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INDUCED SEISMICITY ON THE TERRITORY OF KAZAKHSTAN

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Until 1994, Kazakhstan possessed a network of seismic stations (operated by the Institute of Seismology AS of Kazakhstan, then by SEME MES RK) concentrated at seismically active regions of Kazakhstan – in the south, south-east and partially in the east of the country. The stations deployment plan was aimed at a station location closer to origin zones of earthquakes to record the smallest events from potentially dangerous regions. Therefore, the stations are usually placed along ridges where the highest seismic activity is observed, for instance, the ridges of Northern Tien Shan. In addition, the stations were installed at the regions where large earthquakes happened before. Sometimes, the earthquakes occurred at regions unexpected for seismologists, contrary to the information provided in the maps of general seismic zoning. After such earthquakes the maps of seismic zoning were revised considering new information. An example is Zaysan earthquake of 1990 occurred in the east of Kazakhstan. After this event, Mw=6.9 and intensity at the epicenter 7-8 by MSK-64 scale, a seismic station was installed in Zaysan settlement [1]. However, it should be noted that 80% of Kazakhstan territory including its central, west and north parts have never been monitored by permanent seismic stations.

The result of seismic observations network operation is an earthquake catalogue covering the territory of Northern and South Tien Shan, Dzhyungariya, part of Tarbagatay and Kazakhstan part of Altay [2, 3]. New information regarding active zones revealed by the network is reflected in the current map of seismic zoning of Kazakhstan created in 2003 which is an integral part of Construction Norms and Rules of the Republic of Kazakhstan (construction in seismic regions) [4]. Seismically dangerous zones with possible shake intensity above 5 by MSK-64 scale are located in the south, south-east and east parts of the country, i.e. where the seismic stations are installed.

Starting from 1994, a monitoring network of the Institute of Geophysical Researches (IGR), one of which task is verification of the Comprehensive Test-Ban Treaty compliance, has been created on the territory of Kazakhstan. The network goal was to construct maximally sensitive stations able to record events from any region of the world at close and teleseismic distances. The new monitoring network consisted of arrays of different configuration. Its location, aperture and configuration were selected carefully [5, 6]. Selection of stations location place was independent on seismicity of this or that region. These are located at seismic and aseismic regions of the country. Along with the seismic arrays the network also includes three-component stations supplementing successfully the network at necessary places. The seismic stations of the IGR are located along the perimeter of Kazakhstan (in the west, north, east and south of Kazakhstan) one three-component station is located in the center of the country and some are in the south-east. Such location of the stations ensures effective monitoring inside and outside of the country. Figure 1 shows a chart of location of seismic monitoring network facilities of the IGR RK.

Since 2003, the Data Centre of IGR has been systematically detecting and processing signals, and creating seismic bulletins. During the first years of its operation, the new network of Kazakhstan has revealed many events at regions that traditionally were considered as aseismic. Major part of these events are mining explosions [7] used for mineral deposits development. As known, Kazakhstan possesses huge deposits of various minerals. Namely, in recent decades there was sharp jump in its development, due to which the number of mining explosions and other types of explosions increased significantly.

However, there were events which nature was not explosively-driven. It was to determine the nature of such events, collect archive data about seismological history of the regions where they occurred. A range of such events was revealed in central, west, north and north-east Kazakhstan and was related to the places of active induced impact, such as developing deposits of solid minerals, oil and gas deposits, and Semipalatinsk Test Site. Figure 2 shows a map of epicenters of investigated earthquakes at different parts of Kazakhstan.

The reasons of such earthquakes could be different, but, as rule, they all relate to continuous induced impact on geological environment causing the response reaction in the form of rocks collapse and rock bumps at the places of solid minerals production [8-10], induced earthquakes in productive horizons during oil and gas fields development. In addition, near large active quarries, natural-induced earthquakes with origins related to active tectonic faults [11-12] in close vicinity to the regions of continuous induced impact could appear. At the former places of underground nuclear explosions (UNE) the earthquakes could be due to cavity collapses formed after explosion [13].

The authors of the work had a task to generalize the available information on events of industrial and induced nature on the territory of Kazakhstan using contemporary instrumental data from regional monitoring network, and data from the International Centers for processing of seismological data from global monitoring networks.

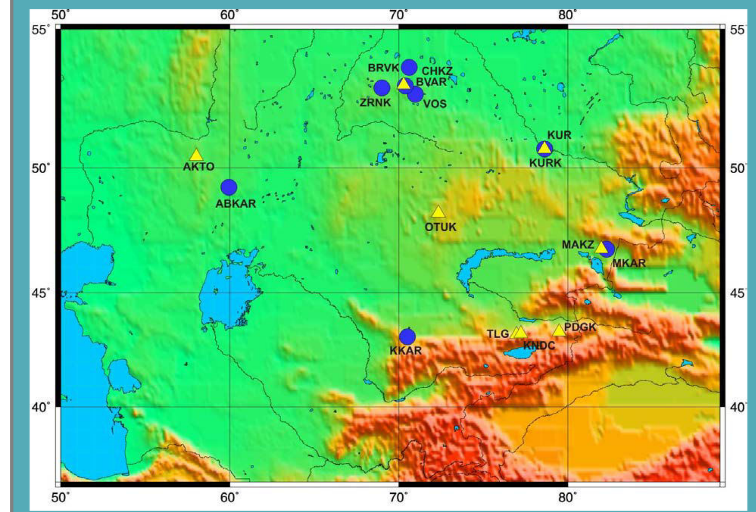

Figure 1. The map of seismic stations location of the Institute of Geophysical Research network. Triangles – three-component stations, circles – seismic arrays.

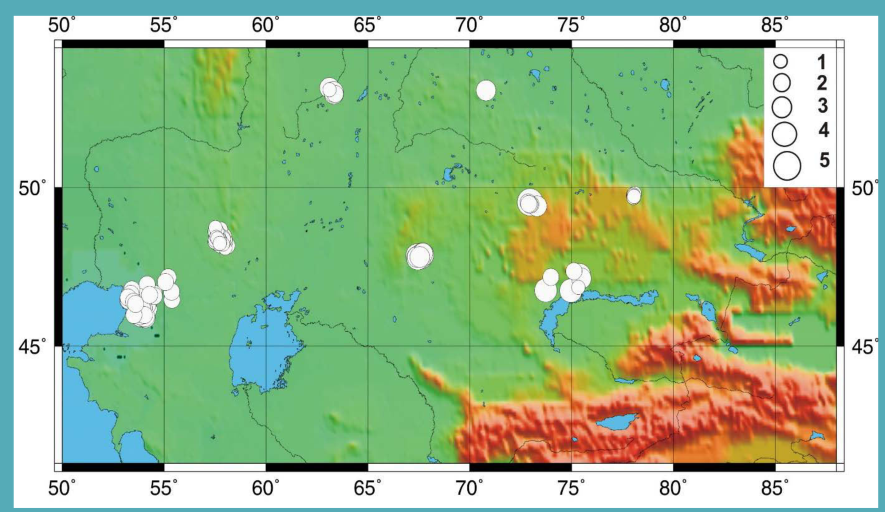

Figure 2. The map of epicenters ocation of seismic events describe in the apaer. The circle size corresponds to event magnitude: 1: mpv<2, 2: 2≤mpv<3, 3: 3≤mpv<4, 4: 4≤mpv<5, 5: mpv≥5.

Induced earthquakes at solid minerals deposits

1. **Zhezkazgan deposit in Central Kazakhstan**

Continuous development of Zhezkazgan deposit of copper (more than 160 years) has led to significant geodynamic changes in the environment resulted in powerful induced earthquakes. The largest of them occurred on August 1, 1994, mb=4.8, Ms=4.5 on the territory of Zlatoyust-Belovskiy quarry near Zhezkazgan town (records by the IGR stations in Figure 3). This was a large-scale collapse that took away 6 lives, and caused destructions of many active underground pits and building on the surface. The earthquake consequences were so large that works at one of the mines were stopped, and several tunnels were closed, surface buildings were moved from the dangerous zone. There were bent railways with overturned coaches [8, 9]. Figure 4 shows a chart of superincumbent rock collapse with outcrop [8].

Another event occurred on 23.06.1996 at Zhezkazgan deposit region, Ms=3.7 was felt in Karazhal settlement (Δ=243 km), Agadyr (Δ=398 km) with intensity 3. The IGR stations also recorded events of 09.09.2002 with Ms=4.4 and of 23.06.2005 with Ms=4.0.

Starting from 1994, 9 seismic events with mpv≥3.7 were recorded at Zhezkazgan deposit region (Figure 5). After 2009 there were no large events at Zhezkazgan deposit region. The reason was that starting from 2010 the techniques of underground copper production has been changed, rock pillars rich of metal content were excluded from dangerous mining (remained from the USSR times); by that time they all were mined. Currently, the underground production is conducted in less volumes; major part of production work is conducted from the surface in open mines (quarries).

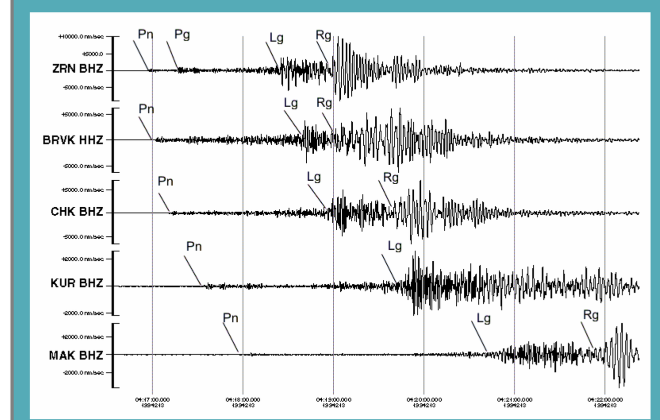

Figure 3. Seismic record of event occurred on August 1, 1994, t0=04-15-39.7, φ=47.833°, λ=67.451°, mb=4.8, K=12.2 at Zhezkazgan region by the IGR stations. Z-components.

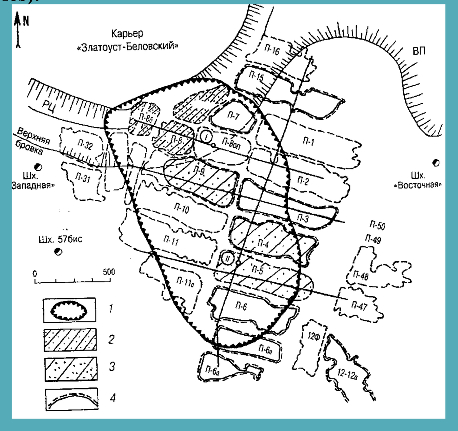

Figure 4. A chart of collapse process happened on August 1, 1994. 1 – collapse area, 2,3,4 – panels laid consistently, laid partially, and weakened [8].

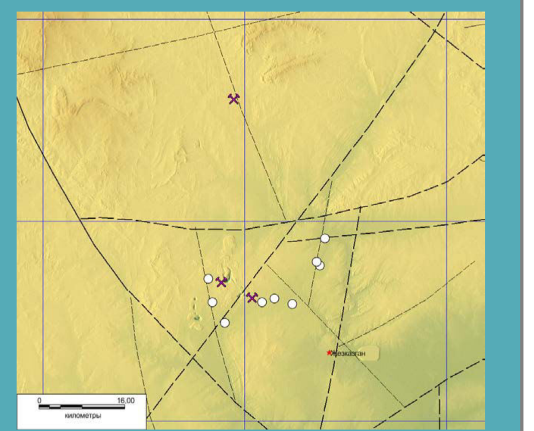

Figure 5. The map of seismic events epicenters location at the region of Zhezkazgan deposit. The map shows rupture disturbances. Circles – events epicenters, cross – quarries.

Figure 6 shows a seismic record of event occurred on August 1, 1994, t_0=04-15-39.7, φ=47.833°, λ=67.451° and recorded by the IGR RK stations network [10]. The record shows domination of surface waves. To reveal specific features of a collapse seismic record we have used a digitized seismogram of peaceful nuclear explosion occurred on September 19, 1973, t_0=03-00-00.2, 230 km south-east of Zhezkazgan, φ=45.758°, λ=67.825°, mb=5.1 (Figure 7). It is seen that the PNE record has more impulsive arrival of P-wave, and less intensive surface waves. Spectra difference is also observed, the PNE record has higher frequencies.

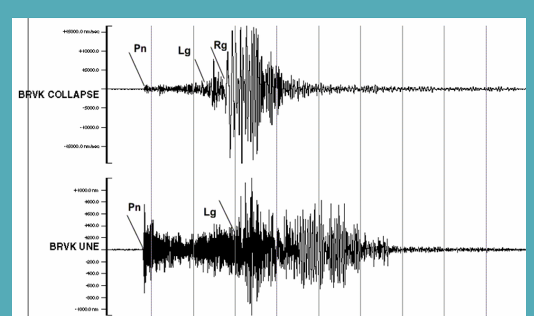

Figure 7. Seismic record of event occurred on August 1, 1994, t0=04-15-39.7, φ=47.833°, λ=67.451°, mb=4.7, K=12.2, Borovoye station (upper seismogram) and seismogram of peaceful nuclear explosion Meridian-2 conducted on September 19, 1973, t0=03-00-00.2, φ=45.758°, λ=67.825°, mb=5.1, Borovoye station (lower seismogram).

2. **Earthquakes near gold ore quarries of Northern Kazakhstan**

In the north of Kazakhstan the earthquakes are very rare, the most interesting of them was an earthquake near Borovoye resort. It occurred on May 8, 2003, 16-08-13.3, φ=52.825°N, λ=70.807°E, magnitude mpv=3.5, energy class 8.6 In Stepnyak town located 6 km away from the epicenter the shocks reached intensity 4 [10]. Windows and walls creaked, domestic animals were anxious. The witnesses said that the earthquake was felt as a strike and strong swaying. In many yards there were cracks of different size on the ground.

In addition to Stepnyak the earthquake was felt in the nearest settlements, and by some citizens of Astana (epicentral distance 193 km) with intensity 2.

Figure 8 shows a map of epicenter location of the earthquake occurred on May 8, 2003, and tectonic and rupture disturbances. The earthquake occurred at the area where tectonic earthquakes are unexpected. However, near the epicenter there are mines and faces of a gold ore mine. Gold production here started hundreds years ago, in 1928 gold placer became a mine, and in 30-s of the past century in mines and faces there was intensive production of ore using mechanisms of hard rock mining industry. Currently, the production at the deposit is suspended, and condition of mines is not supervised. Figure 9 shows seismograms of seismic event of May 8, 2003 by the IGR stations located near Borovoye settlement. The earthquake was recorded by all IGR stations at distance from 15 to 1080 km. It can be stated that, most probably, this was a collapse resulted in specific form of the event record: powerful surface waves, all signs of first arrivals in vertical components of the record are minuses.

The closest seismic station recorded the induced earthquake at Stepnyak settlement was Vostochnaya, epicentral distance 20 km. Figure 10 shows seismograms of events of different nature recorded by VOS station located in Kokchetav massif: collapse record of May 08, 2003, t0=16:08:14.2, φ=52.827°, λ=70.719°, mpv=3.3, epicentral distance 20 km; seismograms of tectonic earthquake of July 27, 1998, t0=17:39:13.0, φ=52.986°, λ=70.187°, mpv=2.9, at 60 km distance; the record of mining explosion of September 23, 2006, t0=10:23:02.4, φ=52.767°, λ=71.463°, mpv=2.6, epicentral distance 33 km. The earthquake record shows distinct arrivals of P- and S-waves, the latter is dominating, As/Ap>1, high-frequency record, S-waves attenuate poorly with time. The explosion record shows domination of low-frequency surface wave, clear arrival of P- and S-waves, the record is of lower frequency in comparison with the earthquake, $As/Ap_{expl} < As/Ap_{earth}$, the collapse record shows high-frequency P- and S-waves, surface waves are dominating, $As/Ap_{colp} < As/Ap_{earth}$.

Induced earthquakes at raw hydrocarbon fields

1. **Tengiz field**

A huge oil and gas field Tengiz is located at Atyrayu region of RK, 160 km away of Atyrayu city. The field was discovered in 1979, in April 1991 the industrial production of oil has been started. Tengiz field region is considered as aseismic region of Kazakhstan. In 1997, the International Seismological Centers have recorded two seismic events on the territory of the field: on February 19, t0=07-09-57.5, mb=3.4, and on April 6, t_0=21-42-10.0, mb=3.5. Until 1997, the international and regional seismic bulletins had no recorded events from that region. In recent years, the number of seismic events recorded by regional seismic networks from the investigated territory increases. In 2015, the IGR RK monitoring network recorded 10 seismic events with epicenters at Tengiz field, with magnitudes mb 2.8÷3.5, and during 2016, 18 events with magnitude mb 2.5÷3.5 were recorded (Figure 11). The closest to the field seismic stations AKTO and seismic array ABKAR are located in the west of Kazakhstan at ~570 km and ~600 km distance, respectively, do not record events smaller 2.1. The largest events for the investigated period, by data of the IGR network and international seismological centers, were the earthquakes of 2011/02/21, t_0=09:03, 2014/05/23, t0=21:03, 2015/06/16 t_0=21:25, 2016/05/07 t_0=19:27 (Figure 12), these were felt at the field with intensity 3 – 4. Some events, in addition to the IGR network, are recorded by global and regional monitoring networks [13]. Figure 13 shows a map of epicenter location of seismic event occurred on May 7, 2016, t_0=19:27:38.9 and seismic stations that recorded the event at regional and teleseismic distances. The event was recorded by 19 stations, the closest was Aktyubinsk AKTO stations included in the IGR and IMS networks and located 596 km away of the epicenter; the most distant seismic array was YKA Yellowknife included into the IMS and located in Canada at 7927 km away of the epicenter.

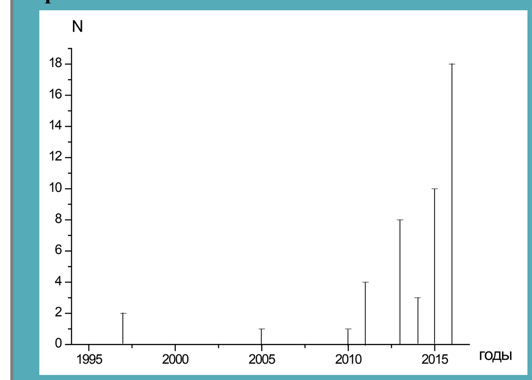

Figure 11. Annual number of earthquakes from Tengiz field region recorded by the IGR seismic network and global monitoring networks.

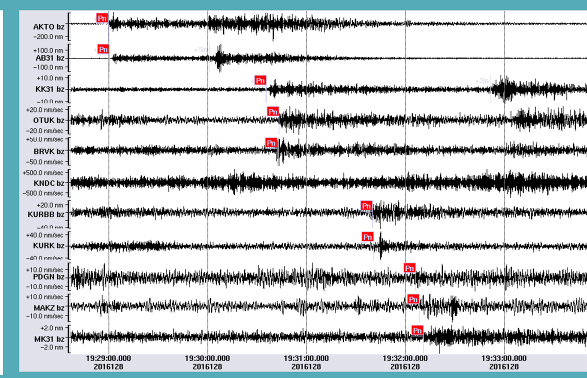

Figure 12. Seismic record of event occurred on May 7, 2016, t0=19-27-41.9, φ=45.97°, λ=53.85°, mpva=3.5, K=8.5 at Tengiz field region and recorded by the IGR stations network. Z-components.

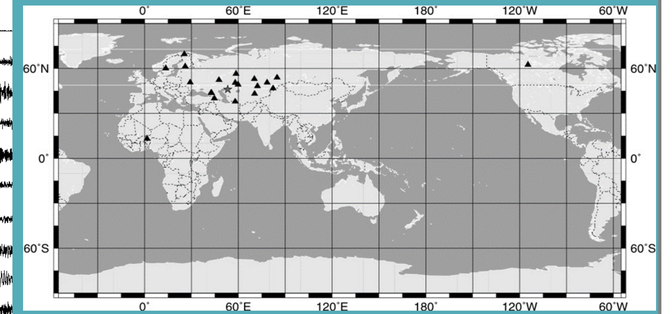

Figure 13. The map of epicenter location of seismic event occurred on May 7, 2016, t0=19-27-41.9 (star) and seismic station that recorded the event at regional and teleseismic distances (triangles).

2. **Zhanazhol field**

The largest in Kazakhstan gas-condensate Zhanazhol field was discovered on the territory of the west Kazakhstan in 1978, and has been developed since 1983. From 2004 the IGR network has recorded more than 80 events with epicenters at the field region with magnitudes 1.3-2.6; Figure 14a shows the events distribution by magnitudes, the major part of events was recorded in 2009 – 2010. Note that events are recorded at night and day time. Figure 14b shows the events distribution by day time. Figure 15 shows the seismograms of a seismic events from Zhanzhol field occurred on January 30, 2009, t0=17:58:01, φ=48.498678, λ=57.697256, mpva=2.1, K=4.7. As all events from the field region are quite small, they are recorded by Akbulak seismic array only (~180 km) and by Aktyubinsk seismic station (~220 km). Supposedly, we consider these events as induced. To precise the nature of seismic events at Zhanazhol field region it is necessary to install a special seismic monitoring network directly on the territory of the field.

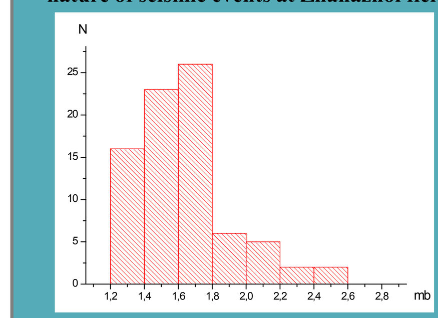

Figure 14a Distribution of events from Zhanazhol field region by magnitudes for the period 2004 – 2016.

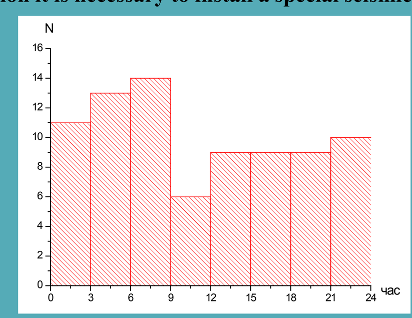

Figure 14b Distribution of events from Zhanzhol field region by day time (GMT).

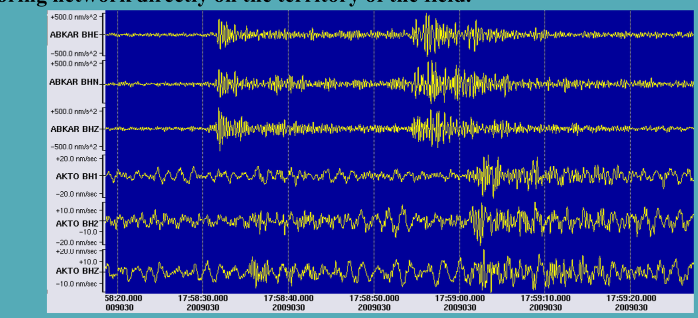

Figure 15 Seismograms of seismic event from Zhanzhol field region occurred on January 30, 2009, t0=17:58:01, φ=48.498678, λ=57.697256, mpva=2.1, K=4.7. Akbulak and Aktyubinsk stations.

Induced seismicity at former Semipalatinsk Test Site

According to the current maps of general seismic zoning of the Republic of Kazakhstan (2003), the territory of the Semipalatinsk Test Site (STS) is considered as aseismic. However, the investigations conducted recently and analyses of archive data showed that tectonic and induced earthquakes occurred in the past and happen currently at the Test Site territory and its vicinity. Maximum magnitude of the recorded earthquakes reaches 5 – 5.9 [14]. During the Test Site operation period, 340 UNE were conducted on its territory. It is known that during the short period of time (several hours – several days) after UNE the explosion cavity collapses [15]. Figure 16 shows one of the examples of seismic record of explosion "aftershock". At the present time, almost three decades later after explosions ceasing, the Test Site shows geodynamic activity at its infrastructure area. One of such appearances are seismic events of low energy. During 2005 – 2010 the IGR monitored the seismicity of the Test Site territory using temporary network of local stations [14]. In 2010, the field seismic station DEG1 recorded small surface events which record form looked like a collapse (Figure 17). Figure 18 shows and example of earthquake record from Degelen site region; epicenters of such events coincide with location of tunnels used at the Test Site.

Figure 19 shows seismograms of events of different nature recorded by DEG1 station located at Degelen site of the STS: seismograms of tectonic earthquake occurred on July 24, 2010, t0=0-58-24.2, φ=49.784°, λ=77.995°, mining explosion conducted at Karazhal quarry on July 24, 2010, t0=14-25-15.7, φ=49.869°, λ=78.049°; record of collapse on May 23, 2010, t0=23-17-27.9, φ=49.7802°, λ=78.0336° recorded at close distances to the station. The earthquake record shows clear arrivals of P- and S-waves, As/Ap>1. The explosion record shows dominating low-frequency surface wave, the high-frequency record of collapse shows clear arrivals of P- and S-waves, As/Ap<1.

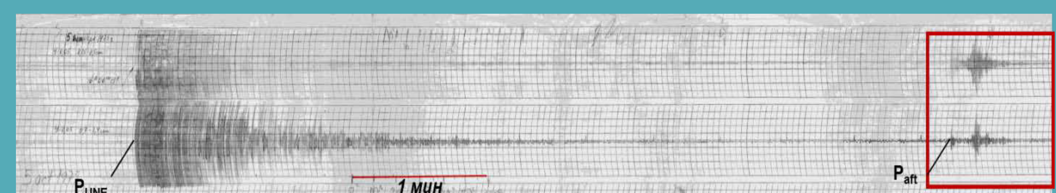

Figure 16. UNE seismogram conducted on October 5, 1975, t_0=04:27:00.0, φ=49.78306, λ= 78.08667, Degelen site. Kurchatov station.

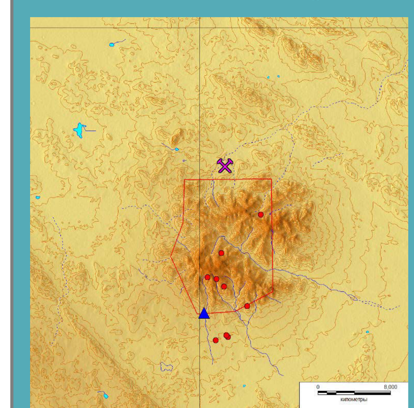

Figure 17. The map of seismic events epicenters location at Degelen site region of the STS. Circles – epicenters, triangle – DEG1 seismic station, cross – quarry.

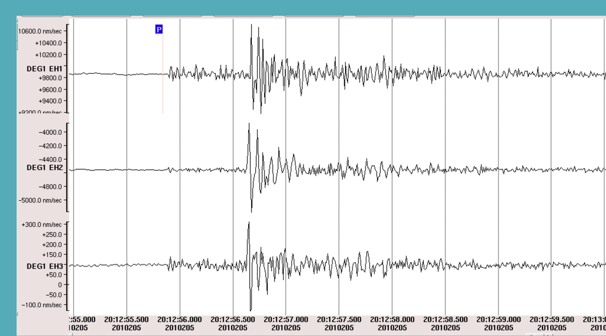

Figure 18. Seismograms of induced earthquake at Degelen site, July 24, 2010, 20:12:55.8, coordinates φ=49.6978°, λ=78.0440°.

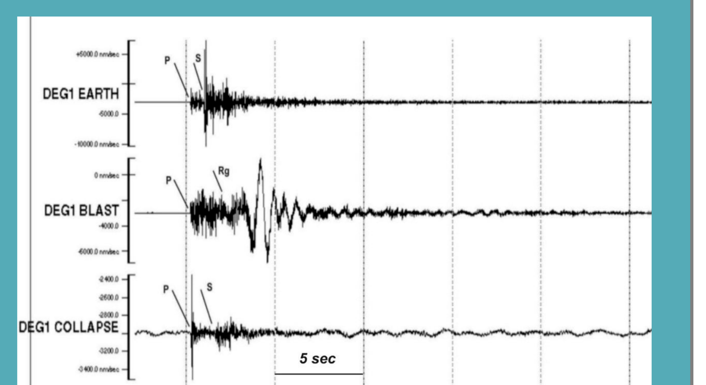

Figure 19. Seismograms of events of different nature recorded by field station DEG1, Z-component. Up – down: earthquake of July 24, 2010, t0=0-58-24.2, φ=49.784°, λ=77.995°; mining explosion at Karazhal quarry of July 24, 2010, t0=14-25-15.7, φ=49.869°, λ=78.049°; record of collapse of May 23, 2010, t0=23-17-27.9, φ=49.7802°, λ=78.0336°.

Natural-industrial (induced) earthquakes

On April 17, 2004, and April 2, 2016 there were earthquakes with magnitudes more than 3 in the north of Kazakhstan near Ryudniy town; the earthquakes were felt with intensity 3 in Ryudniy town. Both earthquakes occurred at night time, at less than 10 km depth, some had aftershocks. Figure 20 shows seismograms of the earthquake happened in 17.04.2004, t0=19:56:54.9 and recorded by the IGR seismic stations network. The region of Ryudniy town is aseismic; however, there are large quarries nearby, for instance, Sokolovskiy, Sarbayskiy and Kacharskiy where powerful explosions with maximum yield 500-600 t, at average 200 t, are conducted. Figure 21 shows a map of earthquakes epicenters (Table 5), faults and quarries near Ryudniy town. The network of the Institute of Geophysical Research records large amount of explosions from the region with energy class K=4.2÷8. The cumulative seismic energy of mining explosions in 50 km radius from the earthquake epicenters (Figure 22) reaches 3 GJ (2010, 2012). It is likely that regular intensive induced impact could cause the fluids uplift and generate and accelerate the process of these tectonic earthquakes preparation.

On August 2, 2003 at 00:53:08.2 GMT at Balkhash Lake bank, near the largest copper field Koyunrad, there was a large earthquake felt in Balkhash town with intensity 3-4 [16]. The event coordinates are φ=46.8032°N, λ=74.9628°E, mpv=4.8, K=11.3 (Figure 23). Despite that the north part of Balkhash Lake is traditionally considered as aseismic, the region experienced the earthquakes in the past, the largest of them occurred on September 27, 1988 westward of Balkhash town, mb=4.5. The earthquake of August 2, 2003 had tectonic nature, its origin related to the tectonic fault, focal mechanism – strike-slip, the event depth was ~13 km. Figure 24 shows seismograms of the earthquake recorded by the IGR stations, the wave pattern is typical for tectonic events of the region. However, the earthquake of August 2, 2003 occurred in close vicinity to Koyunrad copper field where large mining explosions had been conducted during several decades. Regular anthropogenic impact on the environment could accelerate the preparation process of the earthquake.

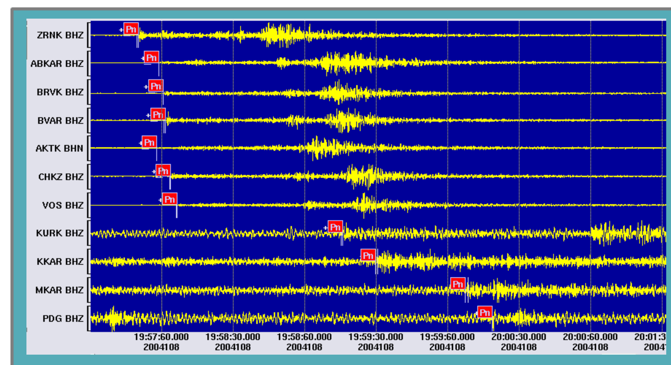

Figure 20. Seismic records of event occurred in 17.04.2004, t0=19:56:54.9 by seismic stations of the IGR network. Z-component.

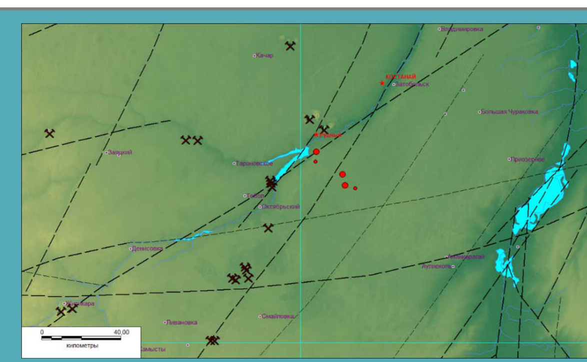

Figure 21. The map of earthquakes epicenters (Table 1), faults and quarries near Ryudniy town.

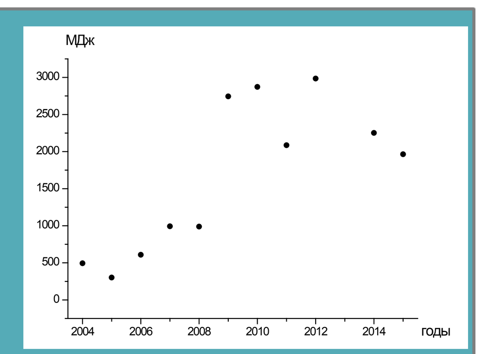

Figure 22. Annual cumulative seismic energy of mining explosions at the region of earthquakes epicenters near Ryudniy town.

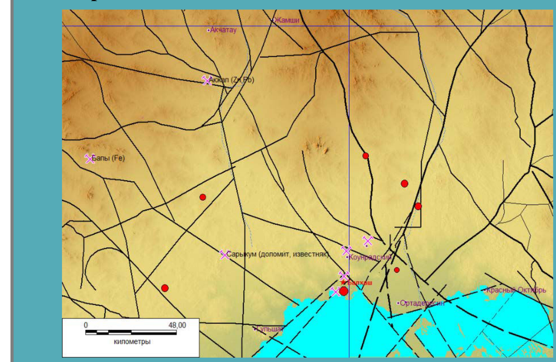

Figure 23. The map of epicenters location near Koyunrad field (circles), and tectonic and rupture disturbances (solid black lines and dashed lines). The map shows Balkhash town (star), mines and pits (cross).

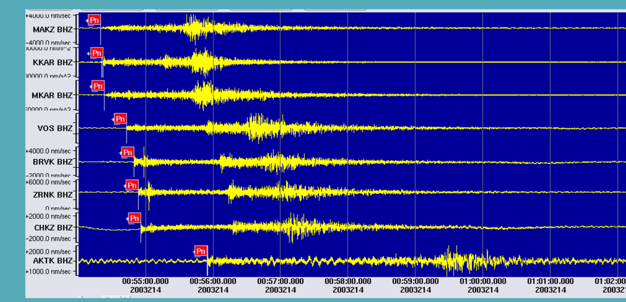

Figure 24. Earthquake seismograms of August 2, 2003 occurred at 00:53:08.2 and recorded by the IGR stations. Z-component.

On June 21, 2014 all seismic stations of the Institute of Geophysical Research network recorded quite large earthquake, mpva=5.2 in Central Kazakhstan near Karaganda city. The closest to the earthquake epicenter station, Ortayu, was at about 160 km south-westward of the epicenter. The event was also recorded by Borovoye (432 km), Kurchatov (426 km), Makanchi and other stations (Figure 25). The event of June 21, 2014 had forshock and aftershocks that were also recorded (Figure 26). The earthquake was felt with intensity 2 – 5 by MSK-64 scale at area 230×190 km [17]. Macroseismic investigation of epicentral territory of the earthquake was conducted by the staff of the Institute of Geophysical Research. Table 1 shows the parameters of seismic impact of the earthquake 06.21.2014, t0=06-30-03.2 by the closest stations of the IGR – ground acceleration A, and shakes velocity V. Figure 28 shows the earthquake response spectra by Ortayu station.

There is no doubts that the earthquake of June 21, 2014 is of tectonic nature; this is testified by its relation to the tectonic fault, reverse-fault mechanism, event depth ~10 km, availability of aftershocks, specific wave pattern and other. However, near the epicenter there is the world third-biggest Karaganda coal-basin, after Kuzbass and Donbass. The first mine opening was conducted in 1857. Currently, at the coal-basin area a large amount of powerful explosions are conducted. Regular induced impact could accelerate the preparation process of the earthquake.

Figure 28 shows the stereograms of focal mechanisms of the largest induced and natural-induced earthquake of Central Kazakhstan. The focal mechanisms were determined by the signs of first arrivals of body waves for three Zhezkazgan and two Karaganda earthquakes. In all cases the focal mechanisms are similar: shift type is reverse-strike-slip, rupture planes are of the north-west and north-east extension that corresponds to the orientation of seismic active faults of the region.

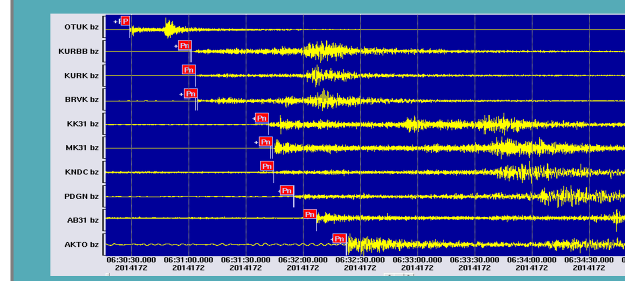

Figure 25. The earthquake records of June 21, 2014 by the IGR stations (Z-components).

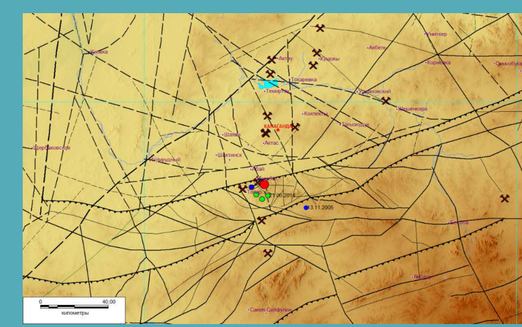

Figure 26. The map of earthquakes epicenters, faults and mines near Karaganda city. Circles – epicenters: blue – before June 21, 2014; red – main shock; green – aftershocks.

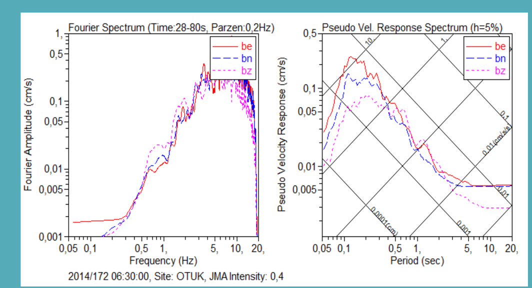

Figure 27. Earthquake response spectra of 06.21.2014 at 06-30-03.2. Ortayu station.

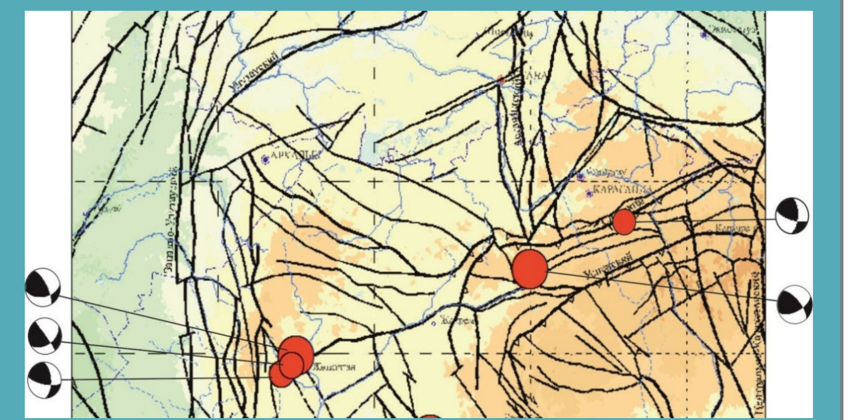

Figure 28. Stereograms of earthquakes focal mechanisms in the fragment of seismic active faults map.

Table 1. The parameters of seismic impacts of earthquake, 21.06.2014 at 06-30-03.2.

Station	Dist., km	Acm/s² E-W	Acm/s² N-S	Acm/s² Z	Vcm/s E-W	Vcm/s N-S	Vcm/s Z	T(A), s	T(V),s
OTUK	154	3,2	1,9	1,2	0,06	0,06	0,03	0.07, 0.2	0.07
KURK	424	0,1	0,1	0,05	0,005	0,003	0,003	0.33, 0.5	0.33
BRVK	432	0,05	0,1	0,04	0,003	0,005	0,003	0.23, 0.33	0.23

Conclusion

The information on the mentioned above regions of Kazakhstan where induced events were revealed is not comprehensive. In general, we have showed the events recorded by the IGR RK stations network for the past decades. Despite huge amount of induced events recorded by the IGR network these do not reflect the whole pattern of geodynamic activity at the regions of intensive induced impact. In total, for the huge territory of Kazakhstan the representative mpv magnitude by the permanent network of seismic observations is 3.5, but there could be small and micro-earthquakes that cannot be recorded so far. It is necessary to install special monitoring networks with dislocation of high-sensitive stations at the regions of large solid deposits, oil and gas fields, and the STS, as large earthquakes at such regions are not dangerous due to numerous victims, destructions and economic loss, but possible severe ecologic problems.

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