

## PRESSURE PERTURBATIONS IN TWO PHASE GEOTHERMAL RESERVOIR ASSOCIATED WITH SEISMISITY

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### **ABSTRACT**

Cycles of the pressure observed during 1995-2002 years in the monitoring well of the two-phase fractured Verkhne-Mutnovsky (Kamchatka, Russia) geothermal reservoir shows 0.9-2.1  $10^{-3}$  Hz frequency range (8-18 min time periods) and 0.2-0.4 bars of amplitude as a dominant cycling parameters. Some earthquakes adjacent to East Kamchatka Volcanic Zone associated with fluid pressure perturbations in two-phase Verkhne-Mutnovsky reservoir: each earthquake may associate its specific pressure perturbation in the form of change cycling parameters (time period and amplitude). The possible models of the pressure cycling in two-phase fractured geothermal reservoir discussed.

### **INTRODUCTION**

Active hydrothermal systems and volcanoes are proved to be very sensitive to seismic events (Hill et al, 1993, Bjornson et al, 2002). East Kamchatka Volcanic Zone extends 500 km in SW-NE direction and include 21 active volcano and 8 large geothermal fields (Fig.1). Associated seismicity occur in a NW 50° dip NE strike subduction zone, where the most earthquakes took place (Fedotov, 1991) (Fig.1). Some examples of the pressure perturbations in Mutnovsky geothermal field associated to earthquakes were revealed and analyzed (Kiryukhin et al, 1998). To study the mechanism of pressure cycling behavior two numerical models (F-W and F-W-F) based on TOUGH2 code used (Kiryukhin and Pruess,2000). Although F-W (fracture-well) model reproduced pressure cycling parameters, "artificial" build-in switch (to open and close a well, depending of steam saturation) needed in the model, remaining the most questionable part of this model. F-W-F (fracture-well-fracture) model is completely closed in relation to external boundary conditions and only internal heat and mass balances used. F-W-F model explained high pressure amplitude (0.5 bar) long time periods (months) cycles, based on non-linear interplay of fast hydrodynamic and slow heat flows,

while F-W-F model was not able to match time periods of pressure cycling in the Verkhne-Mutnovsky geothermal field.

### **GEOLOGICAL SETTING AND PRESSURE MONITORING SYSTEM INSTALLATION**

Verkhne-Mutnovsky two-phase 230-270 °C fracture dominated geothermal reservoir occur in a SE60° dip NE strike fracture zone hosted by miocene sandstones, pleistocene tuffs and lavas intruded by diorites (Fig.2). Pressure monitoring using capillary tubing system was conducted in a well #30 in Verkhne-Mutnovsky during 1995 – 2002 time period. Capillary tubing system was installed at 950 m depth. Small 10-30 g/s steam flowrate assumed at wellhead. Gas composition of steam discharged: CO<sub>2</sub>- 77.2 %, H<sub>2</sub>S - 17.4% , N<sub>2</sub> 2.1%, H<sub>2</sub>-1.6%, weight gas content 7.1 g/kg. Initial feedzone conditions assumed to be liquid at temperature 233° C and pressure 46 bars.

Since Sept. 1999 Verkhne-Mutnovsky pilot power plant (12 MWe) began. Large and rapid pressure drop from 44 to 27 bars which happens Feb. 2001 may indicate switch from natural state heat pipe conditions at 47 bar saturation pressure to exploitation conditions, with 27 bars recharge inflow saturation pressure.

Pressure records 1995-2002 year reveals pressure cycling mode, which interrupted by pressure perturbations associated with earthquakes (Kiryukhin et al, 1998).

### **PRESSURE CYCLING MODE**

Pressure cycling mode of the well 30 was detected clearly from the first hours of pressure monitoring in September 1995, when pressure records were collected every 1 min. At that time pressure cycles were characterized by dominant time periods 7.5 min and pressure amplitudes 0.05 bars, while 9 cycles of 67 min time period and 1.0 bar pressure amplitude were detected too. Since December 1995 pressure

monitoring restarted with frequency of pressure records one per 5 min. In June 1998 it was found, that such frequency of pressure records is not enough to detect pressure cycles with time periods less than 10 min, and since that time pressure records were collected every 2 minutes.

To count pressure cycles parameters (time period, pressure amplitude) the following numerical procedure used: all pressure records were running averaged by 3, then pressure cycles were identified as a time interval between two pressure maximum, and then were counted numerically.

Fig.3 shows distribution of the number of pressure cycles vs of cycling pressure amplitude and cycling time period. The dominant cycles are: (1) - 8-12 min time period and 0.17 – 0.43 bars (17 – 43 kPa) amplitude; (2) - 14-18 min time period and 0.20 – 0.43 bars (20 – 43 kPa) amplitude; (3) 8-12 min time period and less than 0.05 bars (5 kPa) amplitude.

Figs.4 shows example of the pressure cycling (2) with average time period 17 min and amplitude 0.28-0.44 bars (28-44 kPa).

#### **PRESSURE PERTURBATIONS ASSOCIATED WITH EARTHQUAKES (1995-2002)**

Pressure records collected in well #30 Mutnovsky geothermal field during 1995-2002 reveals the pressure perturbations associated with earthquakes, which struck adjacent subduction zone area (158-161E, 51-54N).

**Short-term pressure perturbations.** Following are examples of the short-term pressure perturbations, associated with earthquakes.

***Example 1.*** Pressure perturbations, associated to earthquake (M=4.5, 21 Dec. 1996): pressure cycling amplitude increased up to 0.95 bars, pressure cycling period up to 60 min during 1 day after earthquake (Fig.5).

***Example 2.*** Pressure perturbations associated with earthquake (M=4.1, 25 Jan. 1997): pressure cycling amplitude increased up to 0.85 bars, pressure cycling period up to 90 min during 1.7 days after earthquake (Fig.6).

***Example 3.*** Pressure perturbations associated with earthquake (M=6.3, 1 June 1998): change of the time periods and amplitudes of pressure cycling (Fig.7).

***Example 4.*** Pressure cycling change (amplitude and time period) 20 days before small earthquake (M=4.2, 11 Oct. 2000) which followed by the strong earthquake (M=6.2, 8 Oct. 2001) in the same place one year later (Fig.8).

***Example 5.*** Pressure perturbations associated with earthquake (M=4.5, 21 Oct. 2001): after earthquake pressure cycling amplitude increased up to 5.5 bars. Large earthquake (M=6.2) occurs in the same place 12 days before (Fig.9).

**Long-Term Pressure Perturbations.** Following are the long-term pressure perturbations, which may associate with strong earthquakes (M>5.5) struck adjacent subduction zone area (158-161E, 51-54N) (Fig.10, Fig.1 below right):

Earthquakes #2 and #7: One long term pressure drop (1.7-2.0 bars, 20-25 days long) starting 1-5 months before strong earthquakes (Earthquakes #2 and #7).

Earthquakes #3 and #4-5: A number of pressure short term pressure drops (up to 30 bars) occurred during 5-7 months period before strong earthquakes (Earthquake #3 and #4-5).

Earthquake #6: Change of the time period and amplitudes during 20 days time period ending by a small earthquake (Fig.8), which is a pointer of a place of the future strong earthquake to be later (one year) in the same place.

#### **DISCUSSION OF THE CYCLING FRACTURE (CF) MODEL**

Lets consider two-phase (steam and water) fluid mixture with specified saturation in the open fracture with specified aperture. If the fracture aperture will cycle, then steam-water fluid will expand and compress in cycle mode too. With time periods less than 20 min, fracture aperture greater 0.1 m and pressure amplitude less than a 5 bar heat exchange between fracture fluid (steam 90%, water 10%) and ambient rock may be neglected and process may be expressed in terms of adiabatic (isentropic) expansion/compression of steam-water fluid itself (Fig.11).

Fig.11 shows in particularly that 17.5 % (3.5%) fracture aperture increase will induce 5 bars (1 bar) pressure decrease in two-phase (steam-water) fluid with initial saturation 0.90 hosted in the fracture. Then, pressure cycling with 0.2 – 0.4 bars amplitude observed in the well 30 may be explained by the fracture aperture cycling with the amplitude of 0.7-1.4 %, if the absolute fracture aperture is of order 0.1 m, then this cycling may be almost invisible length of 0.001 m (1 mm).

The possible source of those cycles may come from magma reservoir (volcanoes magma feed channels) cycling. The own frequencies of magma channels cycling may be derived from well known pendulum

formulae:

$$\text{Time period} = 2\pi\sqrt{L/g}$$

,where L - is a vertical length of magma channel, 130-190 km (Fig.12) , g – is gravitational constant, 9.81 m/s<sup>2</sup>. Substituting corresponding values in the formulae above, the time periods 12 - 15 min obtained. Those time periods match to the pressure cycling parameters observed in steam-water fracture dominated geothermal reservoir of the Verkhne-Mutnovsky geothermal field.

### **CONCLUSIONS**

(1) Cycles of the pressure observed during 1995-2002 years in the monitoring well of the two-phase fractured Verkhne-Mutnovsky geothermal reservoir detected 0.9-2.1 10<sup>-3</sup> Hz frequency range (8-18 min. time periods) and 0.2-0.4 bars as a dominant cycling parameters.

(2) Some earthquakes adjacent to Kamchatka subduction zone associated with fluid pressure perturbations in two-phase Verkhne-Mutnovsky reservoir. Each earthquake may associate its specific perturbation.

(3) The possible mechanism of pressure cycling in two-phase (steam-water) fractured geothermal reservoir may be related to adiabatic (isentropic) expansion/compression of the steam-water fluid with high steam saturation due to fracture aperture cycling (CF model). The possible generators of such cycles (0.7-1.7 10<sup>-3</sup> Hz) may be the vertical magma channels (130-190 km depth) of the magma reservoirs beneath of the East Kamchatka Volcanic Zone.

(4) High frequency pressure monitoring aimed to earthquake mechanisms study may be targeted to fracture dominated two-phase (steam-water) geothermal fields and active volcanoes, which cycles in the phreatomagmatic or steam eruptions mode. High frequency geodesic observations may be useful to verify relations between pressure cycling in two-phase (steam-water) geothermal reservoirs, magma reservoirs and strong earthquakes occurrence. Direct numerical modeling of the magma cycling processes in the magma reservoirs of different geometry associated to active subduction zones may be useful tool for this study too.

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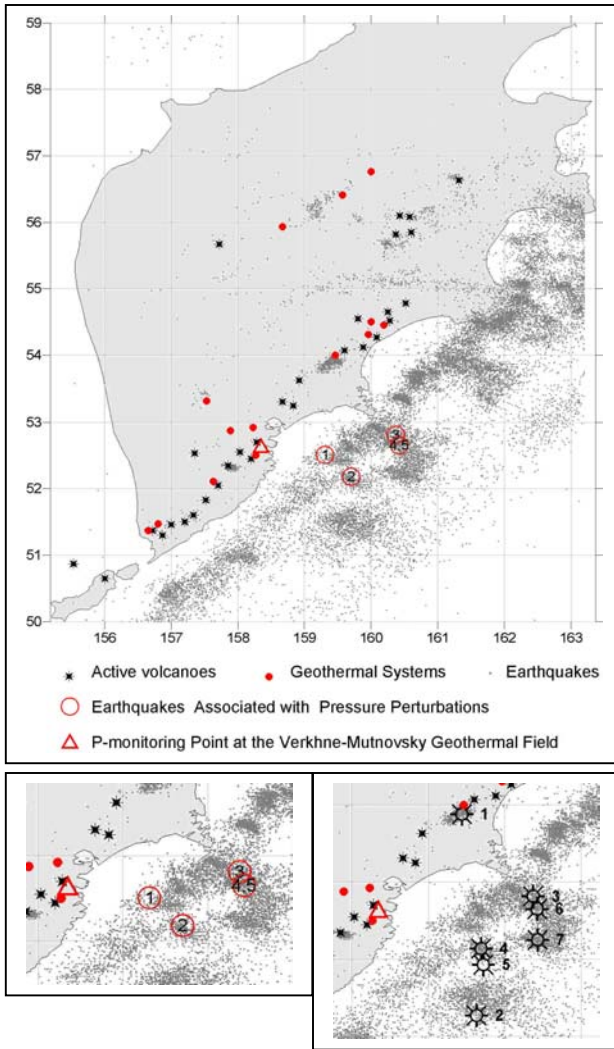


Figure 1. Figure above: Kamchatka active volcanoes, geothermal fields and earthquakes (1966-2002 data of Kamchatka EMSD GS Russia AS).

Figure below (left): enlarge part of figure above. Location of the P-monitoring point and earthquakes associated with pressure anomalies (examples 1-5 in the paper) in the Verkhne-Mutnovsky geothermal field.

Figure below (right): enlarge part of figure above with locations of the large earthquakes ( $M > 5.5$ ) took place during 1995-2002 year period.

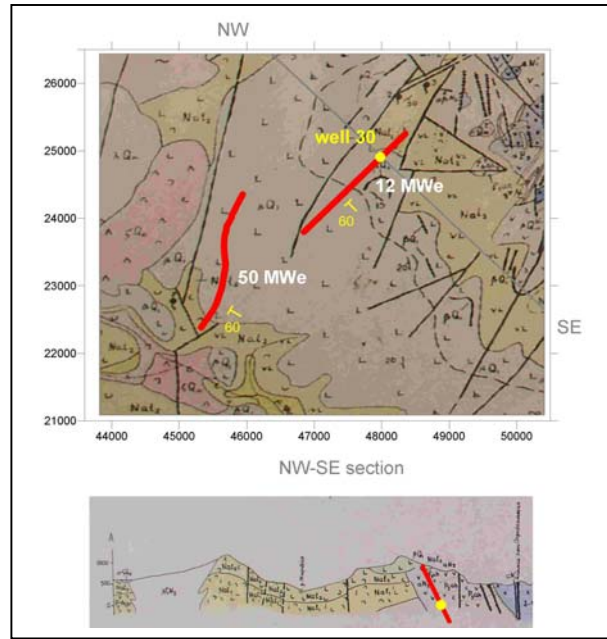


Figure 2 Mutnovsky geothermal field: geological setting (Samylov, 1978) superimposed by principal production zones (at-250 masl). Pressure monitoring point: well #30 (capillary tubing system at 950 m depth).

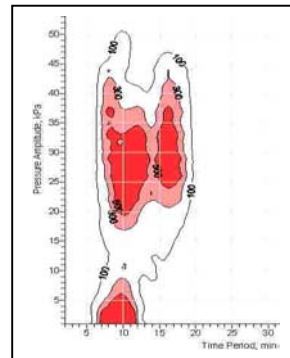


Figure 3 Distribution of the number of pressure cycles vs of cycling pressure amplitude and cycling time period (June 1998 - July 2002) (Number of cycles per unit square: 1 kPa x 2 min). Well 30, Verkhne-Mutnovsky geothermal field.

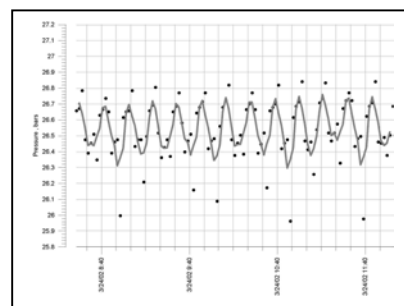


Figure 4 Example of the background pressure cycling: pressure records – black dots, running average (3) approximation – gray solid line. Running averaged time period 17 min, pressure amplitude 0.28-0.44 bar (28-44 kPa).

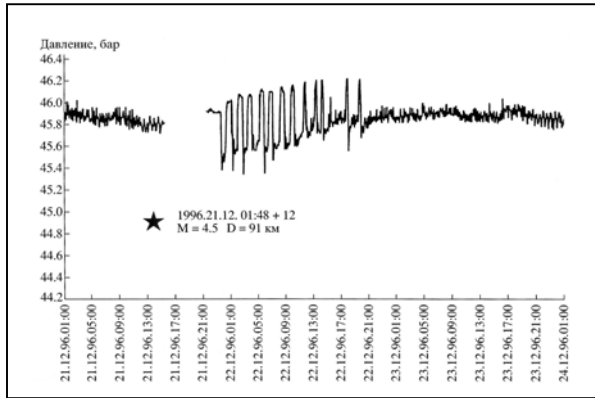


Figure 5 Pressure perturbations in Well #30, Mutnovsky geothermal field, associated with earthquake ( $M=4.5$ , 21 Dec. 1996): Pressure cycling amplitude increased up to 0.95 bars, pressure cycling period up to 60 min.

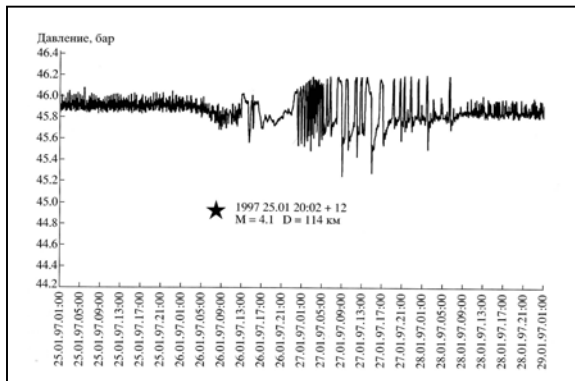


Figure 6 Pressure perturbations in Well #30, Mutnovsky geothermal field associated with earthquake ( $M=4.1$ , 25 Jan. 1997): Pressure cycling amplitude increased up to 0.85 bars, pressure cycling period up to 90 min.

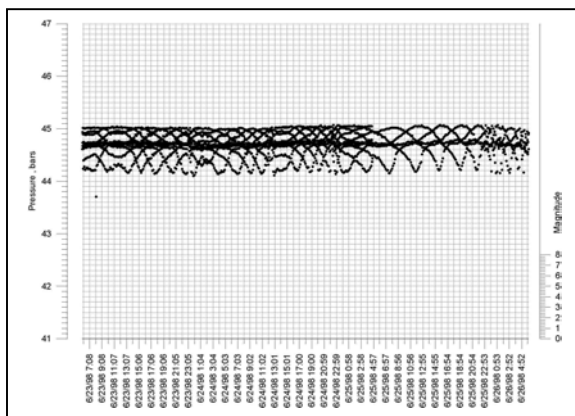


Figure 7 Pressure perturbations in well #30, Mutnovsky geothermal field associated with earthquake ( $M=6.3$ , 1 June 1998): change of the time periods and amplitudes of pressure cycling.

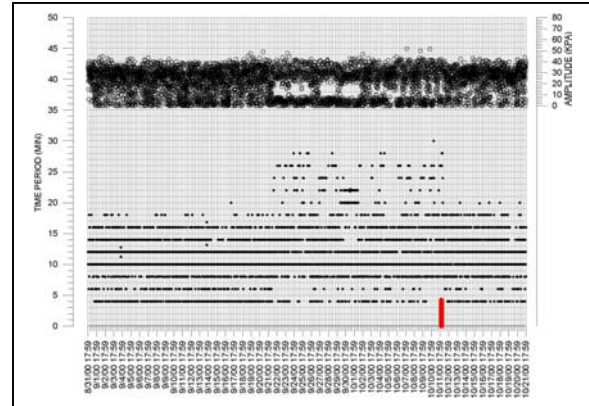


Figure 8 Pressure cycling change (amplitude and time period) in well #30, Mutnovsky geothermal field before small earthquake ( $M=4.2$ , 11 Oct. 2000) which followed by the strong earthquake ( $M=6.2$ , 8 Oct. 2001) in the same place one year later.

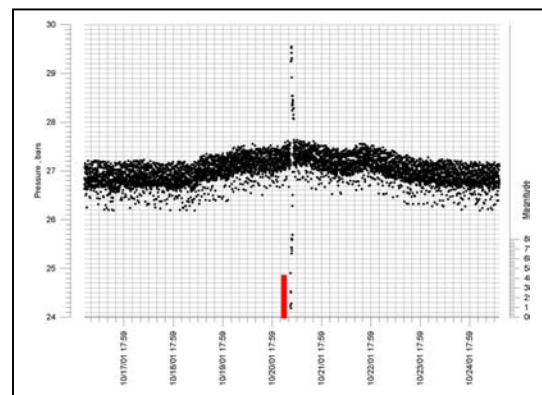


Figure 9 Pressure perturbations in Well #30, Mutnovsky geothermal field associated with earthquake ( $M=4.5$ , 21 Oct. 2001). Large earthquake ( $M=6.2$ ) occurs in the same place 12 days before.

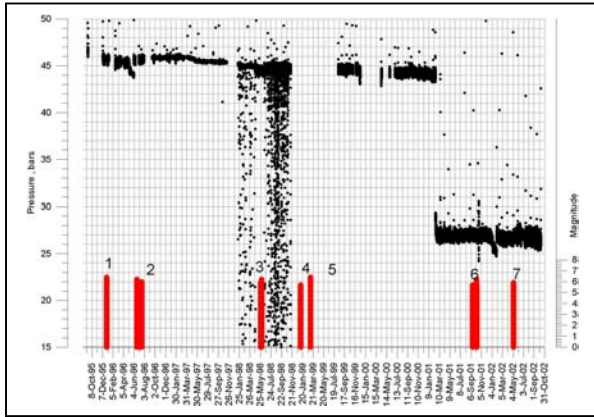


Figure 10 Pressure monitoring data in the well 30, Mutnovsky geothermal field (dots) during 1995-2002 years time period, earthquakes ( $M > 5.5$ ) which struck area (158-161E, 51-54N) numbered by vertical bars.

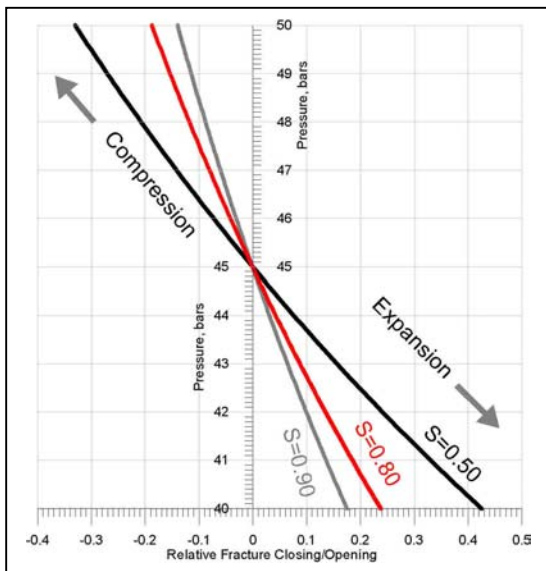


Figure 11 Pressure change (drop or increase) due to isentropic (adiabatic) expansion or compression of two-phase fluid from point of initial pressure 45 bars at different initial saturations (0.5, 0.8 and 0.9 correspondingly) caused by fracture aperture change.

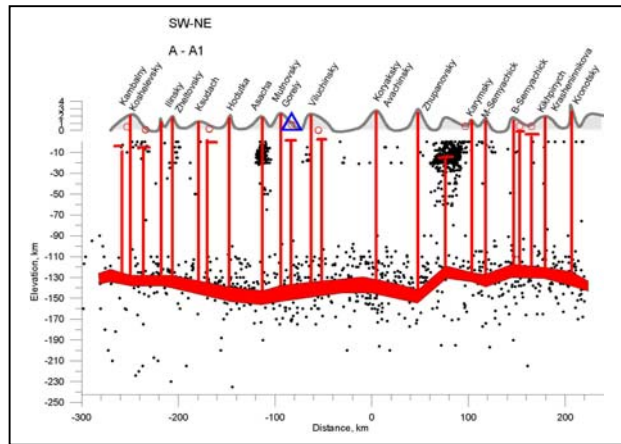
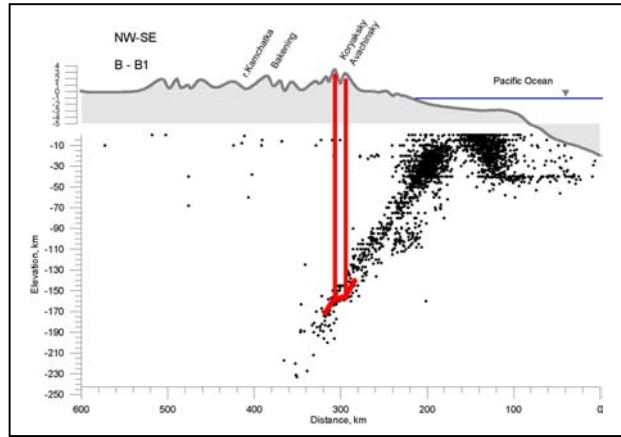


Figure 12 East Kamchatka Volcanic Zone sections: NW-SE and SW-NE cross sections showing earthquake distributions (1966-2002 data of Kamchatka EMSD GS Russia AS), active volcanoes and high temperature geothermal fields (circles) locations, and assumed deep magma reservoirs distributions, including volcanoes and geothermal fields magmatic feed zones (magmatic channels, pipes, dykes and sills). Triangle – pressure monitoring point in the Verkhne-Mutnovsky geothermal field.