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Thermo-Hydrogeomechanical Modeling of Vertical Ground Deformation

during the Operation of the Mutnovskii Geothermal Field

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Abstract—Vertical ground displacements at the Mutnovskii Geothermal Field were measured annually during the 2004–2013 period using a network of borehole markers. Three areas have been identified where the vertical displacements were different in character. Positive vertical deformation (2–5 mm/yr) was recorded in the middle of the Dachnyi Area in 2005–2006, giving way to a later stabilization. The North Test Area where the exhaust heat carrier was reinjected did not show any substantial deformation during the 2003–2006 period. This was followed by an uplift in 2006–2008 (6–7 mm/yr) and then by a subsidence (5–8 mm/yr) in 2009–2013. No vertical deformation worth mentioning was recorded in the Verkhne-Mutnovskii Area prior to 2008, but a rapid subsidence began at a rate of 6–18 mm/yr after 2008. We used the TOUGH-FLAC software to analyze vertical ground deformation. This program is used to perform thermo-hydrogeomechanical (THM) modeling based on the previous TOUGH2 model. THM modeling can explain relative vertical deformation during the exploitation of the Mutnovskii Geothermal Field by separating the geothermal field into two compartments by the Osnovnoi fault, as the two have different tectonic settings and petrophysical properties.

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INTRODUCTION

The experience that was gained during the exploitation of the Mutnovskii Geothermal Field in Kamchatka can be used not only for developing other major geothermal fields in the Kuril–Kamchatka region but also for understanding the relationships among volcanic, hydrothermal, and seismic activities at subduction zones. The large-scale development of the Mutnovskii geothermal reservoir began in 2000, with the heat-carrier discharge being as high as 500 kg/s (700 Mw). This is comparable with the discharge of magma that is supplied to two closely spaced active volcanoes, viz., Mutnovskii and Gorelyi (Polyak and Melekestsev, 1981). The increase in hydrothermal and explosive activity on Mutnovskii Volcano took place simultaneously with the development of the geothermal field. Forty years of repose were followed by hydrothermal explosions and ash ejections from the Mutnovskii crater (March 2000 and April 2007, see (Gavrilenko and Mel'nikov, 2008), and afterwards in May 2012 and July 2013). Gas emission began from Gorelyi Volcano in 2010 at an approximate rate of ~130 kg/s (H₂O ~93%, NCG~7%) (Aiuppa et al., 2012). The crater lakes on Mutnovskii and Gorelyi were drained in 2004 and 2012, respec-

tively. The Kamchatka Branch of the Geophysical Service (KB GS) of the Russian Academy of Sciences reported increased seismic activity in the area of the Mutnovskii Geothermal Field, with 40 earthquakes of magnitude 1.25–2.6 being recorded between February 2009 and December 2013.

The Mutnovskii Geothermal Field is confined to the Severo-Mutnovskii volcano-tectonic zone (SM zone) (Vakin et al., 1976). The latter is a graben-shaped feature that extends as a narrow band (3–10 km) from Mutnovskii to Vilyuchinskii Volcano and can be traced as a series of longitudinal faults, numerous occurrences of dispersed volcanic activity in the form of cinder cones, dikes, and extrusions of varying ages and compositions. The SM zone was found to contain a zone of the youngest subparallel NNE faults (Leonov, 1989). A block diagram of the SM volcano-tectonic zone is shown in Fig. 5.1 (Kiryukhin et al., 2010). Kiryukhin et al. (2013) show the outline of the SM zone somewhat larger, with due account for thermal occurrences (hot springs and fumarole fields) and identified segments striking northeast and nearly north–south. The present paper is concerned with a local fragment of the SM zone that includes the Mut-

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Fig. 1. A hydrogeological cross section along the Mutnovskii volcano-tectonic zone:

(1) basement; (2) Miocene sandstones and Tertiary volcanogenic-sedimentary formations; (3) Miocene dacitic, and rhyolitic, tuffs and lavas; (4) Pliocene to Quaternary basalts, andesites, and andesite tuffs; (5) Upper Pleistocene and Holocene andesites and basalts; (6) minor volcanic edifices composed of mostly dacitic andesite and dacite lavas; (7) heat sources (recent magma intrusions); (8) active conduit of Mutnovskii Volcano; (9) thermal occurrences (1 Active Funnel, 2 Donnoe Field, 3 Verkhnee Field, 4, 5 Severo-Mutnovskii, 7 Dachnye, 9 Medvezh'i, 15 Verkhne-Zhirovskie, 18 Vilyuchinsk); (10) fluid flows: (a) cold, (b) heated; (11) wells with their identification numbers; (12) isotherms, °C; (13) productive zones; (14) level of the thermal water-bearing complex; (15) microseismicity zone, centers of local earthquakes in 2008–2013 (based on data from the KB GS RAS), circle diameter is proportional to magnitude.

novskii Geothermal Field, so we restrict ourselves to the general description of the SM zone that was given above (Kiryukhin et al., 2014).

The nearly north-south segment contains the Osnovnoi productive zone, which supplies much of the steam for the Mutnovskii geoelectric power station (Kiryukhin, 2005). A north-south hydrogeological

cross section (Fig. 1) shows the leading features in the conditions that prevailed during the formation of the Mutnovskii Geothermal Field: (1) the productive zones are confined to a contact intrusion zone in the 200–300°C temperature range; (2) Mutnovskii Volcano (the water recharge region) is hydraulically connected to fumarole fields and hot springs (the area of hydrothermal steam occurrences); (3) a zone where fluids of volcanic origin penetrate (including mag-

matic intrusions) at absolute depths of 3 to 7 km as defined by the coordinates of swarms of local earthquakes; that zone is also dominated by the most favorable conditions for partial melting of host andesite rocks (Simon et al., 2014).

This paper presents a preliminary thermo-hydro-geomechanical analysis of vertical ground deformation during the exploitation of the Mutnovskii Geothermal Field. To do this, we used the TOUGH-FLAC simulator (Rutqvist, 2011), which has been successfully applied to the solution of various geomechanical problems that include injection and ground deformation (Rutqvist et al., 2002; Todesco et al., 2004; Cappa et al., 2009; Rutqvist et al., 2010, 2014). In view of the above, we do not attempt an exact solution of the inverse problem based on data from the

Fig. 2. A map of the Mutnovskii Geothermal Field:

- (1) locations of borehole markers for measurement of vertical ground deformation; (2) areas with different types of deformation behavior: **I** center of Dachnyi Area (wells 016, 26, 029W, 1, 24, and 4E), **II** eastern Dachnyi Area (wells 013, 042, and 037), **III** Verkhne-Mutnovskii (wells 048, 055, and 049), **IV** North Test Area where the exhaust heat carrier is injected (wells 027 and 07); (3) location of “deep marker” (between wells 26 and 24); (4) Mutnovskii geoelectric power station; (5) common highways.

exploitation of the Mutnovskii Geothermal Field, but mostly analyze the key geological parameters and processes. In particular, we investigated the question of whether changes in temperature and pressure in the geothermal reservoir during heat extraction can explain the observed vertical ground deformation. Our variable model parameters include injection discharges in various parts of the geothermal field.

We also note that studies of ground deformation during the exploitation of geothermal fields have long been carried out abroad and are deemed important. A study in New Zealand (Bromley, 2014) of the results from routine leveling work simultaneously with the exploitation of Wairakei, Tauhara, Ohaaki, and Kawerau geothermal fields revealed that the total subsidence reached over 1 m (i.e., the rates of subsidence were over 50 mm/yr). Local subsidence in areas that are

smaller than 1 km² in zones of hydrothermally altered rocks with high compressibilities (2–130 E–3 MPa^{–1}) and porosities (up to 0.65) can reach 15 m during the exploitation-induced lowering of the ground water table. Overall, the Taupo zone experiences an annual subsidence of 3 mm and horizontal extension of 5–20 mm, as inferred from InSAR monitoring and continuous GPS observations (Bromley, 2014).

Data on ground subsidence during the exploitation of the Brady geothermal field in Nevada,

United States (Ali et al., 2014) show that the area of subsidence that occurs at a rate of a few centimeters per year is congruent with the production area (5 by 2 km) that is oriented along the dominant system of NNE faults. THM modeling revealed that the subsidence was caused by lowering of pressure in shallow water reservoirs due to draining as a result of extraction from a

Fig. 3. Vertical ground deformation (relative to the deep marker, see Fig. 2). Types of deformation regime and associated wells (4E, 26, and 029W); type 2, well 027, type 3, wells 049N, 055, 048, 042, 037, and 013.

deep productive reservoir. In contrast to this, no subsidence was observed during the exploitation of the Desert Peak geothermal field at a distance of 7 km; this can be explained by the higher isolation of this geothermal field.

Rutqvist et al. (2014) report data on microseismicity and vertical ground deformation (InSAR) in the test area of an EGS in the northwestern part of the Geysers geothermal field, California, United States, where cold water has been injected since October 2011 at a rate of 20–60 kg/s into a reservoir of 400°C temperature. A downward shift of 1.5–2 km was recorded for microearthquake hypocenters, providing evidence of injection-induced cracks inside an intrusive granite massif. The ground deformation (up to 8 mm) correlates with atmospheric precipitation and the tectonic regime, with the behavior of the NNW zone being the best pronounced. TOUGH-FLAC 3D modeling yielded results to suggest that injection that is accompanied by increasing pressure and decreasing temperature sets preexistent cracks in the reservoir into motion.

2. MEASUREMENT OF THE VERTICAL DEFORMATION

Vertical deformation was measured annually by leveling (in September of each year) between 2004 and 2013 using a network of borehole markers. A Carl Zeiss Ni 005A level was used for these measurements, resulting in an accuracy of 1.0 mm/km. A “deep reference marker” (a specially designed well 10 m deep)

was installed in the western part of the Mutnovskii Geothermal Field between wells 26 and 24 (Fig. 2). The measurement revealed three types of regime in the variation of vertical ground deformation (Fig. 3; and see Fig. 2).

The first regime occurs in the central part of the Dachnyi Area, in the territory that is immediately contiguous to the Mutnovskii geoelectric power station. This zone experienced an uplift of 2–4 mm/yr during 2004–2005 and 3–5 mm/yr during 2005–2006, with no substantial deformation occurring later (see Figs. 2 and 3, wells 029W, 26, and 4E). The most obvious hypothesis to explain the uplift was that the exploitation of the geothermal reservoir causes the ground water table to descend into a zone of higher temperatures with a concurrent increase in the pressure in the shallow steam–water zone that lies under the upper aquifuge. The potential conditions for a hydrothermal explosion were given support in the area by steam explosions in 1989 (during the drilling of well 029V) and in 2003 (around well 022). In recent years the wellhead temperatures at wells 01, 08, and 023 in the area reached 240°C (corresponding to a pressure of 33.5 bars), indicating potential

conditions for a hydrothermal explosion.

A second type of vertical deformation behavior was identified in the North Test Area where the exhaust heat carrier was injected (see Figs. 2 and 3, well 027). An uplift of 6–7 mm/yr was recorded in this area from 2006 to 2008, which then gave way to subsidence at a rate of 5–8 mm/yr from 2009 to 2010. The first hypothesis that was suggested to explain the phenom-

Fig. 4. Geometrization and zonation of the thermo-hydrodynamic model for the Mutnovskii Geothermal Field: Layer 2 (at an absolute height of 2600 m) contains the permeable Tuff2 domain, which consists of rhyolite tuff and contains elements with natural discharge (D, Dachnoe fumarole field; VM, Verkhne-Mutnovskii fumarole field; NZ, Nizhne-Zhirovskii hot springs); Layer 3 (at an absolute height of -250 m) contains the San1 permeable domain, which is a complex of volcanogenic-sedimentary rocks; Layer 4 (at an absolute height of -750 m) contains the Cont1 permeable domain, which is an intrusive contact zone; Layer 5 (basement, at an absolute height of -1250 m) contains zones that the ascending heat carrier reaches (Osnovnoi and Severo-Vostochnaya, that is, Main and NE). Productive and injection wells that reach the respective layers are shown by identification numbers on a lighter background.

enon assumed the existence of a substantial injection into well 027 from 2006 to 2008 and a relatively low injection from 2003 to 2006 and from 2009 to 2013 (no data is available concerning the amount of injection).

A third type of vertical deformation was detected in the Verkhne-Mutnovskii Area (wells 049N, 055, and 048) and in the eastern part of the Dachnyi Area (wells 042, 013, and 037, see Figs. 2 and 3). The ground subsidence in the area began since 2008 at a rate of 6–18 mm/yr. The total subsidence as recorded at the Verkhne-Mutnovskii geoelectric power station reached 50 mm by 2013 (the uncertainty is 2.5 mm). The initial hypothe-

sis that was suggested to explain the deformation envisaged a considerable drop of pressure in the eastern part of the Mutnovskii geothermal reservoir due to extraction.

3. THE THERMO-HYDRODYNAMIC (TH) TOUGH2 MODEL

The present study uses a 3D rectangular TOUGH2 model that consists of 500+ elements with a common porosity value (Kiryukhin et al., 1996, 2013), which has been calibrated using available data from the

Fig. 5. Comparison of the results from THM modeling (the SP_EXPLO+50R variant, continuous lines) and those from observations of vertical deformation (intermittent lines)(see Fig. 3). The plots are shown relative to the reference point (the deep marker).

exploitation of the Mutnovskii Geothermal Field. The data include the history of exploitation between 1984 and 2006 (initial temperatures and pressures, and changes in the enthalpy of producing wells) and other additional data until 2012 inclusive (the variation in total steam extraction for the 2007–2008 period; the variation in reservoir pressure for 2007–2009; the variation in the chlorine–iodine concentration in ten producing wells for the 2002–2006 period; the variation in the concentration of noncondensing gas at well 26 for the 2000–2010 period). This thermo-hydrodynamic model accommodates the observed response of the geothermal reservoir to extraction; the model geometry (zonation and boundary conditions) is displayed in Fig. 4. The next step was to combine the thermo-hydrodynamic (TH) model with a geomechanical model for use in a joint thermo-hydrogeomechanical analysis in application to the history of extraction, or THM modeling.

4. THE THERMO-HYDROMECHANICAL (THM) MODEL (TOUGH-FLAC)

The TOUGH-FLAC model connects the family of TOUGH programs (those for simulation of multiphase heat-and-mass transfer) to the FLAC3D pro-

gram (a commercial program for geomechanical modeling). The first versions of TOUGH-FLAC were presented in (Rutqvist et al., 2002). TOUGH-FLAC was used to simulate crustal deformation due to deep-seated geofiltration flows and associated changes in pressure and temperature that were caused by industrial activities (a CO₂-injection project) at the Salach, Algeria gas field, the Geysers, California geothermal field, and some natural phenomena (the Matsushiro, Japan earthquake swarm of 1960 and the Phlegraean Fields, Italy) (Rutqvist, 2011).

TOUGH-FLAC performs data exchange between TOUGH and FLAC3D by transmitting effective stress σ and strain ϵ as computed by FLAC3D to TOUGH for a more accurate evaluation of porosity ϕ and permeability k from empirical equations. The new ϕ and k are then used to find new values of hydraulic parameters for a porous medium (that is, relative permeability for liquid and gaseous

phases and capillary pressure).

The data stream from TOUGH (pore pressure P , temperature T , and phase saturation S_β) is directed to FLAC3D to find new values of the effective stress $\alpha\Delta P_\beta$ (where α is the Biot effective stress parameter) and thermal strain $\epsilon_T = \alpha_T\Delta T$ (where α_T is the coefficient of thermal expansion). In addition, changes in P ,

T , S_p can induce changes in other mechanical properties: the general modulus of incompressibility K , shear modulus G , coupling G , and the coefficient of internal friction μ).

The combination of TOUGH and FLAC3D is equivalent to the combination of a thermo-hydrodynamic integro-finite-difference grid model of a reservoir and its geomechanical finite-element grid model; for this reason the computation grids have identical geometries and enumerations of the elements. This study restricts itself to the effects of pore elasticity and thermal expansion in the geothermal reservoir, hence the main geomechanical parameters are the elasticity moduli of the medium (volumetric and shear moduli), the coefficient of thermal expansion, and the Biot coefficient. Our modeling uses the following values: $K = 3.33$ GPa for the general modulus of incompressibility, $G = 2$ GPa for the shear modulus, $\alpha_T = 1 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$ for the coefficient of thermal expansion, and $\alpha = 1$ for the Biot coefficient. The above set of parameter values is that used for modeling the characteristics of the Geysers geothermal reservoir, California (Rutqvist et al., 2014).

5. THM MODELING OF THE HISTORY OF OPERATION OF THE MUTNOVSKII GEOTHERMAL FIELD FOR THE 1984–2013 PERIOD

The first stage of this study involved the use of the calibrated thermo-hydrodynamic TH model **SP_EXPLO + 50R** as the basic model for thermo-hydro-geomechanical THM modeling. This TH model is a simplified version (assuming a common porosity for all elements) of the **#12NSEX6A3** model as described by Kiryukhin et al. (2013). The model assumed that 50% of the extracted heat carrier is injected into the reservoir. The geomechanical boundary conditions are specified so as to have zero normal strain at the bottom and lateral boundaries of the model, while the top boundary is assumed to be free of strain.

The reference point (the deep marker) for leveling was located at the head of a specially designed well 10 m deep in the extraction zone of the Mutnovskii Geothermal Field (see Fig. 2). Consequently, the results of THM modeling are presented as relative strain, relative to the reference point and to 2004 observations. The results of THM modeling show (Fig. 5) relative uplift for the markers at the model wells, except for the markers at the wells in the middle of the Dachnyi Area and at the reinjection wells in the North Test Area. It therefore follows that the results from this version of THM modeling are in disagreement with the observations of vertical ground motion.

For this reason we modified the original thermo-hydrodynamic TH model **SP_EXPLO + 50R** to increase the relative pressure drop in the Verkhne-Mutnovskii Area and in the eastern part of the Dachnyi Area compared with the middle of the Dachnyi Area and with the North Test Area of reinjection (see Fig. 2). We achieved this goal by the following transformations (Figs. 6 and 7): (1) an extra mass discharge was specified in the northern part of the model toward the Verkhne-Zhironvskie thermal occurrences (VZ), which were not incorporated previously; (2) an extra water recharge (INF2) was specified in the middle of the upper layer of this model where the basin for storage of exhaust heat carrier is located. This too is a new feature. The next step was to run the **SP_EXPLO_THM3F** TH model, yielding a relative drop of pore pressure in the Verkhne-Mutnovskii Area and in the eastern part of the Dachnyi Area that was greater than the decrease in its middle.

Although the model has been modified as described above, the THM modeling (the **SP_JR_3** version, Fig. 8) still showed relative uplift for all markers in the wells, while the observations recorded considerable subsidences for the Verkhne-Mutnovskii Area and the eastern part of the Dachnyi Area.

6. RESULTS AND DISCUSSION

6.1. Generalized

Ground-surface subsidence by 0.05 m can be achieved with some small decreases in pressure and temperature for a 1-km-thick layer, when the following geomechanical parameters are specified; for example, if we wish to derive approximate estimates, we set the drop in pore pressure equal to 1.5 bars (1.5e5 Pa) and the temperature drop equal to 2°C, a Young's modulus of 5 GPa, and the coefficient of thermal expansion of $1 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$. The negative vertical strain due to pressure drop would then be $1.5 \times 10^5 \text{ Pa} \times 1000 \text{ m} / 5 \times 10^9 \text{ Pa} = 0.03 \text{ m}$, and the negative vertical strain due to

temperature drop would be $2^{\circ}\text{C} \times 1\text{e-}5^{\circ}\text{C}^{-1} \times 1000 \text{ m} = 0.02 \text{ m}$, with the total value being the desired 0.05 m.

Our THM modeling did not reveal any substantial reinjection effect for the North Test Area, because the reinjection is carried out at a depth of about 1 km, mostly into a single model element and local strain in that block does not cause a substantial effect at the ground surface.

On the other hand, the THM modeling showed that water injection (INF2) under subsurface conditions in the middle of the Dachnyi Area (see Figs. 6 and 7) leads to temperature and pressure changes that exert a considerable effect on vertical ground displacements, since the element of the model that is subject to injection is in direct contact with the ground surface.

Fig. 6. A modification of SP_EXPLO+50R model (left) to obtain the SP_EXPLO_THM3F model (right): the added elements are discharge, VZ, and water recharge, Inf2 (for explanation, see the main text and Fig. 7).

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Fig. 7. The INF2 region of additional water recharge corresponds to the basin for the discharge of the exhaust heat carrier, where it can filter into the geothermal reservoir, INF corresponds to an artificial underground lake which also can supply water to the geothermal reservoir.

As well, in order to achieve a better fit of the model to leveling measurements, one could consider a model with comparatively stable geomechanical conditions in the middle of the Dachnyi Area and in the North Test Area of reinjection, while the eastern part of the Dachnyi Area and the Verkhne-Mutnovskii Area tend to descend (see Fig. 2). This is the leading deformation regime: subsidence in the eastern part of the field with a

relative stability of the western part. The small vertical motions in the western part may have been due to some insignificant variation in the amount of injection there.

The subsidence of the eastern part of the Mutnovskii Geothermal Field can also be explained by

the presence of a fault that divides the geothermal reservoir into two hydraulically isolated compartments. A

Fig. 8. Comparison of the results from THM modeling (SP_JR_3, continuous lines) and those from observation of vertical deformation (intermittent lines) (see Fig. 3). The plots are shown relative to the reference point (the deep marker).

compartment is understood here as a connected hydraulically isolated volume in the reservoir (Zoback, 2010). A small difference in pore pressure on one of the two sides relative to the fault plane could cause various ground motions. That is the case when the fault intersects the geothermal reservoir and is impermeable for fluid flows that strike perpendicularly at its plane, i.e., the fault divides the geothermal reservoir into two hydraulically isolated compartments. The greater subsidence for the eastern part of the field that began in 2009 could have been due either to increased extraction of the heat carrier on one of the sides relative to the fault plane or to resumption of the activity of the fault owing to extraction or to tectono-magmatic activity.

6.2. Seismic Activity in the Mutnovskii Geothermal Field Area

Local seismic activity indicates the existence of an extensive zone of critically compressed cracks (Zoback, 2010), with displacements on these recording fluid penetration (more probably penetration of magma, water, or supercritical sc CO₂ at depths of 5–7 km beneath the Mutnovskii Geothermal Field, see Introduction and Fig. 1); for example, the December 2012–January 2013 swarm of earthquakes ($M = 1.25–2.0$) at depths of –5 to –6 km beneath the Mutnovskii

Geothermal Field (these data are from the KB GS RAS) can be interpreted as the effect of a naturally occurring hydraulic fracture at the top of the magmatic plumbing system beneath the Mutnovskii Geothermal Field. The hydraulic fracture as inferred from the coordinates of eight earthquakes had the following parameters: a dip angle of 33°, a dip azimuth of 138°, and a horizontal length of ~5 km.

6.3. The Osnovnoi Fault

The Osnovnoi productive zone is situated within the SM volcano-tectonic zone (Kiryukhin, 2005). That zone strikes NNE and dips EES at an angle of 60°, the average vertical thickness is estimated as 240 m (Fig. 9). The Osnovnoi productive zone was reached by wells 045, 01, 014, 016, 1, 029W, 26, 24, and 4E (see

Fig. 2). Its strike is nearly parallel to the system of active faults and dikes due to the most recent phase of magmatic activation, some of which are found inside the productive zone. Its top was identified from a complete loss of mud circulation during drilling. The plane that fits the top of the Osnovnoi productive zone is given by the equation Z , which was derived from the coordinates of the complete absorption and zones of production of the heat carrier. The above fitting plane traverses the active plumbing system of Mutnovskii Vol-

Fig. 9. The lower layer of the TH model for the Mutnovskii Geothermal Field with the addition of an inner boundary, which is a plane that is fitted to the surface of the Osnovnoi productive zone (Kiryukhin, 2005).

cano at heights of +250 to +1250 m and at a distance of 8 km from the Mutnovskii geoelectric power station. The four extra wells (A1–A4) that were drilled in 2001–2002 and were equipped with filters in the footwall block of the Osnovnoi productive zone had a low output.

The hanging block (relative to the Osnovnoi productive zone plane) is characterized by vertical displacement of the respective geological units by 100–150 m relative to the footwall block, indicating that this is a normal fault. We note that the extensional environment characterizes the SM zone as a graben-like feature. The Osnovnoi fault belongs to the class of “semi-permeable faults.” The top of its footwall block is impermeable (probably owing to temperature inversions and to being sealed with secondary hydrothermal minerals), while the bottom of the hanging block is open for heat carrier flows to travel northeastward.

Based on the conceptual model that was outlined above, the numerical model of the geothermal reservoir was divided into two parts by the Osnovnoi fault plane. These parts had different rates of vertical

ground movements due to the extraction of the heat carrier, the petrophysical properties of the rocks, and the tectono-magmatic activity beneath the geothermal field. The wells that were drilled in the western part of the Dachnyi Area and in the North Test Area seem to be “fixed” in the footwall block of the Osnovnoi fault, while the wells in the Verkhne-Mutnovskii Area and in the east of the Dachnyi Area are sliding downward along with the hanging block.

7. THM MODELING OF THE GEOTHERMAL RESERVOIR DIVIDED INTO TWO COMPARTMENTS

7.1. The Scenario with a “Rigid” Footwall Block

Since the Osnovnoi fault seems to act as a natural semi-permeable boundary that divides the Mutnovskii geothermal reservoir into two compartments (a productive hanging block and a nonproductive footwall block), the model should be modified to fit the geometry that is shown in Fig. 9. To do this, we ascribed

Fig. 10. A comparison of the results from THM modeling (SP_EXPLO2, continuous lines) and those from observations of vertical deformation (intermittent lines) (see Fig. 3). The plots are shown relative to the reference point (the deep marker).

more rigid mechanical properties to model elements in the footwall block, while those in the hanging block retained the original compressibility. The original TH model was the same (SP_EXPLO2, see Section 5), except that the infiltration through the artificial lake (INF1) was kept at zero, while the infiltration discharge into the geothermal reservoir through the basin for collecting the exhaust heat carrier (INF2, Fig. 7) was set at 200 kg/s.

The results of THM modeling of the vertical strain (relative to the reference point since 2004) showed considerably better agreement with the observations of leveling measurements (Fig. 10). Some underestimation of the uplift (–6 mm) in the east of the Dachnyi Area in 2004–2006 can be explained by uncertainties in the infiltration value in this area of the geothermal field.

Although we achieved a better fit between the model and the observations just by modifying the rigidity of the footwall block, a more careful analysis of the geological section can reveal the true causes of this differentiated subsidence in the Mutnovskii Geothermal Field. The phenomenon may be caused either by differences in compressibility or in permeability, as these can produce differences in the lowering of the pore pressure and associated compaction. The use of satellite radar observations to monitor ground deformation can expand the area that is being monitored, including the Osnovnoi fault as a whole and the spatial

distribution of the reservoir compartments on both sides of the fault.

7.2. *The Scenario with a Footwall Block of Low Permeability*

Another possible modeling scenario is to specify a low permeability in the nonproductive footwall block (see Fig. 9). We implemented this scenario by modifying the TH **SP_EXPLO2** model by stipulating that all of the model elements within the footwall block have a low permeability ($1\text{E-}18\text{ m}^2$). This will be referred to as the **SP_EXPLO_THM3F+F3** model. The model is currently being tested for sensitivity to thermal compression and hydrodynamic compaction of the reservoir due to extraction of the heat carrier and its subsequent injection in shallow conditions (INF2, the basin that accumulates exhaust heat carrier, see Fig. 7).

CONCLUSIONS

(1) The leveling observation of the vertical ground movements that was annually conducted in the Mutnovskii Geothermal Field in 2004–2013 revealed areas with different geodynamic regimes, viz., the western part of the Dachnyi Area was characterized by positive vertical movements (2–5 mm/yr) in 2005–2006 that gave way to stabilization in later years; the North Test Area of reinjection showed positive vertical

movements (6–7 mm/yr) in 2006–2009 that gave way to subsequent subsidence (5–8 mm/yr) in 2010–2013; the eastern part of the Dachnyi Area and the Verkhne- Mutnovskii Area showed rapid subsidence at rates of 6–18 mm/yr since 2008.

(2) Thermo-hydrogeomechanical modeling was used to explain the observed geodynamic behavior of ground movements during the exploitation of the Mutnovskii Geothermal Field during the 1984–2010 period. The basic TH thermo-hydrodynamic model was that described in (Kiryukhin et al., 2013).

(3) Thermo-geomechanical THM modeling provides a rough explanation of the relative vertical movements during the exploitation of the Mutnovskii Geothermal Field (including the rapid subsidence of the eastern block since 2008) by invoking the division of the geothermal reservoir into two compartments on the two sides of the Osnovnoi fault, viz., an eastern compartment in the hanging block with a high compressibility and a western compartment in the footwall block with low compressibility.

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