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 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. This volcano is one of the 17 snow-capped peaks of the country and has a maximum altitude of 5311 m asl (Figure 2).

2. NUMERICAL MODELING

The numerical code used for numerical modeling has changed over the course of the work. Initially the research began with the software SHEMAT (Barbets 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 GeoGrid (Arapoglou, 2013) was considered, but it was soon discovered that the heat 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 source, simple to use and offers great 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:

\[ \rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (\rho C_p \mathbf{v} T) = \nabla \cdot (k \nabla T) + q \]

Where \( \rho \) is the density [kg/m³], \( C_p \) is the heat capacity at constant pressure [J/kg K], \( T \) is the temperature [K], \( \mathbf{v} \) is the convection velocity [m/s], \( k \) is the heat conductivity [W/m K] and \( q \) is a source of heat [W/kg] (Rabbach, 2015).

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

\[ -k \nabla T = q \]

Where \( q \) is the specified heat flux [W/m²] and \( k \) is the normal vector to the boundary (Rabbach et al., 2015).

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

\[ T = T_0 \]

Where \( T_0 \) is the temperature [K] and \( T \) can be a constant, a function of time, a position or another variable (Rabbach et al., 2015).

3. NEVADO DEL RUZ 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 shoshic rocks (Table 1).

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

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

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 decaffeinate cells outside the considered profile. In GeoGrid 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 transport as a first step to simulate the subsurface temperature. This first simulation showed a temperature varying from 290°C (max) in the right bottom of the profile to 0°C (min) in the right top of the profile. This large change in temperature is caused by the high flow rate due to the magmatic chamber underneath the profile. The maximum temperatures obtained by Vélez et al. (2015) in the same profile are between 340 and 400°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 apply corrections for temperature computed numerically in this work. 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 OpenGeoSells® (Roldkit 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.
- Couple heat transfer and groundwater flow in porous geomedia to reproduce hydrothermal processes.
- 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.