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Geothermal Systems Simulation: A Case Study

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ABSTRACT

Geothermal reservoir simulation is a key step for developing sustainable and efficient strategies for the exploitation of geothermal resources. It is applied in the assessment of several areas of reservoir engineering, such as reservoir performance and re-injection programs, pressure decline in depletion, phase transition conditions, and natural evolution of hydrothermal convection systems.

The case study of the Las Tres Virgenes (LTV) geothermal field (10 MWe), Baja California Sur, Mexico, is presented. Three-dimensional (3D) natural state simulations were carried out from emplacement and cooling of two spherical magma chambers corresponding to the main volcanic structures in the geothermal field. A conceptual model of the volcanic system was developed on a lithostratigraphic and geochronological basis. The volume of the magma chambers was established from eruptive volume estimations. A Finite Volume (FV) numerical scheme was implemented in a Fortran 90 code to solve the governing equation.

Static formation temperatures from well logs were used for validation of the numerical results. Good agreement was observed in those geothermal wells dominated by conductive heat transfer. For other wells, however, it is clear that conduction alone cannot explain the observed behaviour, so three-dimensional convective models are being implemented for multiphysics simulations.

1. INTRODUCTION

The LTV geothermal field is located in the northern part of the state of Baja California Sur, about 33 km northwest of the town of Santa Rosalía (Figure 1). Exploration activities were started in 1982; first production wells were drilled in 1986. The geothermal power plant started operations in 2001 with two 5 MWe condensation units (Viggiano-Guerra et al., 2009). To date, nine wells have been drilled along with three directional wells. A liquid-dominated reservoir, located in a granodioritic intrusive basement between 950 and 1250 m of mean depth, produces geothermal fluid with temperatures in the range of 250-275 ºC (Viggiano-Guerra et al., 2009).

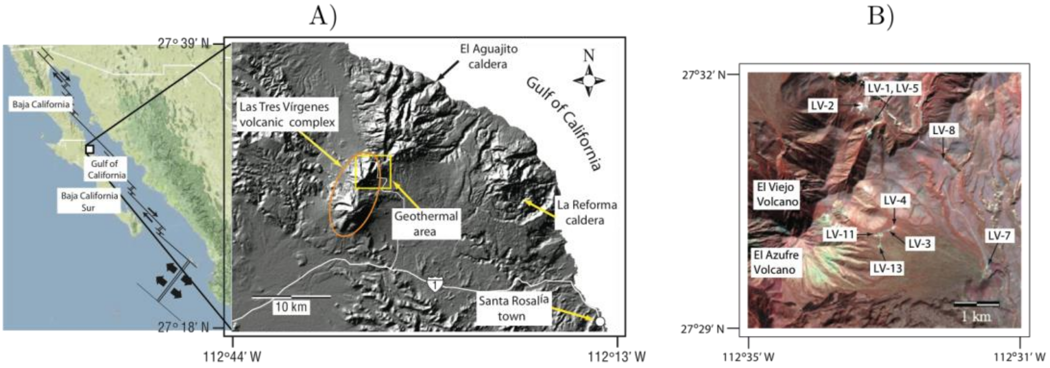

Figure 1: A) Location of the Las Tres Vírgenes geothermal field in the central part of the Baja California Peninsula. B) The geothermal area is shown in further detail.

A three-dimensional (3D) temperature simulation of the Las Tres Vírgenes (LTV) geothermal field, Baja California Sur, Mexico, was presented by Guerrero-Martínez & Verma (2013). This numerical model is a volcanological approach for natural state simulation of geothermal fields. First models of an integrated magma chamber-reservoir for natural state simulation were presented by Verma and Andaverde (2007), they developed a 3D numerical model (TCHEMSYS) of the emplacement and cooling of a cylindrical magma chamber. This approach provides understanding on the volcanological processes that lead to the formation of a geothermal system and is the basis to develop integrated models of geothermal systems for the study of topics such as heat source evolution and magma chamber reservoir interface, among others.

In the present work, new 3D natural state simulations were carried out from emplacement and cooling of two spherical magma chambers using a conductive approach. The new model incorporated a more accurate spatial discretization as well as smaller time step, which led to more consistent numerical results with field measurements in comparison with previous work (e.g. Verma and Anadverde, 2007; Verma et al., 2011).

2. CONCEPTUAL MODELLING

2.1 Geological setting

The geology of the study area has been reported by several authors (e.g. Capra et al., 1998; Demant and Ortlieb, 1981; Garduño-Monroy et al., 1993). Geothermal exploration studies are summarized by López-Hernández (1998). The LTV geothermal field is a Quaternary volcanic field related to the fault system that caused the opening of the Gulf of California (Capra et al., 1998). Two eruptive centers were emplaced in the area at about 6.5 Ma: the Reforma and Aguajito volcanic complexes (Demant and Ortlieb, 1981; Garduño-Monroy et al., 1993; López-Hernández, 1998). Volcanic activity in the Reforma complex (Figure 1) ended in early Pleistocene (about 0.8 Ma). Last eruptive cycle of the Aguajito occurred from about 0.7 Ma to 0.5 Ma (López-Hernández, 1998). The development of a pull-apart system started at the end of the cycle of the Aguajito. This regime led to the emplacement of the LTV volcanic complex composed of a chain of stratovolcanoes, from north to south: El Viejo, El Azufre, and La Virgen (López-Hernández, 1998). The age of the edifices decreases from north to south. El Viejo volcano was emplaced at about 0.44 Ma and the last eruption of La Virgen volcano is dated at 0.03 Ma (Schmitt et al., 2010).

2.2 Conceptual model

The conceptual model of the volcanic system was developed on a lithostratigraphic and geochronological basis. A domain of study of 20 x 30 km was chosen for the surface (Figure 2), the depth of the model was defined as 30 km depth below sea level plus the variable elevation, which maximum value is around 1.7 km above sea level in the LTV volcanic complex (Figure 1-A).

Figure 2: Rectangular coordinate system selected for delimiting the study area: $0 \leq x \geq 20000$ m; $0 \leq y \geq 30000$ m.

Three main lithological units are identified (Figure 3): a granodioritic basement, the Comondú Group and Santa Lucía Formation (López-Hernández, 1998). A sedimentary unit lying in the north portion of the field was also included in the model. The thermophysical properties of the medium were assumed to correspond to the dominant rock in each lithological unit as an initial value, and further calibration was carried out considering histograms of experimentally obtained thermophysical properties of rocks.

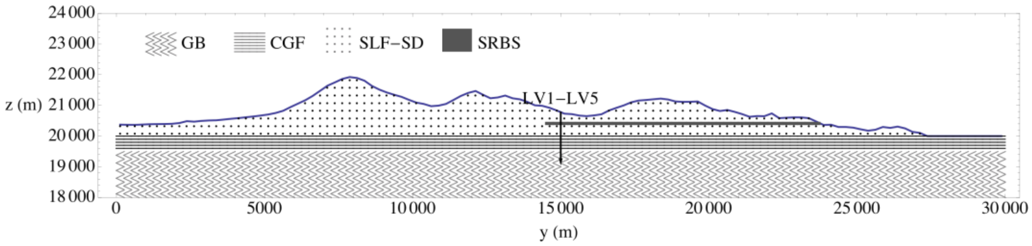

Figure 3: Section A-B (Fig. 2) showing the simplified lithology used in the conceptual model. GB: granodioritic basement; CGF: Comondú Group Formation; SLF-SD: Santa Lucía Formation and surficial deposits; SRBS: Santa Rosalía Basin sediment

A conductive heat cooling (Equation 1) of the magma chamber was considered as a first version of the model. Spatial dependence of the density, specific heat and conductivity was considered according to the distribution of the lithological units.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \tag{1}$$

with ρ, c, k the density, specific heat and thermal conductivity, respectively. The volume of each Magma chamber was established from eruptive volume estimations (Guerrero-Martínez and Verma, 2013) as an initial guessed value and further calibration was carried out. A schematic representation of the volcanic field is shown in Figure 4.

The simulation time was considered from re-activation of the Aguajito caldera, which was modelled as a magma chamber emplacement, until the Present, which implies 0.7 Ma of simulation time. The Reforma caldera was not considered in the model since the volcanic activity ended long ago to have an important thermal effect in the geothermal area. Likewise, it was considered a magma re-injection process related with the last eruption of the La Virgen volcano (Capra et al., 1998).

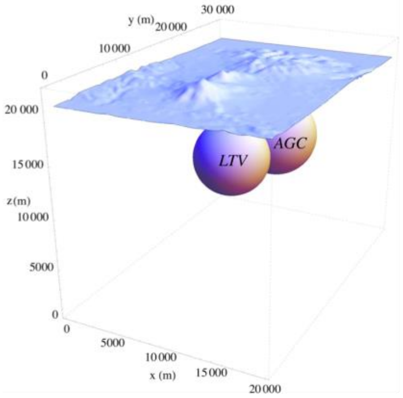

Figure 4: Schematic model of LTV volcanic complex. Present state of the volcanic field (LTV: Las Tres Vírgenes magma camber; AGC: Aguajito Caldera magma chamber).

3. NUMERICAL MODEL

A numerical scheme based on Finite Volume (FV) numerical method (Versteeg & Malalasekera, 1995) was implemented in a Fortran 90 code to solve the heat equation. A Gauss-TDMA subroutine was included to solve the system of algebraic equations with a convergence criterion of $1x10^{-6}$.

A mesh dependence analysis was carried out to choose the mesh of the model, from which a uniform discretization was done in x- and y-directions, with cells of 250 m side, whereas the z-direction was discretized with none-uniform cells, ranging from 500 m in the bottom of the system to 50 m in the middle and top of the model. As shown in Figure 5-B, the finest Δz, was applied in the region comprising the location of magma chambers up to the top, so that the numerical error in the approximation of the heat flux was minimized. The temporal discretization was done following a fully implicit scheme, which is first order approximation and unconditionally stable. A small time step is required to minimize the numerical approximation error. In the present work a time step Δt=100 years was chosen, which amount 7000 time steps for the total simulation time.

As the boundaries of the model lie far from the thermal anomaly, we assumed specified temperature boundaries corresponding to a geothermal gradient of 30 ºC/km with constant 25 ºC in the top boundary. Likewise, this geothermal gradient was chosen as the background temperature for the initial condition of the simulation. Regarding the top boundary, it was considered a mobile boundary to take into account the formation of the volcanic edifices in the complex, as illustrated in Figure 5-A the initial topography was defined after removing the volcanic cones. The topographic evolution was modelled as a linear growth in time.

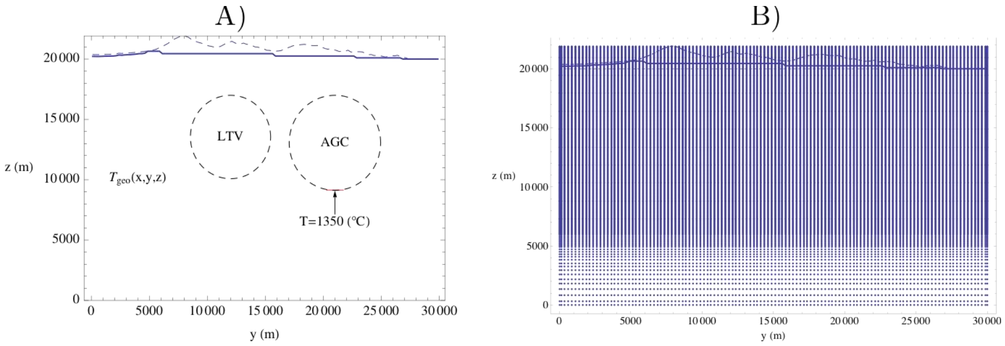

Figure 5: A) Cross section (x=10,000 m; Fig. 2) illustrating the initial condition of the problem. The top boundary (solid curve) has a specified temperature (25 ºC). Dashed circles define the region where the chambers will be emplaced with initial temperature of 1350 ºC. B) Density distribution of control volumes for the numerical model.

4. NUMERICAL RESULTS

A calibration process was carried out to evaluate two different magma chamber depths and seven chamber volumes. Static formation temperatures from well logs (Verma et al., 2006) were used for validation of the numerical results. Figure 6 shows the temperature fields during magma chambers emplacement at two different times in the section x=10000 m (Fig. 2 and 4).

Figure 7 shows the comparison between the simulated thermal profiles and static formation temperatures in four geothermal wells. Good agreement was observed in those geothermal wells dominated by conductive heat transfer (LV-3 and LV-8). For other wells, however, it is clear that conduction alone cannot explain observed behaviour, so two- and three-dimensional convective models are being implemented for future multiphysics simulations.

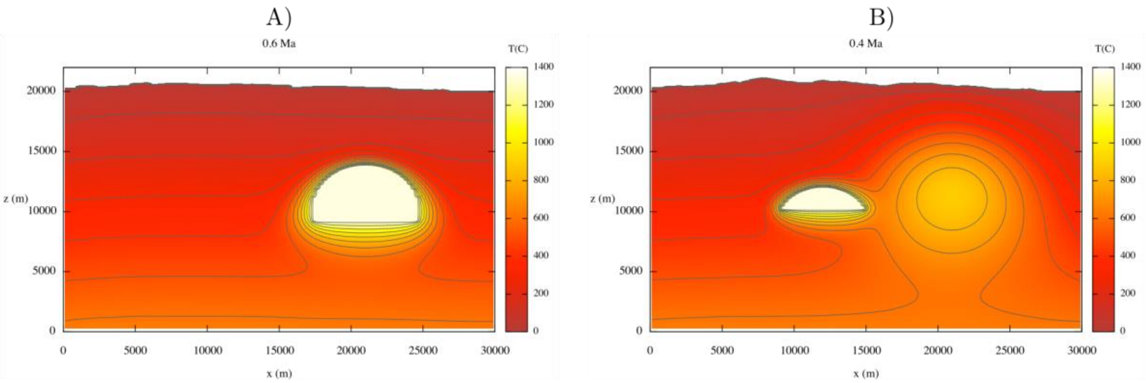

Figure 6: Magma chambers emplacement at two different times. The emplacement is carried out by heating layers from bottom to top of the spherical cavities forming the magma chambers.

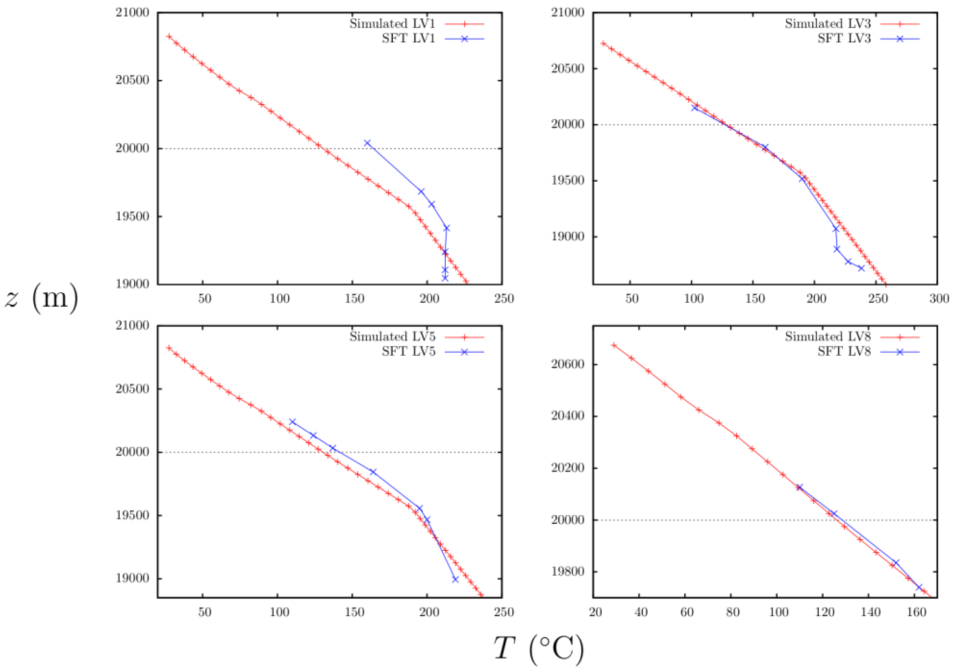

Figure 7: Simulated and estimated temperature profiles in four geothermal wells (sea level is shown in dotted line).

5. ONGOING RESEARCH: 3D FREE CONVECTION IN POROUS MEDIUM

A numerical scheme is being implemented for the problem of natural convection in porous medium. Natural convection in porous medium is a common heat transfer process in geothermal reservoirs. The problem was stated assuming local thermal equilibrium. Fluid flow is described by means of Darcy's law and Boussinesq approximation. The problem was stated in terms of primitive variables following an approach based on projection method (see for example Báez and Nicolás, 2006). The governing equations are the following:

Momentum equation in terms of dimensionless variables:

$$\mathbf{u} + \nabla P = R_{ap}\theta\,\mathbf{e} \tag{2}$$

With **e** the unity vector in direction of gravity and R_{ap} the Darcy-Rayleigh. A poisson equation for the pressure is obtained when the divergence or Equation 2 is applied. Energy equation:

$$\frac{\partial\theta}{\partial t} - \nabla^2\theta + \mathbf{u}\cdot\nabla\theta = 0 \tag{3}$$

Continuity equation:

$$\nabla\cdot\mathbf{u} = 0 \tag{4}$$

It is presented a case study of a tilted 3D homogeneous porous cavity defined in a domain such that $0 \leq x \geq 3$, $0 \leq y \geq 1$ and $0 \leq z \geq 1$. The cavity is tilted 10º with respect to the horizontal (for the 2D version of this problem see for example Moya et al., 1987; Báez and Nicolás, 2006) and the cavity is assumed to be adiabatic at the lateral boundaries and specified temperature is assumed on top and bottom boundaries. A uniform mesh consisting of 150x50x50 control volumes was used and the Finite Volume method was used to discretize the equations and implemented in Fortran 90 code. Second order approximations were used in both time and space. The time step was fixed at $\Delta t = 2\mathrm{x}10^{-4}$, $R_{ap} = 100$ and a total simulation time of 16000 time steps were considered (t=3.2). The initial and boundary conditions are as follows:

Initial conditions:

$$\theta(x,y,z,t)=0,\ P(x,y,z)=0 \text{ for } t=0$$

Boundary conditions:

$$\theta(x,y,z,t)=0, \text{ for } x=0 \text{ and } x=1;\ t>0$$

$$\theta(x,y,z,t)=0, \text{ for } y=0 \text{ and } y=1;\ t>0$$

$$\theta(x,y,z,t)=1, \text{ for } z=0; \text{ and } \theta(x,y,z,t)=0, \text{ for } z=1;\ t>0$$

Neumann boundary conditions are defined for pressure from Equation 2, which means that there must be consistency with the momentum equation. If the boundary is defined as a surface Ω, then the boundary condition can be written as follows:

$$\left.\frac{\partial P}{\partial \mathbf{n}}\right|_{\Omega} = \mathbf{n}\cdot\left.(R_{ap}\theta\mathbf{e}-\mathbf{u})\right|_{\Omega} \tag{5}$$

For which the normal velocity to the surface Ω is assumed to be zero (no fluid crosses the boundary). By the definition of Equation 5, no assumption is necessary for the tangential velocity, although in general, is non zero in porous media.

5.1 Results

The simulation results are shown in Figure 8. The dynamic of the heat transfer process is characterized by the formation of three convective cells as shown by the velocity field in Figure 8. This is in agreement with the 2D version of the problem (see Moya et al. 1987; Báez and Nicolás, 2006). A steady state analysis is being considered as future work.

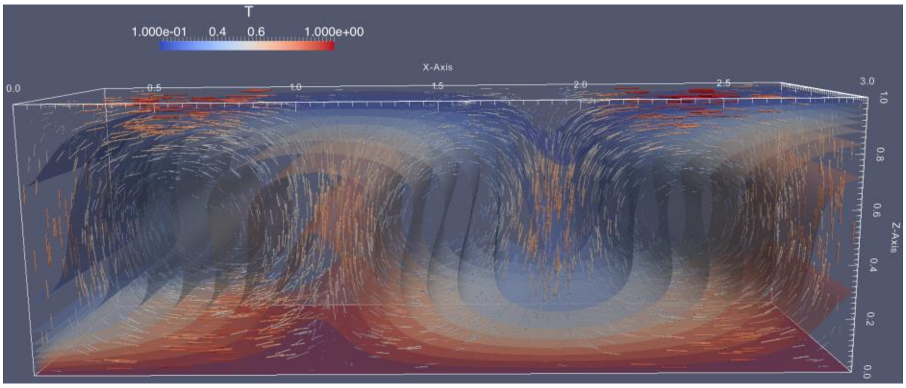

Figure 8: Isothermal surfaces and velocity field in a porous cavity.

6. CONCLUSIONS

A successful natural state simulation of the Las Tres Virgenes geothermal field was achieved. Modelling two magma chambers permitted an accurate reproduction of the volcanic history and the mass distribution of the heat source. Complementary field work on heat flux measurements would be necessary to support further refinements. As expected, conduction alone is not capable of reproducing the thermal regime in geothermal wells dominated by convection, for which multiphysics 3D models are now being implemented.

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