



## NATURAL STATE MODELLING OF THE MUTNOVSKY GEOTHERMAL FIELD, KAMCHATKA, RUSSIA

**Olga Vereina**

SC Geotherm – SC Nauka  
Krasnokazarmennaya st. 9,  
111250 Moscow  
RUSSIA

### ABSTRACT

The Mutnovsky geothermal field is located on a volcanic plateau at 700-900 m a.s.l. Numerous hot springs and fumaroles are found, often at intersections of faults and fracture systems. Systematic analysis of downhole pressure and temperature data in over 30 wells, together with a careful review of older literature on the Mutnovsky resource, has led to the following conceptual reservoir model. An upflow zone of over 300°C resides underneath the Mutnovsky volcano, some 3-4 km to the south of the present well field. The hot fluid flows laterally to the north, towards the Dachny site. There, a shift occurs in the flow direction and the geothermal system is elongated towards northeast, where the Upper-Mutnovsky site is located. Another hot upflow zone to the reservoir may be located there. The reservoir areal extent, as defined by a 240°C temperature contour, is about 10 km<sup>2</sup>, and the reservoir thickness exceeds 1 km. The field is generally liquid-dominated, and at 240-280°C temperature. A steam-cap is found near the top of the reservoir in Dachny. Based on this conceptual model, a natural state numerical TOUGH2 reservoir model has been developed, made of five horizontal layers, each consisting of 160 elements. Three model variants were considered for calibration. All have in common an upflow zone to the south, and an outflow zone to the northeast, while additional upflow zones were modelled beneath the Dachny and the Upper-Mutnovsky areas. Calibration was done against the initial pressure and temperature distribution. It suggests a well field permeability of 30-50 mD, while the outer boundaries and the base layer have permeability below 1 mD. Total source strength of 50-60 kg/s of 1650 kJ/kg enthalpy was needed to reasonably match the available data, while a better match to observed temperature distribution was obtained by spreading out the source instead of considering only one upflow zone.

### 1. INTRODUCTION

The Mutnovsky geothermal field is located in the southern part of the Kamchatka peninsula in NE-Russia, 75 km south of Petropavlovsk-Kamchatsky city. It is located on a volcanic plateau at 700-900 m a.s.l. in an area of recent volcanism, associated with the Mutnovsky volcano (Figure 1). 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). It comprises a rather complicated tectonic structure because of the intersection of different fault systems. Thermal manifestations and hot spring areas are believed to be associated with the intersections of the faults (Figure 2).

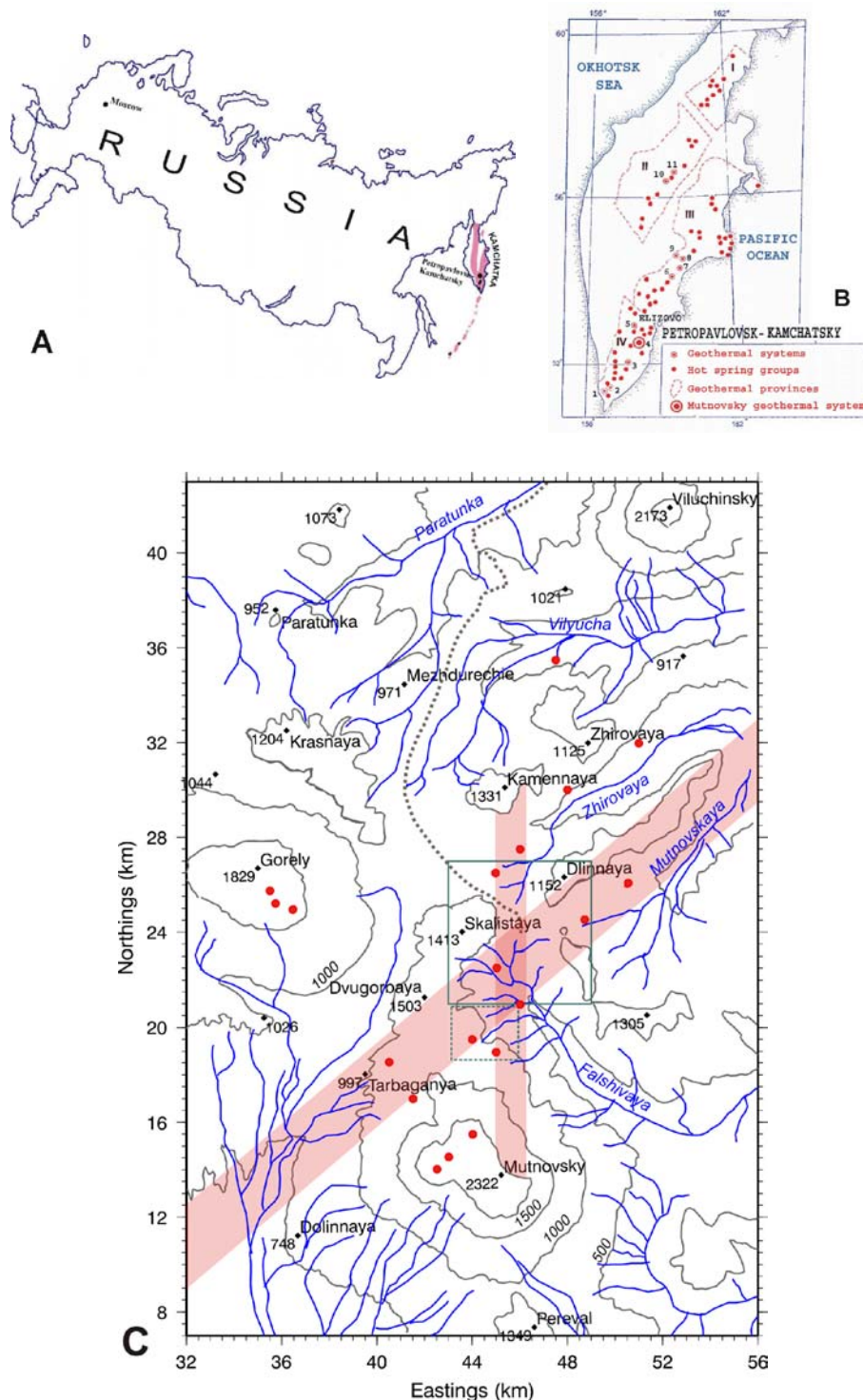


FIGURE 1: Location of the Mutnovsky geothermal field; a) Zone of recent volcanism in the Kurilo-Kamchatsky region (Kononov, 2001); b) Location of the Mutnovsky geothermal area on the Kamchatka peninsula (Kononov, 2001); c) The Mutnovsky geothermal region: The Mutnovsky field as shown in Figure 2 (square), Volcanny site (dashed square), the main fault zones (semi-transparent stripes) and hot springs (dots) (Sugrobov, 1986; Fedotov et al., 2002)

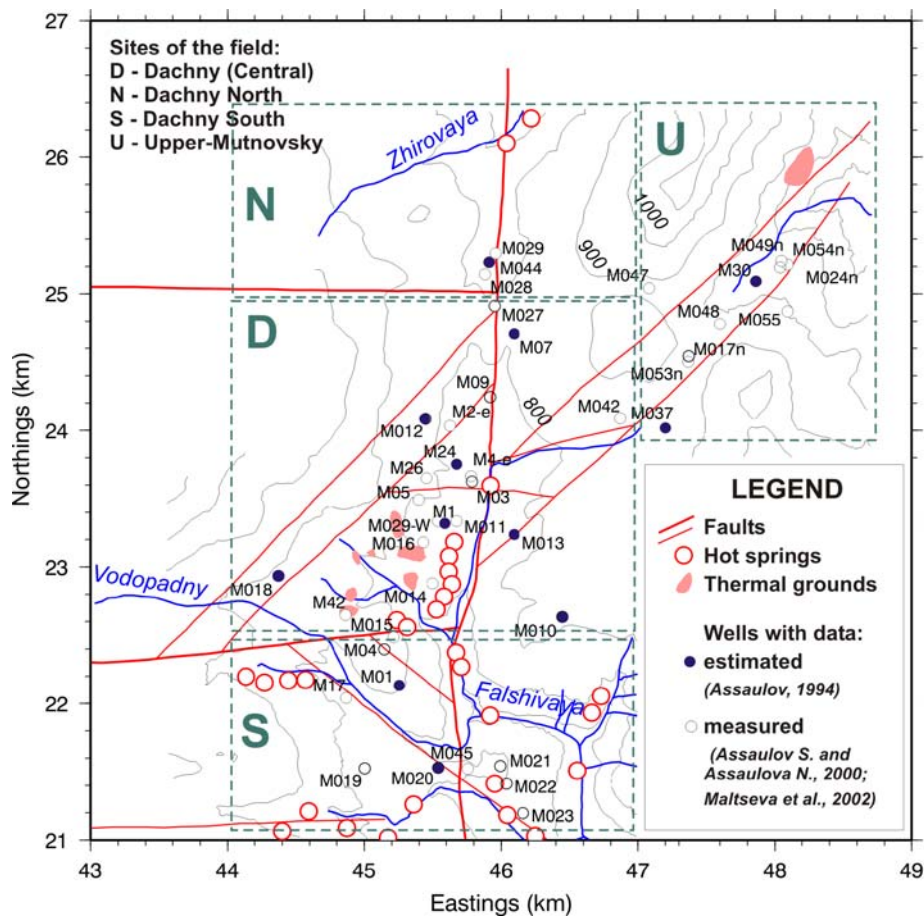


FIGURE 2: The Mutnovsky geothermal field – location of wells and main geothermal features (according to Maltseva et al., 2002)

Exploration drilling at the central part of the field (Dachny) started in 1979, while the surface thermal manifestations at this site were discovered as far back as 1960 (Sugrobov, 1986). At present, about 100 wells of 255-2266 m depth have been drilled. The maximum temperature measured in these wells is 310°C (Maltseva et al., 2002). According to drilling results, the reservoir in the centre of the field is vapour-dominated whereas the remaining part of the system is considered to be liquid-dominated. The estimated resources of the Mutnovsky geothermal area may provide a thermal power of  $6.2 \times 10^8$  W, which corresponds to electrical power of 300 MWe (Kiriyukhin and Sugrobov, 1987).

Based on this estimate, the Mutnovsky geothermal field is considered to be the primary potential source for electric power production in Kamchatka (Povarov et al., 2001). Since 1999, the Upper-Mutnovsky power plant of 12 MWe capacity has been in operation in the Upper-Mutnovsky (NE) part of the field. In 2002, Stage I of the Mutnovsky geothermal power plant, of 50 MWe installed capacity, was commissioned in Dachny. Now, Stage II of the Mutnovsky geothermal power plant of 100 MWe is to be constructed (Povarov, 2003).

Because of the intensive development of the Mutnovsky geothermal field, 3-D numerical modelling of the reservoir takes on special significance. It should be undertaken to verify the current conceptual model and to evaluate more accurately the main characteristics of the reservoir, which is necessary for locating new wells and, furthermore, for predicting the response of the system to long-term exploitation.

This report is devoted to 3-D numerical modelling of the natural state of the Mutnovsky geothermal field. The main purpose is to study the main points of the conceptual model, namely, the locations of heat sources, the locations of boiling zones, the amount of fluid inflow, and the distribution of permeability in the geothermal reservoir and in the surrounding area. This work will, consequently, provide a sound basis for exploitation modelling of the Mutnovsky system.

## 2. GEOLOGICAL OVERVIEW

### 2.1 Brief description of the Mutnovsky field

The Mutnovsky geothermal field is part of the Mutnovsky geothermal region (Figure 1), which is about 750 km<sup>2</sup> in area. The territory of the field represents a volcanic plateau at 700-900 m a.s.l. elevation intersected by the canyon-like valleys of the Falshivaya, Mutnovskaya and Zhirovaya rivers. There are two active volcanoes in the region, namely, Mutnovsky and Gorely, and numerous locations of thermal water and steam discharge as well as manifestations of recent magmatic activity – scoria cones, extrusive bodies, dykes, and large massives of hydrothermally altered rocks (Sugrobov, 1986; Assaulov, 1994).

The stratigraphic sequence of the region is formed by volcanogenic and volcanogenic-sedimentary rocks ranging from Oligocene to Upper-Quaternary age. The region is mainly composed of tuff and lava of andesite, andesidacite and andesibasalt composition with inclusions of subvolcanic bodies and dykes of variable composition (diorite, dioritic porphyrite, basalt) ranging from Miocene to Quaternary age (Assaulov, 1994; Fedotov et al., 2002). The geothermal reservoir coincides mainly with Oligocene-Miocene rocks about 2000 m thick, overlain by a Pliocene-Quaternary caprock of widely varying thickness (200-1200 m). The reservoir rocks are hydrothermally altered, and characterized by quartzitic and carbonaceous crack-filling (Assaulov, 1994).

The tectonic structure in the area of the Mutnovsky field is complicated because of the intersection of fault and fracture systems with different strikes. The field is located in a graben of meridional strike (North-Mutnovsky volcanic zone) intersected by latitudinal and NE-SW striking faults (Vakin and Sugrobov, 1972; Assaulov, 1994). The surface thermal manifestations are mostly located at the intersections of these faults. The Dachny hot springs area, or the central part of the field, is located at the intersection of the three main fault systems (Figure 2).

The Mutnovsky geothermal region is characterized by variable and intensive thermal manifestations at the surface, which can be divided into three groups according to fluid outflow, heat loss, and chemical composition (Sugrobov, 1986):

- Fumaroles located in the craters of the Mutnovsky and Gorely volcanoes. The Mutnovsky volcano is characterized by the most powerful fumarole activity among the active volcanoes of the Kamchatka peninsula.
- Thermal ground, steam jets, and boiling springs of the North-Mutnovsky volcano-tectonic zone. These are located in groups along the meridional fault zone over the 15 km distance from the Mutnovsky volcano to the Zhirovaya river valley (Figure 1). North-Mutnovsky and Dachny are the largest areas of manifestations in this group.
- Hot springs located at elevation less than 200 m a.s.l. in deep river valleys of tectonic origin. Springs of this group constitute the surface outflow of fluid (liquid water) (in contrast to the first two groups which are steam dominated).

Heat loss in the crater of the Mutnovsky volcano is estimated to be 2000 MWt; 60 MWt in the Mutnovsky area; and 30 MWt in the Zhirovaya valley (Vakin and Sugrobov, 1972; Assaulov, 1994).

### 2.2 History of research work and drilling in the field

The first geological studies were carried out in this area at the end of the 19<sup>th</sup> century. From 1960-1964, volcanological exploration in the area of the Mutnovsky and Gorely volcanoes was carried out by special research groups of the Institute of Volcanology and the Geological Institute of the Academy of Sciences of the USSR. During these studies, hot springs in the area (Dachny, North-Mutnovsky and Upper-Zhirovsky) were discovered and described for the first time. Systematic geological studies were started

in 1963, and purposeful hydrological studies in 1973. In 1978, PGO Kamchatgeologia began detailed prospecting work (deep drilling) in the Mutnovsky geothermal field. The first wells drilled in the Dachny hot spring area discharged high enthalpy steam and water-steam mixtures (Kiryukhin et al., 1991).

TABLE 1: Basic information on 36 wells in the Mutnovsky field  
(based on Assaulov and Assaulova, 2000; Maltseva et al., 2002)

Well no.	Year of drilling	Co-ordinates		Elevation (m a.s.l.)	Depth (m)	Type of fluid	Status of well (2000)
		X (E-W) (m)	Y (N-S) (m)				
<b><i>Dachny-Central part</i></b>							
<b>M1*</b>	1980	45540	23336	786	1523	S&W	Heat supply
<b>M24</b>	1984	45673	23754	793	1300	S&W	Production
M26	1984	45455	23650	816	466	Steam	Production
M42	1984	44866	22646	845	948	-**	-
<b>M01</b>	1985	45254	22131	804	1195	S&W	Production
M03	1984	45787	23657	786	1343	S&W	-
M04	1987	45146	22395	820	2100	S&W	-
M05	1985	45396	23491	800	583	-	-
<b>M07</b>	1987	46096	24704	804	1740	-	Reinjection
<b>M010</b>	1985	46446	22634	816	1452	-	-
<b>M012</b>	1987	45447	24084	818	1981	S&W	-
<b>M013</b>	1985	46095	23236	802	2070	S&W	Production
M014	1986	45499	22881	775	1004	S&W	-
M016	1986	45432	23181	788	846	Steam	Production
<b>M018</b>	1988	44373	22936	894	1857	-	-
M019	1987	45005	21525	766	1508	-	-
M4-e	1990	45780	23663	786	1896	S&W	Production
M029w	1988	45591	23320	791	1071	S&W	Production
<b><i>Dachny-North part</i></b>							
M027	1989	45953	24912	813	1050	S&W	Reinjection
M028	1989	45880	25144	788	1541	-	Reinjection
M029	1989	45964	25428	771	1514	-	Reinjection
<b>M044</b>	1989	45912	25229	782	2256	-	Reinjection
<b><i>Dachny-South part</i></b>							
<b>M020</b>	1988	45545	21524	767	1530	S&W	-
M021	1988	45994	21541	717	1518	-	-
M022	1988	46036	21415	702	1532	S&W	-
M045	1989	45756	21522	710	2150	S&W	Production
<b><i>Upper-Mutnovsky part</i></b>							
<b>M30</b>	1988	47860	25090	794	1075	-	Monitoring
M024n	1991	48083	25210	782	1802	S&W	Reinjection
<b>M037</b>	1988	47200	24016	837	1771	S&W	Production
M042	1988	46871	24087	844	1860	-	-
M043n	1992	48076	25208	775	1829	-	Reinjection
M047	1991	47080	25040	891	2266	S&W	Production
M048	1990	47600	24780	834	1247	S&W	Production
M049n	1992	48090	25215	782	1587	S&W	Production
M054n	1991	48097	25213	782	2006	-	Monitoring
M055	1990	48090	24870	801	1458	S&W	Production

\* Wells with estimated pressure and temperature (Assaulov, 1994); \*\* Not determined

At present, about 100 wells have been drilled in the Mutnovsky field. General information on some of these wells based on their present state is given in Table 1. Different parts of the field were defined according to drilling results: Dachny, Upper-Mutnovsky, North Dachny, South Dachny, and Volcanny (Figures 1 and 2). The most studied part, which is considered to be the main part of the field, is Dachny where the 50 MWe geothermal power plant is located. Another perspective part is Upper-Mutnovsky (location of the 12 MWe geothermal power plant), located northeast of the centre of the field. Reinjection wells are located mostly at the North Dachny site. Further studies and expansion of the exploited area are related to the Volcanny site (Figure 1) in the southern part of the field, at the northern foothills of the Mutnovsky volcano (Sugrobov, 1986; Fedotov et al., 2002).

### 3. A CONCEPTUAL MODEL OF THE MUTNOVSKY GEOTHERMAL FIELD

An adequate conceptual model of a geothermal reservoir is the basis for successful numerical modelling. A proper conceptual model should address the following aspects of the nature and properties of a geothermal system:

- Flow pattern in the reservoir;
- Size and shape of the reservoir;
- Location of up-flow zones;
- Location of boiling zones;
- Location of recharge zones;
- Location of barriers and/or main flow paths;
- Heat source for the reservoir.

The conceptual model has to incorporate the principal results of different kinds of research; geological, geophysical, chemical, and reservoir engineering. Therefore, a review of previous studies is a necessary part of developing an appropriate conceptual model of a geothermal field. The conceptual model of the Mutnovsky geothermal system has evolved through time. Its main features will be reviewed here and the conceptual model revised and updated.

#### 3.1 Previous studies

Sugrobov (1986) collected the main results of previous studies of the Mutnovsky field; geological and hydrogeological exploration, early exploration drilling, large-scale geological mapping, infrared air photography, heat flow measurements, geochemical studies etc. According to these data, the following conclusions were drawn:

- The field is located in a graben depression of meridional strike (North-Mutnovsky volcanic zone), which is related to deep regional faults. Another regional northeast striking zone (Mutnovsky zone) has also influenced the field's formation. The **most productive sites** of the field are located at the intersection of these two structures.
- The Mutnovsky geothermal field is part of a large hydrothermal system with magmatic chambers located underneath the North-Mutnovsky volcano-tectonic zone. These chambers are considered the most probable **heat sources** for the system, and are assumed to be located beneath the north foot hills of the Mutnovsky volcano, the west slope of the Zhirovskoy volcano, the Dachny thermal manifestations, and the Skalisty mountain (Figure 1).
- In the main ("deep") part of the reservoir, the fluid is in a liquid state at a temperature of 270°C, i.e. the field is **liquid-dominated**. The steam-water reservoir, or "**steam cap**", is located in a zone of higher permeability, above the main reservoir.

- According to chemical analyses and isotopic studies, the main part of the fluid is considered to be of **meteoric origin**. The studies also indicate a very high rate of water flow and intensive water exchange in the system.
- The fluid **circulation** in the reservoir is **fracture-controlled**; the most water-saturated areas are related to zones of *higher* tectonic fracturing. The **main discharge zone** is located at the site of maximal fissuring, a complex intersection of fault zones in the Dachny hot springs area.
- The Dachny hot springs area was considered to be the part of the field with greatest potential. According to geophysical data, the field may be expanded to the southwest and northeast along the Mutnovsky fault zone of NE-SW strike (Figures 1 and 2). Another part with good potential was believed to be the north foothills of the Mutnovsky volcano, where the North-Mutnovsky hot springs discharge. The prospective area may, therefore, be expanded to the south (Figure 1). It may also be expanded to the east (the west foothills of the Zhirovskoy volcano), as well as toward Skalistaya and Dvugorbaya hills (Figure 1). The Shirotny fault was assumed to be the north boundary of the field (Figure 2).

### 3.2 Conceptual model of the field according to recent studies

The work of Assaulov (1994) presents further development of the conceptual model of the Mutnovsky field based on results of exploration and production drilling, as well as on estimation of the main reservoir conditions (formation pressure and temperature, permeability-thickness, size of reservoir). As a result, the conceptual model of the Mutnovsky field was at that time described as follows (Figure 3):

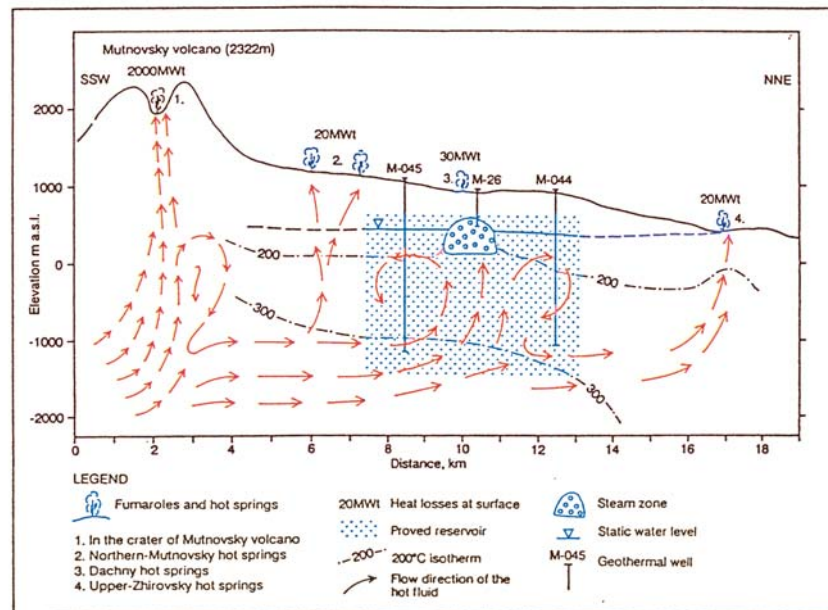


FIGURE 3: Conceptual model of the Mutnovsky geothermal field according to Assaulov (1994)

- **Flow pattern in the reservoir.** The main inflow into the Mutnovsky reservoir was considered to be from the south, and the main outflow towards the northeast.
- **Size and shape of the reservoir.** The reservoir has an elongated shape relative to the main fault zone. The boundaries of the reservoir are assumed to be  
S – open boundary south of wells M-045, M-019, M-020, M-021.  
NE - open boundary close to well M-30.  
N – closed boundary created by the Shirotny fracture.  
E, W – closed boundaries created by N-S and NE-SW striking faults.
- **Location of upflow zones.** The main upflow zone was believed to be located to the south of the reservoir, beneath the Mutnovsky volcano. The upflow temperature was assumed to exceed 300°C.
- **Location of boiling zones, division of the reservoir into subsystems.** The reservoir is considered to be in a liquid-dominated state, i.e. with a free surface and boiling curve with depth condition several hundred metres down except in the upper part. A limited steam zone is located at the intersection of the two main north and northeasterly striking fault zones.

- **Location of barriers and/or main flow paths.** The estimated formation temperature and pressure indicated the fluid flows along fractures from south to north. In the central part of the field (well area), the flow direction changes toward the northeast because of this being the dominant fault direction in the area.

According to the work of Fedotov et al. (2002), who collected the results of previous studies as well as results of drilling and well measurements, and the work of Kiryukhin (2002), the following additions to the conceptual model can be made (Figures 4 and 5):

- Three main **heat sources** (magmatic chambers) are assumed in the field. One is at 3-5 km depth beneath the Mutnovsky volcano, another at 5-8 km depth beneath the Dachny site, and the third beneath the Volcanny site (Fedotov et al., 2002). The most complete scheme of the distribution of heat sources in the Mutnovsky geothermal system is shown in Figure 5.
- **Water recharge** to the system may be provided by the melting glacier in the crater of the Mutnovsky volcano (Kiryukhin, 2002), as well as by inflow from the caldera of the Gorely volcano along a system of radial fractures (Fedotov et al., 2002).

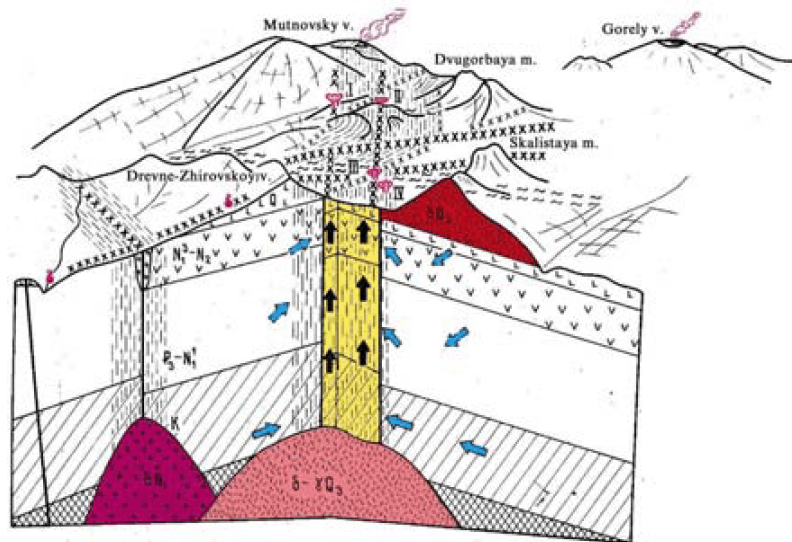


FIGURE 4: Conceptual model of the heat source of the Mutnovsky geothermal field according to Kiryukhin and Sugrovov (1987)

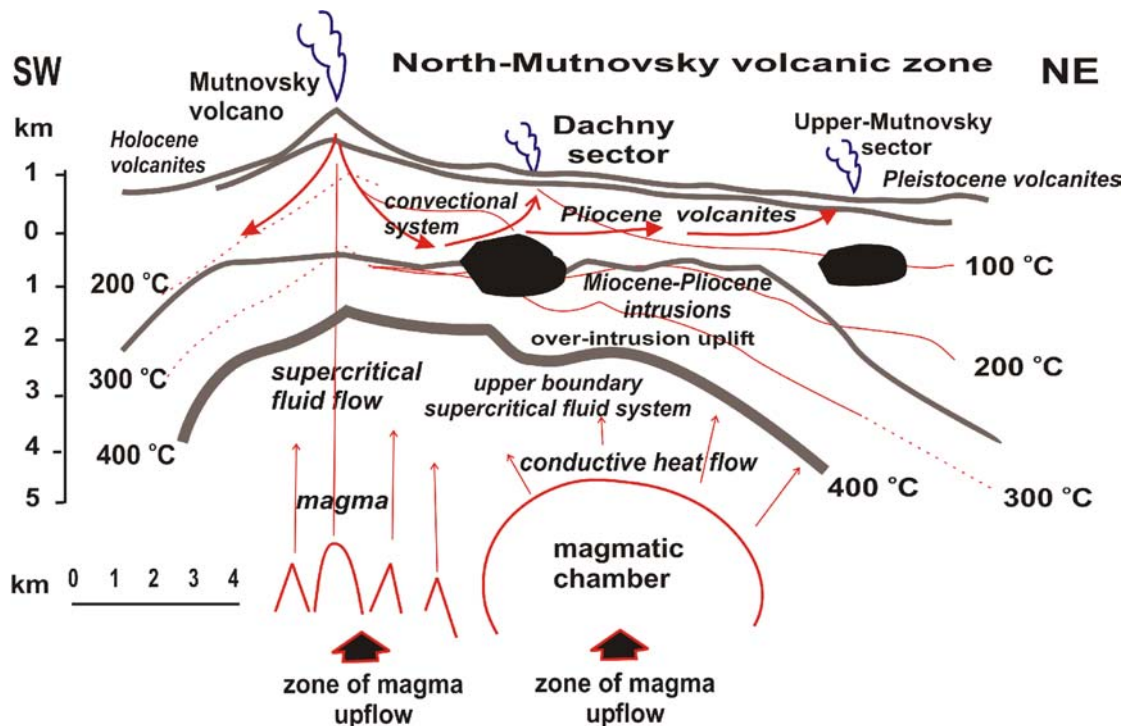


FIGURE 5: Conceptual model of the Mutnovsky geothermal field according to Fedotov et al. (2002)



- Two **up-flow zones** may be located in the field: the “Main” upflow and the “Northeast” upflow (Kiryukhin, 2002). They are related to diorite intrusions located at 1.5-2 km depth beneath the Dachny and Upper-Mutnovsky parts, respectively (Figures 4 and 5). The “Main” upflow is located within the most permeable zone (Kiryukhin, 2002).

### 3.3 Conceptual model of the field: Summary

Based on the data and inferences mentioned above, the following are the main factors in the current conceptual model of the Mutnovsky geothermal field. These provide the basis for the numerical modelling presented in this paper.

- The **main flow direction** within the field is assumed to be along the northeast striking Mutnovsky fault zone. Water **inflow** is assumed to be from the south along the main north striking fault zone (Mutnovsky volcano), but also from the west along latitudinal fractures (the caldera of the Gorely volcano). The main **outflow** is assumed to be to the northeast of the field and may be associated with Voinovsky and Upper-Zhirovisky hot springs (Figure 1) as well as with a main discharge to the ocean.
- The locations of the main **heat sources** are assumed to be beneath the North-Mutnovsky springs area, to the south of the field, and beneath the Dachny area.
- The **boundaries** of the main parts of the field are shown in Figure 2. The most permeable and, therefore, most water-saturated zones, are associated with the main north and northeast striking faults (Figure 2). Fault intersections may serve as paths of good vertical permeability, allowing fluid to escape the surface.
- The field is generally **liquid-dominated**, except at the **steam zone** located within the Dachny area.
- The main **upflow zones** are located within the Dachny, Upper-Mutnovsky and, probably, Volcanny areas as indicated by the Dachny, Upper-Mutnovsky, and North-Mutnovsky hot springs, respectively (Figure 1).

## 4. NUMERICAL MODELLING: THE TOUGH2-SIMULATOR

### 4.1 Numerical modelling: Reasons and basic steps

To estimate the effects of long-term exploitation in a geothermal field (pressure drawdown, cooling, response to re-injection), mathematical methods are necessary. These methods are complicated because geothermal reservoirs are usually non-isothermal, inhomogeneous systems and the associated heat and mass transfer are described by non-linear equations. Therefore, numerical modelling is the only way to make a complete model of the natural state of a reservoir, as well as to predict the response to long-term exploitation, based on incorporation of all available data (conceptual model of reservoir, production history, well testing and tracer test data).

The main steps required for numerical modelling are analysis of a conceptual model of the reservoir, choice of simulator, numerical grid design, specifying the material parameters (rock properties) of the grid elements, as well as boundary conditions and source-sink distribution.

### 4.2 The TOUGH2-simulator: Brief description

The acronym TOUGH means Transport Of Unsaturated Groundwater and Heat. It is a program for simulation of multi-dimensional mass and heat flow for multi-component and multi-phase fluids in porous

and fractured media. It belongs to the MULCOM family of numerical simulators developed at Lawrence Berkeley National Laboratory (LBNL), USA (Pruess et al., 1999). The first version of the program, TOUGH, was developed in 1983-1985 and made commercially available in 1987. TOUGH2 was released to the public in 1991 and updated in 1994, allowing more complex simulations and faster calculations than TOUGH. TOUGH2 is written in Fortran 77, and was developed under a UNIX-based operating system.

The TOUGH2 program was primarily developed for studies of nuclear waste isolation, but now the spectrum of its applications is much wider. The TOUGH2 release in 1991 included five modules for different fluid properties, or EOS-modules (equations of state):

- EOS1: water, water with tracer;
- EOS2: water, CO<sub>2</sub>;
- EOS3: water, air;
- EOS4: water, air, with vapour pressure lowering;
- EOS5: water, hydrogen.

The new version of TOUGH2 contains updated versions of these modules as well as a number of new fluid property modules. In this work, the EOS1-module is used.

### 4.3 TOUGH2: Governing equations

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

$$\frac{d}{dt} \underbrace{\iiint_V M^{(k)} dV}_1 = \underbrace{\iint_{\Gamma} F^{(k)} \cdot \bar{n} d\Gamma}_2 + \underbrace{\iiint_V q^{(k)} dV}_3 \quad (1)$$

where Term 1 accounts for mass/heat accumulation in element (volume)  $V$ ;  
 Term 2 gives mass/heat flow through the surfaces of element  $V$ ; and  
 Term 3 contains sinks/sources of heat and mass;  
 Index  $k$  may be equal to 1 for water, 2 for air, 3 for heat, and 4 for tracer, etc.

Mass and heat accumulation in the volume  $V$  is given by:

$$M^{(k)} = \phi \sum_{\beta=l,g} S_{\beta} \rho_{\beta} X_{\beta}^{(k)} \quad k = 1, 2, 3 \dots \quad (2)$$

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

where  $\phi$  = Porosity;  
 $S_{\beta}$  = Saturation of phase  $\beta$ ;  
 $\rho_{\beta}$  = Density; and  
 $X_{\beta}^{(k)}$  = Mass fraction of component  $k$  present in phase  $\beta$ .

Mass and heat flow is given by:

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

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

where

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

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

In simulating a geothermal reservoir, it is usually assumed that there is one component fluid only (water). In that case, there are 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). So, for a system of N elements, there is a 2N equations system of 2N unknowns. This equation system is solved by a Newton-Raphson iteration scheme (Pruess et al., 1999; Björnsson, 2003).

#### 4.4 TOUGH2: Structure of the input file

The TOUGH2 input file is of strict format and contains several blocks. The main blocks are the following (Pruess et al., 1999):

- ROCKS: material parameters (i.e. rock properties): density, porosity, permeability, specific heat;
- PARAM: initial values of calculated parameters;
- ELEME: list of elements;
- CONNE: list of connections between elements;
- INCON: initial conditions;
- GENER: mass and heat sinks/sources.

Blocks ELEME and CONNE can be provided by the associated program AMESH (Haukwa, 1998). It creates the numerical grid, or the mesh. The input file for AMESH is a list of coordinates of points considered to be centres of elements. These points are selected according to the information available on a reservoir: the more data available the greater the number of “centres” and the smaller the size of elements. Rock properties as well as calculated parameters are assumed to be the same within one element. Parts of the reservoir without enough data are considered as large elements with average properties.

Some of the blocks of the input file are necessary, while others (INCON, GENER) are optional. Note that calculation may include several stages, the output data of the previous stage being the input for the next one. Therefore, some blocks (INCON, for instance) of the input file may be provided by the output file of a previous stage of calculation. The first stage of calculation is called the “gravity test”. It is carried out to check whether the numerical mesh is correct, or not, and provides the initial data for the next calculation stage.

## 5. OVERVIEW OF DATA SOURCES AND WELL MEASUREMENT RESULTS

### 5.1 Data sources

The main data sources for the natural state modelling of the Mutnovsky geothermal system are as follows:

- Previous field studies and the conceptual models of the field as developed and revised by different

authors (see above). This modelling work is mainly based on estimates of field conditions presented in the work of Assaulov (1994); and on the main aspects of the conceptual models of the natural state of the field as presented in the work of Sugrobov (1986), Assaulov (1994), Kiryukhin (2002), and Fedotov et al. (2002).

- A database on the Mutnovsky geothermal field (Assaulov and Assaulova, 2000) incorporating basic information on wells (location, status, design of the wells), results of pressure and temperature measurements in the wells, and studies of the properties of the rocks forming the reservoir as well as other studies (carried out up to 1990).
- Updated information on the status of wells and well measurements, as well as geological and hydrogeological maps of the field, with well locations, from a more recent report on the development of the Mutnovsky field (Maltseva et al., 2002).

## 5.2 Analysis of temperature and pressure data

Figures 6-9 show the distribution of temperature and pressure in the area of Mutnovsky geothermal field based on results of measurements in wells 26, 42, 03, 04, 05, 014, 016, 019, 029w, 4e, 027, 028, 029, 021, 022, 045, 024n, 043n, 047, 048, 049n, and 055 presented in the work of Assaulov and Assaulova (2000) and the work of Maltseva et al. (2002). It is also based on estimated pressure and temperature in wells 1, 24, 30, 01, 07, 010, 012, 013, 018, 020, 037, and 044 presented in the work of Assaulov (1994). Pressure and temperature planes and cross-sections are plotted using DRAW.PLANES and DRAW.CROSS computer programs designed by Björnsson (2003). The following main points of the conceptual model are reflected in the graphs:

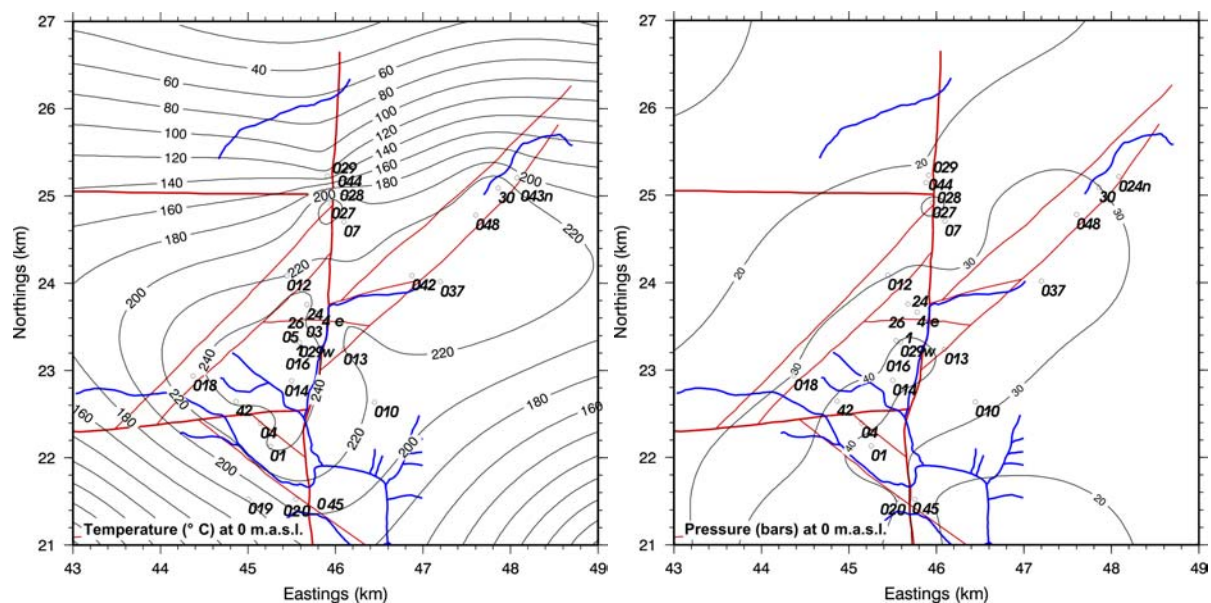


FIGURE 6: Mutnovsky field, temperature ( $^{\circ}\text{C}$ ) and pressure (bar) distribution at 0 m a.s.l.

- **Reservoir flow pattern.** The direction of fluid flow along the northeast-striking fault zone is clear on the graphs of temperature and pressure distribution at 0 and -250 m a.s.l. elevation (Figures 6 and 7). According to the pressure distribution, the main inflow is from the south, which is not clear from the temperature distribution. The main path of the fluid flow and the principal part of the reservoir, are related to the fault zones which are characterized by much higher permeability than the surrounding rocks.

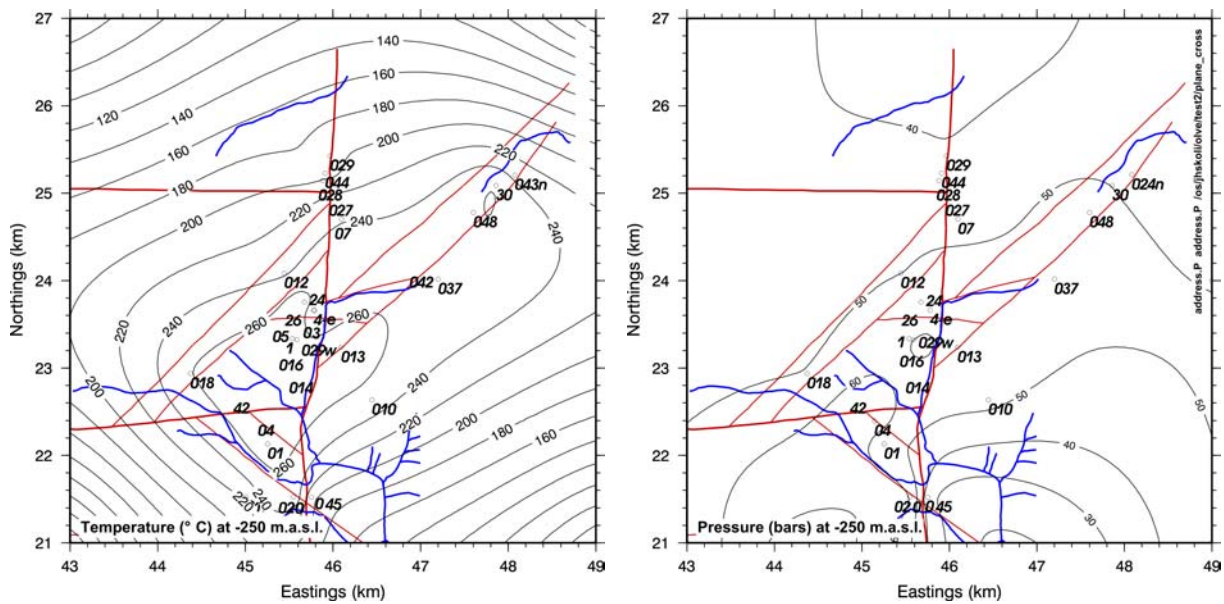


FIGURE 7: Mutnovsky field, temperature (°C) and pressure (bar) distribution at -250 m a.s.l.

- **Size and shape of the reservoir.**

The form and size of the reservoir seems to fit that assumed by Assaulov (1994) and Sugrobov (1986). According to Figure 7, the boundaries of the reservoir are determined by the 240°C isotherm. From this, it follows that the S boundary is close to wells 019, 020, 45, the NE boundary is close to well 30, and the N boundary is defined by the Shirotny fault.

- **Location of up-flow zones.**

According to the temperature and pressure maps and cross-sections (Figures 6, 7, 8 and 9), two main upflow zones are seen in the Mutnovsky system related to the Dachny and Upper-Mutnovsky parts of the field (“Main” and “NE” upflows, according to Kiryukhin, 2002). An 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 the area studied. The upflow temperature is assumed to be about 300°C, or higher.

- **Location of boiling zones, division of the reservoir into subsystems.**

According to pressure and temperature data, the reservoir is in

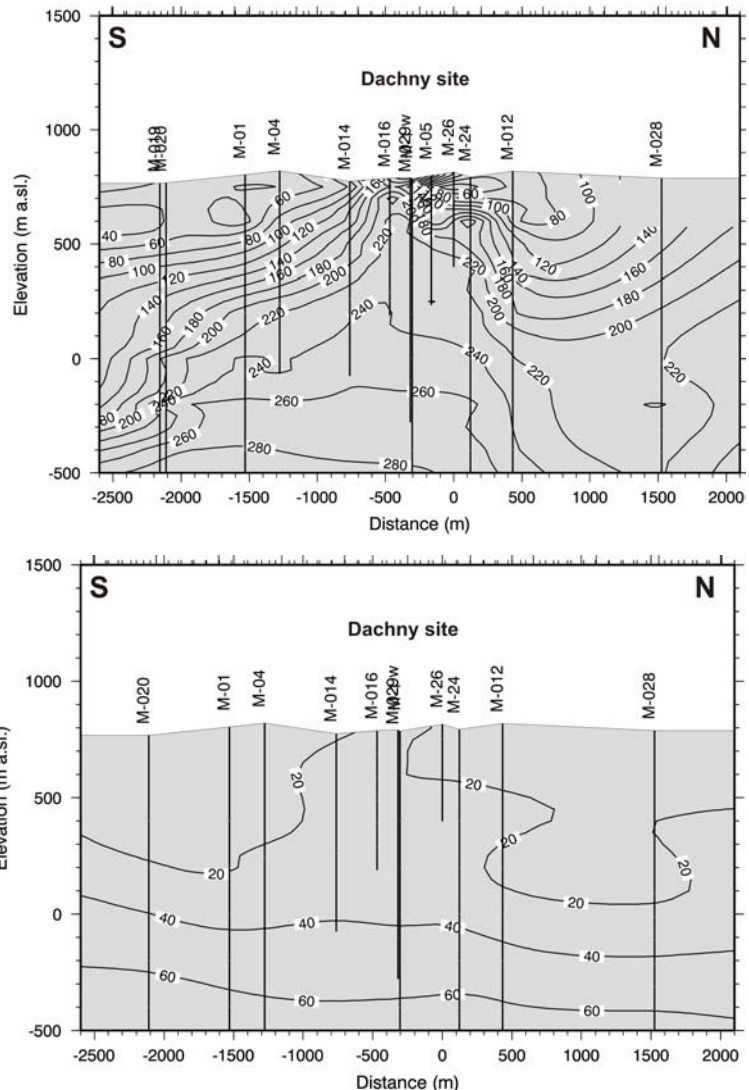


FIGURE 8: Mutnovsky field, temperature (°C) and pressure (bar) cross-sections along the north striking fault zone

a liquid-dominated state almost everywhere. The steam zone is located in the Dachny region approximately in x-coordinate interval 45-46 km, and in y-coordinate interval from wells M-01 to M-012, above -250 m a.s.l. depth at least (Figures 6, 7, 8 and 9).

- Location of recharge zones and heat sources for the reservoir.** According to the pressure distribution in the reservoir, it is reasonable to assume that the main inflow of fluid is from the south because according to Figure 8, increasing pressure towards the south is evident. From the temperature distribution, it can be assumed that there are additional heat sources beneath the “Main” and “NE” upflow zones. It is still not clear whether all the inflow is from the south, or not. Available data don’t provide an exact answer to this question.

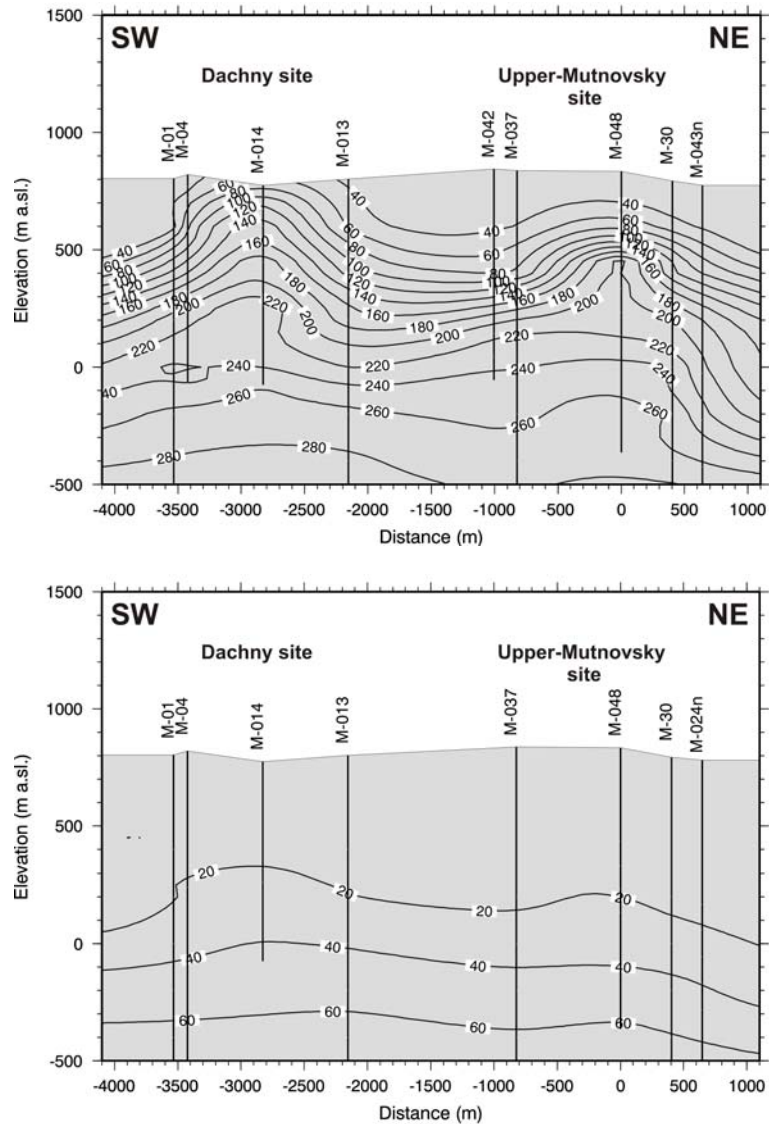


FIGURE 9: Mutnovsky field, temperature (°C) and pressure (bar) cross-sections along the northeast striking fault zone

## 6. NATURAL STATE MODELLING

The aim of natural state modelling of a geothermal field is to compute a pressure and temperature distribution that matches the measured pressure and temperature conditions based on well measurements. Thus, this is a reverse, or inverse, problem: namely, it is necessary to find model parameters that yield the required distribution.

The basics of the natural state simulation are as follows. Firstly, the system (reservoir and surrounding area) is assumed to be cold. Then, at a certain time “heating” of the system starts by a constant inflow of hot fluid. One of the main parameters in such modelling is the maximum time of “heating”, which defines when modelling should be stopped. The model is assumed to have reached steady state, when all parameters remain constant with time (i.e. a local equilibrium). Therefore, the maximum time for modelling is here set as approximately 1 million years. The numerical model is expected to reach the steady state within this time frame.

### 6.1 Numerical mesh; boundary and initial conditions

A 3-D irregular mesh is used for the modelling. The model of the reservoir contains five layers; each layer consisting of 160 elements (Figure 10). The distribution of element centres is irregular. It is dense along the fault zones (the main objects of the modelling); and some elements correspond to wells and hot springs (Figure 10). The thickness of each layer is 500 m and the elevation of the top layer is 250 m a.s.l. (Table 2). The top and the bottom layers are defined as inactive, i.e. constant pressure and temperature are specified in elements of these layers to provide boundary conditions for the model.

Initial conditions are given by a constant temperature gradient (100°C/km) for all layers in the model. So initial temperature is constant for each layer, and increases linearly with depth (except in the last layer where temperature of 280°C is assumed). The initial pressure distribution is hydrostatic and depends on the temperature. It was calculated by the program PREDYP (Arason et al., 2003). Table 2 shows this in more detail.

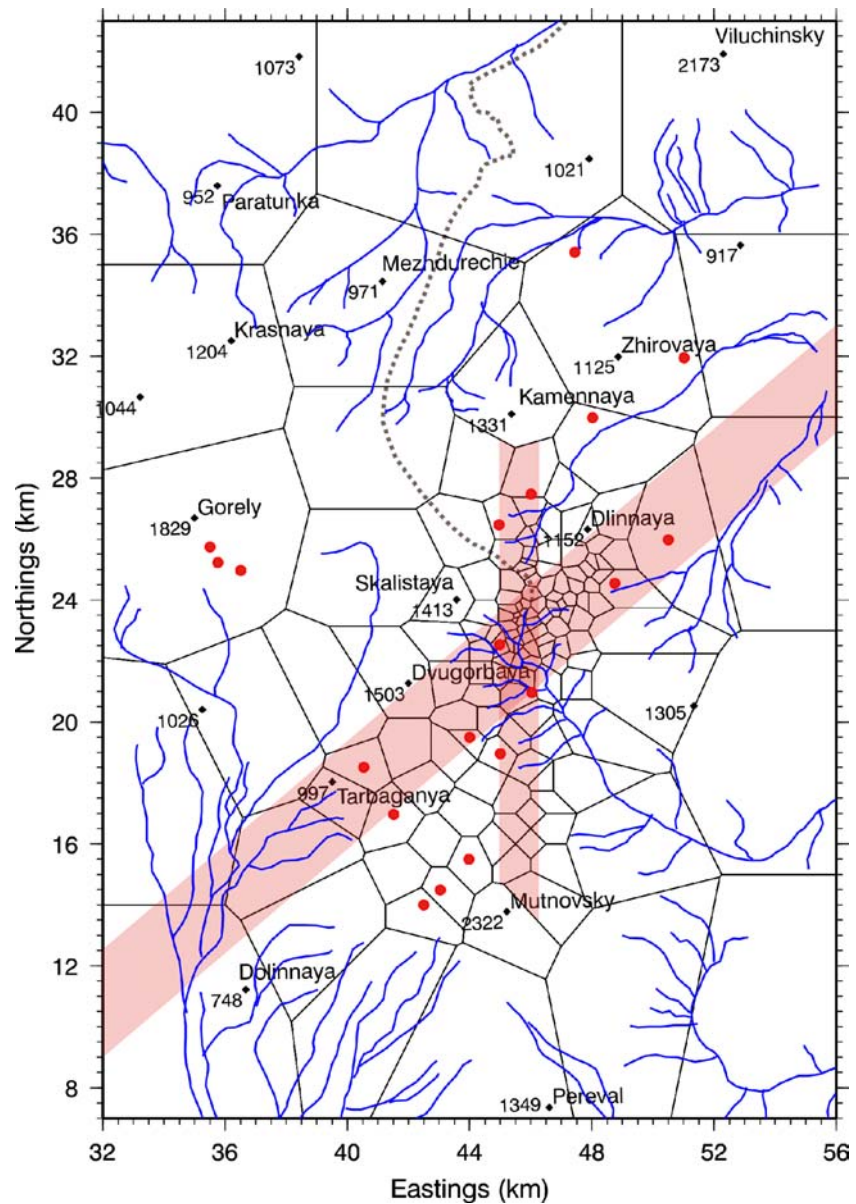


FIGURE 10: Numerical mesh for the natural state simulation together with major rivers, fault zones (shaded), and hot springs (circles)

TABLE 2: Initial conditions in the natural state model for the Mutnovsky field

N	Layer	Layer elevation (m a.s.l.)	Initial temperature (°C)	Initial pressure (bar)
1	A*	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

\* inactive layer

### 6.2 Rock properties

Table 3 shows the rock properties used in the model of the Mutnovsky geothermal field.

TABLE 3: Rock properties for the Mutnovsky geothermal field (according to Kiryukhin, 2002)

N	Layer	Layer elevation (m a.s.l.)	Rock	Density (kg/m <sup>3</sup> )	Porosity	Thermal conductivity (W/m*°C)	Specific heat (J/ kg*°C)
1	A	250	Quaternary ignimbrites, Pliocene lavas, rhyolite tuff	2100	0.2	2.05	1000
2	B	-250	Miocene sandstone	2300	0.08	2.1	1000
3	C	-750	Intrusive contact zone	2400	0.03	2.1	1000
4	D	-1250	Diorite	2700	0.02	2.1	1000
5	E	-1750					

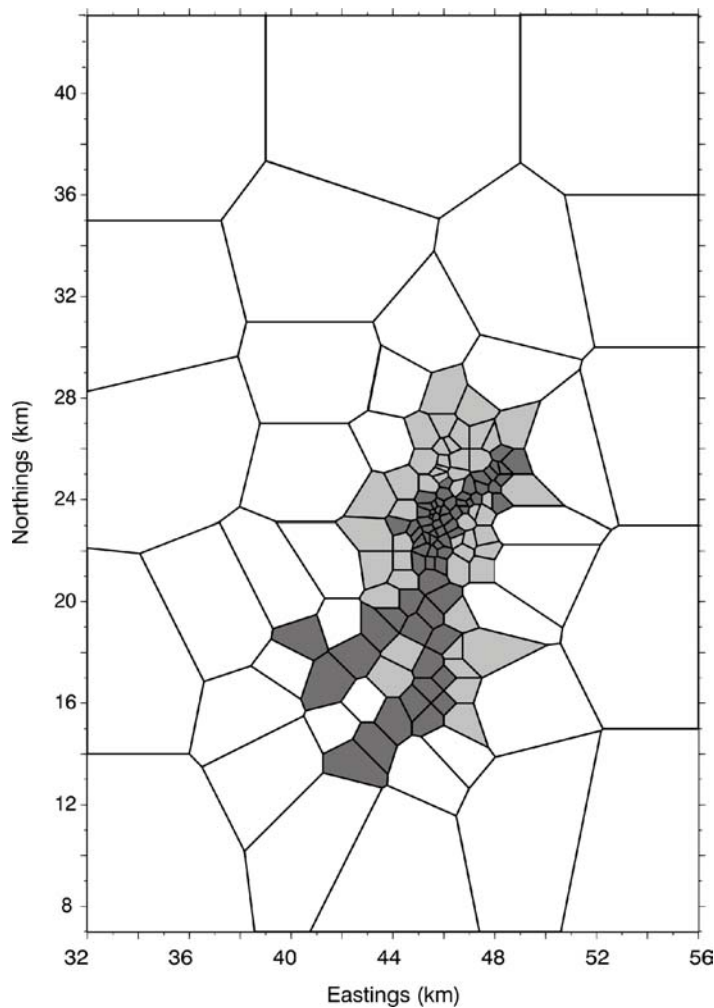


FIGURE 11: Permeability distribution in layer B, permeability increases with darker shades

The rock properties, except the permeability, are given fixed values because their influence on the behaviour of the system (i.e. pressure and temperature distribution) is considered much less than the influence of permeability. The permeability distribution yielding the observed fluid behaviour is then to be estimated. In this work, it was changed until the computed pressure and temperature distribution simulated reasonably well the conceptual model of the reservoir (Figure 11).

Three components of permeability ( $k_x$ ,  $k_y$  and  $k_z$ ) are provided in the TOUGH2 input file, and they may be different for each direction. In the current model, it was observed that the vertical component has to be 1-3 orders of magnitude less than the horizontal one, which is of great influence for the fluid behaviour in the reservoir.

Table 4 shows the model permeabilities which provide the best match to the measured data. Three types of rock permeability are assumed in the model for each layer: Within the *well field* “high-permeability” rocks simulate fault zones; and “low-permeability” is assumed for the surrounding elements. The name of the rock type contains the number of a



layer and the letter “P” (permeable) or “I” (low-permeability, or “impermeable”). For the area outside the field, average rock properties are specified in every layer. This is simulated by the “average” rock type, RCK6N.

TABLE 4: Estimated permeability of rocks in the numerical model

N	Layer	Name of rock type	Permeability (mD)		
			$k_x$	$k_y$	$k_z$
1	A	RCK1P	0.1	0.1	0.01
		RCK1I	0.1	0.1	0.01
2	B	RCK2P	29	29	2.9
		RCK2I	0.1	0.1	0.1
3	C	RCK3P	45	45	4.5
		RCK3I	0.1	0.1	0.1
4	D	RCK4P	38	38	3.8
		RCK4I	0.1	0.1	0.1
5	E	RCK5P	$0.1 \times 10^{-16}$	$0.1 \times 10^{-16}$	$0.1 \times 10^{-16}$
		RCK5I	$0.1 \times 10^{-16}$	$0.1 \times 10^{-16}$	$0.1 \times 10^{-16}$
6	Surrounding area	RCK6N	0.01	0.01	$0.1 \times 10^{-3}$

### 6.3 Sources and sinks

In order to simulate properly the natural state of the Mutnovsky system, sources and sinks of heat and mass have to be simulated, in agreement with the conceptual model of the reservoir. In this model, all sources and sinks are located in layer D (-1250 m a.s.l. average depth), the deepest “active” layer. The first variant of the modelling 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 is in accordance with the main idea of the fluid flow in the conceptual model.

Two other variants of the modelling assume additional heat and mass sources within the field (Table 5). The second variant assumes a second source in an element beneath the Dachny hot springs area. Finally, two additional sources, beneath the Dachny and Upper-Mutnovsky areas, are assumed in the third variant of the modelling. An assumption about additional sources seems to be more correct with respect to fitting the conceptual model, and is confirmed by the modelling results. The location of the sources is shown on Figures 12-14.

TABLE 5: 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

\* sink properties are estimated by the model

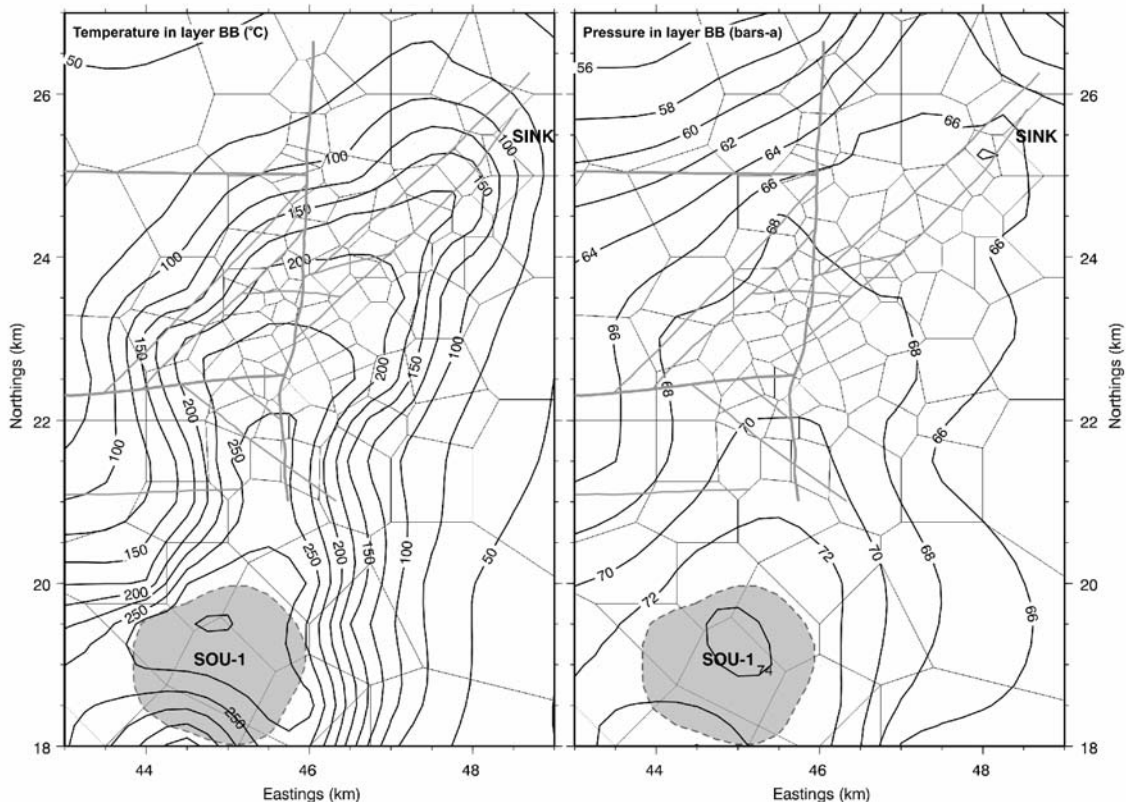


FIGURE 12: Computed temperature and pressure distribution in layer B according to model variant 1; a two-phase zone is indicated by the shaded area

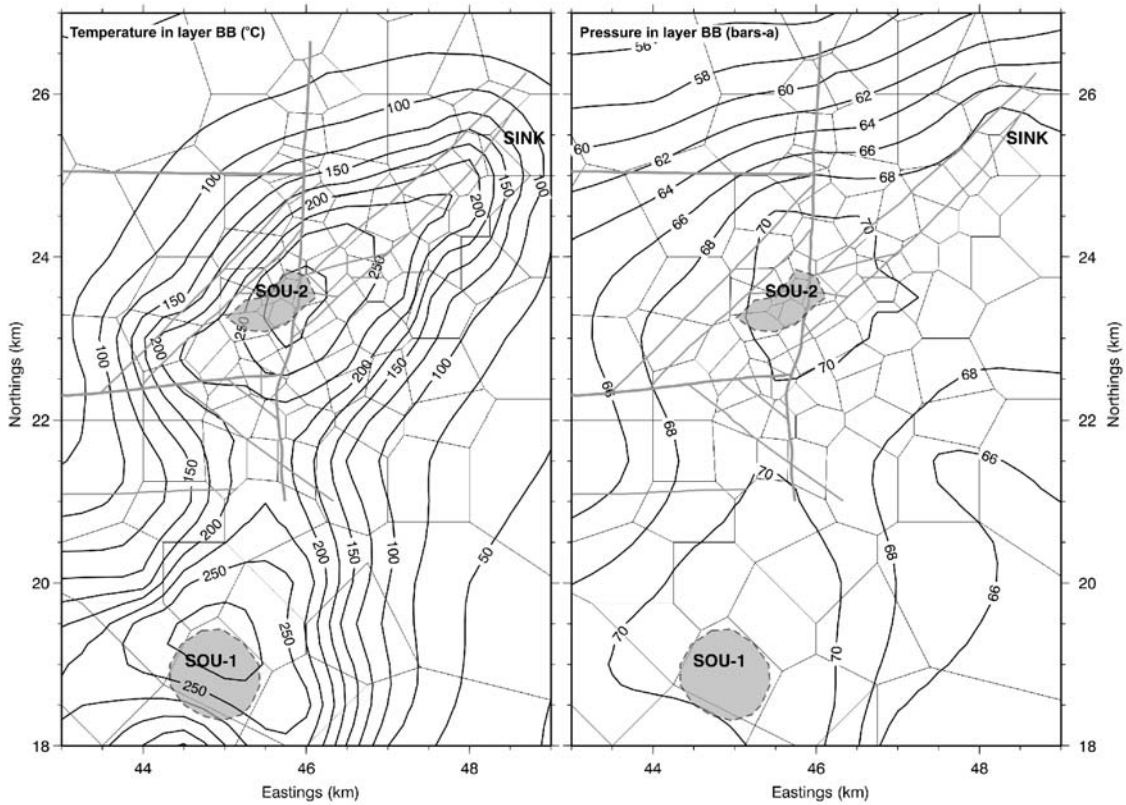


FIGURE 13: Computed temperature and pressure distribution in layer B according to model variant 2; two-phase zones are shown by shaded areas

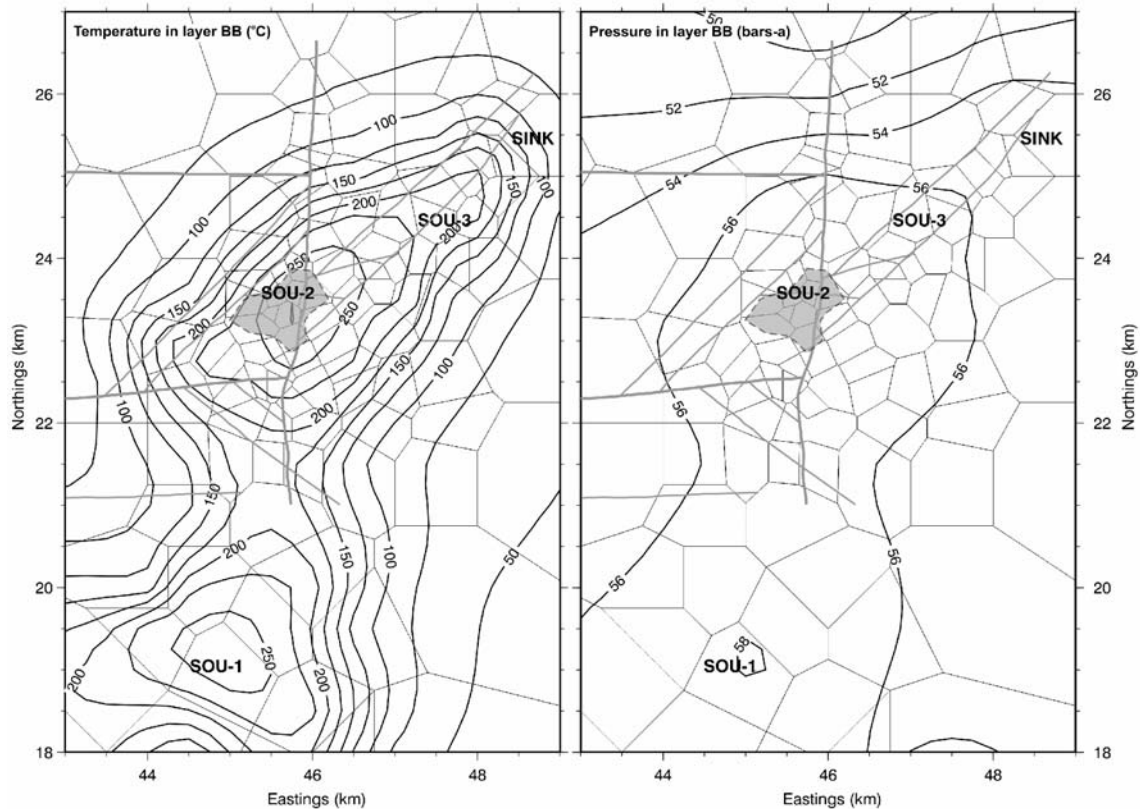


FIGURE 14: Computed temperature and pressure distribution in layer B according to model variant 3; a two-phase zone is shown by the shaded area

#### 6.4 Results of the modelling

Figures 12-14 show the temperature and pressure distribution, as well as two-phase zones in layer B (-250 m a.s.l) in the natural state model of the Mutnovsky field for different assumptions on the number of heat and mass sources (the three variants in Table 5).

Figure 12 shows the results of the modelling with one heat and mass source (model variant 1). In this case, two-phase conditions occur in the elements above the source while single-phase conditions prevail everywhere else in the field area, which does not fit the real conditions. Moreover, the temperature is too low and the pressure is too high compared to the measured data. But the pressure and temperature distribution fits the conceptual model as a consequence of the assumed distribution of permeability: higher permeability for the fault zone and lower for the surroundings.

Figure 13 shows the results of the modelling with two sources (model variant 2). The temperature distribution fits the observed results better than in the previous case, but it is still too low as well as the pressure being still too high. But now, there is a two-phase state in the Dachny area, which seems to fit the real conditions. As in variant 1, the path of the fluid flow fits the conceptual model.

Figure 14 shows the results of the modelling with three sources (variant 3). Now the two-phase conditions in the Dachny region fit the measurement results much better than in variant 2, and there is a rather good agreement for the pressure distribution within the field area. Note that in this case, the total inflow into the reservoir (55 kg/s, see Table 5) is close to the 54 kg/s estimation of Kiryukhin (2002). The location of the sources within the field area also agrees with the model of the Mutnovsky field presented in the same work.

There is not too much difference between the temperature simulation results in variants 2 and 3 (Figures 13 and 14). The simulated temperature is generally too low compared with the measured results. This may be due to the fact that the simulated area is much larger than the actual field area which is under consideration in the present work. Therefore, in this case other probable heat sources outside the field area should be taken into consideration.

## 7. CONCLUSIONS

The following concludes the presented analysis on the Mutnovsky geothermal field:

- The Mutnovsky geothermal resource is located in a plateau at 700-900 m a.s.l. and is hosted in volcanic formations.
- Numerous hot springs and fumaroles are found on the surface, often in conjunction with the intersection of major fault zones and fractures.
- Downhole pressure and temperature data from over 30 wells were collected, stored, and analyzed, resulting in maps and cross-sections of the initial pressure and temperature distribution.
- Additional literature on earlier reservoir studies on Mutnovsky has also been collected and reviewed.
- Based on the present and the earlier work, the following conceptual reservoir model is put forward. An upflow zone of over 300°C resides underneath the Mutnovsky volcano, some 3-4 km to the south of the present well field. The hot fluid flows laterally to the north, towards the Dachny site. There, a shift occurs in the flow direction and the geothermal system is elongated towards the northeast, where the Upper-Mutnovsky site is located. A hot upflow zone to the reservoir may also be located there.
- The areal extent of the reservoir, as defined by the 240°C temperature contour line at sea level, is on the order of 10 km<sup>2</sup>, and the reservoir thickness exceeds 1 km. The field is generally liquid-dominated, with temperatures between 240 and 280°C. A steam-cap is found near the top of the reservoir in Dachny.
- A natural-state, numerical reservoir model has been developed, on the basis of the conceptual model. It is made of five horizontal layers, each consisting of 160 elements. The TOUGH2 numerical simulator was applied.
- Three model variants were considered. All have in common an upflow zone to the south and an outflow zone to the northeast. Additional upflow zones were also modelled beneath the Dachny and the Upper-Mutnovsky areas.
- The model was calibrated against the initial pressure and temperature distribution. Well field permeabilities on the order of 30-50 mD were estimated, while the outer boundaries and the base layer generally have permeability around or far below 1 mD.
- Total source strength of 50-60 kg/s and 1650 kJ/kg enthalpy was needed to match the available data. A better match to the observed temperature distribution was obtained by spreading out the source instead of assuming only one upflow zone residing to the south.

## ACKNOWLEDGEMENTS

My greatest thanks to the United Nations University, Government of Iceland, and to the Director of the UNU Geothermal Training Programme, Dr. Ingvar B. Fridleifsson, for giving me the opportunity to participate in the UNU-GTP course 2003. I also would like to thank very much Dr. Oleg A. Povarov and Dr. Vladimir I. Kononov, for their confidence, and for recommending me for the study at this special geothermal training course in Iceland.

My deepest thanks to the UNU-GTP staff, Mr. Lúdvík S. Georgsson, Mrs. Guðrún Bjarnadóttir, and Mrs. Maria-Victoria Gunnarsson for their kind assistance, patience, and emotional support during the six-month study in a foreign country. I thank sincerely my supervisors, Grímur Björnsson and Arnar Hjartarson, for their valuable guidance and for sharing their knowledge and skills. Thanks to all UNU-GTP lecturers, to the Orkustofnun/ISOR staff, and to everybody concerned with the UNU-GTP course 2003. Thanks to my new friends, who I found in our 2003 group.

Special thanks to my family for the moral support during the time of the study.

## REFERENCES

Arason, T., Björnsson, G., Axelsson, G., Bjarnason, J.Ö., and Helgason, P., 2003: *The geothermal reservoir engineering software package Icebox, user's manual*. Orkustofnun, Reykjavík, report, 53 pp.

Assaulov, S.G., 1994: A conceptual model and reservoir assessment for the Mutnovsky geothermal field, Kamchatka, Russia. Report 1 in: *Geothermal Training in Iceland 1994*. UNU-GTP, Iceland, 1-30.

Assaulov, S.G., and Assaulova, N.P., 2000: *Mutnovsky geothermal field DATABASE // Drilling and reservoir development*. Mutnovsky Independent Power Project, (internal documentation).

Björnsson, G., 2003: *Numerical modelling I and II with special emphasis on the TOUGH code*. UNU-GTP, Iceland, unpubl. lecture notes.

Fedotov, S.A., Karpov, G.A., Delemen, I.F., et al. 2002: *Development of conceptual model of Mutnovsky geothermal field (Dachny and South sites) and assessment of heat carrier resources for production*. Institute of Volcanology of Academy of Sciences of Russia (Far-East division), Petropavlovsk-Kamchatsky, internal report (in Russian).

Haukwa, C., 1998: *AMESH, a mesh creating program for the integral finite difference method: A user's manual*. Lawrence Berkeley National Laboratory, report LBNL-45284, 53 pp.

Kiryukhin, A.V., 2002: *Modelling of production of geothermal fields* (in Russian). Dalnauka, Vladivostok, 216 pp.

Kiryukhin, A.V., Delemen, I.F., and Gusev, D.N., 1991: *High-temperature hydrothermal reservoirs* (in Russian). Nauka Publ., Moscow, 160 pp.

Kiryukhin, A.V., and Sugrobov, V.M., 1987: *Models of heat transfer in hydrothermal systems of Kamchatka* (in Russian). Nauka Publ., Moscow, 152 pp.

Kononov, V.I., 2001: Geothermal resources of Russia and their usage. *Lithology and mineral resources*, 2, 115-125.

Maltseva, K.I., Assaulova, N.P., Kozlov, A.E., et al., 2002: *Project of pilot and commercial development*

of Dachny site of Mutnovsky geothermal field. SC Geotherm, – Akva Ltd., Elizovo, Kamchatsky region, internal report (in Russian).

Povarov, O.A., 2003: Achievements and prospects of geothermal power engineering development in Russia. *Energoprogress - science-technology newspaper, special issue, March*, 1-2.

Povarov, O.A., Postnikov, A.I., and Nikolski, A.I., 2001: Power plants at the Mutnovsky geothermal field (Kamchatka). *Geothermal Resources Council, Transactions*, 25, 543-548.

Pruess, K., Oldenburg, C., and Moridis, G., 1999: *TOUGH2, user's guide version 2.0*. Lawrence Berkeley National Laboratory, 197 pp.

Sugrobov, V.M., (ed.), 1986: *Geothermal and geochemical investigations of high-temperature hydrothermal systems (by the example of Mutnovsky geothermal field)* (in Russian). Nauka Publ. Moscow, 305 pp.

Vakin, Ye.A., and Sugrobov, V.M., 1972: Hydrogeological features of volcanic structures and recent hydrothermal systems. In: Goleva, G.A. (Ed.), *Kamchatka, Kuril and Komandor islands - South Kamchatka geological research expedition (in Russian)*. Hydrogeology of USSR, 29, Nedra Publ., Moscow, 364 pp.