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Passive Seismic Monitoring in Hydrothermal Field: Seismic Emission Tomography

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ABSTRACT

For last years seismic noise has been considered as highly informative field, containing the unique information about a crust structure. The volumes of the crust in which stress condition is differ from background regional stress, radiate seismic noise most heavily. These are zones of increased concentration of cracks, the fractures, the hydroterms and volcanic areas.

In present investigation we use the method of noise seismotomography for reconstruction of endogen microseismic emission field, which was observed by seismic array in hydrothermal area. For localization of seismic radiation sources the parameter Semblance was used. Semblance is the ratio of signal energy summed over all sensors of the array to the sum of energies of individual sensors calculated for each point of medium under the array.

The registration was held in the region of the Mutnovsky geothermal field (Southeast of Kamchatka, Russia). The areas with the high seismic noise activity were detected. They are related to the steam-hydrotermal production zone. The spatial distribution of the active sources is agree with the production zone configuration, the temperature field structure, the distribution of two-phase state and mono-phase state of the heat-transfer in the production zone. Also, sources of induced microseismic emission have been detected as the result of the passage of seismic waves from the teleseismic earthquake.

1. INTRODUCTION

The ability to radiate a microseismic noise is one of the fundamental properties of the geophysical medium along with a heterogeneity, nonlinearity, variability in time, vibrosensibility, tensiosensibility. Some years ago the background noise signals were considered in a seismology as an annoying hindrance only. The conception of a power saturation, microactivity of rock and the seismic emission formed per last 20-25 years, have changed the relation to the natural origin seismic noise. Now the seismic noise is considered as highly informative field, it is containing the unique information about a medium, its structure and stress condition. This conception is used in the directions of the geophysics connected with the application of the natural unexplosive endogen sources of seismic waves.

The seismic noise is a superposition of microearthquakes and macrocrashes appearing spontaneously in a medium under the influence of external and internal factors. The volumes of a medium in which stress condition is differ from background region stress, radiate most heavily. This is zones of increased concentration of cracks, the fractures, areas of high temperature gradients and geochemical processes. The hydroterms and volcanic areas are intensive sources of seismic radiation too. But high level of industrial noise within the large territories and low level of the useful signal are the reason complicating study of seismic emission and evoking the skeptical relation to the fact of this phenomenon existence.

In present investigation we use the method of noise seismotomography for reconstruction of microseismic emission field, which was observed by seismic array in hydrothermal area. The source of information is the field of continuous endogen seismic radiation. It is a non-traditional source of the information. The wave field is registered on a surface by the seismic array. Such approach allows to locate the subsurface sources of the endogenic noise and to reconstruct the field of the emission intensity in the internal points of the medium.

Usually the registered wave field mode is the random process generated by multiple sources in the medium. In this case noise field is not correlated. But the situation changes if there are intensive separate sources of seismic emission in the medium. Then the spatially-coherent signals appears in the multichannel recording of the array we can locate the noise sources and estimate their intensity.

Seismic emission tomography is method of passive seismic monitoring. With the current industry trend toward instrumented oil and hydrothermal fields and smart well completions, the permanent deployment of geophones or other acoustic sensors to complement standard engineering gauges is being promoted as a way to map reservoir dynamics. The biggest push is from the timelapse seismic practitioners, although the deployment of permanent seismic instrumentation also is potentially an ideal route to monitor passive seismicity.

Passive monitoring of acoustic emissions, or small magnitude microearthquakes (microseismicity) associated with stress changes in and around the reservoir, also can be used to image the reservoir dynamics. Passive monitoring has the benefit of more fully utilizing the seismic sensors to monitor during the periods between the conventional seismic surveys and offers complimentary information to both active time-lapse images and engineering measurements. Microseismic events, related to either induced movements on preexisting structures or the creation of new fractures, capture deformations as the rock mass reacts to stresses and strains associated with pressure changes in the reservoir. The microseismicity can be used to localize the fracturing or to deduce geomechanical details of the deformation.

Seismic instrumented exploited fields should open up new potential applications for passive monitoring, whether it be on its own regard or as added value for an active application. With more case studies showing how the technology can be used in reservoir characterization applications, the technology will become more commonplace.

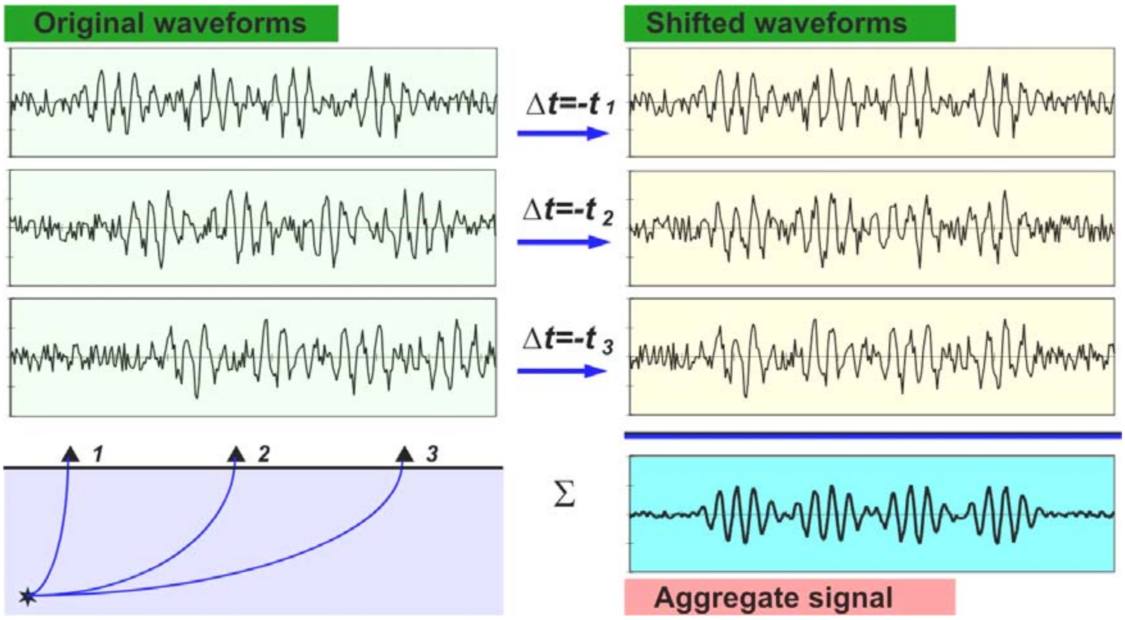

Figure.1. Scheme of the aggregated signal (signal summed over all sensors after temporal shift) construction. Triangles – seismometers of array, "star' – point of seismic array tuning (or emitted point). Length of recorded signal is 15 c.

2. TECHNIQUE

The data are analyzed by the extraction of the signals coming from different points of the investigated volume. The temporal shift (Δt)that appropriates to signal travel-time from array turning point to the recording point (seismometer) is entered. The hodograph (velocity structure) for the researched region is known. Then the recording areas are summarizing. The obtained aggregated seismogram is used for calculation of a power evaluation, which quantitatively characterizes an emission power of a medium in a tuning point.

For determination of seismic radiation sources the parameter Semblance (***S***) was employed (Neidell and Taner, 1971, Nikolaev, 1987, Tchebotareva, 2000). This parameter characterizes the parity between useful signal and hindrance. Semblance estimation is found as a ratio between the energy of a signal summed over all sensors (a_{ijk}) (some aggregated signal) and the sum of signal energies for each sensor separately (b_{ijk}). Parameter ***S*** is calculated for each point of medium under the seismic array:

$$S_{ijk} = \frac{\sum_{n=1}^{N} a_{ijk}(t_n)}{M \times \sum_{n=1}^{N} b_{ijk}(t_n)}$$

$$a_{ijk}(t_n) = \left(\sum_{m=1}^{M} \beta_{ijkm} X_m \left(t_n - \tau_{ijkm} \right) \right)^2 ;$$

$$b_{ijk}(t_n) = \sum_{m=1}^{M} \left(\beta_{ijkm} X_m \left(t_n - \tau_{ijkm} \right) \right)^2$$

M - quantity of seismometric channels, ***N*** - length of signal row, ***n*** - number of count, $X_m(t_n)$ - value of the signal on the ***m*** channel, β_{ijkm} - geometrical spreading of the wave front, τ_{ijkm} - temporal shift of signal for synchronization, ***ijk*** - coordinates indexes for the tuning point.

Semblance is an estimation like signal to noise ratio. It is applied to selection of a weak useful signal, when the hindrance level is great. This estimation reacts to presence of weak coherent components at the signals, registered by array. This approach is well known and used for multichannel data analysis of various nature wave fields. (For example, in radiophysics and hydroacoustics).

The search of emitting sources was made in frequency band 3-6 Hz. The filtration of an initial signal was conducted by the digital octave filter. It was made for deleting of ocean storm microseisms (0.5-2 Hz) and highfrequency hindrance of wind.

The seismic noise is a superposition of the various types of seismic waves, emitting by the independent sources. Unfortunately, the use of monocomponent seismometers does not allow to apply the tuning by signal polarization. It is necessary to be limited of tuning by a wave hodograph only. The parameter Semblance was carried out separately for longitudinal and transverse waves. Thus the array was turned on focusing of the body waves fields independently.

The results were summarized on several parts of recording for easy finding of the most systematically radiating objects.

3. DESCRIPTION OF INVESTIGATED AREA

Kamchatka peninsula is the area of high tectonic, seismic, volcanic and geothermal activity. About 150 groups of thermal springs are known in Kamchatka but only a few of them have surface water temperatures reaching boiling point. Such springs, including geysers, are usually viewed as surface manifestations of high-temperature systems. These systems are confined to volcanic belts composed by fused foots of volcanoes basically of Pliocene-Quaternary age (Leonov, 2000). The main structural elements determining the position of high-temperature hydrothermal systems are faults that bound such troughs. These faults are rarely exposed on the surface, they are usually overlapped with a powerful sedimentary-volcanogene cover, but systems of recent (mainly late Pleistocene-Holocene) fractures stretching along the abyssal boundary are formed above them in this cover. Hydrothermal systems are located in places where faults bounding troughs of the basement intersect complicating faults having transversal or intersecting position. Stable and long-existing zones of permeability are formed in these sites. Magma and hydrothermal fluids are constantly rising along them and complex volcanic structures differing in polyorifice volcanicity and presence of extrusive domes of dacite and rhyolite composition are formed on the surface.

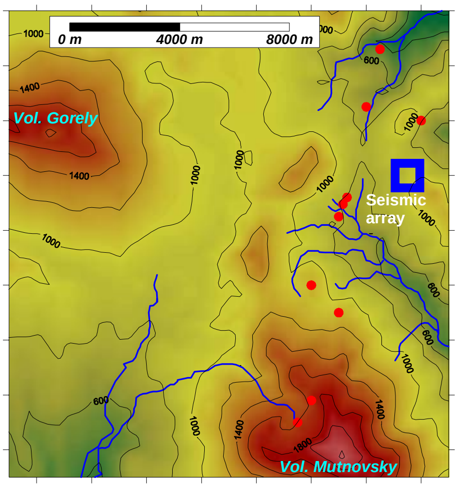

Figure.2. The map of the Mutnovsky geothermal field region. Red points – natural thermal manifestations

The Mutnovsky geothermal field is located in the southeast of Kamchatka peninsula, at an elevation of 800-900 m above sea level. The Mutnovsky high temperature hydrotherms are located at the intersection of fracture system, in the vicinity of youngest igneous rocks.

Hydrothermal field is close to two active volcanoes (fig.2): Mutnovsky volcano (last eruption was in 2000) and Gorely volcano (last eruption was in 1985-1986).

Mutnovsky is a liquid-dominate reservoir with fluid temperature from 250-300°C. Reservoir fluids contain approximately 1% non-condensable gas, mostly CO_2, pressure conditions are close to two-phase, and permeability is fracture-dominant. At the surface the state of heat carried is overheated and saturated steam. 3-D mapping of lithologic units and temperature distribution model within Verkhne-Mutnovsky site of the Mutnovsky geothermal field were presented by (Kiryukchin, 1998), fig.3.

Main specification of steam hydrothermal springs is two-phase state (steam and water) in the seat of discharge. Overheated waters boil up at the depth. On the layer of boiling up the steamisation, degassing and decrease of temperature together with compound physical-chemical transformation of steam-hydrotherms take place. Down from the boiling zone the hydrothermal springs are leached and over the zone the "steam cap" is formed. Two phase conditions are evident from the elevation about 1200-1300 m by drilling data.

According to the seismic risk zoning map Mutnovsky hydrothermal field belongs to an area having seismic intensity 9.

4. REGISTRATION

For the registration of microseismic noise emission in a steam-hydrothermal area 16-channel seismic array was used (Kugaenko, 2004). The disposition of the seismic array was designed for the control of the noise signals coming from the earth volumes adjoining to the North-East (NE) production zone of the Verkhne-Mutnovsky site of the hydrothermal field (two phase conditions, 250-300° C). NE production zone is in control by 4 wells and also natural steam manifestations. This zone has a NE strike and 60° SE dip (by drilling data).

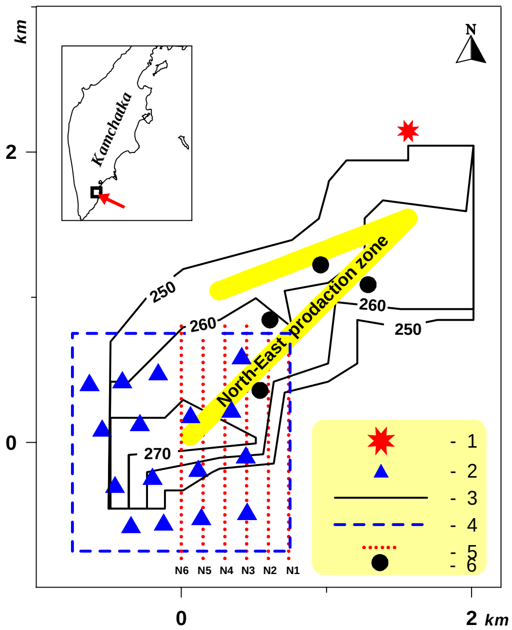

Fig. 3. Seismic array pattern, Verkhne-Mutnovsky site of Mutnovsky hydrothermal field, temperature distribution for the elevation –1000 m (by (Kiryukhin, 1998)), production zone and wells location.

1 – Verkhne-Mutnovsky natural steam manifestations;
2 – sensors of seismic array;
3 – isothermal lines (H=-1000 m); 4 – area of scanning;
5 – lines of vertical cuts;
6 – wells controlling North-East production zone

Main parameters of registration:
number of channels - 16;
sensitivity of channels - 5 nm/s;
dynamic range - 72 dB;
frequency band - 0.5÷20 Hz;
digitization - 1/100 s;
interval of processing - 40÷200 s.
coordinates of every seismometer were detected by GPS.

The employment of the monocomponent vertical seismometers only and the small number of sensors is the essential defect of the registration.

5. RESULTS

The areas with the high seismic noise activity were detected (Fig.4). A volume of the active sources of the microseismic emission was related to the NE production zone of steam-hydrotherms. The spatial distribution of the active sources is consistent with the production zone configuration that is known by the drilling data and the temperature field modelling.

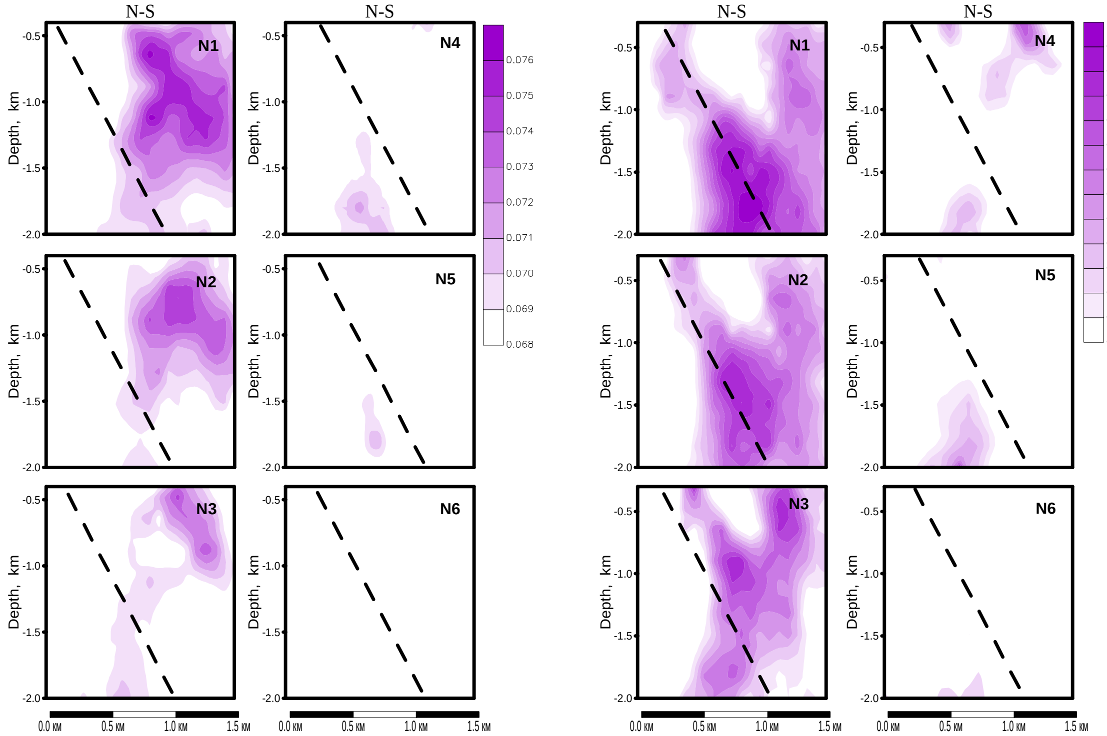

Figure 4. The distribution of seismic emission intensity for the series of the vertical cuts. Focusing by the longitudinal (left) and transverse (right) waves separately. The dot line – North – East production zone of Mutnovsky steam-hydrothermal field (by (Kiryukhin, 1998))]. A most active volume of radiation is related to the NE production zone

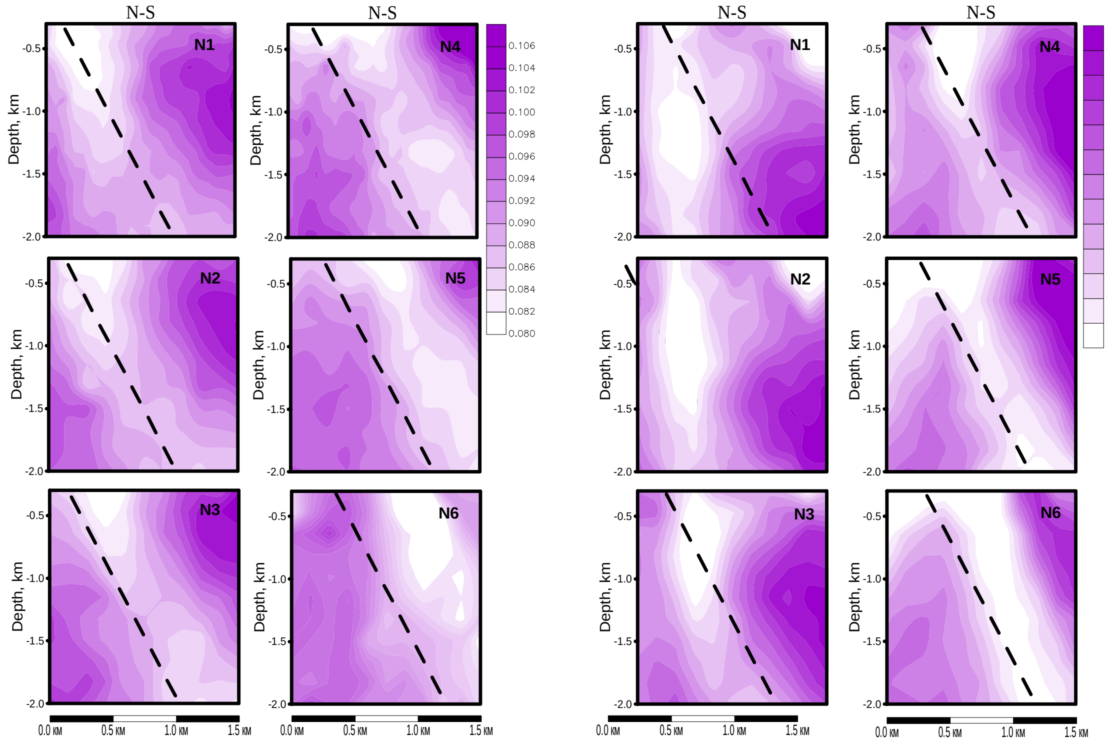

Figure 5. The distribution of seismic emission intensity for the series of the vertical cuts during passage of the waves from far eathquake . Focusing by the longitudinal (left) and transverse (right) waves separately. In this case the medium volumes adjoining to the production zone are emitted stronger than the production zone itself.

The sources of the longitudinal and transverse waves are spaced. The main reason of this phenomenon is boiling up of the overheated water at the depth and the formation of the two-phase (steam and water) mixture. Two phase conditions are evident from elevations above -1200 m in this site of hydrothermal field. The dynamic processes in overheated steam-water mixture are the source of longitudinal waves. The field of the transverse waves is formed by fractures of the fault area and by the high temperature fluid circulation in the production zone.

Also, the sources of induced microseismic emission was detected as the result of the seismic waves passage from a teleseismic earthquake (fig.5). We observe the image inversion. In this case the areas adjoining to the production zone are the most active. They are in conditions of high temperature gradients and active chemical processes. Significant quantity of energy is collected here. This energy is liberated as microseismic radiation by the external initiating influence of earthquake. In this case production zone that has increased permeability and is penetrated by macrocracks radiates much more poorly. Probably, production zone is in the conditions which are not allowing to the stress accumulation. So the radiation and energy release by the spontaneous microdestruction can pass without external influence here. The probable reason of this phenomenon is the various mechanisms of the stress releasing or low-frequency resonance in the porous rock. The basic elements of the initial image are restored through some tens minutes after earthquake (fig.6).

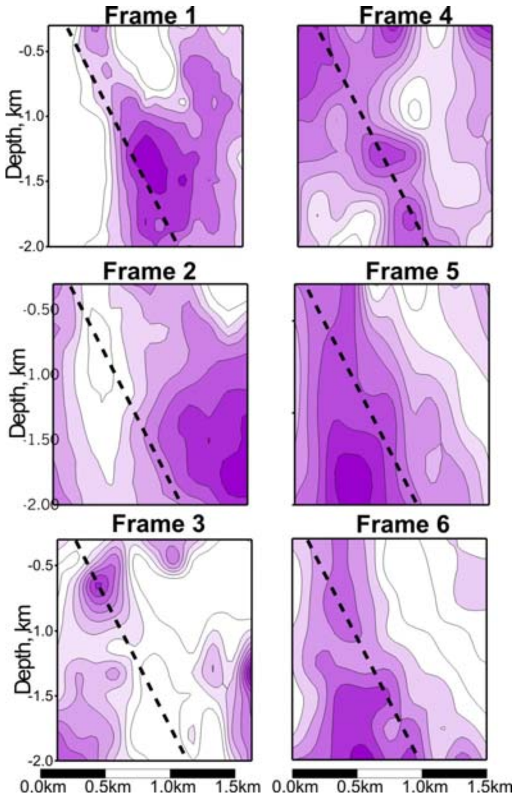

Figure 6. Change of the emission sources distribution induced by the passage of far earthquake waves. The vertical cuts for the various moments of time are given. (Focusing by the transverse waves).

Frame 1 – The distribution of the radiation sources before the moment of earthquake.
Frame 2 – The distribution the radiation sources initiated by seismic waves from earthquake.
Frames 3-6 – Reconstruction of the sources distribution through 2 mines., 10 mines., 20 mines., 30 mines after earthquake waves passage accordingly.

The application of the emissional tomography for research of environment structure and dynamics has some advantages. Application of seismic noise is possible everywhere, and not just in seismoactive areas. The method is simple and not high-priced. It does not require longtime registration and application of an additional source of a sounding signal. In conditions of the local seismicity absence the noise represents the unique information on an internal structure of environment and its dynamics.

6. CONCLUSIONS

Seismic noise active areas related to the North-East production zone of steam-hydrotherms are detected within Mutnovsky hydrothermal field.

Sources of the induced microseismic emission have been detected as the result of the passage of seismic waves from a teleseismic earthquake. The basic elements of the initial image are restored through some tens minutes

The spatial distribution of the active sources is consistent with:

- the production zone configuration that is known by drilling ,
- the temperature distribution and temperature field modeling,
- distribution of two-phase state and mono-phase state of the heat-transfer in the production zone.

The results confirm the availability of the seismic noise tomography application for study of structure and dynamics of a geophysical medium in the hydrothermal areas.

Two Geothermal Power Plants (12 MW and 50 MW) work within Mutnovsky hydrothermal field since 1999 and 2002 accordingly. And in the near future deposit exploitation will be intensified (planed power is about 300 MW). There are not any seismic stations for local seismicity investigation within exploited area.

By long-term observation of Kamchatkan regional seismic network it was considered that the local seismicity is absent within Mutnovsky hydrothermal field. But since 1996 by Kamchatkan regional seismic network data, some shallow earthquakes are happen here every year (Kugaenko, Chebrov, 2004). Probably we observe the appearance of inducted seismicity connected with deep drilling and beginning of geothermal field using. Deposit exploitation can chance reservoir pressure and internal conditions of upper crust and it can be the reason of inducted seismicity. Such earthquakes may cause damage.

In such situation all kinds of seismic monitoring in Mutnovsky hydrothermal field become more and more important. It will bring information on reservoir alteration by man-made influence.

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