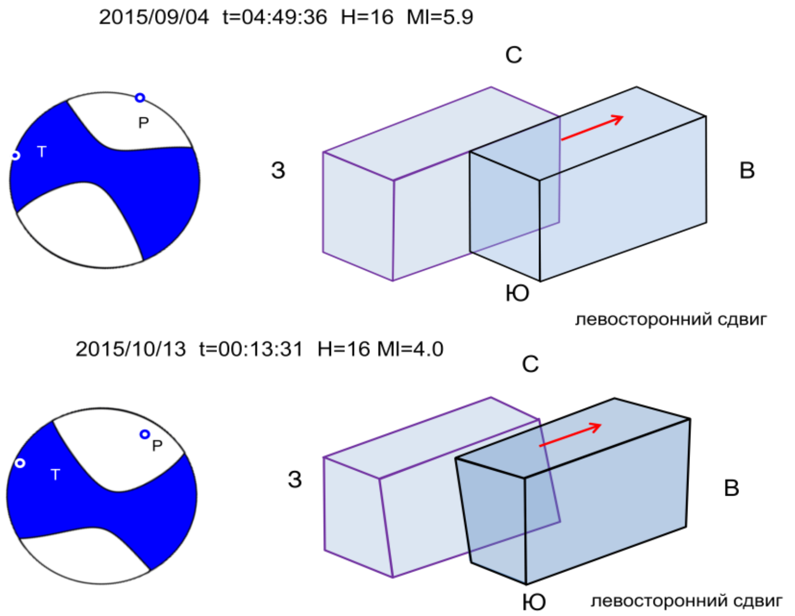


Figure 4. Earthquake source mechanisms, as well as block diagrams of displacement along the NP2 plane

The epicenters of the Oguz earthquakes are confined to the Arpa-Samur fault and can be interpreted as left-side shift deformation in the zone of geodynamic influence of the left-sided Arpa-Samur fault. Figure 4 shows the stereograms of the mechanisms of the sources of the two analyzed earthquakes, as well as the block diagram of the displacement along the NP2 plane corresponding to the specified fault. Figure 5 shows how aftershocks migrate north-eastward along the transverse fault, deepening to a depth of 35 km. It should be noted that the analysis of the mechanisms of the other two aftershocks (2015.09.04 with ml = 3.3 and 2015.09.29 with ml = 3.3) showed the fault type of underthrusts, which is associated with the influence of the North Adzhinour strike longitudinal fault.

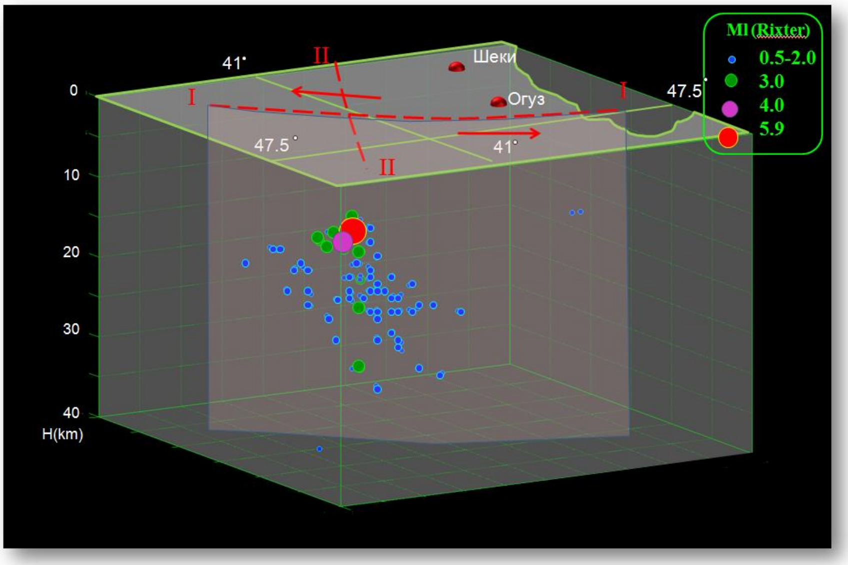


Figure 5. Three-dimensional model of the aftershock field of the Oguz earthquake on September 4, 2015 with ml = 5.9
Faults: I - Arpa-Samur, II - North-Adzhinour

It was said above that the earthquake data were recorded by 18 world agencies. A comparative analysis of the results of solutions of the focal mechanism in different regions was carried out. It was found that the solution of the seismic moment tensor of the centroid USGS and GFZ is close to the solution obtained from the RSSC seismic station network (Fig. 6).

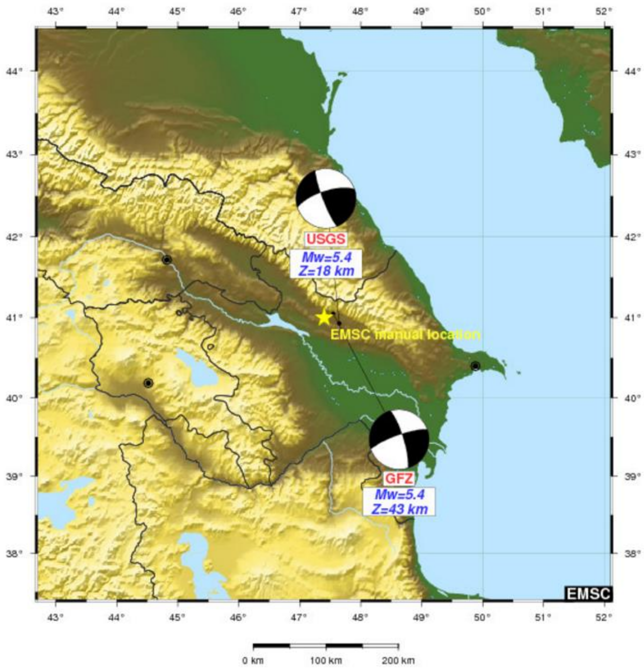
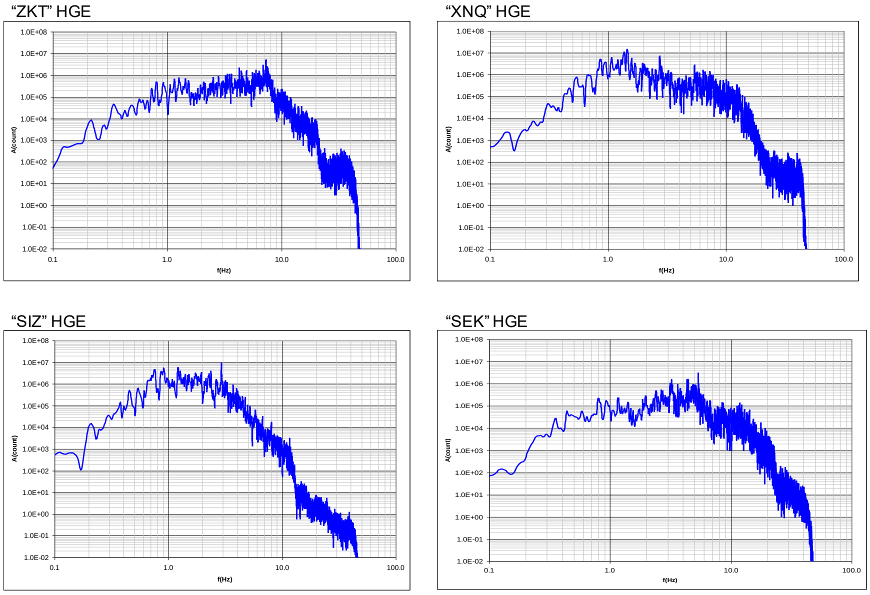


Figure 6. Focal mechanisms of Oguz earthquakes according to USGS and GFZ

Dynamic parameters.

Using the digital seismograms of the transverse waves of earthquakes, the Fourier amplitude spectra were constructed, which made it possible to determine the maximum level of the spectrum and the boundary upper frequency of the maximum level f_0. In the calculations, the classical model of D.Brun [9] was used. To determine the dynamic parameters of the earthquake sources, only S-wave recordings were used at 8 digital stations: Zagatala, Khinalig, Siyazan, Sheki, Saatly, Guba, Gusar and Pirkuli (Fig.7). To determine the parameters of the spectrum, it is approximated by two straight lines - a straight line parallel to the frequency axis (horizontal strike), in the low-frequency region and an inclined straight line in the high-frequency region. The interval of epicenter distances for the stations under consideration turned out to be Δ = 30-200 km.



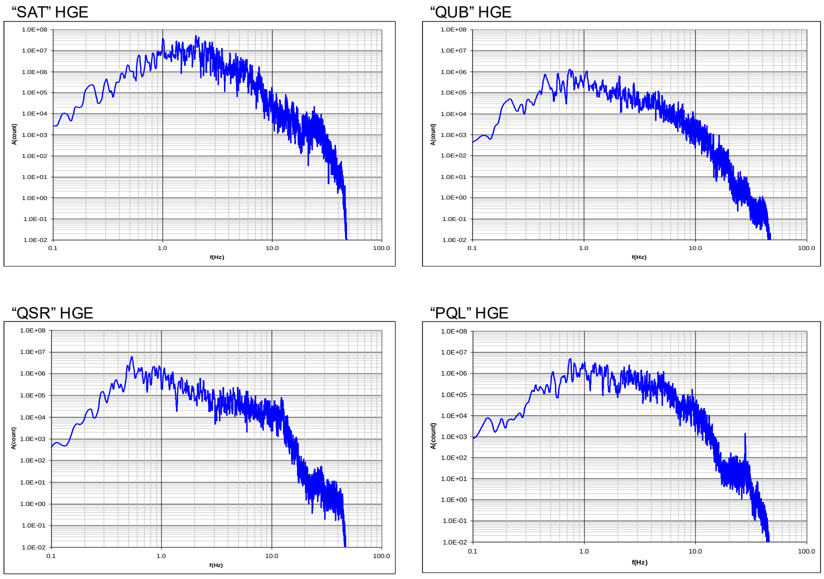


Figure 7. Amplitude spectra of the Oguz earthquake on September 4, 2015

The following spectral characteristics were determined: the angular frequency f_0, the radius of the circular dislocation r_0, the discharged tension $\Delta\sigma$, the source volume V, the average displacement along the discontinuity D. Table 3 also presents the values of the moment magnitude Mw and seismic moment M_0 calculated earlier using the tensor method seismic moment based on the inversion of the low-frequency part of the broadband 3-component waveform [7].

Table 3. Dynamic parameters of the Oguz earthquake of September 4, 2016 with ml = 5.9

№	Ω_0, cm·c^2	F_0, Hz	M_0,10^{24}, dyn-cm	M_W	R_0, km	$\Delta\sigma$, dyn/cm^2	D,10^{-2}, m	V, km^3
1	2	3	4	5	6	7	8	9
1	ZKT	1.1	2.6	5.5	1.25	55.81	1.23	8.2
2	XNQ	1.0	2.6	5.5	1.38	41.93	1.02	11.0
3	SIZ	1.0	2.6	5.5	1.38	41.93	1.02	11.0
4	SEK	1.2	2.6	5.5	1.15	72.46	1.47	6.4
5	SAT	0.9	2.6	5.5	1.53	30.57	0.83	15.0
6	QUB	0.8	2.6	5.5	1.72	21.47	0.65	21.4
7	QSR	0.9	2.6	5.5	1.53	30.57	0.83	15.0
8	PQL	1.1	2.6	5.5	1.25	55.81	1.23	8.2
Average value		1.0	2.6	5.5	1.4	44	1.03	12

The values of the released tension appear to be underestimated. This is due to the fact that the radius of a circular dislocation can vary from station to station, depending on the position relative to the discontinuity plane and the direction of movement in the focus. This analysis showed the possibility of estimating dynamic parameters from observations of one station in a wide frequency range. Thus, the focal parameters of the Oguz earthquake are as follows: angular frequency $f_0 = 1.0$ Hz, seismic moment $M_0 = 2.6 * 10^{24}$, dyn · cm, circular dislocation radius $r_0 = 1.4$ km, released tension $\Delta\sigma = 44$ dyn/cm^2, source volume $V = 12$ km^3, average displacement along the fault $D = 1.03 * 10^{-2}$ m.

It is known that the nature of the movements recorded on the seismogram is determined both by the medium along the seismic wave propagation path and by the source, a comprehensive analysis of the record is required, which would allow obtaining additional information about the earthquake source, and better understand the source mechanism [10].

An important point in the calculation of dynamic parameters is the transition from the station spectrum to the focal spectrum. For such a transition, it is necessary to take into account the influence of the medium ("attenuation") and the amplification factor on the path of the seismic beam. There are various methods for determining station corrections, which are described in works [11–13]. The purpose of the research is the calculation of station corrections (determination of the site effect of the station) based on the analysis of the seismic signal using the Nakamura method [14].

Calculation methodology

As is known, displacements of the earth's crust are measured in three directions: north-south (NS), east-west (EW) and vertically (Z). Nakamura's method is to find the ratio of the spectrum of the horizontal component (H) to the spectrum of the vertical (V). For this, it is necessary to use measurements of the 3 components of the E, N, Z seismogram [14]. The calculation of the component H occurs as the quadratic mean of the spectra of the E and N components, vertical V corresponds to the spectrum of the component Z. Next, the H / V ratio is directly calculated:

$$H(f) = \frac{\sqrt{N^2(f) + E^2(f)}}{2} \qquad (1)$$

$$H/V(f) = \frac{H(f)}{V(f)} \qquad (2)$$

Thus, we analyzed the data of digital records of the transverse wave for the three components HGE, HGN, HGZ of 21 stations of the main shock. In the study, the duration of the recording time window was 60 seconds.

A linear trend is eliminated from the selected recording section and, to prevent spectrum leakage, the signal is smoothed at the ends using a 5% cosine window. Corrections for the measurement error of the instrument are applied to the resulting series and the spectrum is calculated using the Fourier transform [12].

Thus, the spectral ratios were calculated and the amplification factor of 21 broadband digital earthquake stations that occurred on September 4, 2015 in the Oguz region with a magnitude of 5.9 was found (Fig. 8, 9, 10). We divided the result into three classes: stations for which the maximum values of the extension factor fluctuate in the frequency range 0.2-1.0 Hz (stations "ALI", "GBS", "GLB", "LKR", "PQL", "QBL", "QSR", "XNQ", "ZKT",), stations for which the maximum values of the extension factor fluctuate in the frequency range 1.0-4.0 Hz (stations "ATG", "HYR", "IML" "MNG", "QUB" , "SIZ"), and in the range 3.0–7.0 Hz (stations AST, GAN, LRK, ORB, SEK, BRD).

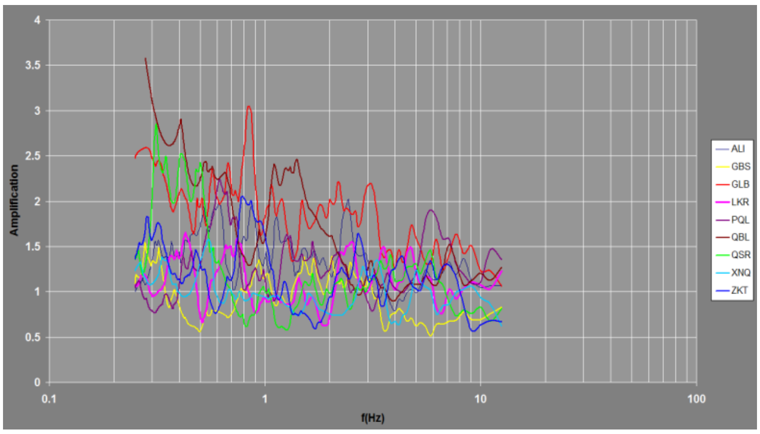


Figure 8. The seismic wave amplification factor at the stations "ALI", "GBS", "GLB", "LKR", "PQL", "QBL", "QSR", "XNQ", "ZKT".

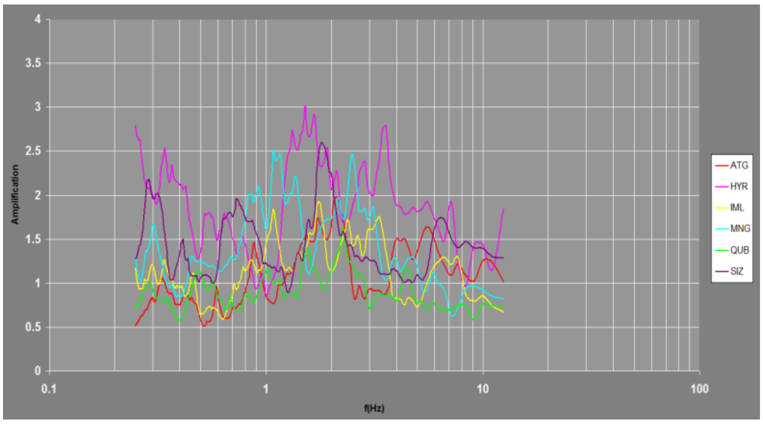


Figure 9. Seismic wave amplification factor at “ATG”, “HYR”, “IML”, “MNG”, “QUB”, “SIZ” stations

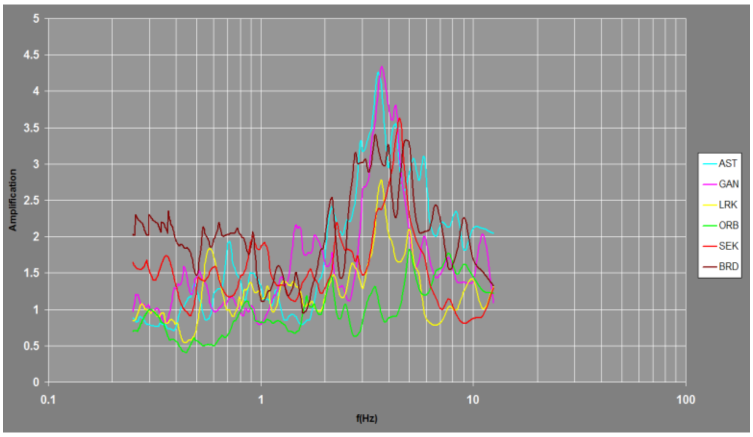


Figure 10. Seismic wave amplification factor at the stations “AST”, “GAN”, “LRK”, “ORB”, “SEK”, “BRD”

This method is based on the notion that the influence of a thin layer (a small layer of the earth’s crust immediately below the seismic station) of the object under study mainly refers to transverse waves (S-wave), which are amplified by this structure and practically do not change longitudinal waves (P -wave). Then the ratio of the spectral characteristics of two horizontal components to the spectrum of the vertical component will characterize the so-called transfer function, which strictly depends on the thin layer under the study object [12]. It was found that the maximum extension factor is characteristic for the stations “QBL” = 3.6, “AST” = 4.3, “GAN” = 4.3, “SEK” = 3.6, “BRD” = 3.4.

Conclusions

Thus, despite the fact that the main source of the Oguz earthquake that occurred on September 4, 2015, 04^h 49^m with ml = 5.9, was located at a depth of 16 km in the granite layer, the depth of aftershocks varies between 11-34 km. The aftershock cloud spread up to 23 km in the direction of the SW and 9 km in the direction of the WE, the area of the main earthquake accumulation was 88 km^2.

Based on the solution of the source mechanism, it was found by the method of inversion of wave forms that the earthquakes that occurred in the Oguz region on September 4 at 04^h 49^m and October 13 at 00^h 13^m occurred under the action of tensile and compressive stresses of similar magnitude. In this case, the compressive stresses in the earthquake source were oriented in the north-east direction (azimuth 18) and acted horizontally (angle with the horizon 0-7), and tensile forces were directed in the west-south-west direction (287-288) at an angle of 0-2 to the horizon. The type of movement of these earthquakes is a shift with a left-side horizontal component. An analysis of the mechanisms of the other two aftershocks (2015.09.04 with ml = 3.3 and 2015.09.29 with ml = 3.3) showed the fault type of movements. Earthquakes are confined to the zone of intersection of the longitudinal Dashgil-Mudrese and transverse Arpa-Samur faults, which are the zone of active manifestation of tectonic movements to this day.

Using the digital seismograms of the transverse waves of earthquakes, the Fourier amplitude spectra were constructed, which made it possible to determine the maximum level of the spectrum and the boundary upper frequency of the maximum level f_0. The focal parameters of the Oguz earthquake are as follows: angular frequency f_0 = 1.0 Hz, seismic moment M_0 = 2.6 * 1024, dyn ин cm, circular dislocation radius r_0 = 1.4 km, released tension $\Delta\sigma$ = 44 dyn / cm^2, source volume V = 12 km^3, average displacement shift D = 1.03 * 10^{-2} m. Based on the said above, the spectral ratios were calculated and the gain factor of 21 broadband digital stations was found. It was found that the maximum extension factor is characteristic for the stations “QBL” = 3.6, “AST” = 4.3, “GAN” = 4.3, “SEK” = 3.6, “BRD” = 3.4.

Summing up, it should be noted that further detailed and comprehensive study of the buried Arpa-Samur trans-Caucasian seismically active seismic-metal-bearing fault zone of deep faults, which has been active for a long time and sharply influenced the structure of the East Caucasus, can provide ample material for understanding geodynamic processes in this part of Mediterranean belt in the alpine cycle.

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