RESERVOIR ENGINEERING APPLICATIONS TO KAMCHATKA (RUSSIA) GEOTHERMAL FIELDS

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ABSTRACT

Geothermal fields in active volcanic areas represent an examples of extreme hydrogeological conditions in the earth crust, therefore their study serve as a test of hydrogeologists ability to describe and forecast underground heat and mass transfer processes based on existing groundwater models and measurements techniques. In addition, geothermal energy demand increase as oil prices rise. Three Kamchatka geothermal fields Paratunsky (95 ^{o}C), Pauzhetsky (225 ^{o}C) and Mutnovsky (310 ^{o}C) cover the range of geothermal resources conventional use from low-temperature (designed for direct geothermal energy use) to high-temperature (suitable for electricity production).

Conceptual models of the production reservoirs derived from integrated analysis of the following data: geological structure of the fields, thermal discharge, temperatures, pressures and feed zones distributions, gas and chemistry of fluids, secondary minerals distributions, geophysical observations, field response to exploitation.

In particular case of the Paratunsky field three hot water upflows (85-95 ^{o}C) zones were detected, which characterized by high permeability in the intervals of depth from 100 – 150 to 1200 m. Diorites contacts outcrops of the uplifted sides of the Paratunka river graben zone (at +500 - +800 m.a.s.l.) serve as channels of meteoric water recharge, according to hydroisotope data.

Production reservoir of the Pauzhetsky geothermal field occurs in the fractured tuffs lake deposits (N_2-Q_1), overlaid by the caprock represented by a 150-m thick layer of alevropelitic tuffs. Dacite extrusion complex (Q_{2-3}) located inside the 190^{o}C zone acts as a structural force for the temperature and permeability distribution. High temperature upflows of 225 ^{o}C occur in Central and South-East sites and characterized by Cl-Na fluids with a TDS of 2.7 – 3.4 g/kg.

Production reservoir of the Dachny site of the Mutnovsky geothermal field represent a single fault with dip of 60^{o}, and average thickness 120 m. There is no explicit lithologic control of the production zone. Roof of the production zone is identified by circulation losses during. The plane of the production zone intersect the active magma channel of Mutnovsky volcano at elevations of +250 - +1250 m.a..s.l. at the distance 8 km apart from production site. The Mutnovsky volcano crater glacier act as a meteoric water recharge area for the fluids producing by exploitation wells. Upflow of the high temperature fluids occur in the south-east part of the production zone, where liquid dominated conditions at 310^{o}C occurs. Ascending fluids transfer to two-phase conditions in the shallow parts of the production zone (above 0 m.a..s.l.), where production zone traced by wairakite-chlorite

secondary minerals association. Main production zone is also detected by Cl/SO4>1 ratios, and high values of Na-K geothermometer.

Numerical modeling (TOUGH2, iTOUGH2, TOUGHREACT) applied to geothermal fields (Paratunsky, Pauzhetsky and Mutnovsky) used as an instrument to verify conceptual models above and to estimate generating capacity of geothermal fields. In this particular modeling study the following results were obtained: (1) Possible long-term exploitation flowrate in Paratunsky geothermal field was estimated as more than 250 kg/s (enthalpy 360-400 kJ/kg) under existing scheme of the exploitation, (2) Pauzhetsky geothermal field (Central Site) may yield 220 kg/s with enthalpy 875-920 kJ/kg (in long-term scale of the exploitation), no additional load recommended (Central Site), (3) Mutnovsky geothermal field 50 MWe power plant stable 10-year period steam supply from the Dachny Site may be achieved based on additional seven wells drilling in the south-east part of the Main production zone.

INTRODUCTION: KAMCHATKA GEOTHERMAL FIELDS

Kamchatka geothermal fields geological setting is illustrated by Fig. 1. The total number of thermomineral springs estimated as 236 (G.F. Pilipenko, 2004). High temperature thermal manifestations occur adjacent to active volcanoes (total number of active volcanoes estimated as 30). Most of geothermal reservoirs occur in porous and fractured Quaternary volcanogenic rocks, and fracture dominated Neogene volcanogenic and sedimentary rocks. A few geothermal reservoirs found in metamorphic Paleozoic rocks.

Conventional geothermal field use include high temperature geothermal fields Mutnovsky and Pauzhetsky, and low temperature geothermal fields: Paratunsky, Essovsky, Anavgaisky aand Malkinsky. Mutnovsky geothermal field recently installed capacity include Verkhne-Mutnovsky PP (12 MWe installed in 1999) and Mutnovsky (50 MWe installed in 2002), also there are plans to install 4MWe binary PP in Verkhne-Mutnovsky site soon, as well as extension of Mutnovsky PP(+50 MWe). Pauzhetsky PP started exploitation in 1966 with 5 MWe installed capacity, at this time a new additional 6 MWe unit is under construction, as well as 4 MWe binary PP feasibility study is on-going. Another attractive possibilities high temperature geothermal reservoirs use are Bolshe-Banny (where 30-40 MWe binary PP may be installed), Kireunskaya (where 10-20 MWe binary PP may be installed) and Nizhne-Koshelevsky (where 50 MWe PP is feasible) (V.M. Sugrobov et al, 2004). Paratunsky geothermal field operated mostly under free discharge conditions of hot 85-95 ^{o}C water with flow rates 220-230 kg/s used for swimming pools, district heating, greenhouses and fish farming. Essovsky and Anavgaisky geothermal fields produce 190 kg/s at 70-80 ^{o}C with similar use. Malkinsky geothermal field operated with pumps delivering 20-30 kg/s at 80-90 ^{o}C. Verkhne-Paratunsky geothermal field use with 280 kg/s of 80 ^{o}C confirmed capacity is a very promising for heat supply of Elisovo city (30,000 population) located 50 km apart.

Future geothermal applications may also include: (1) Scientific drilling projects targeted to conduit zones of Mutnovsky and Avachinsky active volcanoes, located nearly of Petropavlovsk-Kamchatsky city (280,000 population), (2) HDR (Hot Dry Rock) and EGS (enhanced geothermal reservoirs) technologies use.

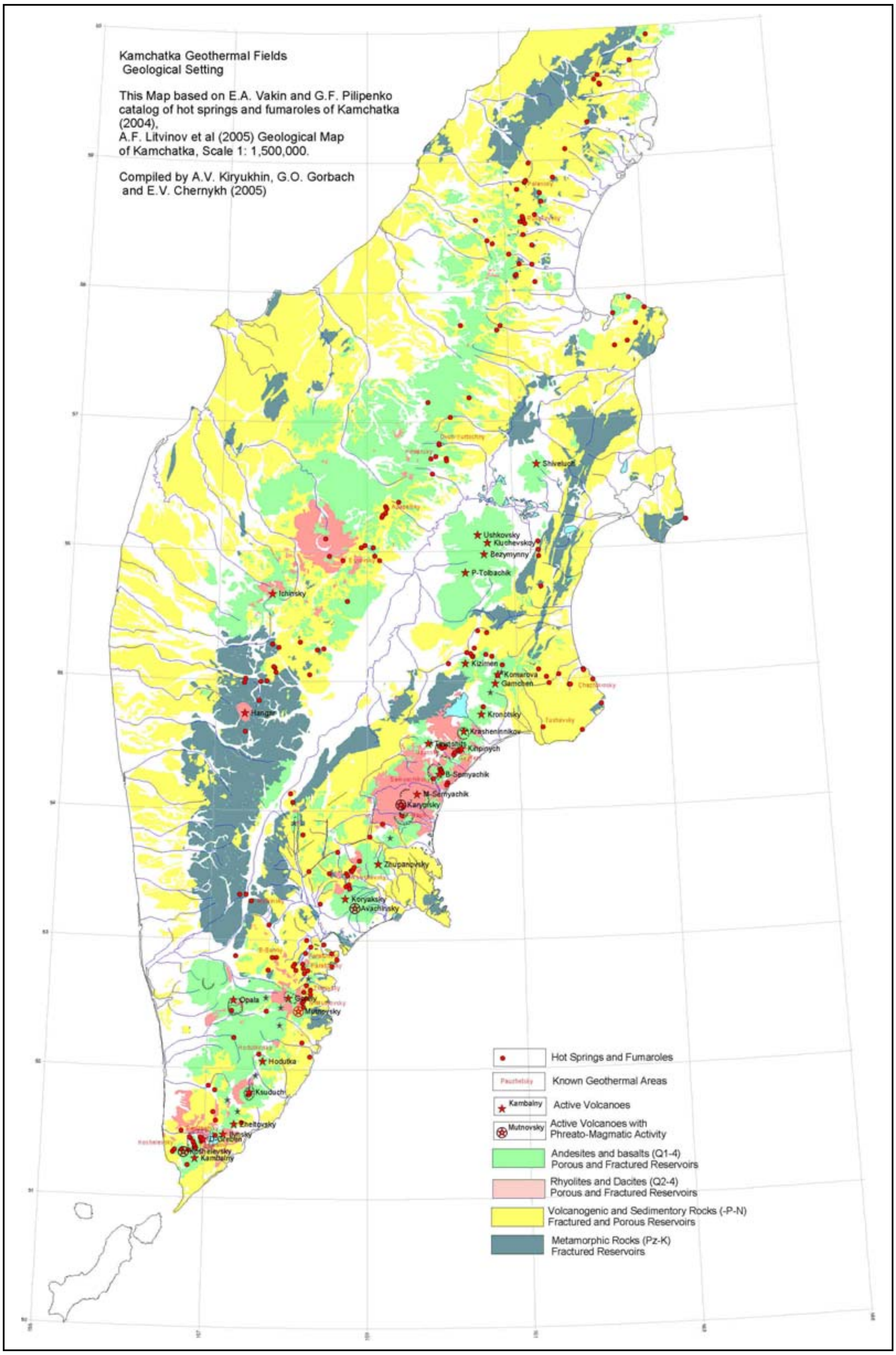


Fig.1 Kamchatka geothermal fields geological setting. This map compiled based on G.F. Pilipenko catalog of Kamchatka hot springs and fumaroles (2004, pers. com.), A.F. Litvinov et al. Geological Map of Kamchatka (Scale 1: 1,500,000) (2005).

Computer modeling of geothermal systems became a mature technology based on long-term exploitation of geothermal fields data and applications in nuclear waste storage and environmental remediation. The most robust instrument of those applications became TOUGH2-family code (K.Pruess, 1991, 1999, S.Finsterle, 1999, T.Xu, K. Pruess, 2001), which used in the following study.

PARATUNSKY GEOTHERMAL FIELD

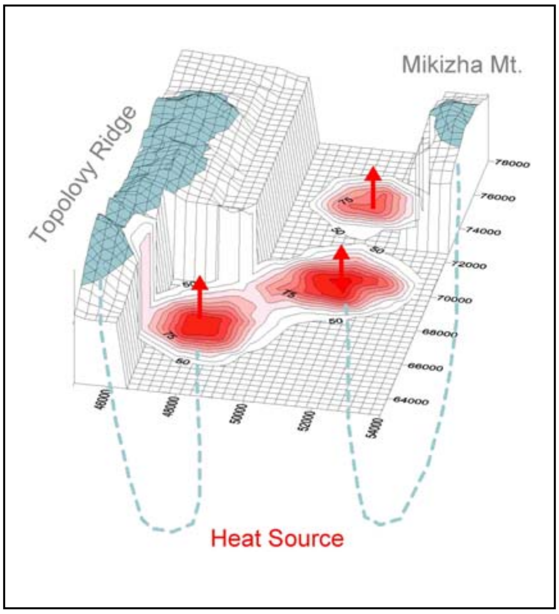
Paratunsky geothermal field exploitation started since 1963. Since 1975 total yield of this field is 200 kg/s (summer) - 250 kg/s (winter) of hot water with temperature of 80-90^{o}C. Specific feature of this field exploitation is mass flowrate extract increase in winter, and decrease in summer. In contrary to this recharge to reservoir increase in summer, and decrease in winter.

Conceptual Model

Conceptual model of the production reservoir (Fig.2) derived from integrated analysis of the following data: temperatures and feed zones distributions, geological structure of the field. Hot water upflows were detected in Sredny, Nizhne-Paratunsky, and North sites of the field based on temperature distributions and natural hot spring discharge data. Feed zones distributions analysis detect low permeability interval from 0 to 100 – 150 m depth (upper Quaternary caprock), then high permeability reservoir in the interval of 100 – 150 to 1200 m where average well flowrate increase up to 17 – 25 kg/s (fractured layers of Miocene “green tuffs”), then low permeability units in the interval from 1200 m to 2500 m where 1-4 kg/s yield only (basement with local vertical channels permeability). Diorites intrusions outcrop in the recharge area of the uplifted sides of the Paratunka river graben zone. Diorites contact boundaries (located at +500 - +800 m.a.s.l. on Topolovy Ridge, Mikizha Mt.) may serve as channels for meteoric water recharge, which occur at +700 m.a.s.l., according to hydro isotope data. This type of reservoir recharge conditions is in agreement with significantly larger pressure variations (up to 1.5 bars) in production reservoir, compare to level variations in the Paratunka river (corresponding to 0.18 bars) and reservoir pressure increase in April 15-20 days before river seasonal flood. Based on above the high elevations of the reservoir recharge area where snow melting took place assumed. Large fraction of sulfate in thermal fluids pointed out to possible location of the upflow zones basement roots within paleovolcanic feed channels. Hot water discharges occur in the deposits of the Paratunka river valley, where constant pressure boundary conditions achieved.

Numerical Modeling

Model design (Fig.2). Numerical grid based on A-MESH, one-layer reservoir with thickness of 1000 m overlaid by 100 m thick caprock was generated. Domains (regions with different petrophysical properties) correspond to North, Nizhny, Sredny, Mikizha sites and ambient regions. Mass sources were assigned in the model in the elements of the upflow zones corresponding to Sredny (360 kJ/kg), North (380 kJ/kg) and Nizhny (400 kJ/kg) sites. Mass sources rates varies accordingly to the seasonal variations represented by coefficients α_0 («winter») and α_1 («summer»). Heat losses to caprock were defined by heat exchange coefficient of 4.2 10^{-3} W/m^2 ^{o}C. Bottom conduction heat flows assigned through heat sources of 0.063 W/m^2. Inactive B-elements used on the external boundaries to make up “seepage type” boundary conditions (P=const, if boundary pressure less than adjacent element pressure, else "no flow"). This type of boundary conditions was proved by exploitation Sredny Site 1979-84 data, when flowrates and wellhead pressures drop simultaneously.



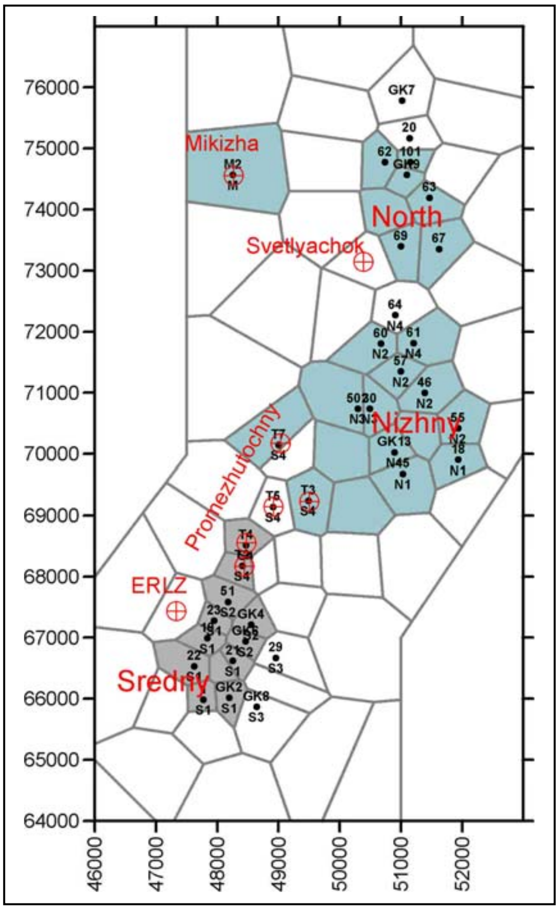


Fig.2 Paratunsky geothermal field.
Left - Conceptual model: fluids streamlines (dashed lines) from recharge areas to layer type production reservoirs systems, temperature distributions at –1000 m.a.s.l.
Right – Numerical model: numerical grid with different permeability domains,
• - exploitation wells, ⊕ - additional exploitation withdrawal zones.

Modeling of the natural state conditions. Natural state defined in TOUGH2 if mass and energy balances are less than 10^{-5} in the model elements, while large time steps of 10^{15} s used. Mass rates in source elements of the model were adjusted to match real and simulated temperature distributions at -1000 m.a.s.l. The following upflow rates were obtained in the model - 80 kg/s, 75 kg/s and 40 kg/s for Sredny, Nizhny and North sites correspondingly. Reservoir pressure seasonal variations match yield $5\ 10^{-9}$ Pa^{-1} compressibility value, and seasonal recharge coefficients (α_0=0.75, α_1=1.25). Significant correction of the parameters above was implemented after modeling of the exploitation (see below).

Modeling of the exploitation 1966-1999. Model calibration based on monthly averaged flowrate (kg/s) and wellhead pressures (converted to m.a.s.l.) data, averaged for the wells located in the same model elements. Pressure variable in the model was also converted to m.a.s.l. to match data. Based on the pressure match the following model parameters were re-estimated: recharge seasonal variation coefficient (α_0=0.95 («winter»), α_1=1.05 («summer»)), hot water upflows mass rates: 138 kg/s - Sredny, 95 kg/s - Nizhny, 60 kg/s - North, in total 293 kg/s. Permeability values: 90 mD - Sredny, 60 mD – Nizhny and North, 15 mD – ambient rocks (North and Nizhny), 50 mD – ambient rocks

(Sredny). Then productivity indexes (PI) were estimated based on the 1966-1999 exploitation data for the following groups of wells (SR1, SR2, NP1, NP2, 20, 69, GK9, GK7). Corresponding PI values are (40, 9, 12, 8, 30, 10, 3 kg/s bar). Flowrates were calculated at each time step in the model:

$$Q_i = PI_i*(P_i-(1000+Z_i)\rho_i g-WHP_i)$$

,where i – model element index, PI_i- productivity index, kg/s bar, Q_i – flowrate, kg/s, P_i – model element «i» pressure, ρ_i – fluid density, g – acceleration constant, Z_i – elevation, m.a.s.l., WHP_i – averaged well head pressure. For this purposes special subroutine (WELLSIM) was implemented in the TOUGH2 code.

Modeling of the exploitation 2000 – 2024. Modeling exploitation of the existing wells for long-term period up to 2024 year was performed with wellhead pressures assigned based on year 1997 monthly averaged data. In this case withdrawal rate became stable in periodical terms after 2-3 years of the exploitation: maximum withdrawal rate - 236.3 kg/s (January), minimum - 180.6 kg/s - (July), average - 206 kg/s. Additional 62.5 kg/s load from Promezhutochny, Mikizha, ERLZ and Svetlyachok sites (where downhole pumps installed) will cause 6-9% mass flowrate drop in basic sites (Sredny, Nizhny, North), nevertheless the total annual withdrawal could maintain more than 250 kg/s.

PAUZHETSKY GEOTHERMAL FIELD

Pauzhetsky Power Plant with 5-11 MWe installed operated since 1966. Exploitation of the geothermal field caused significant drop temperature and pressure, changes of the fluid chemistry conditions in reservoir, and gradual switch-off of the exploitation wells including leaving of the North Site. In this case numerical modeling obviously needed to design efficient exploitation parameters.

Conceptual model

Conceptual model (Fig. 3). Production reservoir of the Pauzhetsky geothermal field occurs in the monocline slope of the Kambalny ridge inside the Pauzhetka volcano-tectonic depression. Production reservoir rocks are Pauzhetka tuffs (N_2-Q_1) which include welded tuffs, tuffecious conglomerates, and psephitic tuffs and Golyginsky Layer (N_2 gol) with total thickness of 700 m, which are fractured by middle-upper pleistocene Dacite extrusion complex (Q_{2-3}) located inside the 190°C zone, and acts as a structural control for the temperature and permeability distribution. Production reservoir includes North, Central and South-East fractured layer type connected sub-reservoirs. Average vertical thickness of the production zone is 334 m (including 4.3 sub-production zones, in average). Rock properties are very much influenced by hydrothermal alteration processes. The most permeable and completely altered (to zeolites and chlorites) production zone is characterized by 0.20 porosity and 1500 – 1800 kg/m^3 density (Ladygin et al., 2000). The caprock represented by a 150-m thick layer of dacitic alevropelitic tuffs. High temperature upflows of 220 °C occur in Central and South-East sites mainly and are characterized by Cl-Na and CO_2-N_2 chemical composition with a dissolved solids content of 2.7 – 3.4 g/kg.

Natural thermal discharges include hot springs in North Site with a measured rate of 31 kg/s, and steaming grounds (Verkhnee and East with a total discharge rate of 0.7 MWt).

Numerical modeling

Model design (Fig. 3). Numerical model was generated based on A-MESH grid generator as a one-layer reservoir with average thickness 700 m, overlaid by caprock of 100 m thickness. The centers of the model elements were located at elevations corresponding to bottom of the Pauzhetka tuffs. The total number of the elements is 131, including 66 well elements, 32 B-elements for boundary conditions assign. Heat exchange through caprock with the earth surface at 5^oC was assigned based on heat exchange coefficient of 0.013 $W/m^2\ ^oC$ (corresponding corrections in QLOSS subroutine were implemented). Additional inactive elements were specified for natural discharges (hot springs and steam jets), where atmospheric pressures and temperature of 100 ^oC assigned, those elements were placed at earth surface elevations above corresponding model elements R1, 135, 5 and 142. Upflow zones were specified in the model with mass sources of 830-921 kJ/kg. Bottom conduction thermal flows 0.063 W/m^2 assigned in the all model elements. Constant pressure and temperature conditions in boundary B-elements assigned.

Modeling natural state conditions was targeting to temperature and pressure match based on mass sources parameters adjustment (mass rates and permeability distributions). Production reservoir permeability estimated as 100 mD, while ambient rocks permeability as 3-10 mD. High temperature fluids upflow rates and enthalpies are – 36 kg/s, 830 kJ/kg (North Site), 188 kg/s, 875-920 kJ/kg (Central Site), 100 kg/s, 900 kJ/kg (South-East Site).

Modeling of the exploitation 1966-2000. Data for model calibration include monthly averaged flowrates and enthalpy data, and reservoir pressures, which were calculated based on monitoring wells leveling and temperature logs:

$$P = P_{atm} + \int_{z0}^{z1} \rho(T,z)\ g\ dz$$

,where P- calculated pressure at z_1, P_{atm} = atmospheric pressure, z_0 = water level, $\rho(T,z)$ = fluid density vs of temperature T and depth z, and g – acceleration constant. Besides of this Na-K geothermometer data ((Truesdell) ($T_{Na/K} = 855.6/(lg(Na/K)+0.8573))-273$) used for flowing enthalpies estimations in exploitation wells. Ten pressure monitoring wells and nine exploitation wells data were used for model calibration. Based on above the following reservoir model parameters were estimated: (1) Pressure values in boundary B-elements, (2) Compressibility coefficient of the production reservoir 5.0 10^{-7} Pa^{-1}, and 2.0 10^{-8} Pa^{-1} for ambient rocks, (3) Thermal expansivity 1.75 10^{-2} $^oC^{-1}$ of the production reservoir (this parameter need to explain reinjection response in the North and Central Sites of the field), (4) Double porosity of the production reservoir (fracture porosity 0.2 (Central Site), 0.1 (North Site), fracture spacing 162 m). Modeling show large difference 20-30 ^oC in matrix and fracture media as a result of cooling induced by exploitation, which mean low efficiency of the heat extraction from production reservoir during exploitation period of 1966-1999 years.

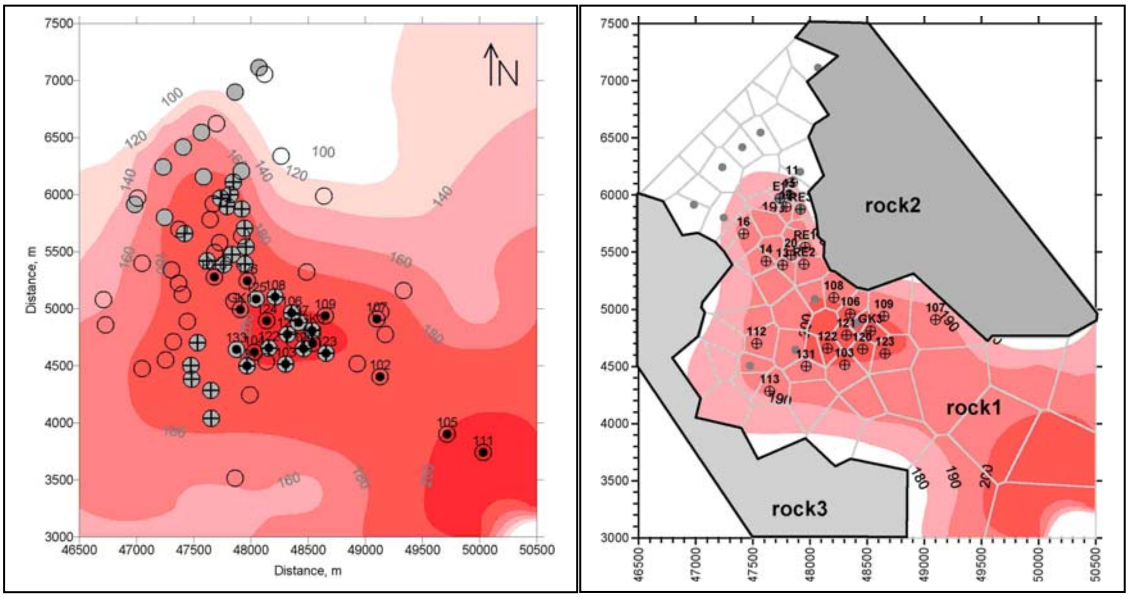


Fig.3 Pauzhetsky geothermal field.
Left - Conceptual model: initial temperature distributions, • wells, penetrated Dacite extrusion complex (Q_{2-3}), acts as a structural control for the temperature and permeability distribution, ⊕ production and exploitation wells, ● reinjection wells with high injectivity.
Right – Numerical model grid, initial temperature distribution in production reservoir (rock1 domain), ambient rocks domains (rock2, rock3), ⊕ exploitation wells, • reinjection wells.

Modeling of the exploitation up to 2030. Basic scenario load include eight existing exploitation wells 103, 106, 108, 121, 120, 122, 123 and GK3 under specified well head pressure (WHP) conditions and reinjection of 30 kg/s of 120° C separate water to wells 142, 143 and 144. Modeling shows steam production decline from 28 kg/s to 24.4 kg/s (WHP= 2.7 bars) and mass flowrate decline from 253 kg/s to 232.9 kg/s during 30 year exploitation period. The key question is boundary conditions response to the exploitation, if withdrawal will exceed natural upflow rate. This case was discussed based on example of the Paratunsky geothermal field above. Pauzhetsky geothermal field may behave in a similar way. Monitoring of the chemical parameters and enthalpies of the exploitation wells show synchronous enthalpy and Cl^- decline when mass flowrate exceed 220 kg/s (critical value for Central and North sites of the field). This mean 17% meteoric water dilution, and mixed boundary conditions took place during exploitation. Therefore two possibilities of the boundary conditions change were investigated in the model.

Four scenarios of the exploitation were considered in the model in addition to basic scenario, aiming sensitivity study of the steam production to different reinjection rates:

1. No reinjection since Jan., 2001,
2. Reinjection of 60 kg/s, 120 ^{o}C in wells 142, 143 and 144;
3. Reinjection of 120 kg/s, 120 ^{o}C in wells 142, 143 and 144;
4. Reinjection of 180 kg/s, 120 ^{o}C in wells. 142, 143 and 144.

Based on modeling it was found 30-60 kg/s reinjection rate has a positive effect on steam production, while shift outside of range 30-60 kg/s cause steam production decline (either from meteoric water, or from reinjected water inflows). Another key exploitation issue is a maximum possible withdrawal rate during exploitation period. Modeling study shows 120-200% number of wells increase has no significant effect on total steam production of the Central Site of the Pauzhetsky geothermal field during long-term exploitation period.

iTOUGH2 (S.Finsterle, 1999) is a robust successor of the TOUGH2 computer code, which offer high-level programming capabilities to inverse problem solutions, including non-linear multi parameters problems. iTOUGH2 applications to the natural state of the Pauzhetsky geothermal field conducted recently. In this study observation data such as temperature and pressure measurements, and natural discharge rate were used to estimate the following parameters of the model: (1) domains permeability, (2) upflow rates and enthalpies, (3) boundary pressure. The next step is iTOUGH2 application to re-calibration of the exploitation model, which is ongoing.

MUTNOVSKY GEOTHERMAL FIELD

Two geothermal power plants with total capacity 62 MWe were installed in the Mutnovsky geothermal field by 2002. This power plants capacity covers 35% of Kamchatka electricity demands. Nevertheless steam supply shortage on Mutnovsky PP where 50 MWe installed (it was only 60% steam supply to PP in 2003) back a modeling study to verify drilling targets and number of wells needed to maintain steam supply required for power plant.

Conceptual model

Concepual hydrogeological model of the Dachny site of the Mutnovsky geothermal field shown in Fig.4. The Main production strikes north-north-east with east-east-south dip 60^o, and average thickness 120 m. The Main production zone in Dachny site is penetrated by wells 045, 01, 014, 016, 1, 029W, 26, 24, 4E, which are characterized by high WHP's (Fig.4). The strike of production zone is subparallel to the system of the active faults (V.L. Leonov, 1986). Host rocks of production zone are: diorites, Miocene-pliocene sandstones, rhyolite and andesite tuffs and lavas. Nevertheless there is no explicit lithologic control of the production zone. Roof of the production zone is identified by circulation losses during drilling along the plane of Main production zone. 75% of all full circulation loss zones and 100% of all production wells are occur to ±150m thick interval of the Main production zone plane. Tracer tests interaction is also preferable along the Main production zone strike. The plane of the Main production zone is intersect the active conduit of Mutnovsky volcano at elevations of +250 - +1250 m.a..s.l. at the distance 8 km apart from production site. The Mutnovsky volcano crater glacier act as a meteoric water recharge area for the fluids producing by exploitation wells in the Dachny. Meteoric recharge accelerated and maintained by melting of the glacier due to high heat flows in the crater. Heat sources of the production zone is connected to magmatic bodies accumulated in the North Mutnovsky volcano-tectonic zone, but this is not clear weather or not those bodies are directly connected to magmatic system of the active Mutnovsky volcano, or just isolated remains of magma intruded in the hydrofracturing plane created by Mutnovsky volcano. Upflow of the high temperature fluids occur in the south-east part of the Main production zone, where liquid dominated conditions at 300^{o}C occurs (Fig. 4). Ascending fluids transfer to two-phase conditions in the shallow parts of the production zone (above 0 m.a..s.l.), where production zone traced by wairakite-chlorite secondary minerals association. Main production zone is also detected by Cl/SO4>1 ratios, and high values of Na-K geothermometer. Four additional wells (A1-A4), recently drilled (2001-2003) outside of the Main production zone were found to be non- or low-productive.

Numerical modeling

Model design (Fig.4). Grid generation based on AMESH preprocessor with additional correction procedure used to avoid “parasitic circulation” in the model. Geothermal reservoir is represented as a combination of two reservoirs: A-reservoir and B-reservoir. A-reservoir numerical grid corresponds to the Main production zone with averaged thickness 120 m, each element of which is located at the specified elevation corresponding to the Main production zone. B-reservoir numerical grid includes three elements corresponding to wells 2E, 5E and O12 diorite intrusion contact permeability zones. In total 24 existing wells, 39 additional interior elements (F-elements and D-element) and 12 boundary (inactive) elements (B-elements) are specified in the model. Figs.4 demonstrates grid and permeability distributions assigned in the model. «Sources», where upflows assigned in the model are O45, F27, F28, F14, F15, F29. Boundary conditions are assigned in B-elements as P=const and T=const (natural state modeling). Heat exchange between the model elements and host rock with average temperature 90°C are specified through QLOSS subroutine where heat exchange coefficient is assigned as 0.0042 W/m^2 °C.

Modeling natural state conditions. Natural state modeling is targeted to temperature, pressure and phase condition match in the key elements to improve model sources parameters, and permeability distribution. Based on above, total upflow rate estimated in the model is 54 kg/s, with mass rates and enthalpies specified as 9 kg/s and 1390 кJ/кg (water 307°C) in each “source” element. Permeability in A-reservoir is estimated as 100 mD. Upflows are directed from south-east part to north-north-east part (liquid discharge) and west part (steam discharge, element D – the so-called Kotel) of the production zone.

Modeling of the exploitation. The total steam production (at 6 bars abs) of the above mentioned wells declined from 64.9 kg/s to 59.4 kg/s (8.5%), the total separate production declined from 117.5 kg/s to 107.5 kg/s (8.5%) during one year exploitation period. Pressure monitoring well O12 shows 0.75 bar pressure drop during one-year exploitation period, but this data does not characterize production zone where exploitation took place. At this stage of calibration the compressibility coefficient was found necessary to be implemented in the model: 5.0 10^{-7} Pa^{-1} in STEAM domain and 5.0 10^{-8} Pa^{-1} in the rest domains.

Special subroutine DEBIT is used for well-reservoir interaction representation in the model. Mass flowrate is determined from well-reservoir non-linear equation, where bottom hole pressures were calculated in the form of electronic tables based on HOLA code. Productivity indexes of five production wells used in the model varies from 0.8 to 9.3 kg/s bar. Exploitation wells are assigned under well head pressure conditions, well 027 is specified at reinjection with mass rate 84 kg/s and enthalpy 700 kJ/kg. The switch to the “no flow” boundary conditions during exploitation is assumed in B-elements of the model.

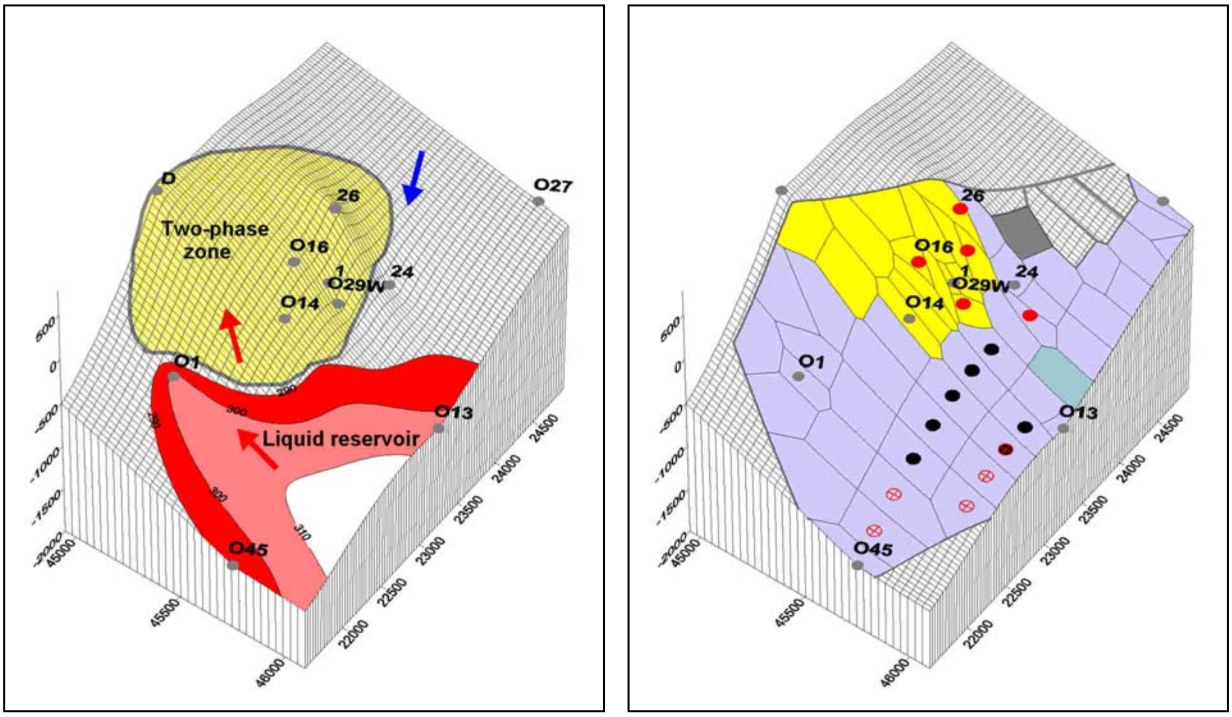


Fig.4 Mutnovsky geothermal field (Dachny Site).
Left - Conceptual model of the Main production zone: plane of the production zone, feed zones of the principle production wells, high temperature fluid upflows, temperature distributions and phase conditions,
Right – Numerical model with different permeability domains, ⊕ - “source” elements in the model, where high temperature upflows assigned, ● exploitation wells, ● drilling targets for additional exploitation wells.

Ten-year period exploitation modeling study show: (1) Additional exploitation load in central part of the Dachny site will not yield adequate steam production increase in stable terms, moreover, it may have negative effect for steam productivity, (2) Seven additional wells are needed to supply steam to 50 MWe power plant, those are directional (deviation angle up to 25^{o}) wells of 1500 – 2250 m depth targeted to the south-east part of the Main production zone (Fig. 4).

This model was refined recently based on TOUGH2 v2.0 which allow automatic well-reservoir interaction representation in the model.

Recent drilling data of the Main production zone (Dachny Site Mutnovsky geothermal field) used to calibrate 1-D thermo-hydrodynamic-chemical (THC-model). TOUGHREACT numerical code used for modeling study. Input data for modeling study include gas and chemistry sampling data (1998-2004) from production wells (O16, 26, O29W, 4E), data of mineralogical, X-ray and microprobe study of rock samples from the Main production zone and from host rocks delivered from drilling wells A2, A3, A4 (cores and ejected samples collected in 2002-2003) and samples ejected from well 26 during exploitation period (2004). Dominant secondary minerals found in production zone are chlorite, wairakite, quartz. Minor fractions are epidot, phrenite, adularia, albite. Wairakite and quartz are typically occupy void fractions of rocks or replace plagioclase (And). THC modeling (2-phase flow with base temperature 300 ^{o}C) show quartz and wairakite deposition as a main factor of porosity reduction. Laumontite, smectite and illites are found in the model at temperatures below 230^{o}C. There is no significant indication of chlorite deposition according to modeling results, that mean possibility chlorite observed in rocks was created before active fluid circulation in production zone.

CONCLUSIONS

1.Paratunsky geothermal field 34-year period of exploitation modeling study reveals natural upflow rates as following: 138 kg/s - Sredny Site, 95 kg/s - Nizhny Site, 60 kg/s – North Site, in total 293 kg/s (annually averaged values). Upflow rate summer increase up to 307 kg/s, and winter decrease to 278 kg/s. Production reservoir transmissivity estimated as 30-60 D*m, compressibility 5 10^{-6} m Pa^{-1}. Seepage type boundary conditions were detected during exploitation. Modeling exploitation of the existing wells for long-term period up to 2024 year show the total annual withdrawal could maintain more than 250 kg/s.

2. Pauzhetsky geothermal field 35-year exploitation modeling study reveals natural upflow rates as following– 36 kg/s, 830 kJ/kg (North Site), 188 kg/s, 875-920 kJ/kg (Central Site), 100 kg/s, 900 kJ/kg (South-East Site). Production reservoir is characterized by transmissivity is 70 D*m, compressibility 3.5 10^{-4} m Pa^{-1}, thermal expansivity and double porosity. Reinjection has conditional effect on steam productivity: positive if range of 30-60 kg/s, else negative. Load increase above 220 kg/s will have no significant positive effect on steam production in the Central Site of the Pauzhetsky geothermal field, if existing technology of the exploitation will remain. Binary technologies may be implemented in the Pauzhetsky geothermal field, having in account Pauzhetsky is a geothermal analog of the Casa-Diablo geothermal field (Long Valley caldera, USA), where 40 MWe PP installed.

3. Conceptual hydrogeological model of the Dachny site Mutnovsky geothermal field was verified based on mapping of active fracture zones, circulation losses and production zones distribution data, gas and fluid chemistry data, secondary minerals distributions, recent results of drilling and geothermal analog data. Central part of the Dachny represent a “single fault” type geothermal reservoir with the Main production zone of 120 m thickness, north-north-east strike and 60^o east-east-south dip. TOUGH2 based numerical model strongly related to the particular wells and Main production zone has been developed (A-Mesh grid generator with corrected vertical connections parameters, one parameter-specified heat exchange to host rocks). Upflow of the high temperature fluids (54 kg/s 1390 kJ/kg) occur in the southeast part of this zone, where liquid dominated conditions at 300 ^{o}C occur. Production reservoir transmissivity 12 D*m, compressibility 6 10^{-5} m Pa^{-1}. Steam production at 7 bars from the existing production wells in the central part of the Dachny site in the Mutnovsky geothermal field (016, 26, E4, 029W, E5) is limited. Seven additional directional wells targeted to south-east portion of the Main production zone with depth range of 1500-2250 m are recommended for Mutnovsky 50 MWe PP steam supply during 10-year exploitation period.

The modeling results show necessity of reliable and regular (per month) enthalpy-flowrate data receipt from production wells under exploitation conditions. Chemistry and gas monitoring data obtained during exploitation may be useful to detect the boundary conditions. Reservoir pressure data in the central part of geothermal reservoir is desired too. All the above data are necessary for proper calibration of the numerical model and accurate forecast of steam production scenarios. In terms of stable conditions of steam supply to 50 MWe Mutnovsky Power Plant the possibility to use Verkhne-Mutnovsky site located 1.5-2.5 km northeast from Dachny site should be analyzed. This study is ongoing.

4. Computer modeling of geothermal systems based on TOUGH2-family codes confirm to be a robust instrument to understand and predict complex non-linear hydrogeological processes in existing range of geothermal energy use.

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