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Three-dimensional Numerical modelling of geothermal systems: a case study

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ABSTRACT

Geothermal reservoir simulation is a key method of analysis for the characterization of deep geothermal 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 conductive cooling of two spherical magma chambers corresponding to the main volcanic structures of the geothermal field. 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 two- and three-dimensional convective models in porous media are now being implemented for multiphysics geothermal reservoir 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-A). 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 C. Currently the Federal Commission of Electricity operate two 5 MWe condensation units (Viggiano-Guerra et al., 2009).

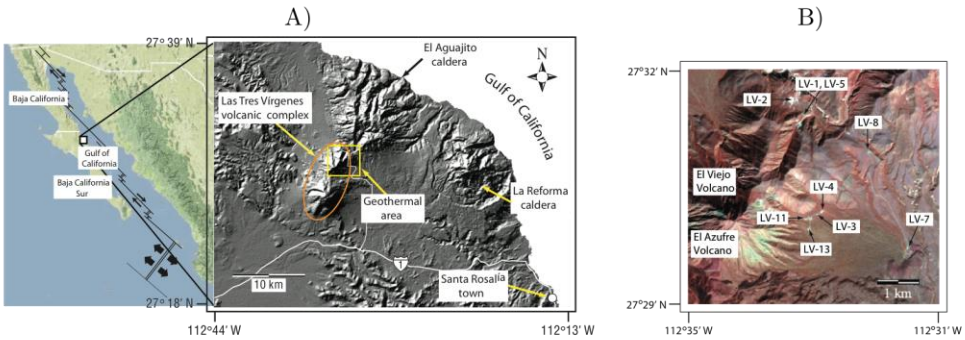

Figure 1: A) Location of the Las Tres Vírgenes geothermal field in the central part of the Baja California Peninsula. B) The geothermal area is shown in further detail.

A 3D temperature simulation of the Las Tres Vírgenes (LTV) geothermal field, Baja California Sur, Mexico, was presented by Guerrero-Martínez & Verma (2013) which applies a volcanological approach for natural state modelling of the geothermal field. The model provided good agreement with temperature well logs in those geothermal wells governed by conductive heat transfer. Ongoing research is now focused in 2D and 3D convective models for future multiphysics simulation.

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; Garduño-Monroy et al., 1993; 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 (Garduño-Monroy et al., 1993; López-Hernández, 1998). Volcanic activity in the Reforma complex (Figure 1-A) 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, which is composed of a chain of stratovolcanoes. The age of the edifices decreases from north to south. The last eruption in the complex was 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, the depth of the model was defined as 20 km depth below sea level plus the topography, which maximum elevation is around 1.7 km above sea level. Figure 2 shows the main lithological units that have been identified in the area (López-Hernández, 1998). 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.

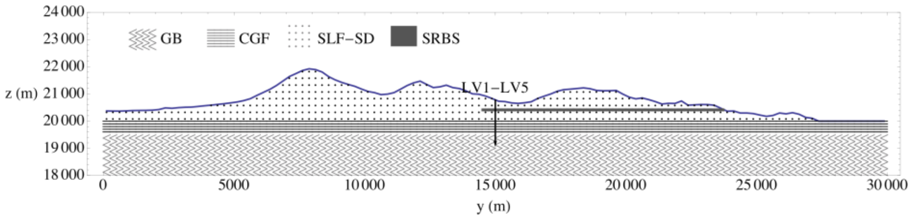

Figure 2: Sechematic section of the volcanic field showing the simplified lithology for the conceptual model. GB: granodioritic basement; CGF: Comondú Group Formation; SLF-SD: Santa Lucía Formation and surficial deposits; SRBS: Santa Rosalía Basin sediment

A conductive 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 *r, c, k* the density, specific heat and thermal conductivity, respectively. The volume of the Magma chambers 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 3. 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.

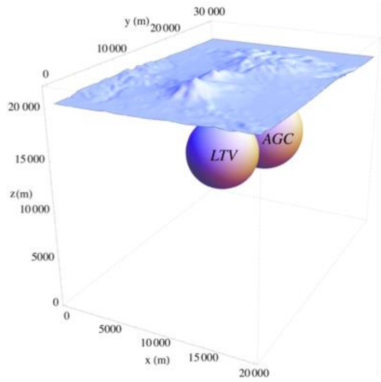

Figure 3: Schematic model of LTV volcanic complex at Present (LTV: Las Tres Vírgenes magma camber; AGC: Aguajito Caldera magma chamber).

3. NUMERICAL MODEL

The numerical scheme was based on Finite Volume and non-uniform mesh (Figure 4-B). Temporal discretization was done following a fully implicit scheme, which is first order. 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 C/km with constant 25 C 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 4-A, the initial topography was defined without the volcanic cones.

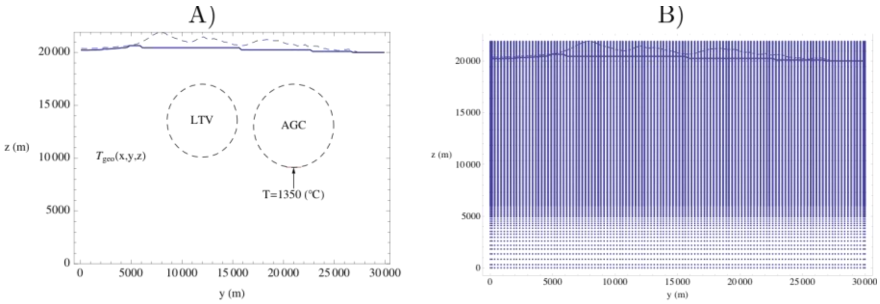

Figure 4: A) Section x=10,000 m (Fig. 3) illustrating the initial condition of the problem. The top boundary (solid curve) has a specified temperature (25 C). Dashed circles define the region where the chambers will be emplaced with initial temperature of 1350 C. B) Density distribution of control volumes 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 5 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; Fig. 1-B).

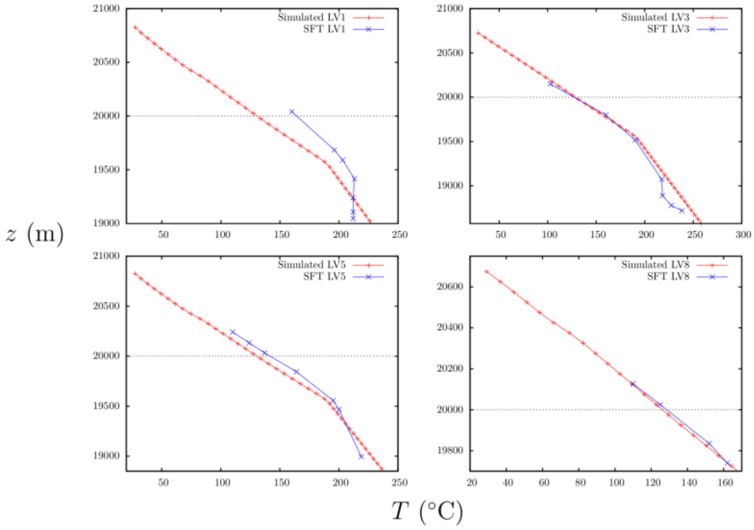

Figure 5: Simulated and estimated temperature profiles in four geothermal wells (sea level is shown in dotted line).

5 ONGOING RESEARCH

A numerical scheme was 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. The buoyancy term resulting from the thermal gradient is given by the Boussinesq approximation. The problem was stated in terms of primitive variables following an approach based on projection method (see Báez and Nicolás, 2006). This method makes possible the 3D analysis unlike the traditional stream function approach (e.g. Moya et al. 1986).

Momentum equation in terms of primitive and dimensionless variables is:

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

With R_{ap} the Darcy-Rayleigh (Moya et al., 1987). When the divergence of Equation 2 is taken, a Poisson equation for pressure is obtained. Energy equation is as follows:

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

It is presented a case study of a 2D cavity defined in a domain such that $0 \le x \ge 1$ and $0 \le y \ge 1$. A uniform mesh consisting of 100x100 elements was used, a second order Crank-Nicolson scheme was used for the temporal discretization. The time step was set at $\Delta t = 1\text{x}10^{-4}$ and $R_{ap} = 500$. Dirichlet boundary conditions were defined such that θ(x,y,t)=0, for x=0 and x=1; θ(x,y,t)=1, for y=0; and θ(x,y,t)=0.5, for y=1 with t>0. The initial condition, t=0, is P=0 and θ=0.

5.1 Numerical results

The simulation results are shown in Figure 6. The dynamic of the heat transfer process is characterized by the formation of two symmetric thermal plumes at the bottom corners of the cavity, this gives rise to the formation of a cold region in the middle zone (t=0.01 and 0.02). As a consequence, the thermal plumes gradually move towards the centre and coalesce in only one central thermal plume. This late stage is characterized by a more homogeneous temperature distribution in the cavity.

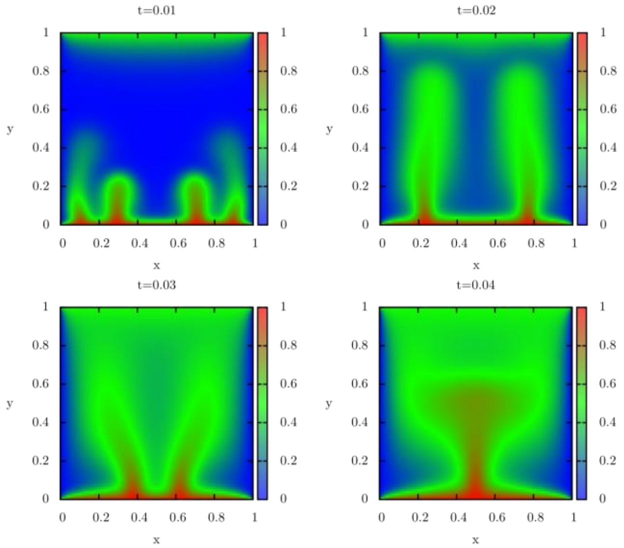

Figure 6: Formation and coalescence of thermal plumes in a porous cavity.

6 CONCLUSIONS

A successful natural state simulation of the Las Tres Virgenes geothermal field was achieved. The modelling of 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. Multiphysics simulation is now being implemented for to couple convective effects in 3D.

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REFERENCES

Báez E., and Nicolás A.: 2D natural convection flows in tilted cavities: Porous media and homogeneous fluids, *International Journal of Heat and Mass Transfer*, **49**, (2006), 4773–4785.

Capra L., Macías J.L., Espíndola J.M., Siebe C.: Holocene plinian eruption of La Virgen volcano, Baja California, Mexico. *Journal of Volcanology and Geothermal Research*; **80**, (1998), 239-266.

Garduño-Monroy V.H., Vargas-Ledezma H., Campos-Enriquez J.O.: Preliminary geologic studies of Sierra El Aguajito (Baja California, Mexico): a resurgent-type caldera, *Journal of Volcanology and Geothermal Research*, **59**, (1993), 47-58.

Guerrero-Martínez F.J. and Verma S.P.: Three dimensional temperature simulation from cooling of two magma chambers in the Las Tres Vírgenes geothermal field, *Energy*, **52**, (2013), 110-118.

López-Hernández A.: Síntesis geológica de la zona geotérmica de Las Tres Vírgenes, B.C.S., México, *Geotermia, Revista Mexicana de Geoenergía*, **14**, (1998), 3-14.

Moya S. L., Ramos E., Sen M.: Numerical study of natural convection in a tilted rectangular porous material, *International Journal of Heat and Mass Transfer*, **30**(4), (1987), 741-756.

Schmitt A.K., Stockli D.F., Niedermann S., Lovera O.M., Hausback B.P.: Eruption ages of Las Tres Vírgenes volcano (Baja California): a tale of two helium isotopes, *Quaternary Geology*, **5**, (2010), 503-511.

Verma S.P., Pandarinath K., Santoyo E., González-Partida E., Torres-Alvarado I.S., Tello-Hinojosa E.: Fluid chemistry and temperatures prior to exploitation at the Las Tres Vírgenes geothermal field, Mexico, *Geothermics*, **35**, (2006), 156-180.

Viggiano-Guerra J.C., Sandoval-Medina F., Flores-Armenta M.C., Pérez R.J., González-Partida E.: Aplicación del SPCALC en la especiación química y termodinámica de fluidos: ejemplo del caso de los pozos LV-4A, LV-11 y LV-13, del campo geotérmico de Las Tres Vírgenes, BCS. *Geotermia, Revista Mexicana de Geoenergía*, **22**, (2009), 12-27.