# Numerical Modelling of the Nevado del Ruiz Geothermal Reservoir (Colombia)

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## 1. INTRODUCTION

Geothermal energy is one of the least researched energy sources in Colombia mainly due to the high development of the hydroelectric power plants, currently the main source of electricity in the country. Because of the country's high diversity of landscapes and climates, and commitment to reduce greenhouse gas emissions, there is a growing interest in the expansion and diversification of the energy market with focus on the renewable and sustainable sources of electricity, such as geothermal energy. Among the areas of potential geothermal interest, the Nevado Del Ruiz (NDR; Figure 1) volcano is the case of study considered in this work, since information related to this site is easily available because the NDR is the country's most observed and studied volcano (Alfaro, 2015). The study area is located in the middle of the central Andes mountain range of Colombia (Figure 1). This volcano is one of the 17 snowy peaks of the country and has a maximum altitude of 5311 m.a.s.l. (Figure 2).


**Figure 1:** Location of the Nevado del Ruiz Volcano.
Source: Google Earth.

**Figure 2:** Nevado del Ruiz Volcano.
Source: http://geologiia.blogspot.ca/2013/05/glaciares.html.

## 2. NUMERICAL MODELING

The numerical code used for numerical modelling has changed over the course of the work. Initially the research began with the software SHEMAT (Bartels et al., 2003) but some problems arose with the mesh generation: only structured meshes were available making the definition of an irregular boundary, such as the topography in the profile, complicated; moreover, set inactive cells outside of the considered profile was not explained in the documentation and the solution was not found. Then, the software HydroGeoSphere (Aquanty, 2013) was considered, but it was soon discovered that the heat transport boundary condition required, a specified flux applied to the bottom of the domain, was not available; obviously the source code could have been modified to account for this boundary condition, but it would have required time and resources which were not available. A first conductive heat transfer simulation was thus made with the software Elmer: it is free and open sourced, simple to use and offers great compatibility with third party software such as OpenCascade, NetGen and others; . However, Elmer only supports the Navier-Stokes equation for flow, which will have to be adapted to simulate groundwater flow in porous media.

### 2.1. ELMER

Elmer has graphical user interface developed by the CSC (Centre of Scientific Computing), the Finnish IT Centre of Science, that offers multiple third party software compatibility as well as its own post-processing software. Elmer usually considers 3D domains, but with the use of third party software (like GMSH or NetGen) it is possible to run 2D simulations.

The main equations considered here are those used to simulate heat transport. The governing equation for heat transfer with incompressible flow is expressed as:

$$\rho C_P\left(\frac{\partial T}{\partial t}+\left(\vec{u}\cdot\nabla\right)T\right)-\nabla\cdot\left(k\nabla T\right)=\rho h \qquad (1.0)$$

Where $\rho$ is the density [kg/m³], $\boldsymbol{C_P}$ is the heat capacity at constant pressure [j/kg*K], $\boldsymbol{T}$ is the temperature [K], $\vec{u}$ is the convection velocity [m/s], $\boldsymbol{k}$ is the heat conductivity [W/m*K] and $\boldsymbol{h}$ is a source of heat [W/kg] (Råback et al., 2015).

For the constant heat flux boundary condition, the equation solved is:

$$-k\frac{\partial T}{\partial n}=q \qquad (1.1)$$

Where $\boldsymbol{q}$ is the specified heat flux [W/m²] and $\boldsymbol{n}$ is the normal vector to the boundary (Råback et al., 2015).

For the constant temperature boundary conddition, the Dirichlet boundary condition is considered. The equation reads as:

$$T=T_b \qquad (1.2)$$

Where $\boldsymbol{T}$ is the temperature [K] and $\boldsymbol{T_b}$ can be a constant, a function of time, a position or another variable (Råback et al., 2015).

## 3. NEVADO DEL RUIZ CASE STUDY

For the first numerical model, a steady-state simulation with a rock layer of uniform thermal properties was considered by using only the properties of the "Pes" layer which consists mainly of shcist rocks (Table 1).

**Table 1:** Rock types of the main layers of the cross section.

| Relevant Rock Layers | Rock Type | Geological Formation Name |
|---|---|---|
| Pes | Metamorphic | Cajamarca Complex |
| NgQa | Extrusive | Andesitic Lava Flows |
| Ksc | Volcanic and Sedimentary | Quebradagrande Complex |

The boundary conditions consisted of constant temperatures at the upper surface and a constant heat flux at the bottom of the domain while the vertical boundaries were adiabatic. Input data (Table 2) and domain geometry (2D profile) were taken from the previous work of Vélez et al. (2015) who made a preliminary assessment of the geothermal potential of the NDR and built a conceptual model of the volcano area.

**Table 2:** Simulation imput parameters (From: Vélez et al., 2015).

| Parameter | Value | Units |
|---|---|---|
| Thermal conductivity | 2.89 | W/mK |
| Heat Capacity | 970 | J/kgK |
| Basal heat Flux | 0.19 | W/m² |
| Rock Density | 2370 | kg/m³ |
| Surface Temperature | 295 - 268 | K |
| Heat Source | 4.39E-10 | W/kg |

The geothermal potential estimation process described by Vélez et al. (2015) was applied in a geological cross-section profile of 16 km long and 5 km deep (Figure 3).

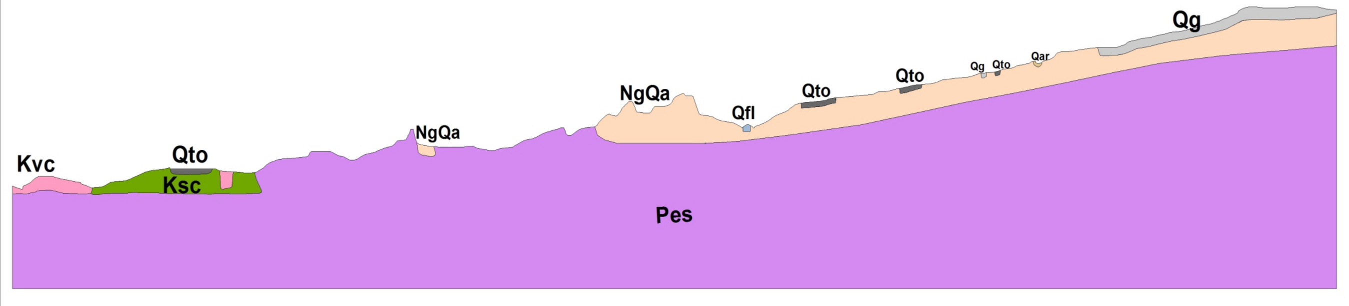


**Figure 3:** Cross-section used for numerical modeling (from Vélez et al., 2015).

The mesh generated with Elmer had 21526 volume elements, 8434 surface elements and 12651 edge elements (Figure 4).

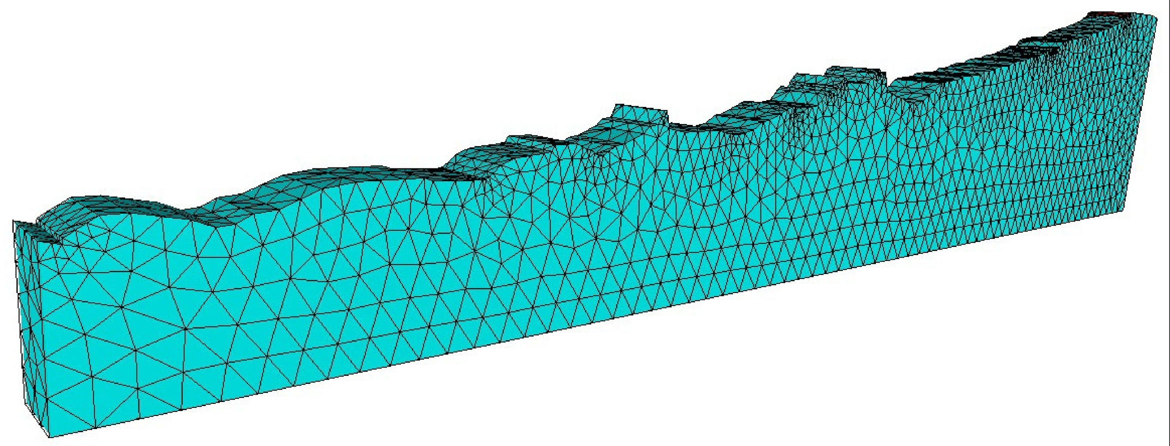

**Figure 4:** The finite-element mesh built with Elmer.

In order for the profile to be read by Elmer, a 3D body had to be built using the software Autodesk© Inventor©. The final result of the simulation was a preliminary view of the behaviour of the heat transfer within the profile (Figure 5).

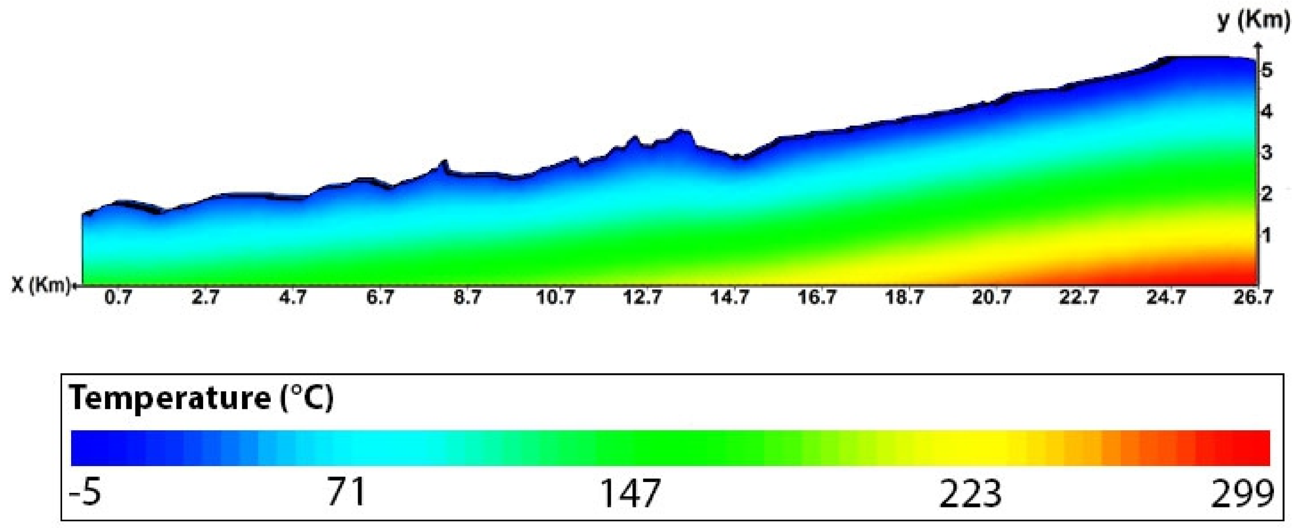


**Figure 5:** The final preliminary heat transport model using simple data in Elmer.

## 4. CONCLUSIONS AND FURTHER WORK

The problems encountered were mainly due to software limitation problems: In SHEMAT it was not possible to define the real topography, and was not possible to deactivate cells outside the considered profile. In HydroGeoSphere it was not possible to define a constant heat flux boundary condition required at the bottom of the domain. Elmer was used for conductive heat transfer as a first step to simulate the subsurface temperature. This first simulation showed a temperature varying from 299°C (max) in the right-bottom of the profile to -5°C (min) in the right-top of the profile. This large change in temperature is caused by the high heat flow due to the magmatic chamber underneath the profile. The maximum temperatures obtained by Vélez et al. (2015) in the same profile are between 360 and 402 °C. This difference can be explained by the different approaches used. Vélez et al. (2015) calculated temperature analytically, used a two layers model that took into account the upper insulating volcanic rocks "NgQa" (Figure 3) and did not applied corrections for topography. Temperature computed numerically in this work did not account for the two layers but add a varying topography, which can explain the lower temperatures. Further simulations are expected to take into account layers of different thermal conductivities and incorporate groundwater flow in the model developed with ELMER. The program OpenGeoSys (Kolditz et al., 2012) may also be used for further simulations of heat transfer and groundwater flow, advantageously taking into account discrete fracture flow in two dimensions.

The next steps to achieve a better prediction of subsurface temperature are:

- Include in the model all rock layers of the profile (Figure 3)
- Couple heat transfer and groundwater flow in porous geological media to reproduce hot spring temperature.
- Conduct a sensitivity analysis to identify the impact of input parameters such as the thickness of geological layers.
- Build another profile adding the geological faults crossing the area of interest represented as highly conductive zones or discrete fractures.

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