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Numerical Modelling of the Natural State of the Mutnovsky Geothermal Reservoir (Kamchatka, Russia)

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ABSTRACT

The paper presents results of modelling the natural state of the Mutnovsky geothermal reservoir. TOUGH2-simulator developed in National Laurence Berkeley Laboratory, USA is used for modelling. The work was carried out in the context of the United Nations University Geothermal Training Programme 2003.

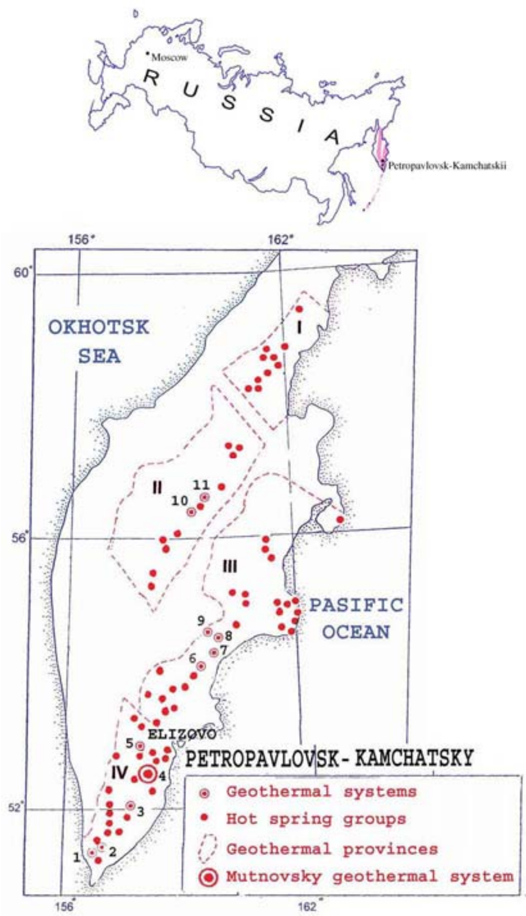

Figure 1: Location of Mutnovsky geothermal area at Kamchatka peninsula (Kononov, 2001).

The conceptual model of the Mutnovsky geothermal reservoir resulted from previous studies is put into base of the work together with well test data. The aim of the work was to verify the conceptual model and to create the base for simulation of production response of the reservoir. The main points of the conceptual model–location of heat sources, flow pattern, location of boiling zone–are confirmed by presented results.

1. INTRODUCTION

The Mutnovsky geothermal field is located in area of recent volcanism in the south part of the Kamchatka peninsula, NE-Russia (Fig. 1). It is considered as a primary source for electric power production in Kamchatka (Povarov et al., 2001). At present two power plants are in operation at the field: Upper-Mutnovsky GeoPP of 12 MW_e capacity at the Upper (NE) site and Mutnovsky GeoPP of 50 MW_e installed capacity at the Central (Dachny) site of the field (Fig. 2).

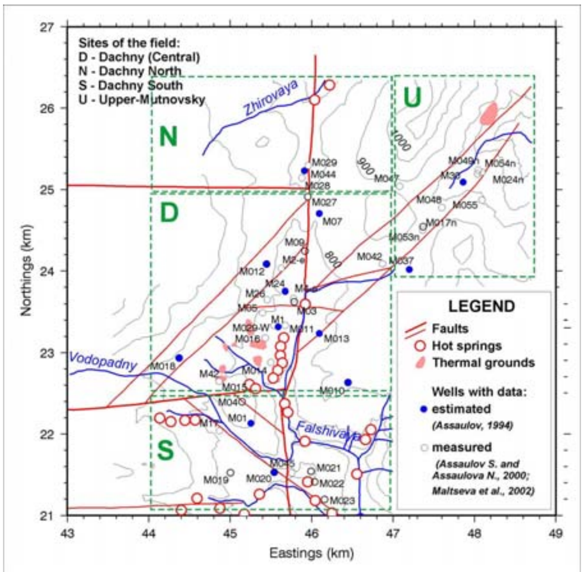

Figure 2: The Mutnovsky geothermal field. Location of wells and main geothermal features are shown according to (Maltseva et al., 2002).

The Mutnovsky field is located 75 km south of Petropavlovsk-Kamchatsky city on a volcanic plato of 700 - 900 m.a.s.l. and related to activity of Mutnovsky volcano (Fig. 3). The area of the Mutnovsky field is characterized by volcanogenic and volcanogenic-sedimentary rocks, recent volcanic formations, numerous hot springs and steam manifestations (Kiryukhin and Sugrobov, 1987; Assaulov, 1994). Its tectonic structure is rather complicated because of intersection of different fault systems. Thermal manifestations and hot springs areas are related to the intersections of the faults (Fig. 2, 3). The maximum temperature measured in these wells is 310 ^oC (Maltseva et al., 2002). According to drilling results the reservoir in the center of the field is vapor-dominated whereas the remaining part of reservoir is considered to be liquid-dominated. The predicted resources of the Mutnovsky geothermal area may provide the thermal power of $6.2*10^8$ W which corresponds to electrical power of 300 MW_e (Kiryukhin and Sugrobov, 1987).

3-D numerical modeling of the Mutnovsky reservoir is of great importance because of intensive development of the field. The natural state modelling is undertaken to verify the conceptual model and provide the base for predicting the response to long-term exploitation.

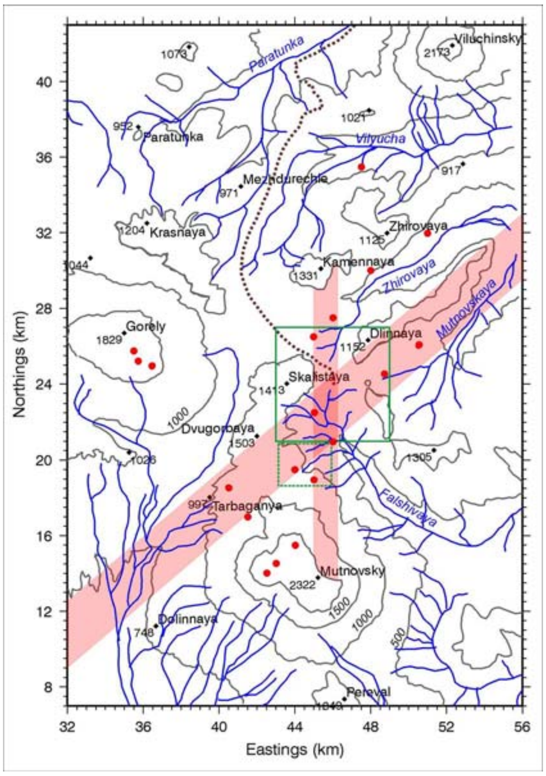

Figure 3: Location of Mutnovsky geothermal field, main fault zones (semi-transparent stripes) and hot springs (red dots) (Sugrobov, 1986, Fedotov et al., 2002).

2. A CONCEPTUAL MODEL OF THE MUTNOVSKY GEOTHERMAL FIELD

The basis for the numerical modeling is provided by conceptual model of the reservoir. A proper conceptual model should describe the flow pattern in reservoir, size and shape of reservoir as well as location of recharge zones, heat sources, up-flow zones, boiling zones and main flow paths. The conceptual model used in this work is based on previous studies as well as on well data analysis.

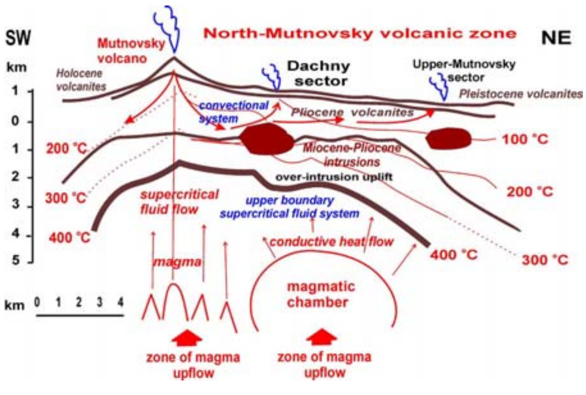

Figure 4: Conceptual model of the Mutnovsky geothermal field according to Fedotov et al, 2002.

2.1. Conceptual Model: Drawing Out

Based on previous studies the following conceptual model of the Mutnovsky geothermal field was accepted as a basis for numerical modelling.

1. The field is located at graben-like depression of meridional strike (North-Mutnovsky volcanic zone) related to the regional deep fault (Sugrobov, 1986); another regional zone of NE strike (Mutnovsky zone) also influenced on the field formation (Fig. 3). The boundaries of the main parts (sites) of the field are shown in Fig. 2. The most permeable and, therefore, most water-saturated zones are related to the main faults of N and NE strike (Fig. 2). So, the most productive sites of the field are located at the intersection of two regional fault structures. Dachny hot springs area is considered to be the most perspective site of the field (Sugrobov, 1986).

2. According to (Sugrobov, 1986), the Mutnovsky geothermal field is a part of a large hydrothermal system with magmatic chambers located underneath the North-Mutnovsky volcano-tectonic zone. These chambers considering as the most probable heat source for the system, are assumed to be located beneath the north foot of Mutnovsky volcano, the west slope of Zhirovskoy volcano, the Dacny thermal manifestations and the Skalisty mountain (Fig. 3). According to (Fedotov et al, 2002) anomalous heat sources are located at the field (in addition to regional background): the feeding channel beneath Mutnovsky volcano, additional magmatic chamber beneath its north foot and Miocene-Pliocene extrusive bodies at less depth (Fig. 4).

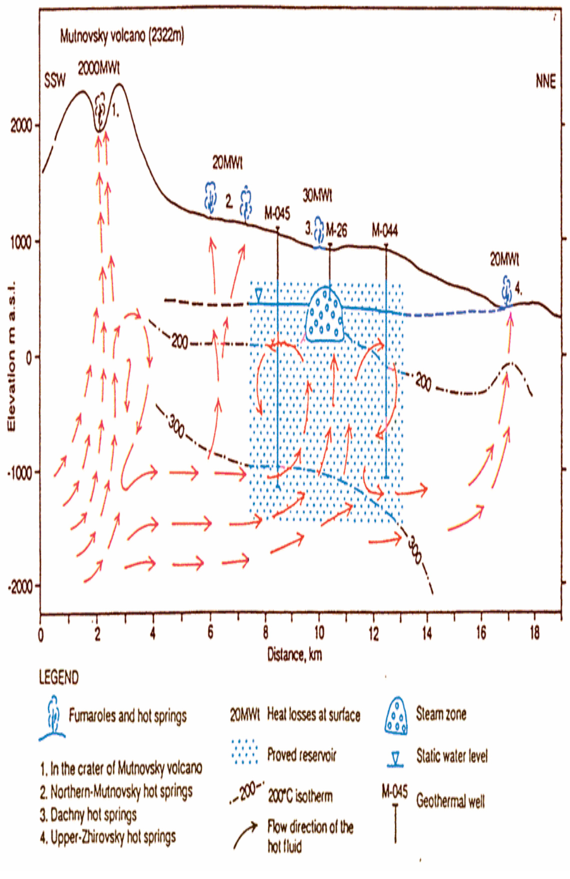

Figure 5: Conceptual model of the Mutnovsky geothermal field according to (Assaulov, 1994).

3. The main flow direction within the field is assumed to be along the Mutnovsky fault zone of NE strike (Fig. 5). Water inflow is assumed to be from the south along the main fault zone of N strike but also from the west (from the caldera of Gorely volcano) along latitudinal fractures. The main outflow is assumed to be to the NE of the field and may be related to Voinovsky and Upper-Zhirovsky hot springs (Fig. 3) as well as to the main discharge to the ocean (Assaulov, 1994; Fedotov et al., 2002; Kiryukhin, 2002).

4. According to (Sugrobov, 1986; Assaulov, 1994) the field is generally liquid-dominated except the “steam cap” located in zone of higher permeability within the Dachny site (Fig. 5).

5. The main upflow zones are located within the Dachny, Upper-Mutnovsky and, probably, Volcanny sites as indicated by the Dachny, Upper-Mutnovsky and North-Mutnovsky hot springs (Fig. 5), respectively (Assaulov, 1994; Kiryukhin, 2002).

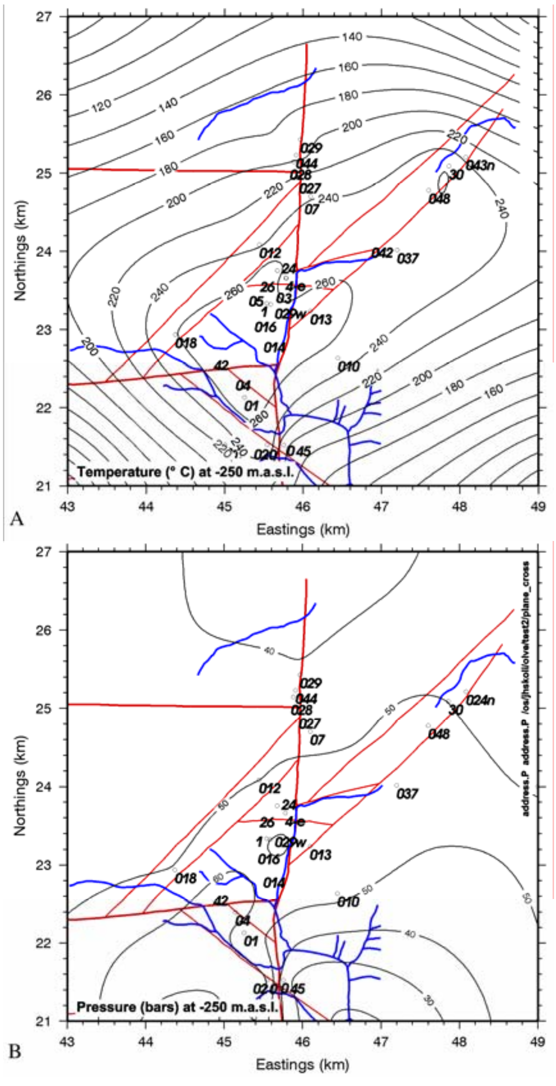

Figure 6: Temperature (A) and pressure (B) distribution at -250 m.a.s.l.

2.2. Conceptual Model: Well Data Analyses

Figures 6-7 show the temperature and pressure distribution in the area of Mutnovsky geothermal field based on results of well measurements collected in (Assaulov and Assaulova, 2000; Maltseva et al., 2002) as well as on pressure and temperature estimations from (Assaulov, 1994). Pressure and temperature planes and cross-sections are plotted using DRAW.PLANES and DRAW.CROSS computer programs designed by G. Bjornsson. The main points of the conceptual model are the following:

1. Flow pattern in the reservoir. The direction of fluid flow along NE-strike fault zone is clear on graphs of temperature and pressure distribution (Fig. 6). According to pressure distribution the main inflow is from the south. The main path of fluid and main part of the reservoir is related to the fault zones which are characterized by much higher permeability than surrounding rocks.

2. Size and shape of the reservoir. According to temperature distribution the boundaries of the reservoir are determined by isotherm 240 ^{o}C (Fig. 6A). Therefore, the southern boundary is close to wells 019, 020, 45, whereas NE boundary is close to well 30. The northern boundary is formed by the Shirotny fault. These form and size of reservoir seem to fit the assumed in (Assaulov, 1994; Sugrobov, 1986).

3. Location of up-flow zones. Two main upflow zones may be noted at the field (Fig. 6, 7). They are related to the Dachny and Upper-Mutnovsky sites, or “Main” and “NE” upflows according to (Kiryukhin, 2002). Upflow zone south of the field (beneath the Mutnovsky volcano, or North Mutnovsky hot springs) cannot be seen from the graphs because it is outside of measurements area. The upflow temperature is assumed to be not less than 300 ^{o}C.

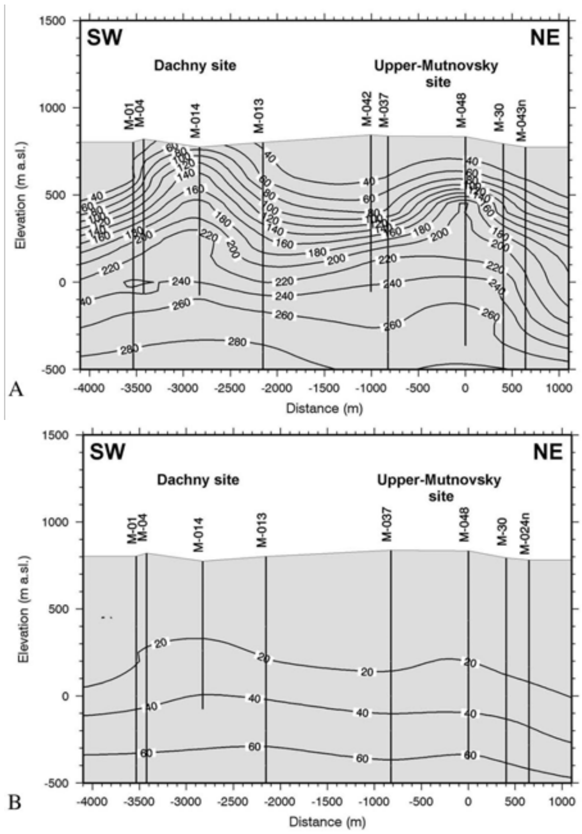

Figure 7: Temperature, ^{o}C (A) and pressure, bar (B) cross-sections along NE-strike fault zone.

4. Location of boiling zones, division of the reservoir into subsystems. According to pressure and temperature data the reservoir is in a liquid state almost everywhere. The steam zone is located in Dachny site approximately in x-interval

45-46 km, in y-interval from M-01 to M-012, above -250 m.a.s.l depth at least (Fig. 6, 7).

5. Location of recharge zones and heat source for the reservoir. According to pressure distribution in the reservoir (Fig. 6B) it is reasonable to assume the fluid inflow mainly from the south because pressure increases towards the south. From temperature distribution (Fig. 6A) we can assume the additional heat sources beneath the "Main" and "NE" up-flow zones.

3. TOUGH2 SIMULATOR: BRIEF DESCRIPTION

The TOUGH2-simulator used in this work belongs to MULCOM family of numerical simulators developed at Lawrence Berkeley National Laboratory (LBNL), USA (Pruess et al., 1999) for simulation of multi-dimensional mass and heat flow for multi-component and multi-phase fluids in porous and fracture media. TOUGH2 is written in Fortran 77 and was developed under a UNIX-based operating system.

The governing equations of TOUGH2-simulator are mass- and energy-balance equations since heat and mass transfer is simulated. The object of modelling (porous-fractured medium) is considered as set of elements connected to each other. Mass and heat accumulated in each element, mass and heat flow through boundaries of element and possible mass/heat sinks/sources (inflow, wells, hot springs) have to be defined. Therefore, mass- and energy balance equations for each element of volume V are written as (Pruess et al., 1999; Bjornsson, 2003):

$$\frac{d}{dt}\iiint_V M^{(k)} dV = \oint_\Gamma F^{(k)} \cdot \vec{n} d\Gamma + \iiint_V q^{(k)} dV \qquad (1)$$

where first term is mass/heat accumulation in element V, second term is mass/heat flow through the surfaces of element V, and third term contains sinks/sources of heat and mass. Index *k* may be equal to: 1 (water), 2 (air), 3 (heat), 4 (tracer) etc.

Mass and heat accumulation is given as:

$$M^{(k)} = \Phi \sum_{\beta=l,g} s_\beta \rho_\beta X_\beta^{(k)} \qquad (2)$$

$$M^{(3)} = (1-\Phi)\rho_R C_R T + \Phi \sum_{\beta=l,g} s_\beta \rho_\beta X_\beta^{(k)} \qquad (3)$$

where Φ is porosity, S_β is saturation of phase ß, ρ_β is density and $X^{(k)}_\beta$ is mass fraction of component *k* present in phase β. Mass and heat flow is given as:

$$F^{(k)} = \sum_{\beta=l,g} F_\beta^{(k)} \qquad (4)$$

$$F^{(3)} = -K\nabla T + \sum_{\substack{\beta=l,g \\ k=1,2}} h_\beta^{(k)} F_\beta^{(k)} \qquad (5)$$

where

$$F_\beta^{(3)} = -k\frac{k_{r\beta}}{\mu_\beta}\rho_\beta X_\beta^{(k)}(\nabla P_\beta - \rho_\beta g) \qquad (6)$$

All equations are non-linear, therefore, they can be solved only by numerical methods.

In simulating a geothermal reservoir we usually assume that fluid is of one component only (water). In this case we have 2 equations of 2 unknowns for each element. Unknowns are pressure and temperature (in single phase conditions) or pressure and saturation (in 2-phase conditions). For system of N elements we have 2N equation system of 2N unknowns. It is solved by Newton-Raphson iteration scheme (Pruess et al., 1999; Bjornsson, 2003).

4. TOUGH2 NATURAL STATE MODELLING

The aim of a natural state modelling of a geothermal field is to compute a pressure and temperature distribution of a model that matches data obtained in wells. Thus, we deal with a "inverse" problem: namely, we have to find the model parameters which can provide the required distribution of output parameters, i.e. pressure and temperature.

The basics of the natural state simulation are as follows. Firstly, the system (reservoir and surrounding area) is assumed to be cold. Then, at certain moment, the "heating" of the system starts due to constant inflow of hot fluid. One of the main parameters in modeling is the maximum duration of "heating". The model is assumed to be steady-state one, when all parameters remain constant (i.e. the local equilibrium). Therefore, the maximum time for modeling is set as approximately 1 million years. The numerical model is assumed to reach the steady state within this time frame.

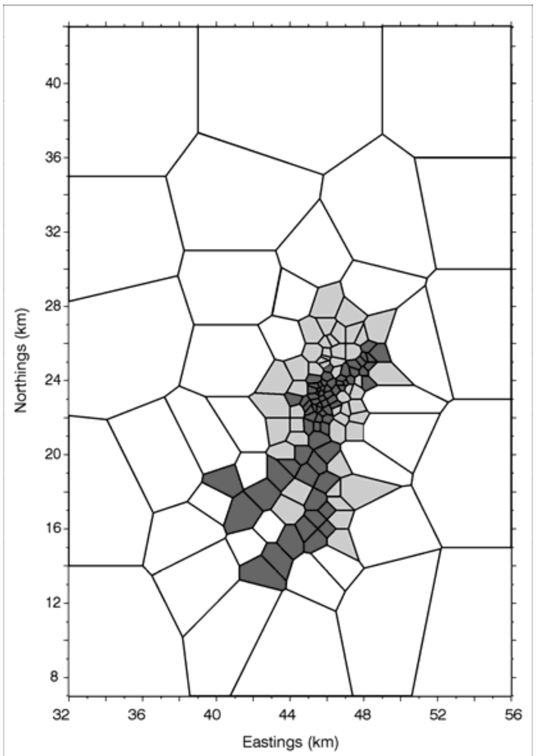

Figure 8: Numerical mesh for the natural state simulation and permeability distribution in layer B.

Table 1 Initial conditions in the natural state model

N	Layer	Layer elevation (m.a.s.l.)	Initial temperature (°C)	Initial pressure (bar)
1	A*[1]	250	30	1.04
2	B	-250	80	49.45
3	C	-750	130	96.46
4	D	-1250	180	141.53
5	E*	-1750	280	166.00

4.1. Numerical mesh; boundary and initial conditions

3-D irregular mesh created by the AMESH computer program (Haukwa, 1998) is used for the modelling (Fig. 8). The model of the reservoir contains five layers; each layer consists of 160 elements. The distribution of element centers is irregular. It is dense along the fault zones (some elements correspond to wells and hot springs). The elevation of the top layer is 250 m.a.s.l., the thickness of each layer is 500 m (Table 1). The top and the bottom layers are defined as inactive, i.e. the constant pressure and temperature are specified in elements of these layers to provide boundary conditions for the model.

Initial conditions are given in Table 1. Initial temperature is constant for each layer and increases linearly with the depth (except the last layer where temperature 280 °C is assumed). The initial pressure distribution is hydrostatic and calculated by the PREDYP program (Arason et al., 2003).

4.2. Rock properties

Table 2 shows the rock properties used in the model of the Mutnovsky geothermal field according to (Kiryukhin, 2002). Except the permeability, the rock properties are given constant because their influence on the behavior of the system is considered much less then that of permeability. The permeability distribution corresponding to the fluid behavior is to be estimated. In the current model it is observed that the vertical component has to be 1-3 orders of magnitude less than the horizontal one which is of great influence on the fluid behavior in the reservoir.

Table 2 Rock properties for the Mutnopvsky geothermal field according to (Kiryukhin, 2002)

Layer	Rock	Density (kg/m³)	Poro-sity	Thermal conductivity (W/m*°C)
A*	Quaternary ignimbrites, Pliocene lavas, rhyolite tuff	2100	0.2	2.05
B	Miocene sandstone	2300	0.08	2.1
C	Intrusive contact zone	2400	0.03	2.1
D	Diorite	2700	0.02	2.1
E*				

Table 3 Estimated permeability of the rocks in the numerical model

Layer/Rock type	Permeability (D)		
	k_x	k_y	k_z
A*/RCK1P	$0.1*10^{-3}$	$0.1*10^{-3}$	$0.1*10^{-4}$
A*/RCK1I	$0.1*10^{-3}$	$0.1*10^{-3}$	$0.1*10^{-4}$
B/RCK2P	$0.29*10^{-1}$	$0.29*10^{-1}$	$0.29*10^{-2}$
B/RCK2I	$0.1*10^{-3}$	$0.1*10^{-3}$	$0.1*10^{-3}$
C/RCK3P	$0.45*10^{-1}$	$0.45*10^{-1}$	$0.45*10^{-2}$
C/RCK3I	$0.1*10^{-3}$	$0.1*10^{-3}$	$0.1*10^{-3}$
D/RCK4P	$0.38*10^{-1}$	$0.38*10^{-1}$	$0.38*10^{-2}$
D/RCK4I	$0.1*10^{-3}$	$0.1*10^{-3}$	$0.1*10^{-3}$
E*/RCK5P	$0.1*10^{-19}$	$0.1*10^{-19}$	$0.1*10^{-19}$
E*/RCK5I	$0.1*10^{-19}$	$0.1*10^{-19}$	$0.1*10^{-19}$
Surrounding area/ RCK6I	$0.1*10^{-4}$	$0.1*10^{-4}$	$0.1*10^{-6}$

Table 3 shows the permeability distribution which provide the best match to the measured data. Three types of rock permeability are used in the model for each layer: within the field area the “high-permeable” rocks simulate fault zones, and the “low-permeable” are assumed for surroundings. The name of the rock type contains the number of layer and the letter “P” (permeable) or “I” (low-permeable, or “impermeable”). For the area outside the field the average rock properties are specified in every layer simulated by ”the “average” rock (RCK6N).

[1] Inactive layer

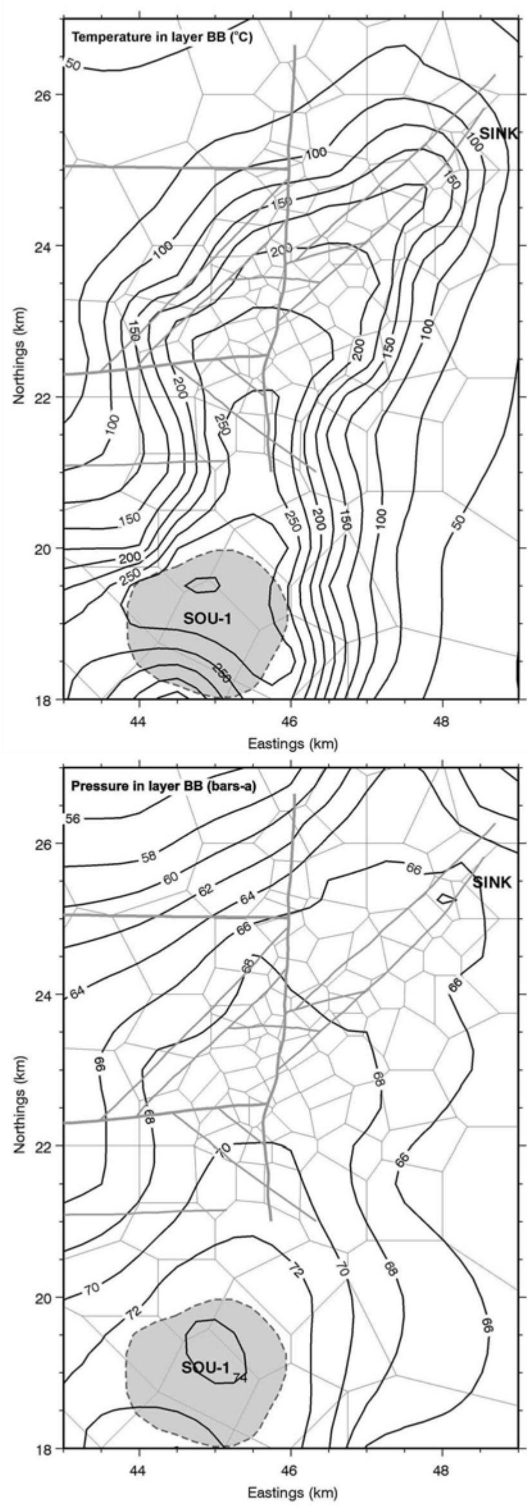

Figure 9: Computed temperature and pressure distribution in layer B (V-1). Two-phase zone is indicated by the grey area.

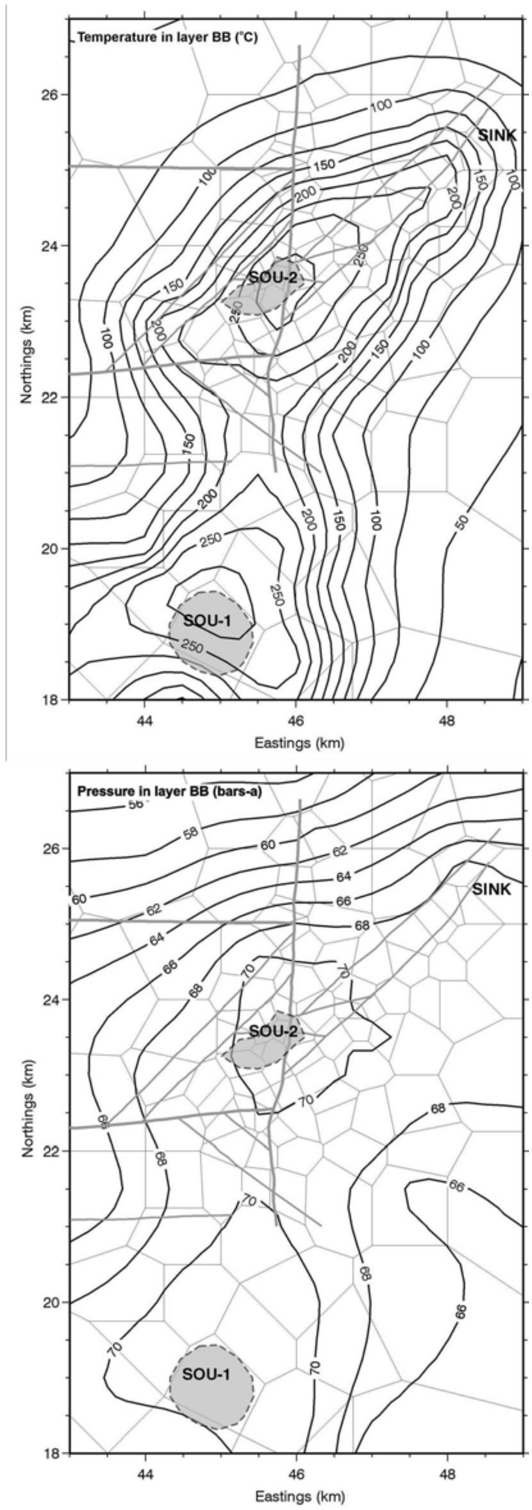

Figure 10: Computed temperature and pressure distribution in layer B (V-2).

4.3. Sources and sinks

Figs. 9, 10 and 11 show the location of the sources and sinks for three variants of the modelling. In order to simulate properly the natural state of the Mutnovsky system, sources and sinks of heat and mass have to be disposed according to the conceptual model of the reservoir. In this model all sources and sinks are disposed in the the deepest “active” layer D (-1250 m.a.s.l.).

The first variant (V-1) of the modeling assumes one mass/heat source to the south of the field in an element corresponding to the area beneath the North-Mutnovsky hot springs, and one sink (simulating discharge of fluid) in an element at the NE boundary of the field. This assumption agrees with the main idea of the fluid flow in the conceptual model. Two other variants of the modeling assume additional heat and mass sources within the field. The second variant (V-2) assumes a second source in element beneath the Dachny hot springs area. Finally, two additional sources, beneath Dachny and Upper-Mutnovsky sites, are assumed in the third variant (V-3) of the modelling. An assumption about additional sources seems to be more correct with respect to the fitting the conceptual model which is confirmed by the modeling results.

5. TOUGH-2 MODELLING: RESULTS

Figs. 9, 10 and 11 show the temperature and pressure distribution and locations of two-phase zone in the layer B (-250 m.a.s.l) resulted from the modeling the natural state of the Mutnovsky field with different assumption about the heat and mass sources.

Fig. 9 shows the results of the modelling with one heat and mass source (V-1). In this case the single-phase condition is everywhere in the field area except two-phase zone above the source which is not fit to real conditions. Moreover, the temperature is too low and the pressure is too high as compared to the measured data. Fig. 10 shows the results of the modeling with two sources (V-2). The temperature distribution is more similar to the measurement results than in previous case (V-1) but it is still too low as well as the pressure is still too high. But in V-2 there is a two-phase state at the Dachny site which seems to fit the real conditions. In both cases (V-1 and V-2) the path of the fluid fits the conceptual model.

Fig.11 shows the results of the modeling with three sources (V-3). Now the two-phase state in the Dachny site fits the measurement results much better than in variant 2 and there is rather good coincidence for the pressure distribution within the field area. Note that in V-3 the total inflow into the reservoir (55 kg/s, see Table 4) is close to 54 kg/s estimated by Kiryukhin (2002). The location of the sources within the field area also agrees with the model of the Mutnovsky field derived in the same work.

Table 4 Mass sources and sinks in the numerical model

Variant of the modelling	Source/Sink	Flow rate (kg/s)	Enthalpy (kJ/kg)
1	SOU 1	50	1650
	SIN 1	21	728
2	SOU 1	30	1650
	SOU 2	20	1650
	SIN 1	22	959
3	SOU 1	20	1650
	SOU 2	20	1650
	SOU 3	15	1650
	SIN 1	45	1152

In both 2nd and 3d variants of modelling (Figs. 10 and 11) simulated temperature is too low as compared to measured results. This may be due to the size of the simulated area which is much larger than the field area which is under consideration in the work mentioned above. Therefore, in this case another probable heat sources outside the field area should be taken under consideration.

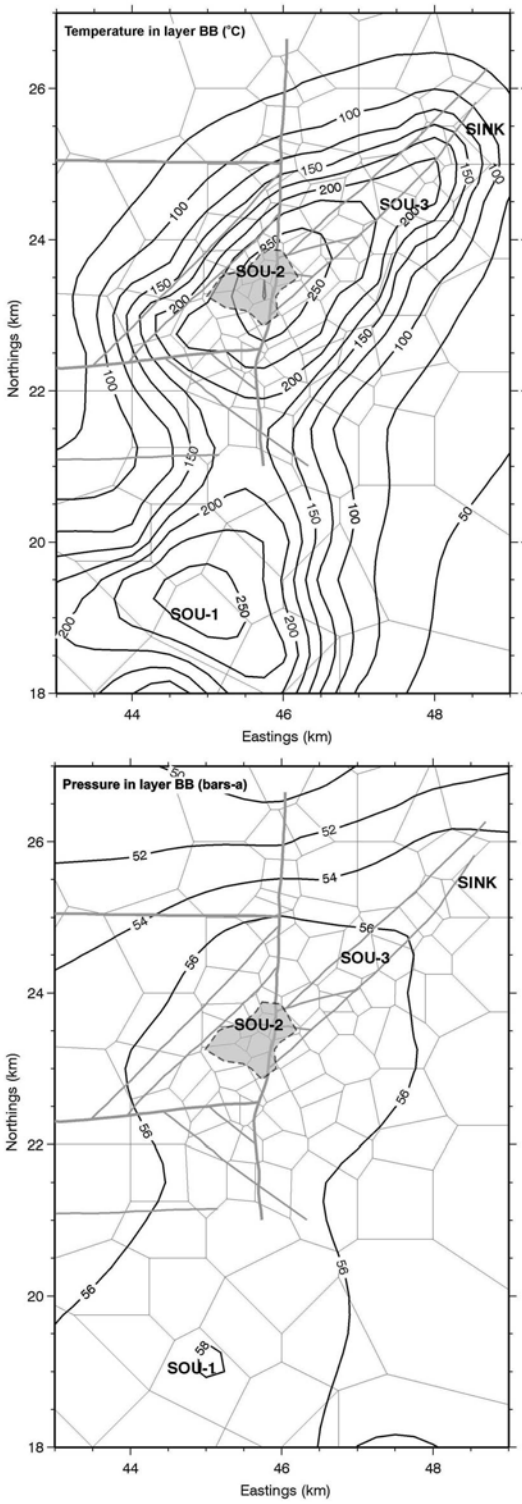

Figure 11: Computed temperature and pressure distribution in layer B (V-3).

6. CONCLUSIONS

The modelling of natural state of the Mutnovsky geothermal field was carried out by TOUGH2-simulator in order to verify the conceptual model of the reservoir. The modelling allowed us to make the following inferences:

1. One heat source is located to south of the field, and two additional heat sources are probably located within the field. According to the hot spring areas and up-flow zones related to them, one additional heat source is situated

beneath the Dachny site, whereas another one lies beneath the Upper-Mutnovsky site.

2. The flow pattern in the Mutnovsky geothermal reservoir is confirmed by pressure-temperature distribution simulated by TOUGH2.

3. Permeability distribution in the system is the most important factor defining fluid flow paths in porous-fracture medium and the location of the main part of the reservoir. Modeling indicates the higher pressure and temperature in the area where permeability is assumed to be higher.

4. The location of the boiling zone depends on two factors: permeability and location of heat sources. Boiling zone at the Dachny site of the field is located in the zone of higher permeability, and in the same time, above the heat source.

The presented model can be useful for further studies to simulate flow rate histories of the wells and to estimate the production potential of the Mutnovsky geothermal system as well as the response of the field to interaction of reinjection and production wells during the long-term exploitation.

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