Induced seismicity in the area of nuclear test sites

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Introduction

Interest in seismicity induced by UNE is associated with several aspects:

1. Registration of UNEs aftershocks is one of the methods of the CTBTO On-Site Inspection. Passive seismological monitoring to localize the search area and help determine the nature of the events [Treaty, 1996; Ford, Labak, 2016].
2. Aftershocks can cause the destruction of cavities, increase crack formation, which can lead to environ mental consequences.
3. It is possible to predict the effects of postseismic activity of large earthquakes by studying UNEs aftershocks [Kitov, Kuznetsov, 1990].

Characteristics of aftershock sequences, such as dynamic characteristics, duration, total energy, etc. depend on the yield of the explosion, as well as seismotectonic activity in the area of the explosion.

Duration of the manifestation of induced seismicity was recorded in the range from 5 days to 25 months. The total energy release during aftershocks is 1% of the total explosion energy [Adushkin, Spivak, 1995].

An explosion produces an aftershock sequence that is similar in character to a sequence from earthquake, so the same Omory decay in time and Gutenberg-Richter distribution in magnitude [Ford, Labak, 2016].

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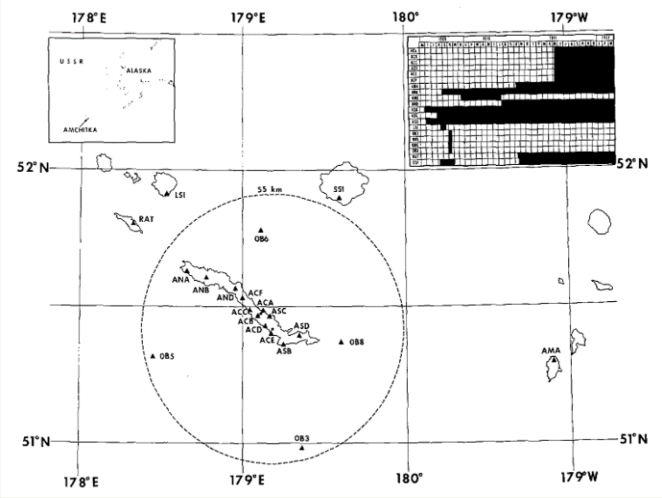
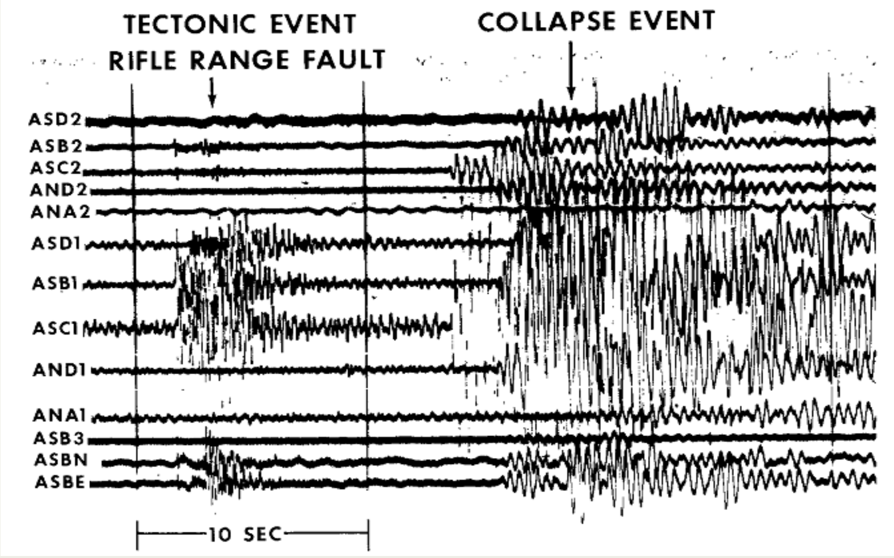
Cannikin and Milrow USA

Well-documented UNE-induced aftershocks were the seismic events on Amchitka Island (USA). A network of sensitive seismic stations and several ocean-bottom stations were installed specifically to record the powerful Milrow UNE of about 1 megaton on October 2, 1969, the Cannikin explosion of about 5 megatons on November 6, 1971, and the induced earthquakes [Engdahl, 1972].

The researchers considered three types of impacts: 1) seismic activity associated with the collapse of the explosion cavity, 2) induced tectonic activity in the upper crust of the island, and 3) impact on the natural seismicity of the region [Engdahl, 1972]. Each explosion was immediately followed by hundreds of small, discrete events (mB < 4), of similar focal mechanism and with a characteristic low-frequency signature, which were apparently related to the deterioration of the explosion cavity. This activity intensified, then terminated within minutes of a large, complex multiple event and concurrent formation of a surface subsided area that signaled complete collapse of the explosion cavity (MILROW, 37 hr; CANNIKIN, 38 hr). [Engdahl, 1972].



Map of Amchitka Island region showing distribution of seismograph stations. [Engdahl, 1972].



Two types of CANNIKIN seismic events recorded by Amchitka network about 18½ hr after detonation. [Engdahl, 1972].

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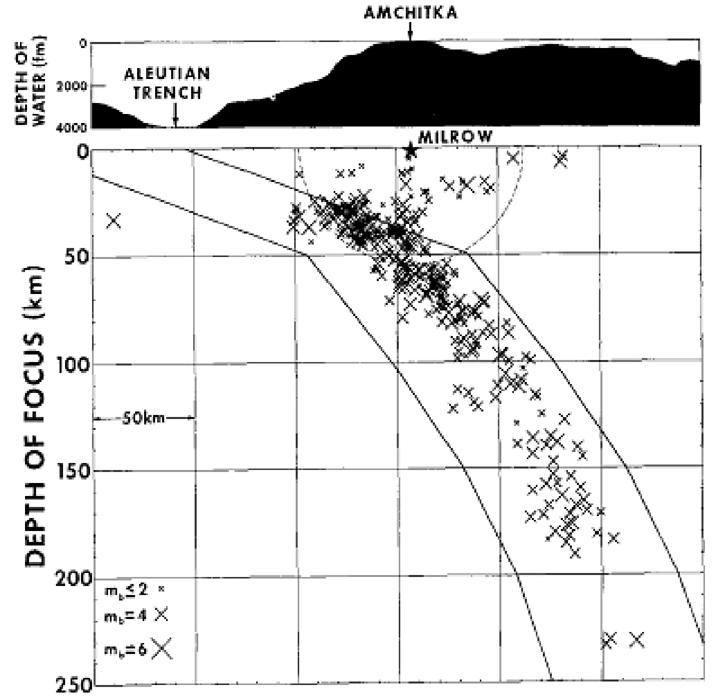
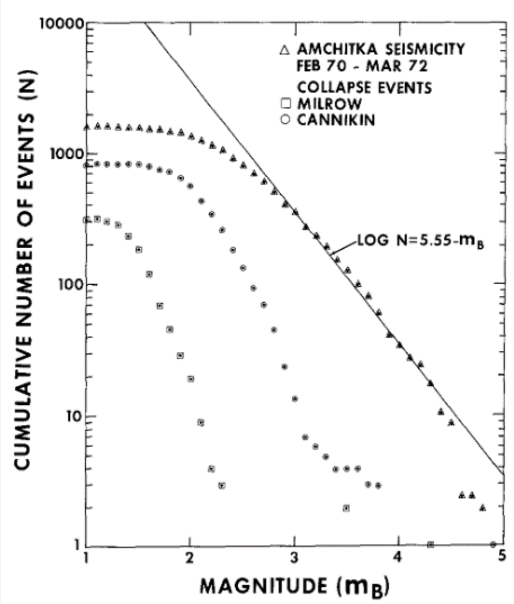
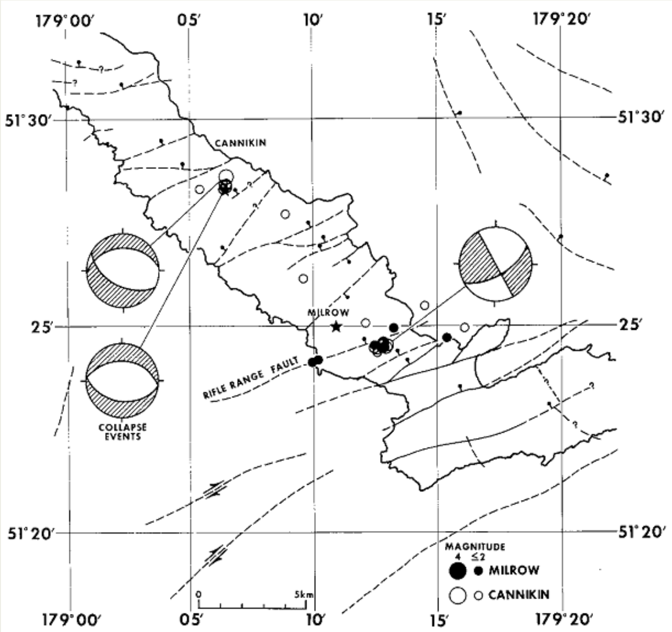
A number of small explosion-induced tectonic events, occurred intermittently for several weeks following each explosion—near the explosion cavity and up to 13 km southeast of CANNIKIN ground zero along the Island. These events were confined to the upper crust of the Island, had characteristic high-frequency signatures, and, near the Rifle Range Fault, had focal mechanisms which could be correlated with pre-existing faulting. The evidence points to a short-term interaction of the explosions with local ambient tectonic stresses. [Engdahl, 1972].



Focal depth distribution of natural seismicity in the Amchitka Island region. [Engdahl, 1972].



Cumulative number of events



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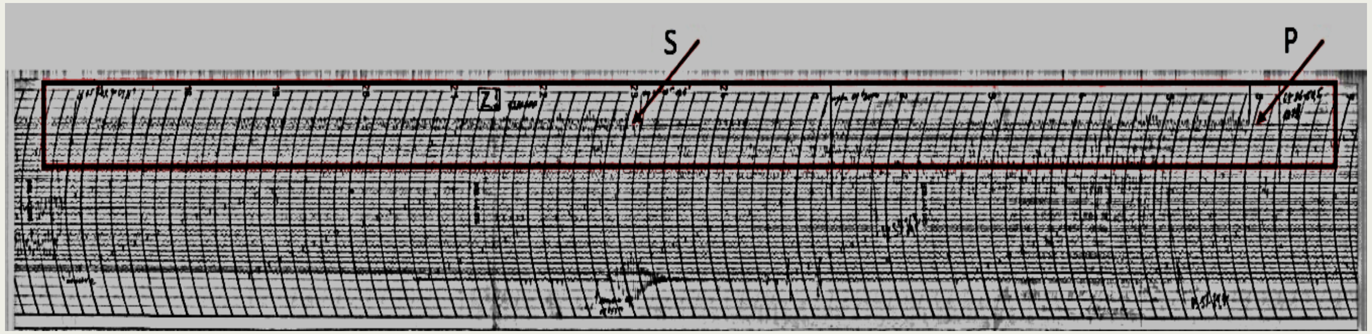
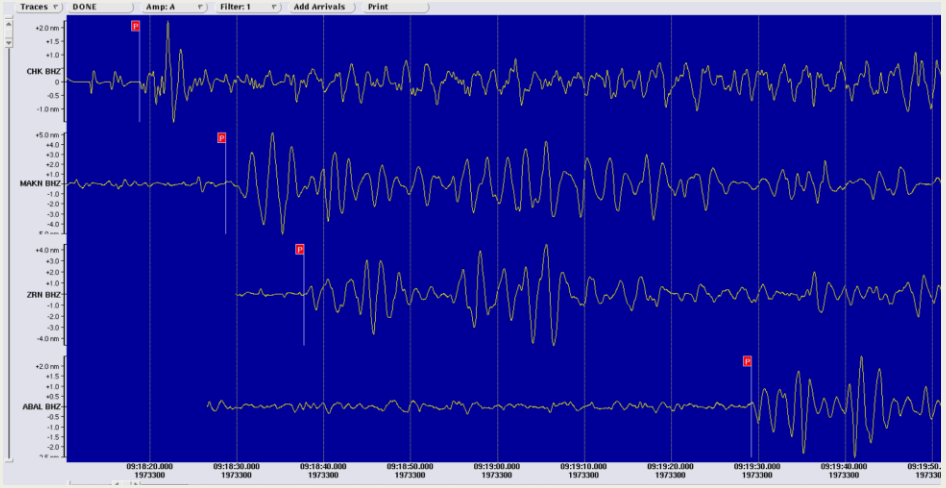
Novaya Zemlya USSR

Another example described in the literature is a multi-megaton explosion with a capacity of 4.2 Mt, produced at the Novaya Zemlya test site on October 27, 1973, with a magnitude of mb=6.9 [Khalturin et al, 2005; Adushkin, Spivak, 2007]. Within 14 hours after the UNE, 19 earthquakes were registered by global monitoring networks. Of these, nine events with magnitudes mb from 4.0 to 4.8 were processed by the International Seismological Center ISC.



Seismogram of the aftershock of the UNE at the Novaya Zemlya test site, 1974/07/22, t0= 01:32:19.5, φ=70.9797°, λ=52.1529°, Δ=2180 km. Zerenda station.



Seismogram of the aftershock of the UNE at the Novaya Zemlya test site, 1973/10/27, t0= 9:13:53.1.

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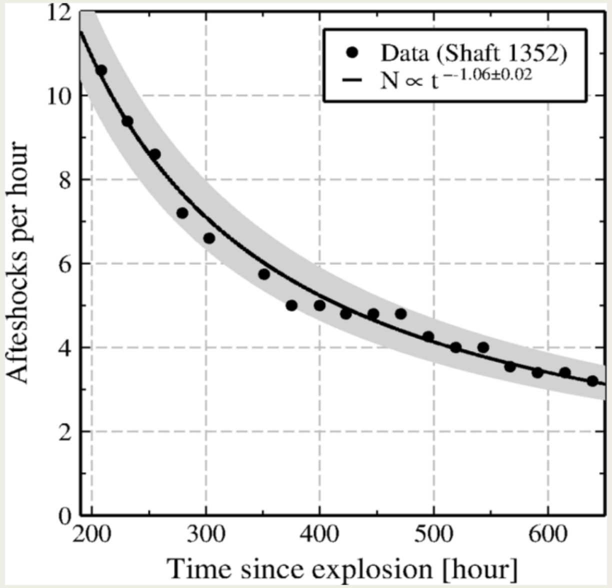
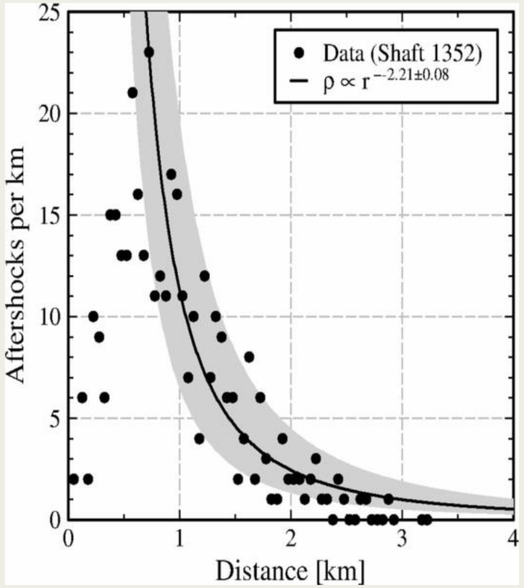
Semipalatinsk test site (USSR)

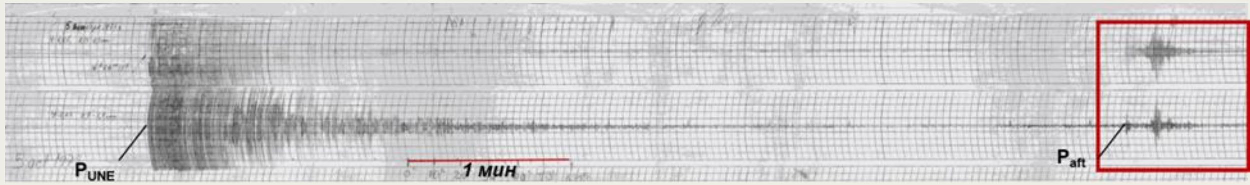
During 1981-1989, experiments were conducted at the STS to record UNE aftershocks using a small-aperture seismic array [Adushkin, Spivak, 1995]. A total of 5 UNEs with a capacity of 0.3-110 kt were studied, 4 UNEs were conducted in boreholes at the Balapan site, 1 in a tunnel at the Degelen site. Figures shows a graph of the number of aftershocks depending on the distance from the explosion produced in borehole 1352 (8 Jul 1989, Y=35 kt) and a graph of the number of aftershocks depending on the time after the explosion produced in well 1352 (8 Jul 1989, Y=35 kt) [Adushkin, Spivak, 1995].



Aftershock rate for the Shaft 1352 explosion [Adushkin, Spivak, 1995]. The shaded area is the formal error in the model



Aftershock linear density for the borehole 1352 explosion [Adushkin, Spivak, 1995]. The shaded area is the formal error in the model



Seismogram of the UNE on October 5, 1975, t0=04:27:00.0, φ=49.7831, λ= 78.0867, and its aftershock, Degelen site. Kurchatov station.

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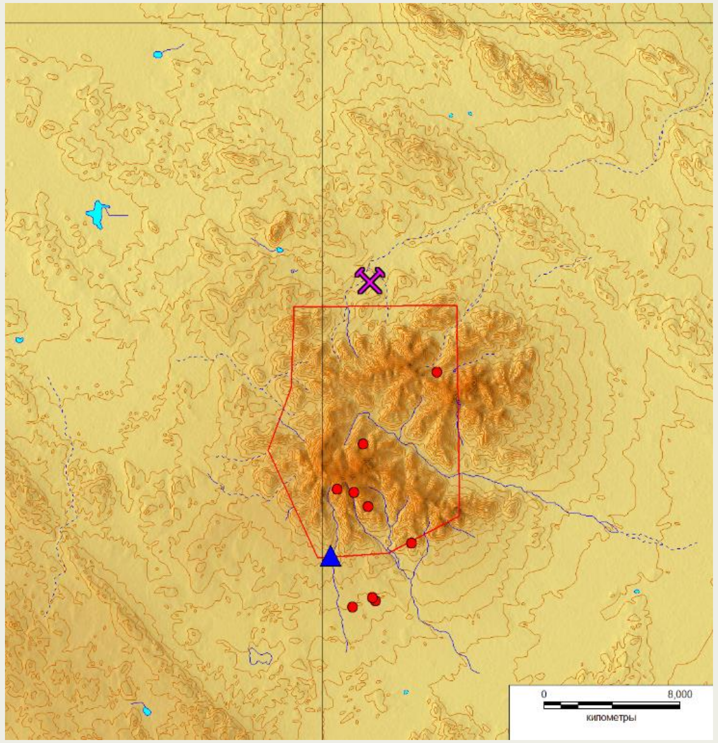
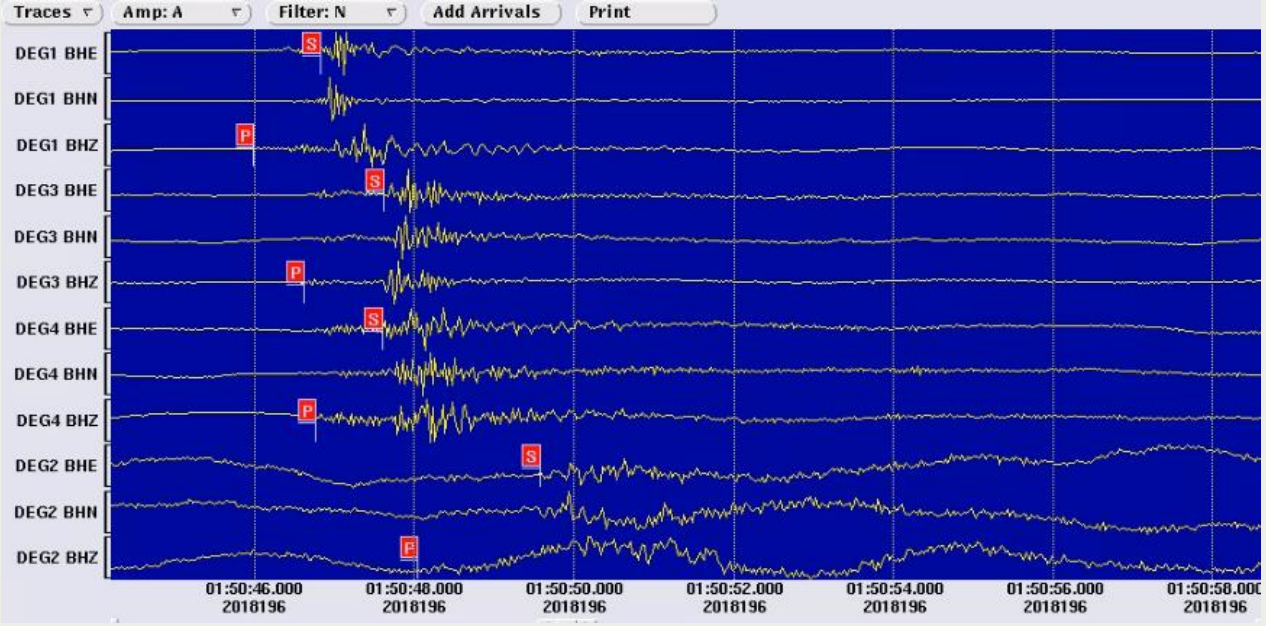
The local network stations managed to register seismic events with epicenters near tunnels in the area of the STS (the Degelen test site) during the projects for monitoring of local seismicity 2005-2010, 2018-2023. These events had small magnitudes. All events registered by the local network stations can be divided into 2 classes: earthquakes and collapses. It should be noted that weak events at the STS area are registered almost 30 years after the UNEs.



Map of the epicenters of seismic events in the area of the Degelen test site, registered in 2010. Circles are epicenters, triangle is the DEG1 seismic station, cross is the quarry.



Recordings of the collapse at the Degelen site, 7/15/2018, t0=1:50:45, with coordinates φ=49.7922º, λ=78.1088º, mpva=1.4, K=2.3.

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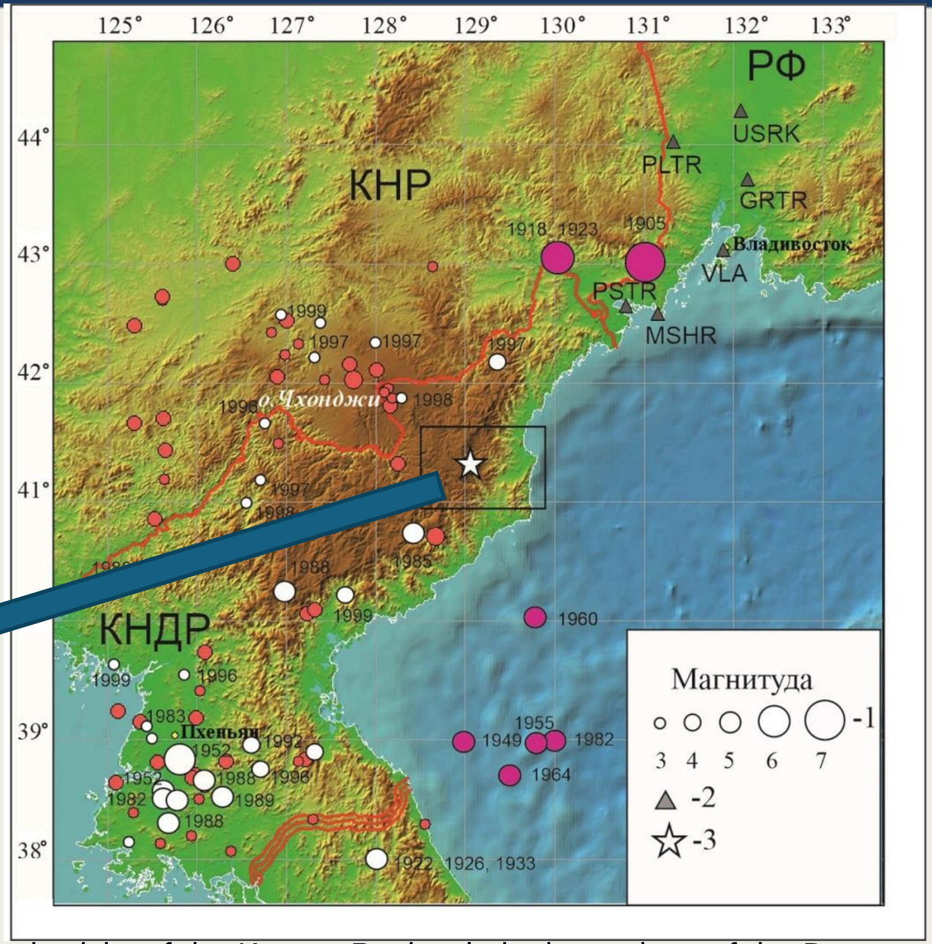
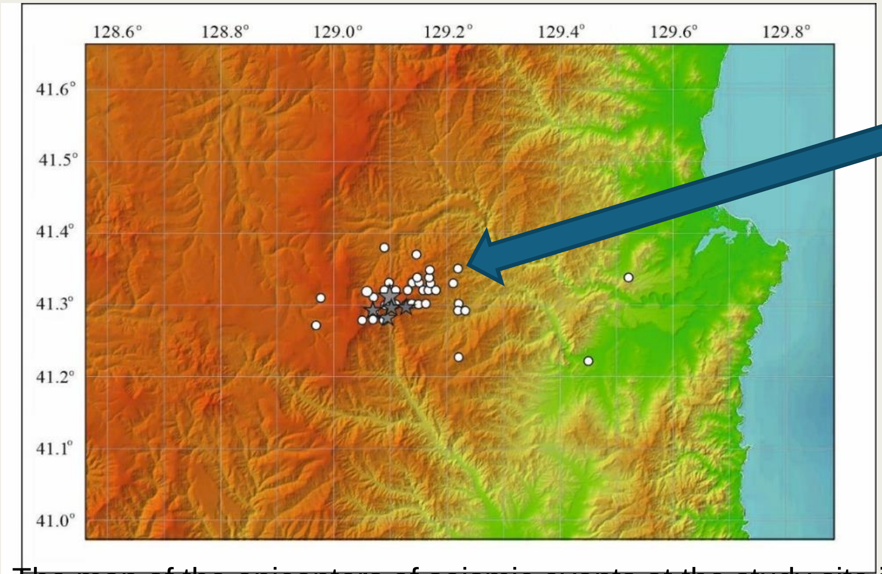
Punggye-ri test site (DPRK)

The most recent tests were conducted in the DPRK at the Punggye-ri test site in 2006–2017. Seismicity of the Korean Peninsula is of the low-level intraplate regime, which is typical of stable continental crust. It should be noted that in the territory of the study area near the Punggye-ri test site, no tectonic events were recorded for the period up to 2006.



Map of seismicity of the Korean Peninsula in the territory of the Democratic People's Republic of Korea according to ISC data.

1– earthquakes according to magnitude: circles filled in white – seismicity from 1900 to 1999; circles filled in red – seismicity from 2000 to 2006, before the first nuclear test, deep focuses (h≥400 km) are marked in pink; 2 – seismic stations of the network of the Federal Research Center of Geophysical Survey of the Russian Academy of Sciences; 3 – location of the test site. The black rectangle outlines the boundaries of the study area near the Punggye-ri test site.



The map of the epicenters of seismic events at the study site in 2018–2023 according to the South Korean Seismological Service (KIGAM–Korea Institutes of Geoscience and Mineral Resources)

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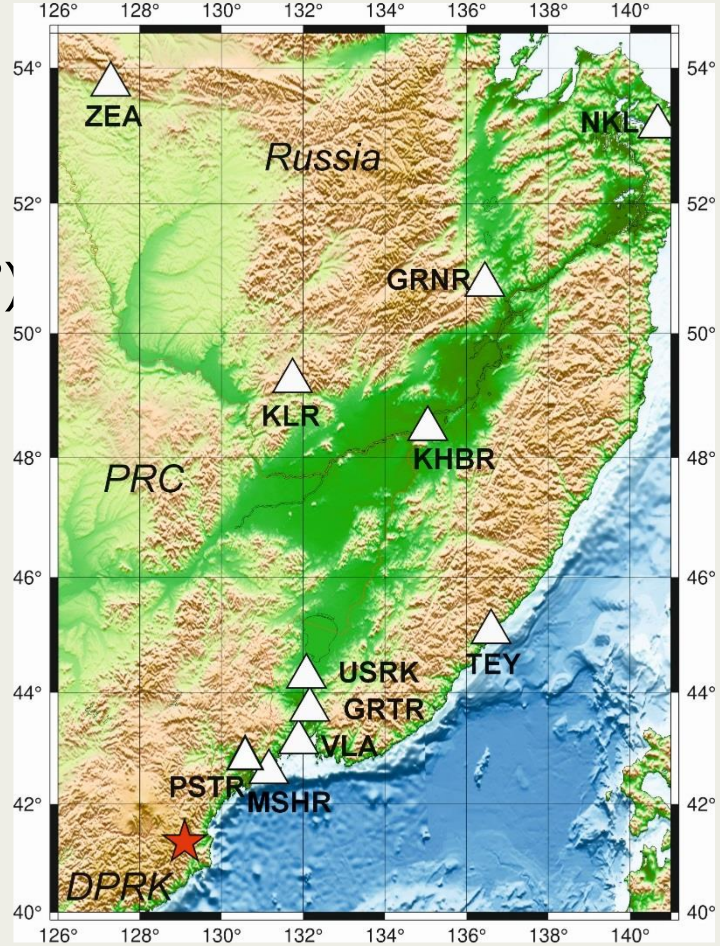
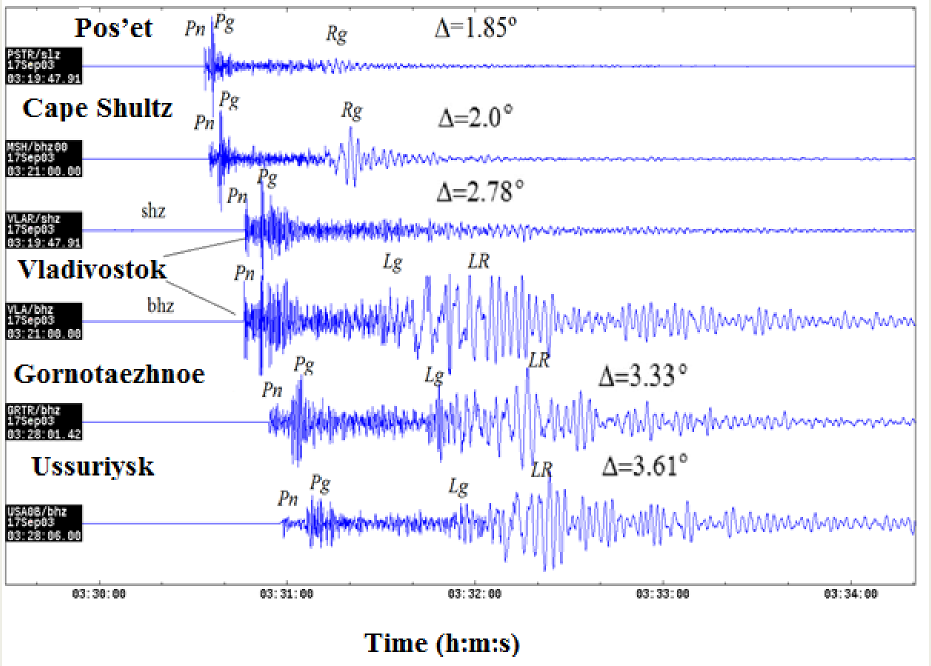
The Russian seismic network in Primorsky Krai

Pos'iet PSTR (Δ = 1.85º),
Cape Shultz MSHR (Δ = 2.00º),
Vladivostok VLAR (Δ = 2.78º),
Gornotaezhnoe GRTR (Δ = 3.33 °),
Ussuriysk USRK (Δ = 3.61 °),
Terney TEY (Δ = 6.64 °),
Kul'dur KLR (Δ = 8.17º),
Khabarovsk KHBR (Δ = 8.32),
Gornoe GRNR (Δ = 10.76 °),
Zeya ZEA (Δ = 12.48 °)



Map of the locations of the GS RAS stations in the Primorsky and Khabarovsk Krai of the Russia. Triangle – seismic stations; asterisk – location of the Punggye-ri test site.



The records of UNE 03.09.2017 at the nearest Russian stations

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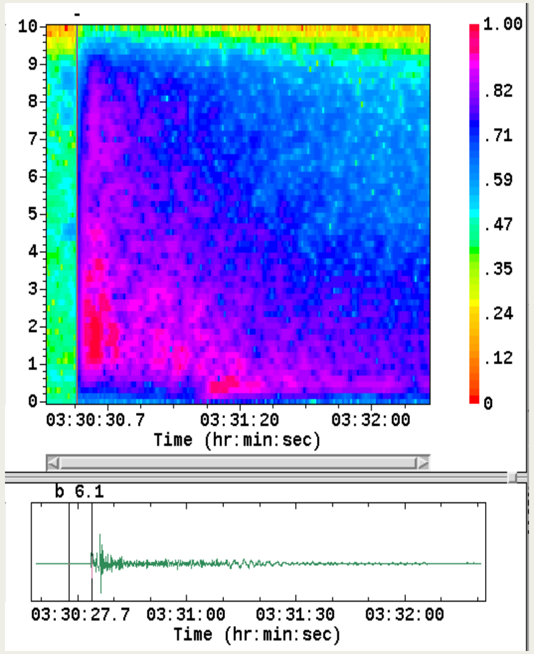
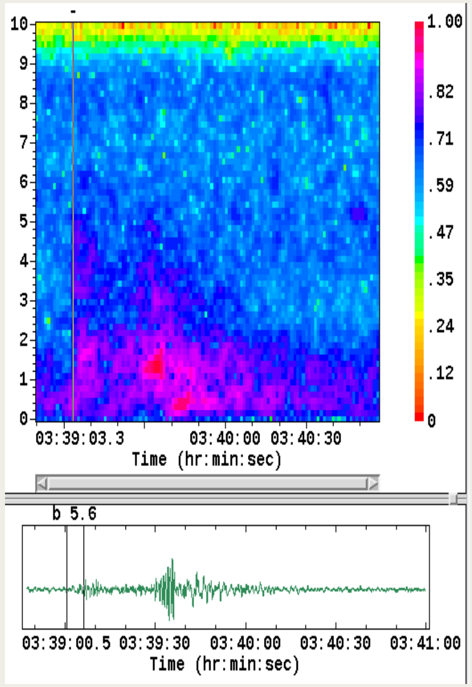
Station "Pos’iet" PSTR

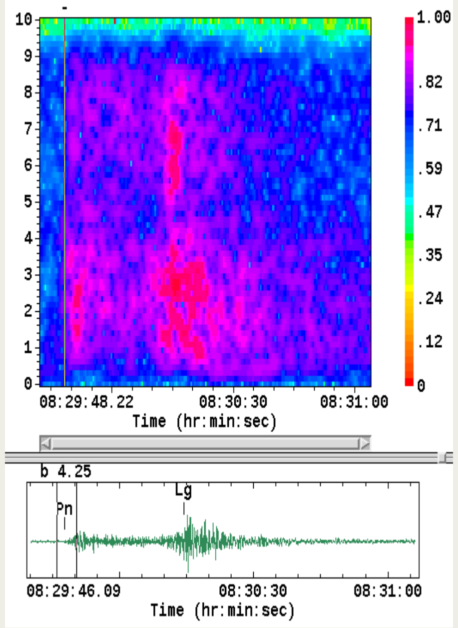
Differences in the spectral composition are also clearly visible on the spectrograms constructed from the records of the Posiet station. In accordance with the color legend common to the three figures, where the maximum energy is shown in red, we note that for UNEs the main energy is concentrated in the Pg-wave (Fig. a). for a collapse event in a surface wave (Fig. b), for an earthquake in shear waves (S, Lg) in a broad frequency band (Fig. c).



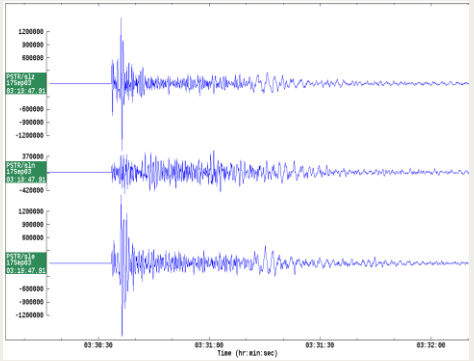
(a) UNE 03.09.2017 03:30

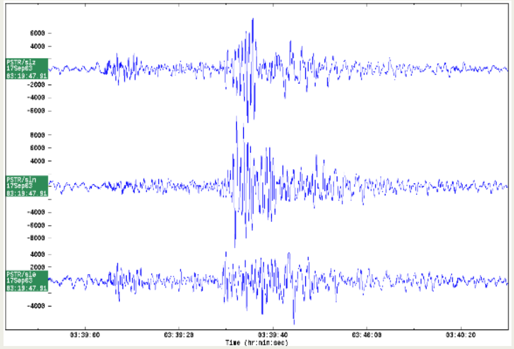


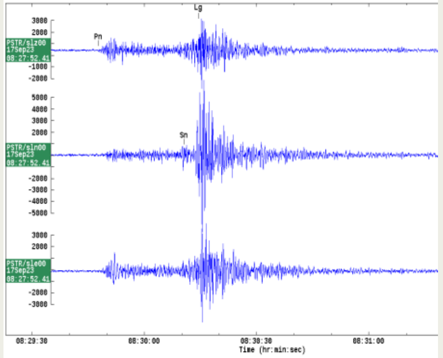
(b) Collapse 03.09.2017 03:38



(c) EQ 23.10.2017







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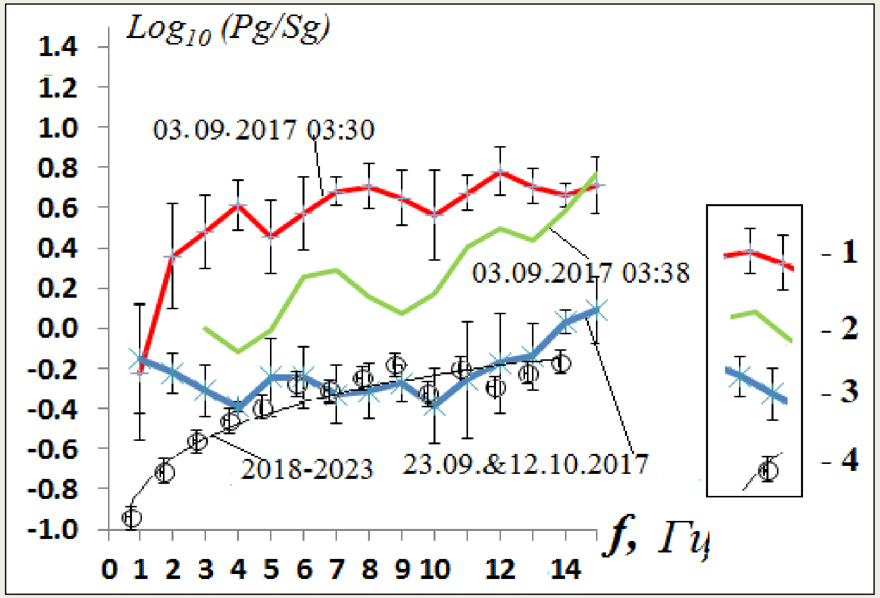
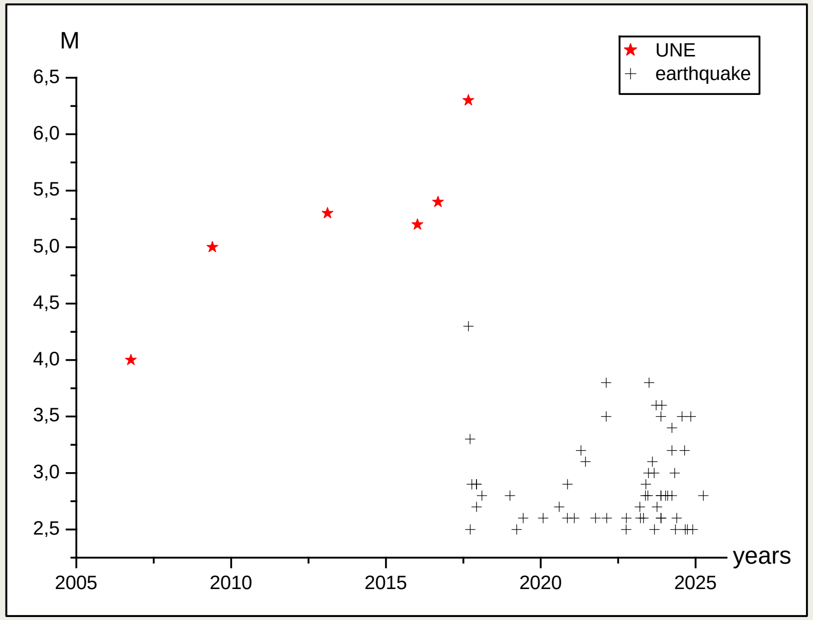
The graph of the spectral discriminant in comparison with previous events - UNE, collapse and earthquakes with the superposition of the results of a similar parameter of spectral amplitudes Pg/Lg for spectral amplitudes Pg/Lg of seismic events at the test site in 2018–2023 indicates that they belong to earthquakes.

Figure shows the dependence of seismic events from the Punggye-ri test site over time, it is clear that there has been a significant increase in the number of earthquakes in recent years (~7 years after last explosion), while the duration of aftershock sequences from UNE usually does not exceed 25 months.



Comparison of graphs of average network values of the spectral amplitude ratio Pg/Lg. 1 – for the UNE of 03.09.2017; 2 – for the collapse event (only for the Posiet station); 3 – for earthquakes before the UNE; for earthquakes of 2018–2023 after the UNE.



Realization of seismic events from the Punggye-ri test site area in time.

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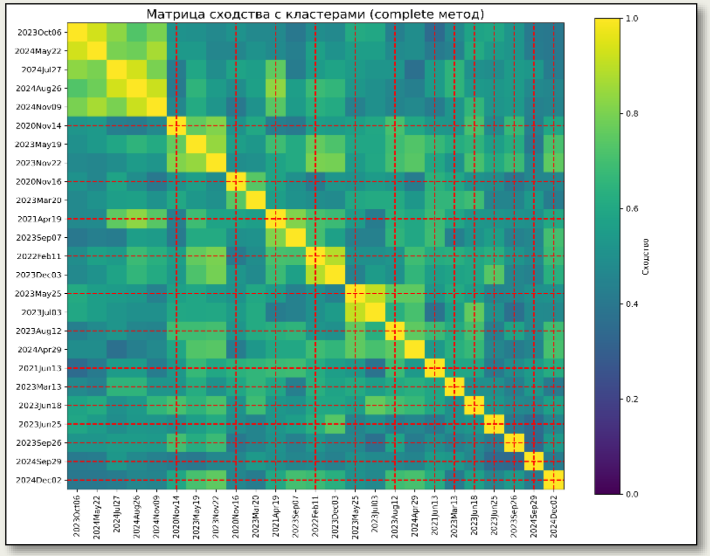
General ideas about methods of classifying events using cluster analysis are presented in [Ayvazyan et al., 1989]. For the analysis, a matrix of mutual pairwise distances is first constructed, $\{D_{ij}=D(X_i, X_j)\}$, recalculated from the correlation matrix using the formula:

$$D(s_1 s_2) = (1 - r_{12}^2)/r_{12}^2$$

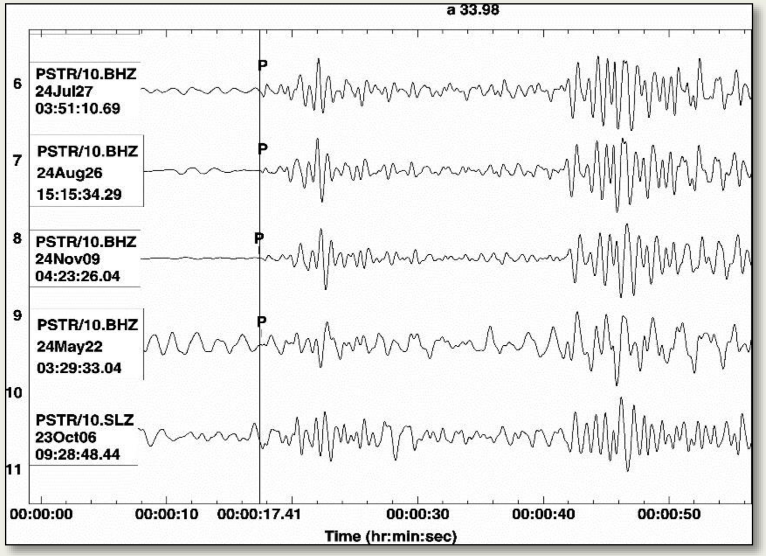
where r_{12} is the maximum value of the mutual correlation function for two events. We “complete” method of establishing a connection between the objects of the sample are implemented.

Analysis showed that the events from the Punggye-ri area were seismic swarms.

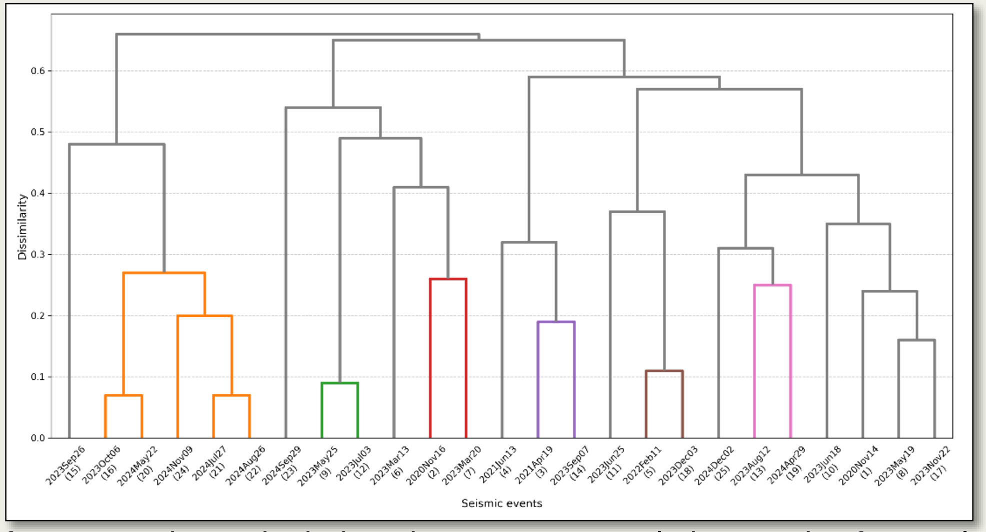
To construct the hierarchical dendrogram, the script “CLUSTER” was used, written for the software “ObsPy” (Beyreuther, M., Barsch, R., Krischer, L., Megies, T., Behr, Y., and Wassermann, J. (May/June 2010), ObsPy: A Python Toolbox for Seismology, Seismological Research Letters, 81 (3), 530-533.



a)



b)



c)

Clustering of Punggye-ri test site induced events. a - correlation matrix of mutual pairwise distances, {Dij=D(Xi, Xj)}, b - waveforms of seismic swarm events at PSTR station, filtered in the 1-2 Hz band, vertical component, c - dendrogram by the most distant neighbor method or complete link.

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Conclusion

The trigger effect occurrence of weak seismicity is observed in the vicinity of the epicenter of UNEs, which can be attributed to aftershock activity in a short period (on Amchitka Island, USA - several weeks in the immediate vicinity of the epicenter of the explosion).

Seismic events from the Punggye-ri test site registered ~7 years after last explosion. For these events, Omori's law is not observed. Analysis showed that the events from the Punggye-ri test site area were seismic swarms.

It is assumed that this effect is associated with the rise of deep fluids in the lithosphere, caused by the intense technogenic impact of UNEs on the geological environment.