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MODELING OF BOUILLANTE GEOTHERMAL FIELD (GUADELOUPE, FRENCH LESSER ANTILLES)

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ABSTRACT

Since the January 2005 commissioning of its second production unit, the Bouillante geothermal field has been supplying the Guadeloupe Island (French Lesser Antilles) with 6 to 8% of its consumption of electric energy. The consequent increase in geothermal fluid withdrawal induced a change in reservoir behavior and well head pressures evolution. Altogether with the need for the reinjection of the produced brines these observations raised several questions whose answers needed better reservoir characterization and modeling.
As a first step towards this, available data is currently gathered to build a conceptual geological model integrating both regional and reservoir scale data. Lumped parameters models were used as first exploration tools to test conceptual schemes of the geothermal field and forecast pressure evolutions. Current modeling efforts are focusing on the development of reservoir and regional scale hydrothermal modeling to understand both the main physical processes controlling the behavior of the geothermal field and help exploration activities aimed at developing its potential.

THE BOUILLANTE GEOTHERMAL FIELD

Location and geological context

The Bouillante geothermal field is located in the French West Indies in the Guadeloupe archipelago. This archipelago forms part of the 850-km-long N-S-trending Lesser Antilles volcanic arc located at the northeastern edge of the Caribbean plate where the Atlantic lithosphere subducts beneath the Caribbean plate (Feuillet et al., 2002). The geothermal field is on the west coast of Basse-Terre Island, which is the westernmost and highest island (1467 m) of the Guadeloupe archipelago. It is contained within a volcanic substratum largely attributed to sub-product of the axial Pitons de Bouillante volcanic chain cropping out along the N-S axis of Basse-Terre Island and lies near two recent units: the ‘axial Chain complex’ (1.023 to 0.445 Ma; Samper et al., 2007) and the ‘Bouillante Chain complex’ (1.1 to 0.2 Ma; Gadalia et al.,1988).
The persistence of volcanic activity in the area for almost 1 Ma and the associated magmatic differentiation argue in favor of a deep magma reservoir below the Bouillante Chain complex. The magma is thought to come from the partial melting of the subducted oceanic crust and would be blocked at an undetermined depth to form a common magma reservoir. This deep magma reservoir is the most likely heat source of the Bouillante geothermal system (Bouchot et al. 2010). It is likely that the magmatism is tectonically controlled because i) at regional scale Bouillante Chain complex is developed along the regional NNW-SSE trending transfer fault and ii) at local scale volcanic centers are focused within a N90-120°E corridor, immediately north of Bouillante city (Marsolle-Machette corridor, *cf.* Figure 1 and Bouchot et al., 2010).
Surface expressions of the geothermal field are characterized by direct discharges of geothermal fluid along the coast and offshore hot springs and hot soils, with gas emissions (e.g. He, CO2, CH4, Rn). The density of surface indicators is the highest in the Bouillante Bay where submarine springs and gas emissions can reach ~120 °C. These manifestations are also located along a 6 km long N-S alignment within the volcanic chain that reflects spatial fluid leakage from a high-temperature geothermal reservoir (Bouchot et al. 2010 and Figure 1). These geothermal surface indicators vanish southward though the local toponymy may still reflect their former presence.

Conceptual model of the geothermal system

Previous works on the Bouillante area include a structural analysis of the geothermal conduits, both offshore and onshore geophysical investigations, characterization of the geothermal alteration, numerical geological modeling of the developed field, fluid geochemistry characterization, tracer tests and hydrogeological modeling. Many of these results were integrated in a conceptual model of the geothermal system (Bouchot et al. 2009, 2010). This conceptual model is briefly summarized below.

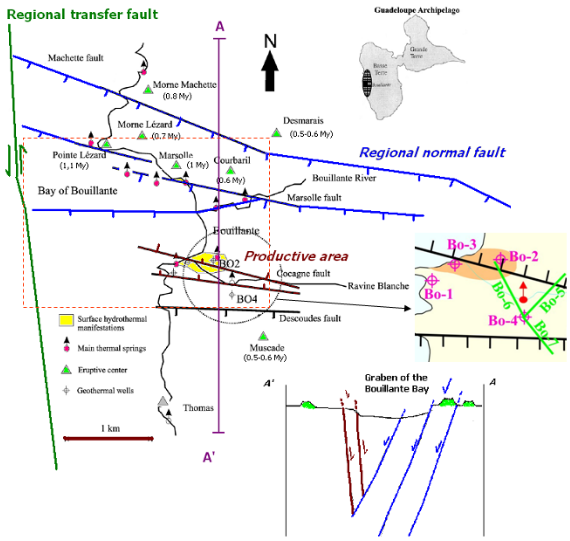

Figure 1: Location map showing the Bouillante area and the existing wells (map from Bouchot et al., 2010). The red dashed box corresponds to the approximate extension of the geothermal field (Bouchot et al., 2009)

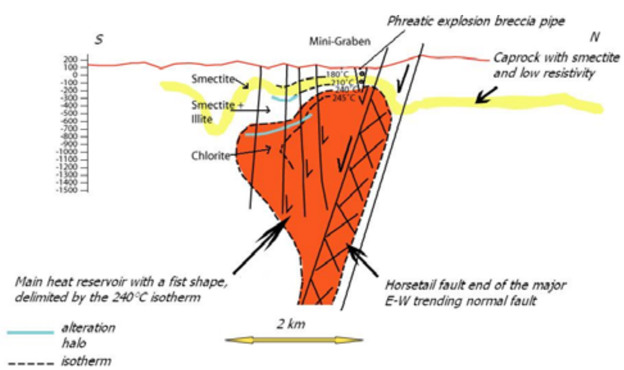

Figure 2: Conceptual model of the Bouillante geothermal system along a N-S section (Bouchot et al., 2010).

The heat reservoir corresponds to a large rock volume affected by pervasive hydrothermal alteration. The temperature inside this heat reservoir is quite homogeneous and is in a 250-260 °C range. Under reservoir temperature and pressure conditions the geothermal fluid is in liquid state. The top of the reservoir is located at the base of an illite smectite alteration zone. It deepens from north (~300 m) to south (~600 m) of the geothermal field, moving away from the apical zone of the reservoir centered on Bouillante Bay. In a N-S section the envelope of the heat reservoir is in the shape of a fist, and it is about 2 km wide between Descoudes and Pointe Lézard. Its extension is controlled by the geometry of the Bouillante Bay mini-graben that is likely to drive fluid circulation through a hydraulic network made up of permeable faults zones and fractures and a few relatively shallow porous aquifers (Figure2).

The envelope of the heat reservoir could be rooted at about 2500-3000 m deep in the Marsolle – Pointe Lézard corridor at the depth where mixing of the geothermal fluid is thought to occur. Based on ^{7}Li isotopic arguments, this mixing zone would be at the transition between the ocean floor and the overlying andesitic lavas (Sanjuan et al., 2008). Yet, the location of this interface is not precisely constrained. It is estimated to be about 3 km deep but could even be deeper. Then, the reservoir would be at least 2.5 km thick.

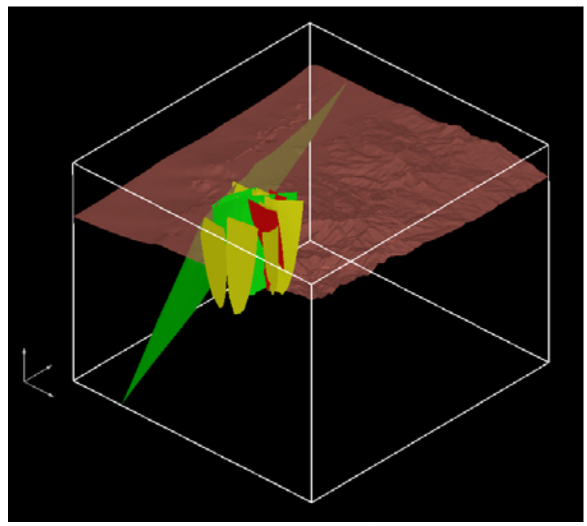

Figure 3: 3D view from S-E of the regional scale geological model (South part) integrating both onshore and offshore structural data. The domain size is 15km from W to E, 16km from S to N and 12km along vertical. It is centered on the productive area presented in Figure 1.

There are many geothermal fluid discharges along the E-W axis of the Bouillante Bay graben. This gives indications about the offshore extension of the reservoir. The width of the reservoir could then be of the order of 1 km onshore and 2 km offshore eastward up to a major N160°E fault (Figure 1).

Current work is focusing on building a regional scale geological model that will integrate previous reservoir scale modeling (Sanjuan et al., 2008). The aim of this regional model is twice. First, the 3DGeomodeller[1] software (Calcagno et al., 2008) is used to integrate geological observations in a consistent framework and resolve possible ambiguities, in particular between offshore and onshore domains (Figure 3). Then, as the possibility to mesh complex geological objects has been recently

[1] http://www.geomodeller.com

introduced into the software, the resulting meshes will be used to test hydrogeological hypothesis about the genesis and dynamic behavior of the geothermal field.

Geothermal field exploitation

The geothermal field was explored in the 1970s, developed in the 1980s, and first brought into production in 1986. Development operations were undertaken at the end of the 1990's with thermal stimulation of an old vertical well (Tulinius et al., 2000) and the drilling of three directional wells. Two of this wells (BO-5 and BO-6) were successful while the third one (B0-7) was hot but with low productivity. To absorb this new production capacity, the old power plant was extended with a new 10MWe turbine (GB2). This extension brought the total power capacity of the Bouillante plant to 15 MWe (GB1+GB2) and was put into service in 2003. The consequent increase in geothermal fluid withdrawal induced a change in reservoir behavior and a rapid pressure drop inside the reservoir (Figure 6).
The well head fluid specific enthalpy is in a 1100-1150 kJ/kg range. The plant electricity production now represents 6 to 8% of the island's annual electricity needs (Sanjuan and Traineau, 2008). These needs are increasing as the population is steadily growing. This called for the development of the geothermal capacities of the Bouillante field and an exploration program has been set up (Bouillante 3 project). New exploration wells should be drilled with the aim to reach a 40MWe electrical power production within the coming years.
From 1986 to 2002 the BO-2 well has been the only producing well of the field. This well is located on the bay shoreline (Figure 1). It is a shallow vertical 300 m deep well that exploited the top part of the reservoir. Since it was shut in July 2002, it has been used to monitor the reservoir pressure. A complete well overhaul was performed in 2009 and it should now be used as an injection well. After BO-2 production was stopped in 2002, wells BO-5 and BO-6 have been alternatively producing the geothermal fluid supplied to GB1. Over this period, the well-head pressures were monitored for each well and interferences between wells could be studied. Since GB2 was put into service, wells BO-5 and BO-6 have been the main producers with an additional production from the stimulated well BO-4.

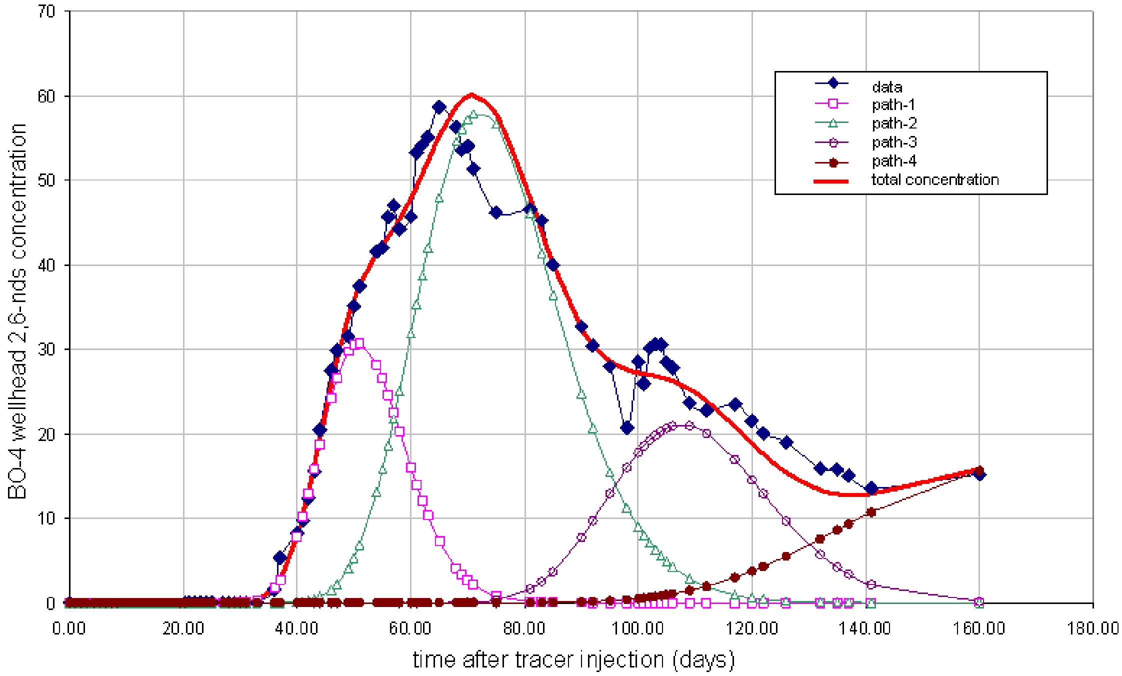

Figure 4: Multi-channel interpretation of 2007 2,6-nds tracer test - BO-4 well data (Sanjuan et al., 2008)

Hydraulic connections

Wether it is sampled at the well head or in hot springs, the geothermal fluid shows a very homogeneous composition. There are very little spatial or temporal variations. It is a sodium chloride (NaCl) brine with a salinity approaching 20 g/l and a pH of around 5.3 ± 0.3 at 250-260 °C. Its chemical and isotopic compositions is that of a mixture of sea water (58%) and fresh meteoric water (42%). The geothermal fluid is at chemical equilibrium with its host rock at a temperature of 250-260 °C (Sanjuan et al., 2001). In the reservoir, the fluid is in liquid state.

Continuity of the geothermal reservoir has been demonstrated by the pressure interferences recorded between all producing wells (BO-2, BO-4, BO-5 and BO-7). Due to its impermeable smectite bearing cap rock, the geothermal reservoir seems to have a very low leakage rate. This leakage rate is estimated to be in the range of 1-10 m3/h (Lachassagne et al., 2009) and corresponds to the hot springs that can be found both onshore and offshore in the bay.

Over the whole production period, tracer tests were regularly performed to improve the understanding of hydraulic connections inside the reservoir and possibly identify regional flows. The latest tracer test was carried out in October 2007. Diluted tracers (2,6-naphthalene disulfonate and fluoresceine) were injected in well BO-2 and the chemical composition of the fluid was monitored for each producing well (BO-4, BO-5, BO-6).

Tracers appeared very quickly in the fluid produced by BO-6 and a few days later on the fluid produced by BO-4 (cf. restitution curve on Figure 4). The tracers are thought to have circulated in shallow parts of the geothermal reservoir with an average 0.3-0.4 m/h pore velocity, following a N-S orientation (Sanjuan et al., 2008). Nevertheless, several months after the tracer injection, less than 10% of the injected tracer mass was recovered and notable tracer concentrations were still measured in the fluid from a hot spring located near the injection point ("source cave BO-2").

This result was quite different from a previous 2003 test where tracer injection had been performed on well BO-4 while wells BO-5 and BO-6 were producing. The tracer was probably injected in lower parts of the reservoir and it took more than one year to appear in the produced fluid. This slow spreading could be explained by a vigorous natural N-S flow inside the reservoir or by different connection patterns in the bottom part of the reservoir. To answer this question and prepare the reinjection of the separated fluid, a new tracer test has been planned in 2010 with tracer injected in both BO-2 and BO-4 wells.

FIRST MODELING APPROACHES

Physical background

Lumped parameters models have been used extensively to characterize and predict pressure evolution in geothermal systems for several years (e.g. Whithing and Ramey, 1969, Grant et al. 1982, Axelsson et al. 2005 among many others). Though the parameters of these models can be linked, to a certain extent, to some physical quantities they are mostly used to estimate the production potential of a geothermal field and pressure responses to various exploitation strategies. Despite their relative simplicity, experience has shown that lumped parameters models are quite reliable (Axelsson et al. 2005 and case studies presented therein).

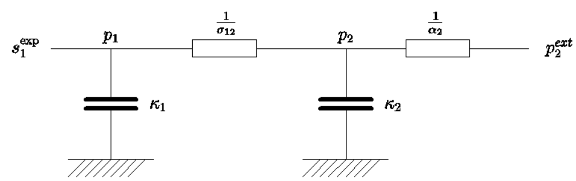

Figure 5: Electrical analogue of a two tanks open model.

The physical background for lumped parameter model is based on mass and energy balance equations written for connected tanks. Each tank represents a part or the whole of a geothermal system. It has a storage capacity κ_i which characterizes its ability to store or release geothermal fluid under a pressure variation. Connections between tanks are characterized by their conductance σ_{ij} which quantifies the flow of geothermal fluid through the connection when it is submitted to a pressure differential between its extremities. There exists a direct electrical analogue of lumped parameters model with pressure being the analogue of electrical potential (cf. Figure 5).

Physical basis of lumped parameter models are briefly summarized below but details about their implementation are presented by Axelsson 1989. Sarak et al. (2005) propose an enhancement of the fitting method and Onur et al. (2008) present a non-isothermal version of lumped parameter modeling.

The mass M_i of geothermal fluid in tank *i* is given by:

$$M_i = \phi_i V_i \rho \qquad (1)$$

where ϕ_i is the tank porosity, V_i is the tank volume and ρ is the geothermal fluid density.

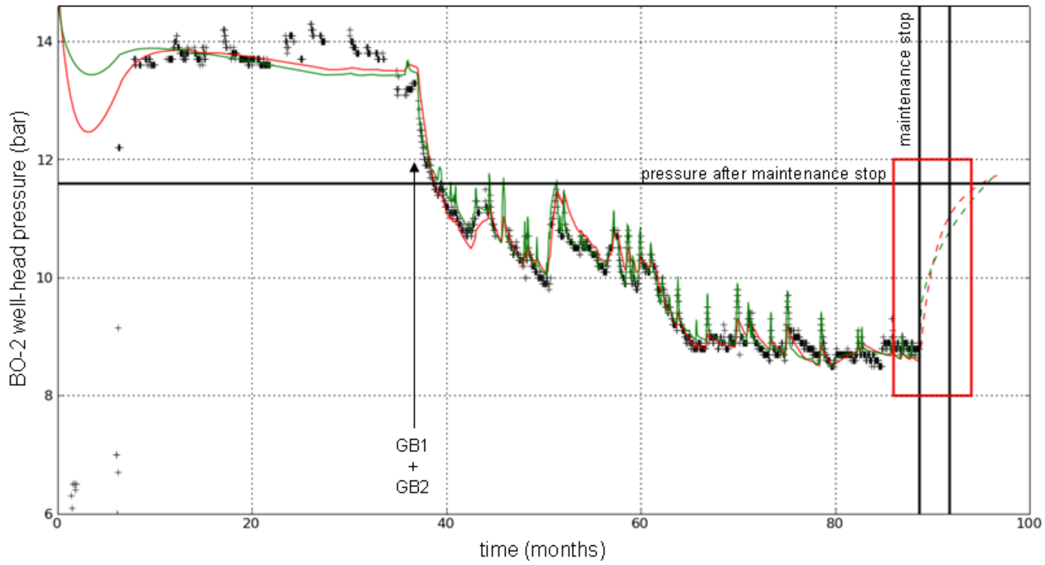

Figure 6: Two tanks open model fitted on BO-2 well head pressure data (red dashed curve).Black crosses are pressure data. The pressure drop following the commissioning of GB2 is indicated with the vertical arrow. The model underpredicts the reservoir pressure build-up that happened during a maintenance stop (vertical black lines).

Assuming that the fluid is isothermal, the temporal variation of mass is written:

$$\frac{\partial M_i}{\partial t} = V_i\left(\phi_i \frac{\partial \rho}{\partial p_i}\big|_T + \rho \frac{\partial \phi_i}{\partial p_i}\big|_T\right)\frac{\partial p_i}{\partial t} = Q_i \qquad (2)$$

with Q_i being the total fluid flow coming into the tank i either from other tanks, external recharge or exploitation and p_i is the pressure into tank i.

Then the capacity κ_i of tank i is defined as :

$$\kappa_i = V_i \phi_i \rho\left(\chi_F + \chi_{Pi}\right) \qquad (3)$$

with:

- $\chi_F = \frac{1}{\rho}\frac{\partial \rho}{\partial p}\big|_T$ being the fluid isothermal compressibility
- $\chi_{Pi} = \frac{1}{\varphi_i}\frac{\partial \phi_i}{\partial p}\big|_T$ being the so-called "pore compressibility" of tank i (e.g. Pruess *et al.*, 1999).

Finally the governing equation for tank i writes:

$$\kappa_i \frac{\partial p_i}{\partial t} = Q_i \qquad (4)$$

The total flow Q_i entering or leaving tank i - depending on the sign of Q_i - is broken up into three parts:

$$Q_i = q_i + s_i^{exp} + s_i^{ext} \qquad (5)$$

q_i is the total flow rate coming through connections to other tanks. It is computed from the connections conductance σ_{ij} and the pressure differential between tank i and other tanks connected to it:

$$q_i = \sum_{j \neq i} \sigma_{ji}\left(p_j - p_i\right) \qquad (6)$$

$s_i^{\exp}$ is the total flow rate pumped or injected into tank i and s_i^{ext} is the flow rate corresponding to the external recharge. External recharge is simulated with a connection between tank i and a constant pressure source.

<u>Tuning the parameters of the model</u>

Traditionally well-head pressure histories and production flow rates at some wells are known and the parameters of the lumped model are fitted to match the pressure temporal series taking exploitation flow rates as input data.

One of the softwares that can be used to fit a corresponding solution to pressure observations is the computer code *LUMPFIT* (Axelsson and Arason, 1992). Here we resorted to the python programming language and the scipy optimize package which provides a modification of the Levenberg-Marquardt algorithm for least squares minimizations[2].The BO-2

[2] Information about the scipy module can be found at http://www.scipy.org. All scripts used to fit the lumped parameters models presented here should be available soon at : http://www.geothermie-perspectives.fr/

well head pressure history was the target of the fitting procedure with the input being the total exploitation flow rate over a period ranging from July 2002 to September 2008. The best match was obtained with a 2 tanks open model (cf. Figure 6). An open model is a rather optimistic modeling choice (Axelsson *et al.*, 2005), nevertheless, the fact that pressure data are well fitted and that model predictions are in relatively good agreement with observations seem to confirm the existence of a vigorous recharge coming from unexploited parts of the reservoir. The open model even seems to underpredict the reservoir recharge (cf. reservoir build-up after maintenance stop on Figure 6).

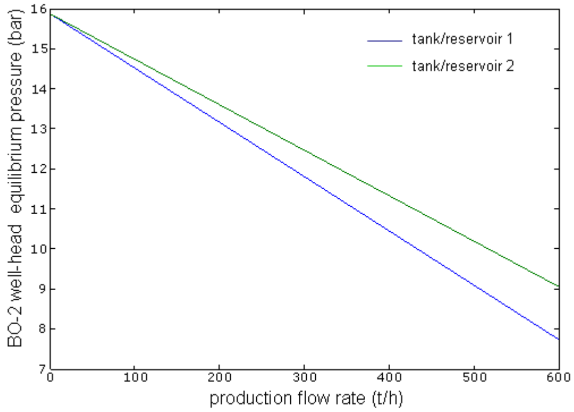

Figure 7: Equilibrium pressures in reservoirs as a function of production flow rate.

Equilibrium pressure

In the following, we'll be considering that the lumped parameters model is open, *i.e.* that outer parts of the geothermal system are supplying recharge to the exploited parts. As noted previously, this seems to be the case for the Bouillante geothermal field. Then, once the model parameters are fitted and correctly reproduce pressure evolutions, the stationary version of equation (4) can be used to determine equilibrium pressures inside the tanks that correspond to a given exploitation flow rate. These equilibrium pressures do not exist for a closed system whose exploitation at constant flow rate would induce a steady pressure decline.

Figure 7 presents the tank equilibrium pressures as a function of the exploitation flow rate for a two tanks open model whose parameters have been fitted on the Bouillante exploitation history. Without exploitation ("natural state"), BO-2 well-head equilibrium pressure is expected to be of the order of 16 bars. This is in good agreement with the well-head pressure that was recorded at BO-2 just after drilling, before production started.

As the Bouillante geothermal field is located under a urban area, this type of diagram relating exploitation and pressure inside the reservoir is very important in terms of safety. Indeed, it can provide thresholds for the exploitation flow rate in order to prevent the pressure inside the reservoir from dropping below the flash point. Respecting this safety threshold stops the development of a vapor cap inside the reservoir that could increase the risks of a phreatic eruption. Based on this study, the pressure inside the reservoir was successfully stabilized above prescribed safety thresholds.

Reservoir parameters

Using the capacity definition given by equation (3) one can estimate the volume of geothermal fluid from the fitted parameters (e.g. Khalibad and Axelsson, 2008). We took the value of the isothermal compressibility of the geothermal fluid χ_F to be the same as the isothermal compressibility of pure water at reservoir pressure and temperature conditions that is $\chi_F \approx 1.6\ 10^{-9}\,Pa^{-1}$. Neglecting the pore compressibility χ_{Pi} equation (3) gives the volume of geothermal fluid in tank *i*:

$$V_i \phi_i = \frac{\rho \chi_F}{\kappa_i} \qquad (7)$$

and calculations lead to a total volume of geothermal fluid of 4.9 km^3 with respectively 0.29 km^3 in tank 1 and 4.6 km^3 in tank 2.

From previous studies (*cf.* the conceptual model section and Bouchot at al., 2009), it is thought that the geothermal field lies between 300 m and 3000 m deep and stretches over a surface of a few squared kilometers (a 3 km x 2 km domain). Its porosity is estimated to be around 10%. Considering these figures, the total volume of geothermal fluid present in the porosity of the geothermal system would then be 1.6 km^3 which is of the same order of magnitude as the previous result.

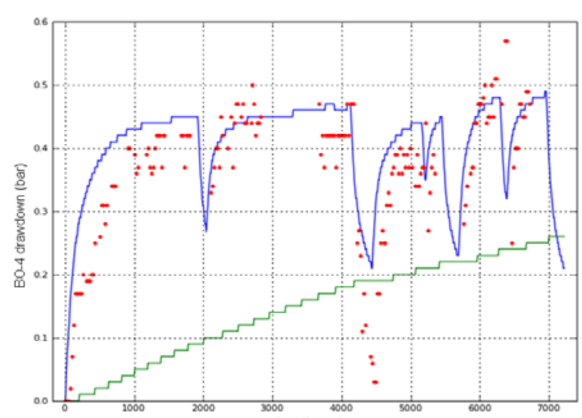

Figure 8: TOUGH2 numerical model reproducing pressure interferences recorded at well BO-4 while well BO-5 was producing. The blue line is the pressure drawdown inside the fracture continuum. The green line is the pressure drawdown inside the matrix continuum.

Double porosity model

A simple numerical model centered on the BO-4, BO-5 and BO-6 wells has been fitted on the pressure interferences data recorded between July 2002 and April 2003 when the well BO-5 was the only producing well. The model reproduces the hydrodynamic properties of the reservoir via the MINC method (Multiple INteracting Continua). (Pruess, 1992) which generalizes the “dual porosity” model of Warren and Root (1963). The reservoir is conceptually decomposed into a "fracture" medium and a "matrix" one, each characterized by specific properties such as porosity, permeability and pore compressibility. Flow is occurring mainly in the fracture media and both fracture and matrix media communicate with the possibility for the flow of matter and heat between them.

Simulations were fitted to data both manually and automatically. Manual fit of parameters allowed the physical understanding of the influence of each parameter on the pressure curves. Yet, given the large number of simulations to run, we also performed an automatic fit using optimization algorithms from the *scipy* package. The resulting curves are presented in figure 8**.** They satisfactorily reproduce the rapid pressure transients characterizing fractured media.

A comparison with lumped parameter models could be made, considering that the “fracture” medium corresponds to the smallest tank from which the geothermal fluid is extracted and that the “matrix” medium corresponds to the largest tank. The fit of the TOUGH2-MINC model cannot be obtained without increasing the pore compressibility χ_{Pi} of the fracture media up to values of the order of 10^{-7}. Then, taking this pore compressibility into account the volume of geothermal fluid inside the “fracture” media, *i.e.* tank 1, would be 100 times lower, which is to say of the order of $2.10^{6}\,m^{3}$.

CONCLUSIONS

This extended abstract presents current modeling works of the Bouillante geothermal field. At regional scale a geological model is developed to integrate available data in a consistent framework. Then, this model will be used as a tool to guide exploration and development of the field. Hydrothermal modeling will be performed both at regional and reservoir scale to validate or improve the current geological conceptual model of the field.

In parallel, simple lumped parameter models were used to forecast pressure evolution inside the reservoir and serve as a decision tool for management of the field. They have been successfully used to specify a flow rate that stabilized the reservoir pressure above a given threshold. Some indications about the volume of geothermal fluid inside the reservoir can be obtained from these models. Nevertheless these figures must be taken with care, especially until the reservoir storage mechanism is not well understood and the relative mechanical roles of fracture and matrix compressibilities can be specified.

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