Impact of injection pressure during cold water reinjection on the state of stress in geothermal reservoirs

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Abstract

During cold water injection into geothermal reservoirs, pore pressure increases and the reservoir rock is brought closer to fracturing conditions. The fracturing may cause early cold water breakthrough into production wells. A 2-D reservoir simulator describing fully coupled fluid flow, thermal flow, and geomechanical behavior was used in this study. The objective of this work is to investigate the evolution of the stress state in liquid-dominated reservoirs and to establish how principal stress directions change during injection pressure increase. The paper describes simulated fracturing pressure changes due to cold-water injection. It also discusses how to predict orientation/re-orientation of hydraulic fracture propagating from an injector.

Keywords: numerical modelling, re-injection, state of stress.

1 Introduction

The mechanical behavior of a body, i.e. the changes in its dimensions (its deformation), or in some cases its failure, depends on the external and internal forces distribution acting on the body. Considering an infinitesimal cube isolated from the body, it is held in equilibrium by forces imposed on its surfaces. The cube can be oriented in such a way that only forces normal to its surfaces are present. Under these conditions there are three pairs of independent forces since the cube is in equilibrium. The physics of the geomechanical behavior of a geothermal reservoir, and its mathematical description, are rather complex due to the porous nature of the rock coupled with fluid flow (multiphase flow) through the pores. The strain concept is used to describe deformation of a material and it is directly related to displacement through strain/displacement relations. When modeling deformation of a poro-elastic medium we use the continuum mechanics (continuous medium) concept, which states that every infinitesimal sub-volume of the material is occupied by the medium consisting of solid skeleton and porous space, and its properties (porosity, permeability, etc.) either vary smoothly from one point to another or are the same everywhere.

One of the main ideas of the theory is that the stress in a saturated porous material is 'carried' partially by the pore fluid and partially by the solid matrix. This is the so-called total stress and it refers to the bulk volume of the rock. The part of the total stress carried by the solid rock matrix, is called effective stress, and it represents the actual state of stress in the solid rock grains.

Fluid injection into a reservoir, and production from the formation, perturbs the local in-situ stress state. The stress can either be altered by changes in pore pressure, or by temperature perturbations in non-isothermal flow.
During cold water injection into geothermal reservoirs, pore pressure increases. Sufficiently accurate estimation of reservoir stresses becomes essential in many geothermal injection–production operations when a reservoir is brought closer to fracturing conditions. This is because induced stress changes may cause formation fracturing. The fracturing may cause early cold water breakthrough into production wells. In naturally fractured/stress sensitive reservoirs the state of stress changes cause opening or closing of existing fractures and permeability variations.

2 Formulation of the coupled model

A fully coupled fluid flow, thermal flow, and geomechanical behavior model incorporates the fluid flow equation with energy conservation and stress equilibrium equations. Energy balance law was assumed under the following assumptions (Rewis, 1999):

- the only energy transfer to the system is by convective and conductive heat transfer through the boundary, and mechanical work done by surface traction,
- kinetic energy changes are small compared to those of the internal energy,
- negligible viscous dissipation,
- instantaneous local thermal equilibrium between rock and fluid.

To determine stress variations in the system, the following governing equations from the theory of poro-thermo-elasticity are used. Computer code is used to solve the following system of equations (Chen et al., 1995):

\[
G \cdot \nabla^2 \mathbf{u}_i + (G + L) \frac{\partial}{\partial t} ( \nabla \cdot \mathbf{u} ) + \alpha_B \cdot \nabla \frac{\partial P}{\partial t} + (2 \cdot G + L) \cdot \frac{\partial (\alpha_T \cdot T)}{\partial t} = 0 \quad i = x, y \quad (1)
\]

\[
\nabla \cdot \left( \frac{k}{\mu_f} \cdot \nabla P \right) = c_i \cdot \frac{\partial P}{\partial t} - \beta_t \cdot \frac{\partial T}{\partial t} - \alpha_B \cdot \frac{\partial (\nabla \cdot \mathbf{u})}{\partial t} \quad (2)
\]

\[
\nabla \cdot (\lambda \cdot \nabla T) - \nabla \cdot \left( \frac{\rho_f \cdot k \cdot C_f \cdot T}{\mu_f} \left( \nabla P + \frac{P}{\rho_f} \right) \right) = \frac{\partial}{\partial t} \left( (1 - \phi) \cdot \rho_s \cdot C_s \cdot T + \phi \cdot \rho_f \cdot C_f \cdot T \right) \quad (3)
\]

Where:
- \( \mathbf{u} \) – displacement vector, m,
- \( G \) – shear modulus, Pa,
- \( L \) – Lame’s constant, Pa,
- \( \alpha_B \) – Biot’s poroelastic coefficient,
- \( P \) – pressure, Pa,
- \( \alpha_T \) – coefficient of thermal linear expansion, 1/K,
- \( T \) – temperature, K,
- \( k \) – permeability, \( m^2 \), mD
- \( \mu_f \) – viscosity of fluid, Pas,
- \( c_i \) – total isothermal compressibility of reservoir, 1/Pa,
- \( \beta_t \) – total isobaric compressibility of reservoir, 1/K,
- \( t \) – time, s,
- \( \lambda \) – thermal conductivity, W/mK,
- \( C_f, C_s \) – heat capacity of fluid and solid, J/kgK
- \( \rho_f, \rho_s \) – density of fluid and solid, kg/m^3,
- \( \phi \) – porosity, -.
The numerical simulator solves the system of P.D.E. given above in a two-dimensional domain, under a plain strain assumption using control-volume finite difference discretization (Rewis, 1999; Osorio et al., 1999).

3 Thermal stress during injection into geothermal reservoir

The response of a reservoir volume was analyzed to investigate the effects of temperature changes on stress perturbations during injection of cold water. The plane strain condition is assumed and also single-phase, slightly compressible fluid flows. No fluid or heat flow in the vertical direction is allowed. Following these assumptions, pore pressure, temperature, displacement, and the stress field will not change in the vertical direction and the problem can be solved in 2D. Furthermore, the grid boundaries coincide with the directions of the initial principal horizontal stresses. Constant injection rate is specified at the well. Because of symmetry, a quarter of the area is considered and no flow boundary conditions along left and bottom boundary. Constant pressure along right and top boundary is assumed (see Figure 4).

3.1 Numerical simulation

In the following, we analyze simulation results where we consider a square area of 1000 m by 1000 m, as shown in Figures 4-6. The orientation of the initial principal stresses coincides with the grid boundary. Because of symmetry, a quarter of the area is considered with the injection well located in the corner. We assume an initial reservoir pressure of 15 MPa and an initial reservoir temperature of 80°C. The average porosity is assumed 13%. In the simulated cases, three different values of permeability are used: 250 mD, 500 mD and 1000 mD. Injected water temperature is assumed to equal 15°C.

Figures 1-3 show well pressure changes in time for the cases analyzed. Higher injection rate requires higher injection pressure, which results in faster and further growing fracture. Due to lower permeability of rock (250 mD), 140 m³/hr injection flow rate causes fracturing of rock after 700 days of injection. In 1000 mD permeability rock, fracture is initiated after 1400 days at 350 m³/hr water rate injection. Such rock fracturing may result in faster cold front movement towards the production well.

Water injection induced fracturing is often encountered in cases of tight/low permeability formations. This type of reservoir is the most stress sensitive reservoir, where permeability may be expected to be stress dependent.

Figures 4-6 show pressure, temperature and incremental horizontal stress after 1500 days of injection. As expected, the greatest temperature-change occurs in the near-well region. Cooling of the formation (by the cold injected water) results in tensile stress development, which overcomes the incremental compressive stresses resulting from the injection-induced fluid-pressure increase. The cooling effect can bring the reservoir closer to fracturing conditions. Analysis of the simulation runs suggests the possibility of local stress reorientation (which depends on the relative magnitude of the stress perturbations compared to the initial state of stress).
Figure 1: Simulated well pressure for three different injection rates and a rock permeability of 250 mD.

Figure 2: Simulated well pressure for three different injection rates and a rock permeability of 500 mD.

Figure 3: Simulated well pressure for three different injection rates and a rock permeability of 1000 mD.

Figure 4: Pressure, temperature and incremental horizontal stress after 1500 days of injection for rock permeability of 250 mD and injection rate of 140 m$^3$/hr.
4 Conclusions

Water injection induced fracturing is often encountered in cases of tight/low permeability formations. These types of reservoirs are the primary candidates for stress sensitive behaviour, where permeability is stress dependent.

A numerical model to determine the impact of injection on geomechanical behavior of a geothermal reservoir has been developed. Compared with the conventional isothermal or thermal reservoir simulators, description of the flow- and thermal-induced evolution/distribution of reservoir stresses is the unique feature of the simulator presented here. Simulation results show that the thermal-induced stresses overcome the incremental compressive stresses resulting from the injection-induced fluid-pressure increase. The thermal stresses alter the in-situ stress anisotropy in both magnitude and direction. The results also show that the magnitude of the tensile stresses resulting from cold-water injection increases, when injection pressure decreases, due to higher reservoir permeability, and as time of the injection increases.

Estimation of geothermal reservoir stresses enables to determine optimal injection rate to avoid rock fracturing (and early cold water breakthrough) in geothermal
management. The analysis of geomechanical behaviour of geothermal reservoir presented in the paper can be used to predict hydraulic fracture propagation due to cold-water injection. A 3-D model extension could deliver more detailed information about mechanical behaviour of a rock.

5 References


Evolution of selected geochemical and reservoir factors influencing the exploitation of the Podhale geothermal system, S-Poland

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Abstract

The Podhale system was the first in Poland where geothermal space heating and other uses were initiated in the 1990’s. In 2001 the main facilities of a regional heating system were started. It will be one of the largest in Europe in its capacity and heat production. Water discharged from Mesozoic and Eocene carbonates, has a temperature of 76-86°C at the outflows, and forms a good basis for multipurpose uses. To assure proper current production and project development, the investments have been accompanied by research and monitoring of the system. Recently, a study was done using selected methods (X-ray analysis, fluid inclusions, geothermal geochemistry) including those used to analyse thermal evolution of sedimentary basins (e.g. Oxyreactive Thermal Analysis, for the first time applied for Podhale). They combined cognitive and practical aspects to define factors controlling processes crucial for geothermal evolution, exploitation and use. The paper presents some results of the mentioned research and monitoring of the Podhale system in reference to sustainable longterm production for space heating and other uses. It focuses on such issues as water-rock equilibrium, secondary mineralization, scaling, corrosion, and results of almost 10-years of hydrodynamical and chemical monitoring. Considering curative features of geothermal water, the prospects of extending uses applications by balneotherapy and recreation are presented. These services should be widely developed in Podhale – the main tourist area in Poland. The subject is supplemented by a brief paleohistory of those components of the system, which are essential for its understanding, optimum exploitation, and use.

Keywords: Podhale, geothermal system, geochemical and reservoir factors, direct uses.

1 Introduction

The Podhale system was the first in Poland where geothermal space heating and other direct uses were initiated in the 1990’s. Water produced from Mesozoic and Eocene carbonates has a temperature of 76-86°C at the outflows and forms a good base for multipurpose applications. There, one of Europe’s larger regional geothermal heating project has been under realisation (target capacity 50 MWt, heat production ca. 600 TJ/y; Dlugosz, 2003). In 1990-2001 one doublet of wells was in operation. In late 2001 the heating system was expanded considerably by two new wells, other facilities and linking some part of receivers in Zakopane – the main city of the region (population 30,000, over 3 million tourists/y). Until 2005 geothermal will supply a prevailing number of buildings in this city and the whole region. Simultaneously, the PAS MEERI Geothermal Laboratory has conducted R&D works on cascaded uses (Bujakowski, 2000). These activities have been accompanied by basic research and new methods were introduced recently, the results of which are presented in this paper. Some studies were carried out within the framework of a Research Grant No. 5T12B00822 financed by the State Committee for Scientific Research (Poland).
2 Geological and geothermal setting

The Podhale system is located within the Inner Carpathians – a part of alpine orogene (Figure 1). It is one of the systems of similar origin, which surround the Tatra Mts. The main geothermal aquifer occurs in the Middle Triassic limestones and dolomites and Middle Eocene carbonates (depths up to 2.5-3.5 km). The reservoir temperatures vary from 20 to 90°C. The water flowrates from the wells amount to 55-150 l/s. The static wellhead artesian pressure is up to 26 bar. A caprock for geothermal aquifers is built by the Paleogene (Late Eocene-Oligocene) flysch (up to 2.5-3.2 km thick). Over ten geothermal wells were drilled within this area (Kepinska, 2000). The rocks, which built the Podhale system, underwent long and complex geological evolution. The Middle Triassic rocks are ca. 235 Ma, while the sedimentation of the Middle Eocene carbonates started ca. 50 Ma ago, and the Podhale flysch 45 Ma ago. Their common history as a geothermal system began after the flysch had been deposited, ca. 22 Ma ago.

![Figure 1: A sketch of the Podhale geothermal system. a-c geothermal wells: a. production, b. injection, c. not in use, d. other wells, e. locality with geothermal space heating system on-line (2003), f. localities planned to be geothermally heated (by 2005), g. geothermal base load plant, h. geothermal heating plants planned, i. central peak heating station, j. geothermal bathing centre under construction (2003), k. main transmission pipeline, l. transmission pipelines planned. Framed is the area of study presented in this paper.](image)

3 Methods and area of study

To assure proper geothermal water production and project development, investments have been accompanied by investigation and monitoring of the Podhale system. Recently, there have been introduced some methods of geothermal geochemistry, X-ray analysis, fluid inclusions microthermometry and also methods of studying thermal evolution of sedimentary basins, e.g. the thermal transformation of illite/smectite and the evaluation of organic material maturity. The latter involves a new type of thermal analysis, the Oxyreactive Thermal Analysis, OTA (Cebulak et al., 1999). These researches combine both cognitive and practical aspects to learn factors crucial for the evolution of the geothermal system as well as its current exploitation and field
development planning. The issues presented in this paper are based on the data and investigations made for several geothermal wells. All the wells but one (Poronin PAN-1) are located within the exploitation sector of the system (Figure 1). High reservoir temperatures up to 80-90°C, high water flowrates up to 150 l/s, and high total and effective thickness of reservoir formation (up to 800 and 100 m, respectively) characterize it. Moreover, this sector is affected by deep faults, which favour intense fluid circulation and hydrothermal processes.

4 Selected factors controlling the Podhale geothermal system

4.1 Temperatures

The present reservoir temperature reaches 80-90°C at a depth of 2-3 km within the discussed sector. Figure 2 shows the present deep temperature in the vicinity of the Bialy Dunajec PAN-1 well (line a), the paleotemperature derived from the fluid inclusion microthermometry (that was made for very small but abundant calcite crystals, sometimes quartz), as well as degree of thermal transformation of illite/smectite group (lines b and c).

Figure 2: The Podhale geothermal system - present and past subsurface temperatures in the area of study. Case of Bialy Dunajec PAN-1 well (based on Kepinska, 2001) A. Temperatures shown against geological profile: a - present, b - presumed maximum paleotemperatures (after Oligocene), c - approximate paleotemperatures within the Middle Triassic rocks before the Upper Cretaceous orogenic movements. Figures mark the ranges of the fluid inclusion homogenisation temperatures (bolded are more frequent intervals); I/S - temperature ranges according to the illite-smectite group thermal transformation study, intermitted line shows temperature range in the Middle Triassic rocks (before alpine orogeny). B. Temperatures shown against geological profile before erosion of ca. 1–2 km of flysch cover: a - present temperatures, b - presumed paleotemperatures (as shown at A).
In the Podhale flysch case, the maximum temperature of rocks and fluids amounted to 100-165°C. These values occurred in the early stage of the system lifetime, when the complex of the youngest flysch sediments, being at least 1-2 km thick, was not yet eroded. Then the geothermal gradient reached 3-4°C/100 m, while at present it is ca. 2°C. Locally, in the nearfault zones (at a depth of 1850 m), the inclusions recorded temperature up to 230°C. Chlorite and illite are also observed there. Similar effect is known from the Paris Basin, where the higher fluid inclusion homogenisation temperatures and more advanced illite/smectite thermal transformation occur in the fault zone rather than in the area more distant from the faults (Bril et al., 1994).

The maximum paleotemperatures of reservoir rocks and fluids reached a level of 200-230°C in the Middle Triassic. It concerns a period of their maximum burial before thrusting to the present location in the Late Cretaceous and before the sedimentation of the Podhale flysch. After the Oligocene, i.e. after the Podhale system had been formed, the maximum temperature decreased to 165-170°C (Figure 2). Such geothermometers as secondary quartz and dolomite, as well as the examination of the organic matter transformation degree including OTA also confirmed these ranges of the paleotemperature.

Following from the above the Podhale geothermal system has cooled down by at least 70-80°C during its lifetime (about 22 Ma). Fig. 3a shows a sketch scenario of the thermal history of the Middle Triassic and Paleogene formations.

Figure 3: The Podhale geothermal system, area of study - sketch scenarios of changes of the main parameters of the Middle Triassic reservoir rocks vs. geological time. a. temperatures, b. secondary permeability, c. TDS of geothermal fluids. Presumed intervals of maximum temperatures and recorded present values are given. 1 - main stages of alpine orogeny, which affected the Middle Triassic rocks, 2 - lowering and uprising movements, respectively.

4.2 Secondary mineralization

The secondary mineralization in the flysch caprock results mostly from diagenesis, while that in the Middle Triassic reservoir formation from hydrothermal processes.
Secondary minerals, which fill veins and pockets, occur in the clay interbeddings, and replace primary minerals in the matrix. The secondary mineralization in the fractured Triassic rocks developed in greater degree than that in the weakly permeable flysch. Thermal transformations of illite/smectite and organic matter, which happened in the parent rocks of both formations, were independent from the rock permeability. The qualitative composition of the assemblages of secondary minerals within the veins both in the Paleogene and Middle Triassic formations does not differ essentially. Secondary calcite (sometimes dolomite) predominates both within the Paleogene flysch and the Middle Triassic rocks. Quartz, plagioclases, illite/smectite mixed-layers group, illite, Fe-chlorite, and pyrite occur as admixtures. In the Middle Triassic formation galena, gypsum, celestine and sylvinite are found in very minor amounts, too.

The illite/smectite mixed-layers serve as an important geothermometer for the Paleogene and the Middle Triassic rocks. The high degree of order (R1) and low content of the smectite layers in the flysch show that these rocks were affected by the paleotemperatures of 100-165°C. In the Middle Triassic rocks, lack of the expanding packages indicates the transformation being influenced by hot solutions or the temperature being higher than 165°C. Illite and chlorite might also precipitate directly from the solutions (Kepinska, 2001).

Generally, the secondary mineral assemblages confirm the regularity (Browne, 1984), that the type of the hydrothermal mineralization in low-temperature systems is mainly controlled by the composition of parent rocks. In the case of Podhale system, the predominant component of reservoir rocks-calcite, sometimes dolomite, also forms secondary mineral assemblages.

The secondary mineralization results in decrease of permeability of the reservoir rocks. In the past the rocks passed through the periods of higher permeability with its probable maximum in Paleocene-Early Eocene. It was after their thrusting in the Late Cretaceous, when they were uplifted, unstressed, outcropped, and affected by the karst processes. The second minor permeability maximum but concerning the geothermal system being already formed may have occurred in the Miocene and was favoured by alpine vertical movements. Following this period, the progress in the secondary mineralization probably resulted in the decrease of permeability. Nevertheless, this process weakly or not at all influenced some fractures and breccia zones. The present permeability amounts to a maximum value of 1000 mD in the discussed sector, where the reservoir rocks are considerably fractured. A sketch scenario of permeability changes with time for the Middle Triassic rocks is given in Figure 3b.

### 4.3 Chemistry and thermodynamics of geothermal water

In the discussed sector, the total dissolved solids of geothermal waters amount to 2.5-3 g/dm³. Waters are of Na-Ca-SO₄-C1 type. There are young meteoric waters, washed many times, with freshening tendency. The calculations of thermodynamical water-mineral equilibria (using i.e. WATCH-programme; Bjarnason, 1994) showed that these waters are not in equilibrium with the reservoir rocks. They are slightly oversaturated with calcite and dolomite, as well as clays (smectites and chlorites). In contrary, they are close to equilibrium with chalcedony and unsaturated with other minerals. The waters are slightly corrosive against steel elements.

In the course of their evolution, reservoir rocks contained both seawater (Middle Triassic-Cretaceous, Middle Eocene-Oligocene) and meteoric water (Late Cretaceous-Early Oligocene, Oligocene to the recent). Predominant content of calcite
in veins of all origins proves that the past waters were also oversaturated with this mineral. Rough examination of the separate fluid inclusions revealed the paleofluid concentration not exceeding the concentration of the seawater. A sketch history scenario of the mineralization of the geothermal fluids for the Middle Triassic reservoir rocks is given on Figure 3c.

5 Production history

From 1990 to 2001 the Podhale system was exploited by one doublet of wells: Banska IG-1 (production) and Bialy Dunajec PAN-1 (injection). Water flowrate varied from 8-16 l/s while outflow temperature was 76-80°C. The maximum capacity reached 1.8 MW, heat production ca. 40 TJ/y. As already mentioned, in late 2001 the system was expanded by two new wells and other facilities. The doublet Banska IG-1 and Bialy Dunajec PAN-1 has been monitored since 1990 (flowrate, temperatures, pressures, TDS). Until 2001, before two new wells started the flowrate and temperature of the produced water was observed as being stabilised. However, some slight pressure drop at production well and pressure increase at the injection well was recorded. Among others, the reason for this may be the slight decrease of permeability of the reservoir rocks, due to precipitation of secondary minerals and introducing products of corrosion of the transmission pipeline into the reservoir. Monitoring showed also some decrease in TDS of the produced water – from 2.9 to 2.5 g/dm³ while the type of water did not change.

In general, monitoring of the wells Banska IG-1 and Bialy Dunajec PAN-1 in 1990-2001 showed the stability of the basic operation parameters of the exploited system. The recovery features of the reservoir are maintained. In reference to sustainable longterm production, the further monitoring of the system and keeping stable level of the parameters are essential for the water production to be considerably increased in relation to 2001.

6 Implications for exploitation

For the last decade the Podhale geothermal was exploited for space heating and some other uses. Extension of the heating network requires the increase in output of geothermal water (up to about 180 l/s) and probably the joining of a new injection well. Therefore, the above-described factors have practical aspects for stable longterm exploitation.

In particular, the scaling trend of calcite and dolomite exists. With time, the secondary minerals proceed in filling up fractures and fissures. Water is also oversaturated with smectites and chlorites. Though clays are found in small amounts, they may silt both the reservoir and in the surface equipment. This effect may decrease the permeability of reservoir rocks. From the other hand, reciprocal processes, i.e. washing out and dissolving of rock components by water, occur. In spite of this, at the present stage of evolution, the Podhale system is still capable to discharge large amount of water, especially in the zones affected by tectonics (the most perspective for siting new wells). The calcite scaling and corrosion tendency involves geothermal exploitation in the closed system. The precipitate scaling due to the secondary mineralization has also a positive effect, which may protect pipes decreasing their corrosion.

In order to maintain stable production and injection capability of the reservoir rocks for a long time with scaling tendency being present, it is very advisable to perform periodical soft acidizing treatment to mitigate for that effect. This has been successfully implemented in the Paris Basin (Ungemach, 1996). It may limit scaling
of carbonates and other components. This option is considered in the Podhale field, as it is more simple and cheaper than routine acidizing of the carbonates for increasing their production and injection capacity.

7 Further prospects of geothermal uses

Apart from the district heating, which has been essential for the ecological reasons, the other important applications of geothermal waiting for realisation for many years are balneotherapy and recreation. Due to chemical composition (i.e. H₂S, sulphides, bromium, iodium, potassium, silica) the Podhale geothermal waters have curative properties in the case of dermatological, rheumatic, endocrinological and contagious diseases. Until 2001 only one geothermal bathing pool operated in Zakopane – the main city in the region. There are exceptionally great possibilities to build healing and recreation centres in this region. There are two projects, one of which is just being realised in Zakopane at the site of the existing pool. It includes the construction of the full range healing and recreation complex. This is a long expected project, indispensable to increase the tourist offer and to improve the quality of recreation in this important tourist centre. For Podhale, geothermal balneotherapy and bathing appear to be a very important chance for sustainable development of tourism and economics.

8 Conclusions

The age of the Podhale geothermal system was estimated to be about 22 Ma. The thermal apogee was in its past, when the temperature of rocks and circulated fluids reached at least a value of 165-170°C. With time, during evolution the system was cooled down to a level of 80-90°C. Certainly, the permeability of the reservoir rocks reached its maximum value in the past, too. Since the Late Miocene filling of cracks and fractures has proceeded due to the secondary mineralization. Despite this the system is still active, producing water at high flowrates and temperatures. For maintaining its stable long-time operation, proper current exploitation and development planning is most important. The system offers very favourable conditions for space heating and other multipurpose uses that give the Podhale region the opportunity to introduce an ecological and sustainable development strategy.

The complementary application of both standard methods and those serving the study of geological and thermal evolution of sedimentary basins shown in the present paper is important for the recognition and management of this complex geothermal system. They all enable to reveal various aspects of this interesting geothermal system and provide the information essential for its optimum exploitation and use.

9 References


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Reinjection of thermal waters into sandstone reservoirs in the North German Basin

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Abstract

Intensive investigations into the utilisation of the geothermal potential in the North German Basin began already in the early 1980s. The first tests of production and reinjection of thermal water from / into sandstone reservoirs were started in 1982. As a result, these led to the commissioning of the first geothermal heating plant for heat supply of a residential area in the town of Waren (Müritz) in 1984. More plants were put into operation in Neubrandenburg, Neustadt-Glewe and Berlin. The use of the sandstone reservoirs for heat storage produced new technical solutions. The exact knowledge of the geological and geochemical conditions forms the essential prerequisite for the successful planning, construction and operation of the geothermal plant. In the following, technical solutions and practical experience are presented along with the geological and geochemical conditions.

Keywords: reinjection, thermal waters, sandstone reservoirs.

1 Hydrogeothermal energy use and storage

For the utilisation of hydrogeothermal energy, the thermal water is produced via a well from deep formations up to the surface (production well) and after heat absorption reinjected into the host formation via a second well (injection well).

On one hand, the normally required reinjection of the waters into the underground is to maintain the hydraulic regime, and on the other hand, especially highly mineralised waters must not be disposed off into surface water bodies for reasons of environmental protection. The thermal water is circulated between production and injection wells in a primary closed loop. Via heat exchangers, the heat is absorbed from the thermal water and supplied to the consumers via a secondary loop. As a rule, a geothermal storage system consists also of two wells or two groups of wells developing the same aquifer. Both wells are equipped with pumps and an injection casing allowing the unit to be flown through in either direction. Heat exchangers, which are integrated in the surface pipe system connecting both wells, allow charging and discharging of energy. The conditions described here refer to the North German-Polish Depression, exclusively. The North German-Polish Depression forms the core of the Central European Depression, which includes also the Danish-Polish and the North Sea Depression (Rockel, W. and Schneider, H., 1992).

2 Hydrogeological and geochemical conditions

2.1 Reservoir characteristics

The economically efficient use of low-enthalpy (40-100°C) hydrogeothermal reservoirs requires large thermal water resources and flowrates (50-100 m³/h/well). Therefore, use is tied to several geological conditions (Seibt, P., 1991):
• the existence of a productive water-bearing rock formation (productive horizon)
• a sufficient vertical and lateral extension of this rock formation in order to guarantee longevity (productive reservoir)
• an economically interesting temperature level in the productive reservoir
• the principle suitability of the deep water for the technological process of heat production (material and system compatibility in the thermal water loop).

Along with a sufficient lateral extension of the productive horizon, the high flowrates and the granting of long-term stable production and reinjection require above all certain minimum values as regards porosity, permeability and net thickness, thus resulting in considerable requirements on a pore reservoir usable for hydrogeothermal purposes. There are required sufficiently thick, high-porous and low-matrix sandstones whose primary pore space and grain structures are little changed diagenetically. However, definite limits can just be given for concrete, site-specific conditions. But the following orienting values for sandstones result from the experience gathered in projects implemented hitherto (Rockel, W. et al., 1997):

• effective porosity > 20 %
• permeability > 0.5 \times 10^{-12} \text{ m}^2
• thickness > 20 \text{ m}.

Such sandstones are found in the North German Basin down to depths of approx. 3,000 m.

2.2 Thermal water characteristics

The Mesozoic deep waters developed in NE Germany are classified as high-saline Na-(Ca-Mg)-Cl waters. The depth-depending salt concentration can amount to more than 300 g/l. The main components are chloride ions with almost 50 mmol(eq) % and sodium ions with 43... 47 mmol(eq) %. As secondary and trace components magnesium, calcium, potassium, iron, strontium, manganese, barium as well as sulphate, bromide and iodide ions are dissolved in the thermal water. Silicic acid and borate ions play a minor role only.

The thermal waters contain small shares of solute gases, so called “formation gases”. Predominantly, they consist of nitrogen and carbon dioxide. Methane may occur as a secondary component. Ethane, hydrogen and helium are to be detected in traces only.

The Mesozoic deep waters show a reduced condition; the identified pH values indicate an acid character of the waters (Rockel, W. et al., 1997), (Seibt, P. and Kellner, T., 2002).

2.3 Reinjection of the thermal water

The operator of a geothermal plant has to pay special attention to the reinjection of the cooled-down thermal water into the respective porous and permeable layer, as economic operation is guaranteed only when the thermal water can be reinjected over longer periods of time at little expenditure of energy, i.e. no blockings occur in the injection horizon. Any reductions of the permeability are mainly due to solids. These may originate from (Rockel, W. and Schneider, H., 1992), (Rockel, W. et al., 1997):

• mobilisations of particles (erosion) due to too high injection and production flowrates
• chemical incompatibility of the cooled-down injected fluid with the formation fluid
• entry of oxidation or corrosion products from the thermal water loop
• bacterial activities
• technical insufficiencies of installation and equipment.

The zone endangered mainly is the near-well area.

The reinjection of the cooled-down thermal water (i.e., the flowing-off of the thermal water via the well completion, the near-well zone, and the flowing through the reservoir rock) is equal to filtration. That is why high requirements are put on the quality of the thermal water intended for injection.

3 Technical concept of the thermal water loop

3.1 Underground installation

Completion
Once the well is drilled properly, it has to be completed. The final installation of a geothermal well in the immediate reservoir section can be done according to the variants “open-hole” and “cased-hole” completion. In case of open-hole completion, the last set casing ends above the reservoir layer, thus leaving it open (i.e., the reservoir layer is not cased).

Providing sufficient stability of the rock, this variant surely represents the most favourable option in terms of cost, in particular when re-using old wells where the later liner installation may restrict the usability. In addition, this variant of installation offers better hydraulic conditions. However, the work in the open section of the well can be implemented only at high technical risk.

In case of low stability of the reservoir rock (e.g., sandstone reservoirs tending to desanding when under hydraulic load), special additional completion measures need to be carried out. Gravel-pack – the typical variant of completion of geothermal wells in sandstone reservoirs down to a depth of 2,500 m - implies the filling of the annular space remaining after extension of the well in the reservoir section and installation of a wire-wrapped screen with filter gravel adapted to the grain size of the reservoir sand.

Cased-hole completion is the casing of the reservoir layer and cementing of the annulus between casing and reservoir. Subsequently, this sealing between reservoir layer and borehole must be removed by perforation of the casing wall and the grouting behind it.

This variant of completion does not restrict the technical options of stimulation measures and implies little technical risk.

Testing of geothermal horizons
In this context, a test means the investigation of the hydrodynamic characteristics of geothermal reservoirs. In order to be able to identify the suitability of the reservoirs for geothermal energy supply by targeted tests in the drilling phase already, flowrate, drawdown, formation temperature and pressure, chemism and gas content of the water as well as the stability of the rock are determined.

Investigations into clastic sediments show that the potential injectivity index (i.e., the thermal water injection flowrate which is possible at a certain pressure) can be concluded from the results of the geoscientific investigations and the production tests. Thus, injection tests can be obsolete – which always imply the risk of reservoir
damaging due to the potentials for chemical precepitations existing during production, storage an reinjection.

As a rule, a casing lift test is carried out as a cumulative test upon development of the reservoir, allowing temperature and pressure to be measured in different production regimes as well as recording of the influx throughout the reservoir section.

Based on the data obtained during the drilling process and available from regional geological investigations as well as of the parameters obtained from the tests, the hydro- and thermodynamic behaviour of the geothermal reservoir can be modelled during the operation of a Geothermal Heating Plant. The most important findings are the maximum water head changes to be expected (with the aim to prove the technical feasibility of the production and injection flowrate) and the time of the beginning of the temperature drop as the proof of the required service life of the plant or the temperature development in the production well.

3.2 Surface installation

The technical concept of the surface installation must consider the problems presented above. Important details are highlighted in the following (Seibt, A. et al., 1997).

**Thermal water production**

Due to the high salt content of the thermal water, special submersible motor pumps are applied for the production.

The pump itself is made of corrosion-resistant materials (e.g. red bronze for the running wheels). Also the rising pipes of the pumps and the finishing pipes have to be made of coated or inert material in order to prevent corrosion and, thus, leakage into other aquifers, in particular groundwater-bearing beds with usable freshwater resources.

**Avoidance of the entry of oxygen**

While in operation and idle, the system is kept under permanent overpressure in order to possibly exclude the entry of oxygen and any relevant consequences (cf. 2.3). For that, extensive protective gas systems are installed. The surface tank systems and the annular spaces in the wells are charged with nitrogen.

**Materials**

Up to the early 1990s, the geothermal heating plants in Waren and Neubrandenburg were operated with unprotected metallic pipes. Corrosion damages indicated that the entry of small amounts of oxygen into the system could not be avoided absolutely, thus making the process of corrosion uncontrollable, in particular of unalloyed and low-alloy steels.

However, a wide range of suitable materials is available for the use in the thermal water loop. The choice depends on the particular type and temperature of the thermal water, the pressure and the adequate processing of the materials. Plastics and compound materials (plastic/glass fiber), specially and rubber coated metals as well as high-alloy steels are applied in different combinations.

**Thermal water filtration**

Along with technological measures aiming to reduce or avoid potential precipitations as described under 2.4, the thermal water has to be filtered in order to protect the geological reservoir from blockings. Moreover, filtration prevents the entry of traces
of oils and greases – partly coming from the submersible water pump – into the injection well and, thus, into the reservoir horizon.

4 Implemented projects

Waren
Since 1985, i.e. for 17 years, cooled-down thermal water has been reinjected successfully via an injection well on the site of the first geothermal heating plant in Germany in the town of Waren / Federal Land of Mecklenburg-West Pomerania. The aquifer is formed by Hettangian sandstones in a depth of 1,470 m providing flowrates around 60 m³/h. When produced, the thermal water temperature is 62 °C, when injected, it ranges from 20 to 40°C. The salt content of this NaCl brine is 158 g/l, iron content is 12 mg/l (Seibt, P. and Kellner, T., 2002), (Seibt, P. et al., 1994).

Neustadt-Glewe
The site was explored in 1989. It was found to be characterised by extreme conditions. With a thermal water temperature of 100°C, a salt content of 220 g/l, iron about 80 mg/l, and high gas contents in the fluid the heating plant is in basically smooth operation since 1995. The thermal water is produced from and injected into a sandstone layer in a depth of 2,200 m at flowrates of max. 125 m³/h.
Via a defective regulating valve, oxygen entered the otherwise closed system over a short period of time in 1998, resulting in iron precipitation which caused an increase of the injection pressure. Upon inspection of the injection well and intensification, the injectivity could be restored by 100 % (Seibt, P. et al., 1994); (Seibt, P. et al., 1994); (Menzel, H. et al., 2000).

Berlin
The aquifer thermal energy store forming an essential part of the integrated energy supply system of the buildings of the German Parliament in Berlin (Reichstag plus new buildings) is installed in a weakly consolidated sandstone in a depth of about 300 m. The thermal water has an initial temperature of 19°C and a salt content of 29 g/l (Poppei, J. et al., 1998), (Seibt, P. et al., 1996), (Seibt, P. and Kabus, F., 1997). For two years now, waste heat coming from the vegetable oil driven cogeneration plant is stored and recovered without any technical problem (Zenke, J. et al., 2000).

Neubrandenburg
The Geothermal Heating Plant was commissioned in 1989. The thermal water is produced from two fine sandstone horizons in depths of 1,150 and 1,250 m, with temperatures of 52 and 54°C, salt contents of 113 and 133 g/l, respectively, at flowrates of up to 100 m³/h, and reinjected into the host aquifers. In the early 1990s, the surface plant was rehabilitated, however, without installation of a nitrogen charging system. Consequently, the injectivity deteriorated continuously. The GHP is being reactivated at present and retrofitted for the combined use as geothermal plant and waste heat aquifer store of a Gas and Steam Cogeneration Plant plus the production of brine for therapeutic purposes. The new thermal water loop is installed according to the state-of-the-art.

5 References


Reinjection experiments in the basement geothermal reservoir, Tianjin, China

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Abstract

The end of 2001, about 196 production wells, (including 12 reinjection wells) had been drilled in Tianjin. The annual production rate was 22 Mm\textsuperscript{3} in 2001 and the reinjection rate was about 1.66 Mm\textsuperscript{3}. The depth to the water level ranges from 22 to 70 m and the draw-down rate is 6-9 m/year. The effect of reinjection in the WR45 doublet is analysed, but no temperature changes have been observed in surrounding geothermal production wells, up to the present. The main side effect anticipated from reinjection is a cooling of the reservoir. Tracer tests are very important for understanding the mode of transport and flow-channel/fracture-space characteristics in doublet production/reinjection systems, and to estimate the possible cooling resulting from injection.

Keywords: reinjection, basement reservoir, tracer test, mathematics modelling.

1 Introduction

Tianjin is located in the northeast part of the Hua-Bei plane in NE-China, with the Yan Mountain to the north and Bohai Bay to the east. The total area of the region is about 11300 km\textsuperscript{2}. Most of the area is covered by Quaternary stratum. Base rock outcrops are limited to the mountain area of Ji County in the north (Wang Kun et al., 2001).

In Tianjin, the main productive reservoirs are porous sandstone reservoirs on one hand (2 productive zones) and karst/fractured basement rock reservoirs (3 productive zones). The depth to the top of the karst/fractured base rock reservoir is over 950 m. Until now the maximum drilling depth is near 4000 m. The maximum discharge rate for a single well is more than 100 m\textsuperscript{3}/h, with wellhead temperatures ranging from 55 to 100°C. The water from this reservoir is mainly used for space heating, physical therapy, bathing, fish farming etc. In total 196 geothermal production wells (including 12 reinjection wells) had been drilled in Tianjin by the end of 2001. The annual production rate reached 22Mm\textsuperscript{3} in 2001 and the reinjection was 1.7 Mm\textsuperscript{3}. Currently the depth to the static water level varies between -35 and -90 m, with an annual drawdown rate of 6-9 m (Wang Kun et al., 2001).

In recent years extensive research has been conducted into the technology of geothermal utilization, reinjection, reservoir engineering and digital system of geothermal monitoring/management. But some problems are still awaiting further investigation.

Since 1996, reinjection experiments have been conducted in the basement reservoir in Tianjin. Till now, there have been drilled 12 production/reinjection doublets, 10 of them located in Tianjin urban area. These doublet wells are essential for the protection, and sustainable use, of the geothermal resource in Tianjin. This paper describes the results of these reinjection experiments.
2 Basement reservoir reinjection

2.1 Geological setting

The WR20 doublet was drilled in 1993, which is the first doublet drilled into the basement reservoir in Tianjin. The production well of this doublet is drilled into the Wumishan group of the Jixianian formation from the Proterozoic and the reinjection well is finished in an Ordovician formation reservoir. Figure 1 shows a sketch of the design of the WR20 doublet (Wang Kun et al., 2001).

The WR45 doublet is the second production-reinjection doublet drilled into the basement reservoir, having been drilled in 1995. Figure 2 shows a sketch of the design of the WR45 doublet. Both of the production and reinjection wells were drilled into the Wumishan group of the Jixianian formation from the Proterozoic (Wang Kun et al., 2001).

2.2 Analysis of the WR45 reinjection tests

The main lithological units of the productive zone of the WR45 doublet are composed of dolomite and limestone. Karst-type fissures are well developed in the area of the doublet.

The first reinjection test was carried out with a high-pressure pump in October 1996. Figure 3 shows some of the monitoring data collected during this test (Zeng Meixiang et al., 2002). After removing some abnormal data, caused by equipment problems, we found that the reinjection flow-rate was inversely proportional to the reinjection pressure during the test. When the pump pressure was 0.02 MPa, the...
reinjection rate was 100 m$^3$/h. But the reinjection rate decreased to 86 m$^3$/h when the pump pressure was increased to 0.05 MPa. During the last stage, the pump pressure was 0.09 MPa and the reinjection rate settled at ~50 m$^3$/h, more or less. This behaviour can be explained by the following:

The WR45 doublet is located in the part of the Wumishan reservoir, where karst fissures are well-developed. This is a double porosity porous-fractured medium. At the beginning of the reinjection test, flow along fissures dominates and the pump pressure had little effect on the reinjection rate. The reinjection water entered the aquifer quickly because of increasing pressure gradient between reinjection and production well. As the reinjection continues, the effect of seepage into the porous medium started to increase. The velocity of the reinjection water in the reservoir became slower, and the flow-rate decreased. As a whole, the pump pressure increased and the injection rate decreased, gradually, as the reinjection test continued.

During the space-heating periods (November-March) of 1999/2000 and 2000/2001, the WR45 doublet has been operated by gravity, without pumping. All the geothermal water extracted was reinjected into the reservoir directly after utilisation for heating. Because there are several geothermal wells around WR45 used for space heating simultaneously (Fig. 4), the reservoir pressure decreased rapidly, and the water level
in the reinjection well is now at about 30 m depths. But no temperature changes have been observed in the surrounding production wells, up to the present.

## 3 Tracer test in the basement reservoir

To investigate the connections between the reinjection and production wells of the WR45 doublet, a tracer test was conducted in the winter of 1998-1999. We selected 10 kg of potassium iodide (KI) as the tracer. Meanwhile the chemical content of the water produced from the surrounding wells was monitored carefully. The resulting data are presented in Figure 5.

![Figure 5: The recovery curves of the tracer concentration in observation wells around WR45.](image)

The monitoring data shows that the tracer concentration is almost constant in the production well, i.e. no noticeable recovery. On the other hand, observation well GC45-2 shows some iodine recovery. This means that the hydro-geological connection between the production and reinjection well of doublet WR45 is indirect,
but that there may be a direct (fast migration) channel between the reinjection well and other nearby geothermal production well, such as production well GC45-1, which is about 2.5 km from the reinjection well.

Table 2: Calculated parameter of the tracer test.

<table>
<thead>
<tr>
<th>Fissure</th>
<th>Cross section area $A \phi$</th>
<th>Dispersivity $\alpha_L$</th>
<th>mass recovered (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.50 m$^2$</td>
<td>356 m</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>15.7</td>
<td>142</td>
<td>39</td>
</tr>
<tr>
<td>3</td>
<td>29.5</td>
<td>10.1</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>54.7</td>
<td>162</td>
<td>22</td>
</tr>
</tbody>
</table>

A mathematical model simulated the results from GC45-2, try to understand the nature and structure of the fractures connecting GC45-2 and the reinjection well. Figure 6 and Table 2 show the simulated recovery and model parameters, respectively. The simulation curve is composed of 4 pulses, corresponding to 4 flow channels/fractures. When the tracer was injected into the aquifer, it travels rapidly along the most direct path, which has the smallest cross section. For this channel the tracer moves quickly to the production well and reaches the maximum concentration in a very short time. If, on the other hand, the reinjected water diffuses into a large reservoir volume, only a small fraction of the tracer will be recovered and the time it takes to reach peak value will be much longer. In the latter case the thermal breakthrough time will not be a problem for the doublet system operation. Therefore, tracer tests are very important for understanding the mode of transport and flow-channel/fracture-space characteristics in doublet production/reinjection systems.

4 Mathematics modeling of the doublet system

The main side effect anticipated from reinjection is a cooling of the reservoir involved (Axelsson, G. et al., 1995). Therefore, it is necessary to estimate the thermal breakthrough time for different injection-production well spacing, i.e. the time from initial injection until a significant cooling is observed in a producing well.

At present, the main reinjection mode in Tianjin is through doublet systems. Therefore, the TOUGH2 computer program was used to simulate the changes in the temperature field around a typical doublet system in the Wumishan aquifer, for ten years into the future. Another doublet system WR82/83 is considered here, with the distance of 4m at wellhead and 980m at the bottom. Taking the heat exchange between the reservoir and other strata at the top and bottom, a multi-aquifers model is set up to predict the temperature changes in the reservoir during reinjection. Figure 7 shows the simulation results. It appears that locating reinjection wells at a distance of about 100 m from production well should not cause a thermal break-through in less than 10 years.

It should be pointed out that reinjection is only carried out in wintertime in this case. The reinjected water will extract more thermal energy from the rock matrix when geothermal wells are shut down in summer, resulting in slower cooling rates. However, the result is highly uncertain because the flow channel dimensions are unknown. So, tracer tests are recommended in future research.
5 Summary
The main conclusions and recommendations of this work may be summarized as follows:
1. The main side effect anticipated from reinjection is cooling of the reservoir involved and the thermal breakthrough time depends on the geological structure of the reservoir. If the reinjection water diffuses into a large reservoir volume the thermal breakthrough will not be a problem in doublet systems. But tracer tests are very important for understanding the mode of transport and flow-channel/fracture-space characteristics in doublet production/reinjection systems.
2. The reinjected water will extract more thermal energy from the rock matrix when geothermal wells are shut down in summer, resulting in slower cooling rates. However, the result is highly uncertain because the flow channel dimensions are unknown. So a tracer test must be conducted to study the flow paths between injection and production wells, and estimate the possible cooling resulting from the injection.
3. Long-term monitoring of the Tianjin geothermal field must be further improved and equipped, so that any changes caused by reinjection will be observed as soon as possible.

6 References
A preliminary update of natural state numerical model of Olkaria geothermal system, Kenya

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Abstract

A field-wide 3-D natural state numerical model of the entire Olkaria geothermal system was developed in 1987 by G.S.Bodvarsson and K.Pruess. The model simulated the geothermal system to be recharged at a total rate of 600 kg/s from two major distinct upflow zones located in Olkaria Northeast and Olkaria West. The upflow zone in Olkaria Northeast recharged the system at 250 kg/s of 1290 kJ/kg water and the one in Olkaria West at 350 kg/s of 1090 kJ/kg of water. The recharge from the two upflow zones mixed near well OW-201 and discharged at 260.5 kg/s to the south and 175.1 kg/s to the north through Oloolbutot fault and Olkaria fracture, respectively. Steam loss from the system amounted to 126 kg/s. Between 1987 and 2000, 46 new additional wells were drilled and tested in the greater Olkaria geothermal system. While data from some of the newly drilled wells have agreed quite well with those calculated by the 1987 model, several other data, especially from the Olkaria Central wells, have shown big variations. An attempt has therefore been made to recalibrate the 1987 model with the new data acquired from the 46 additional wells. The same numerical grid has been used and the results have indicated a slight variation in recharge rates and enthalpies. The upflow in Olkaria West in the updated model is 245 kg/s of 1200 kJ/kg water and that in the East (both Northeast and east field) is 320 kg/s of 1290 kJ/kg water. The discharge to the south in the updated model is 304.3 kg/s and to the north is 134.4 kg/s. Steam loss from the system is 128 kg/s.

Keywords: Olkaria, natural state, TOUGH, simulation.

1 Introduction

Olkaria geothermal system is located in the East African rift valley to the south of Lake Naivasha and 120 km northwest of Nairobi city. The geothermal system covers an area of more than 120 km² and is associated with a central volcano that is among several ones situated within the central Kenyan rift.

Exploitation of this resource for the purpose of producing electricity started in 1981 in Olkaria East Field when the first 15 MWe generation unit was put online with the second and the third 15 MWe in 1982 and 1985, respectively. From 1985 through the 90s intense surface exploration and deep drilling was done in the neighbouring areas resulting in demarcation of adjacent fields in Olkaria West, Northeast, Central and Domes (Figure 1). A 13 MWe binary plant installed by Ormat Inc. started operation in August 2000 in Olkaria West and a 64 MWe plant is nearing completion in Olkaria Northeast.
The geothermal system is liquid dominated and is recharged by hot upflowing fluids from zones in the West, Northeast and East fields. The upflow zones are associated with the intersection of prominent faults within the geothermal system such as the NE trending Olkaria fault and the NW, NNW trending faults (Figure 2).

Figure 1: Location of wells and fields within the greater Olkaria geothermal system.

Figure 2: Geological structural map of Olkaria geothermal system. In the numerical grid, inflow and outflow through the prominent faults (Olkaria Fracture, Olkaria Fault and Ololbutot fault), are represented by alphabetical letters A, B, C, D and E.

Between the upflow zones in the east and west is a low temperature and pressure zone of Olkaria Central, which is associated with the N-S trending Ololbutot fault. Temperatures and pressures in wells drilled in the upflow zones follow boiling point with depth with steam cap forming below the caprock. Wells in Olkaria Central field have temperature inversions at depth. Subsurface stratigraphy of the wells show that from the surface (which is at an average of 2000 m a.s.l) to 1400 m a.s.l, the rocks consist of quaternary comendites and pantellerites with an extensive cover of
pyroclastics. Below these, the dominant rocks are trachytes with thin intercalations of basalts and tuffs. The rock stratigraphy is essentially horizontal (Muchemi, 1999).

A field-wide 3-Dimensional natural state numerical model was developed in 1987 by Bodvarsson and Pruess (Bodvarsson and Pruess, 1987) and was calibrated against the thermodynamic data obtained from the wells that had been drilled by then. The model agreed quite well with the measured data and the conceptual model. From 1987 to present, more than 46 new wells have been drilled in the greater Olkaria geothermal system and there has been a serious need to update the numerical model to conform to the new findings. This paper presents a preliminary update done to the old model in 2002 (Ofwona, 2002) whereby the thermodynamic data from most of the new wells have been incorporated.

2 Model description

2.1 Grid geometry

The TOUGH2 model developed to represent Olkaria reservoir covers an area of 110 km² and is partitioned into 128 blocks. Vertically, the model assumes an impermeable caprock of 700 m thick beneath which underlies a permeable reservoir of 850 m that is further partitioned into three layers giving a total of 384 grid blocks (Figure 3).

![Grid block layout](image)

**Figure 3**: Grid block layout.

2.2 Boundary conditions

The major hydrogeologic features of the Olkaria system include Olkaria fracture, Olkaria fault, Suswa fault, Gorge farm fault and Ololbutot fault (Figure 2). In the model, two major upflow zones located near the western and eastern ends of the Olkaria fault recharge the hydrothermal system. The fluid from the upflow zones move along the Olkaria fault as they undergo conductive cooling as well as cooling by steam loss to the surface and converge in Olkaria Central zone. Major outflow with substantial loss of steam and cooling occurs towards the south along the Ololbutot fault and towards the north along Olkaria fracture zone. The reservoir is assumed bounded in the east and west by no flow boundaries and in the north and south by constant pressure boundaries of 45 bars at 1075 m a.s.l and 28 bars at 1075 m a.s.l,
respectively. The hot upflows are treated as the source of hot fluids at the base of the model.

2.3 Fluid and rock properties

The rock properties used were similar to those in the 1987 model and changes were made only where well tests had shown otherwise and in cases where no information was available, the values chosen were simply guessed. A rock type with defined rock properties (values of permeability, porosity, density and thermal conductivity) was assigned to each model element. Table 1 shows the rock properties assigned to the major structures in the geothermal system.

Table 1: Rock and fluid properties.

<table>
<thead>
<tr>
<th>Rock properties</th>
<th>Fluid properties</th>
<th>Permeabilities, m² (x 10⁻¹⁵)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>Density: 2650 kg/m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat capacity: 1000 J/kg °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity: 2.0 W/m°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative Permeabilities: kₚ(Sₛ) = (Sₛ – 0.05)/0.55</td>
<td>Approximated as pure water and all properties based on steam tables</td>
<td>Olkaria Fault 230 230 x 230</td>
</tr>
<tr>
<td>kᵣw(Sₘ) = (Sₘ – 0.40)/0.60</td>
<td></td>
<td>Olkaria Fracture 250 250 x 250</td>
</tr>
<tr>
<td>Oloolbutot Fault 500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4 Match to measured data

The natural state was simulated for 10,000 years until a steady situation agreeing closely with the current temperatures and pressure values in most parts of the reservoir was found. It was a long trial and error procedure, slightly changing the rock parameters and boundary conditions. Important adjustable parameters in the model were the strength of the upflow (both enthalpy and flow rate), vertical and horizontal permeabilities, and the strength of outflow and steam losses along the prominent hydrogeologic structures. The observations were measured or inferred downhole temperature and pressure profiles and surface heat flow estimated to be 400 MWt (Glover, 1972).

3 Results

The results of simulation are shown graphically for a few selected wells in the Figures 4-7. They show graphs detailing pressures and temperatures calculated by the recalibrated model (open squares connected with lines) and those from the 1987 model (filled black stars) in relation to the measured or inferred formation temperatures and pressures (broken lines). We can observe that the 1987 model matches the data pretty well except for the wells within the low temperature zone in Olkaria Central field. To obtain a reasonable match for these wells, I had to reduce the upflow rate from the west and permeability in the Olkaria fault and Olkaria fracture zones and increased the permeability of the East field thus allowing more fluid to divert south through the present production field instead of moving to the Central field. Other minor adjustments in permeabilities on other elements were also necessary. Table 2 shows the updated flow rates compared to those obtained by the old model.
Figure 4: Match to temperature and pressure in well OW-201.

Figure 5: Match to temperature and pressure in well OW-32.

Figure 6: Match to temperature and pressure in well OW-401.
4 Conclusions

The present simulation results should be considered preliminary because the model did not consider deeper layers even though most of the wells are now drilled to depths below 0 m a.s.l. However, a reasonable match between calculated and observed values is obtained for the depth considered and the numerical model confirms pretty well the conceptual model. It shows that quite a huge quantity of water is circulating in Olkaria system in the natural state suggesting that good recharge can be expected during the exploitation life of the field. The challenge now will be to extend the vertical grid in order to cover the deeper zones.

5 References


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**Table 2: Flow rates.**

<table>
<thead>
<tr>
<th>Flow rates (kg/s) and Enthalpies (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
</tr>
<tr>
<td>Inflow</td>
</tr>
<tr>
<td>Outflow</td>
</tr>
<tr>
<td>Enthalpy</td>
</tr>
</tbody>
</table>

Figure 7: Match to temperature and pressure in well OW-720.
Study on diffuse degassing and alteration mineralogy in the Berlín Geothermal Field

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Abstract

Due to its recent geothermal development in El Salvador, various monitoring activities are periodically undertaken in Berlin geothermal field to provide more data and information for the construction of the conceptual model of the field and to give an idea of the chemical, physical and thermodynamic behavior of the field. Among these activities are the study of diffuse degassing and the periodic monitoring of fumaroles. Radon and thoron contents show anomalies at the northeastern part of Alegria City, which could be a possible area for investigation. The study of gases and alteration mineralogy is very much related. The type of hydrothermal minerals also depends on the permeability and chemical content whether it is gas or liquid. High and high gas anomaly mainly CO₂ are observed in the central part of the field mainly in Tronador y Tronadorcito fumaroles. Alteration and gas studies confirm the upflow zone of the field. Almost all of the fumaroles are related with geologic structures, which provided passage for hydrothermal fluids to reach the surface. Likewise, most of the gas anomalies are located in fault zones.

Key words: diffuse degassing, alteration mineralogy, conceptual model, Berlin field.

1 Introduction

Due to its recent geothermal development in El Salvador, various monitoring activities are periodically undertaken in Berlin geothermal field to provide more data and information for the construction of the conceptual model of the field and to give an idea of the chemical, physical and thermodynamic behavior of the field. Among these activities are the study of diffuse degassing and the periodic monitoring of fumaroles.

This paper includes the results of the study of gases mostly CO₂, radon and thoron relating gas anomalies with permeable zones and movement of fluids while the monitoring of fumaroles suggests the variation in area and type of alteration and the prediction and prevention of geologic hazards that may occur (i.e. hydrothermal eruption).

The study area comprises a total area of 29 km² and part of the southeastern part of the field. It is worthwhile mentioning that the study of diffuse degassing was carried out for the first time in December 2000 before the strong earthquake in January 13, 2001, which devastated a lot of properties.

2 General description of Berlin

Berlin geothermal field is located at the eastern part of El Salvador in Central America (Figure 1), 100 km. east of San Salvador city, the capital of El Salvador. It lies at the northern slope of the Berlín-Tecapa volcanic complex and has an area of about 24 km² with an estimated geothermal power potential of 85 MWe.

In 1992, a backpressure unit was commissioned using well TR-2 as a production well and wells TR-1 and TR-9 as reinjection wells. Expansion of the
geothermal field was a priority to address the growing demand of electrical energy of the country.

To date, 31 wells have been drilled in Berlin with a total number of 10 wells used for producing an installed capacity of 56 MWe, two units of 27.5 MWe from a single flash condensing power plant, 11 reinjection wells and the rest as exploratory wells and/or without commercial use (Artola, S. pers.com. 2002).

Based on the geoscientific studies, the upflow zone is located beneath the Berlin-Tecapa volcanic complex, at the southern part of the field near where TR-5 wells are situated. Hydrothermal fluids
flow laterally along the circular faults of the Blanca Rosa and Berlin calderas in a north-northwest direction (Barrios et al., 2001). Measured reservoir temperature is 305°C while calculated temperature based on different geothermometers is 350°C. The outflow zone is assumed to be at the northern part of the area. See Figure 2.

3 Results of study

A. Diffuse degassing
Radon gases in soils and fumaroles are used to identify convective flow areas and to monitor degassing changes through time. $^{222}$Rn ($t_{1/2} = 3.8$ days), $^{220}$Rn ($t_{1/2} = 55$ sec) and $^{219}$Rn ($t_{1/2} = 3$ sec) form the isotopic group which decay from radioactive natural elements such as $^{235}$U and $^{238}$Th. $^{222}$Rn are soluble in water and its solubility increases with decreasing temperature (Mania et al., 1995). Due to the half-life of radon, in areas where slow diffusive flow exists, the average depth of origin is approximately 2 m (Connor et al, 1996). Therefore the high concentrations of radon are more likely to be due to convective movement of gases rather than diffusive processes.

Thoron gas ($^{220}$Rn) disintegrates rapidly and is present only a few minutes after the collection of sample. Its half-life is 55 sec (Hutter, 1995), and it is difficult to obtain an exact quantitative measurement of its concentration.

High fluxes of hydrothermal gases are usually discharged at the end of the faults or where multiple faults intercept (Chiodinni, G., et al, 1994). CO$_2$ gas is the most abundant gas after water vapor, hence it is considered very useful to monitor volcanic changes, magma movements and usually related to permeable zones in volcanic geothermal fields.

Results of radon survey are shown in Figure 3 where anomalies are observed in: a) an inferred fault (based on geophysical survey) parallel to Guallinac Fault at the eastern part of the field, b) northern part of the fumarole in Vuelta de San Juan and c) northeastern part of Alegria City along the inferred faults (based on geological studies), which are seen at the southeastern part of the field.

Anomalies of thoron content as observed in Figure 4 show almost the same areas observed in radon survey and in Caserio La Corriente at the northern part of San Juan fault and coincide with the present alteration in the area.

In Figure 5, the presence of CO$_2$ anomalies are well observed along the area of Guallinac Fault and the inferred fault west of this fault which indicates areas of high emanation of CO$_2$ along a permeable zone where ascent of magmatic fluids are present. This coincides with the upflow zone located at the Berlin-Tecapa volcanic complex.
Figure 3: Results of radon survey at southeast area of Berlin Geothermal Field (0-300 pCurio/L).

Figure 4: Results of thoron survey at southeast area of Berlin Geothermal Field (0-900 pCurio/L).
B. Fumaroles

Results of the monitoring of fumaroles are seen in Table 1, which presents a summary of the characteristics of the fumaroles. Figure 6 shows the distribution of fumaroles in the Berlin geothermal field. Most of the acid alteration is observed at the southern part of the field. High content of sulfur and the presence of sulphate minerals were observed in the fumarole in Laguna de Alegria, which coincides with the upflow zone of the field. Acid-bicarbonate minerals such as gypsum and anhydrite are mostly observed in Tronador fumarole where mixing of fluids has occurred, however, high temperature (<95°C) are also observed in this area. Clay minerals mostly nontronite and montmorillonite are mainly concentrated at the northern part of the field.

Figure 5: Results of CO₂ survey at southeast area of Berlin Geothermal Field (0-500 g/day-m²).

Figure 6: Location of fumaroles in Berlin Geothermal Field.
Table 1: Characteristics of fumaroles in Berlín.

<table>
<thead>
<tr>
<th>Fumarole</th>
<th>Area (m²)</th>
<th>Temp (°C)</th>
<th>Mineralogy</th>
<th>Type and intensity of alteration</th>
<th>Related Structures</th>
<th>Type of rock formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tronador</td>
<td>21,770.98</td>
<td>83-97</td>
<td>gypsum, hematite, rectorite, alunite, kaolinite, anhydrite, halloysite, nontronite, quartz, heulandite, saponite, albite</td>
<td>Acid alteration, intense</td>
<td>El Tronador Fault, San Jose Fault</td>
<td>Lahars</td>
</tr>
<tr>
<td>Tronadorcito</td>
<td>24,389.35</td>
<td>96</td>
<td>anhydrite alunite, ammoniojarosite, jarosite, kaolinit pyrite, natroalumite, cristobalite goeetite</td>
<td>Acid alteration, intense</td>
<td>San José Fault, La Planta Fault</td>
<td>Lahars</td>
</tr>
<tr>
<td>TR-10 (Bálsamo)</td>
<td>16,994.80</td>
<td>94-98</td>
<td>nontronite, alunite, natroalunite, anhydrite, heulandite, cristobalite, albite, goethite</td>
<td>Moderate o intense alteration</td>
<td>La Plata Fault, El Balsamo Fault</td>
<td>Lahars</td>
</tr>
<tr>
<td>Crater de Huyon</td>
<td>-</td>
<td>96</td>
<td>pyrite, sulfur, kaolinite, natroalumite, anhydrite, cristobalite, quartz, pyrite, pyrite, goethite</td>
<td>Acid alteration, intense</td>
<td>El Huyon Fault, El Huyón crater</td>
<td>Lavas by</td>
</tr>
<tr>
<td>Laguna de Alegria</td>
<td>3731.81</td>
<td>25-88</td>
<td>halloysite, anhydrite, quartz, pyrite, pyrite, cristobalite</td>
<td>Acid alteration, intense</td>
<td>Tecapu crater</td>
<td>Lavas by</td>
</tr>
<tr>
<td>La Vuelta San Juan</td>
<td>Approx. 60m²</td>
<td>80</td>
<td>nontronite, albite, calcite</td>
<td>Moderate, neutral</td>
<td>San Juan Fault, border of the caldera</td>
<td>Lavas by</td>
</tr>
<tr>
<td>La Flecha</td>
<td>8,449.97</td>
<td>80</td>
<td>nontronita y heulandita</td>
<td>Moderate, neutral</td>
<td>El Tronador Fault</td>
<td>Boulders of lavas Lahars y lavas</td>
</tr>
<tr>
<td>La Cruz</td>
<td>Approx. 100m²</td>
<td>55</td>
<td>albite, calcite, hematite, halite</td>
<td>Moderate, acid alteration</td>
<td>Berlin- Tecapa volcanic complex</td>
<td>Boulders of lavas Lavas by</td>
</tr>
<tr>
<td>El Trujillo</td>
<td>Approx. 100m²</td>
<td>92</td>
<td>halloysite, jadeite, corrensite, hematite</td>
<td>Moderate, neutral</td>
<td>Las Crucitas Fault</td>
<td>Lavas by</td>
</tr>
<tr>
<td>La Joyona</td>
<td>Approx. 50m²</td>
<td>80</td>
<td>saponite, nontronite, cristobalite, albite, jarosite, hematite</td>
<td>Moderate, neutral</td>
<td>San Juan fault</td>
<td>Lavas bm</td>
</tr>
<tr>
<td>El Pinal</td>
<td>Approx. 2500m²</td>
<td>76-80</td>
<td>nontronite, albite, cristobalite, quartz, halite, magnetite</td>
<td>Acid alteration, intense</td>
<td>Berlin-Tecapa volcanic complex</td>
<td>Lavas by</td>
</tr>
</tbody>
</table>

A schematic diagram (N-S) of the distribution of alteration minerals are shown in Figure 7 where neutral chloride alteration are observed at a lower elevation in Trujillo fumarole, however, fumaroles at the flanks such as La Joyona, la Flecha and Vuelta de San Juan also contain this type of alteration probably due to the materials of landslide which have covered the fumaroles.

Figure 7: Schematic diagram of the distribution of alteration minerals.

4 Discussion

Most of the permeable zones identified by diffuse degassing coincide with the eastern border of the caldera along the Guallinac fault. Moderate anomalies by thoron survey in the area of Vuelta de San Juan coincide with the clay alteration (montmorillonite
and nontronite), a low-grade alteration, which have controlled the release of gases. Materials brought about these clay minerals during landslide (Henríquez et al, 2003).

High CO\textsubscript{2} content coincides with the high temperature and acid-bicarbonate minerals observed along the flanks of the volcanic-complex near fumaroles Tronador and Tronadorcito. The release of magmatic CO\textsubscript{2} and acid sulphate waters brought the formation of anhydrite and gypsum minerals.

5 Conclusion

Radon and thoron contents show anomalies at the northeastern part of Alegría City, which could be a possible area for investigation.

The study of gases and alteration mineralogy is very much related. The type of hydrothermal minerals also depends on the permeability and chemical content whether it is gas or liquid.

High and high gas anomaly mainly CO\textsubscript{2} are observed in the central part of the field mainly in Tronador y Tronadorcito fumaroles. Alteration and gas studies confirm the upflow zone of the field.

Almost all of the fumaroles are related with geologic structures, which provided passage for hydrothermal fluids to reach the surface. Likewise, most of the gas anomalies are located in fault zones.

6 References


