3D Modelling of Faulting and Intrusion of the Nevado del Ruiz Volcano, Colombia

Chelsea Cervantes[1], Juliet Newson[1], Daniela Blessent[2], Jacqueline Sanchez Lopez[2], David Moreno[2]

[1]Reykjavik University, Iceland School of Energy. Reykjavik, Iceland.
[2]Universidad de Medellin. Medellin, Colombia.

RESUMEN

The Nevado del Ruiz stratovolcano located in the Northern Andes Mountain Range of Colombia has been evaluated for its geothermal potential for the past decade. Though geothermal prospects are a promising source of baseload energy, they are often unattractive and classified as high-risk projects, due to uncertainties in the nature of the energy source and high capital costs of initial production. A potentially useful, emerging tool in efforts to decrease geothermal project risk and enhance confidence in decision-making has been 3D modelling. 3D modelling provides a platform for the integration of qualitative and quantitative geoscientific data into a visualization to aid understanding of the geothermal system while being accessible for evaluation from different industry domains.

The purpose of this study is to create the best possible 3D and conceptual model for the Nevado del Ruiz geothermal prospect using Leapfrog Geothermal modelling software by Seequent, given the available public data of a denoted area of study. The resulting model indicates the exploration stage of the Nevado del Ruiz based on available data and provides insight towards which facets of the geothermal system are not yet fully understood and are requiring further study before the project progresses.

1 Introduction and Background

Over the past decade Latin America has become more active in implementing renewable energy technologies. Colombia has abundant mineral, oil and gas resources, and the country generates most of its electricity from hydroelectric resources. While this is considered a renewable source, it leaves the generation vulnerable to drought.

Diversification of energy sources would increase the country's energy security. Geothermal energy as baseload energy for Colombia is a high-potential prospect. At least five potential geothermal areas have been identified in Colombia, including: Nevado del Ruiz, Tufino-Chiles-Negro, Paipa, Azufral, and San Diego [1]. The geothermal area consisting of the Nevado del Ruiz Volcano (NRV) in the department of Caldas is considered to be the site that has the greatest potential for geothermal energy production at this time. Various studies have been implemented to further understand the geological, geochemical and geophysical characteristics of the Nevado del Ruiz geothermal area in an effort to understand its volcanic system and energy potential.

2 Objective

The aim of this study is to use the available data to provide a 3D visualization of the working hypotheses that depict the relationships between the faulting, magmatic intrusions, and seismicity of the NRV. This will provide a basis to develop a conceptual model of the Nevado del Ruiz geothermal system. This study uses data derived from current publicly available geological, geochemical, and geophysical knowledge of the Nevado del Ruiz volcanic system.

The study area is an extension of the region where previous heat transfer studies were conducted, shown in Figure 1 [2]. This encompasses a majority of the important fault systems in the Nevado del Ruiz area, and the sites of significant thermal manifestations. Leapfrog Geothermal geological modelling software, developed by Seequent, is the main tool in this study used to create an integrated 3D model. The 3D model can be the basis for more detailed conceptual and 3D modelling as more information becomes available.

Figure 0. The study area of this work in reference to the rest of Colombia, denoted by the red rectangle.

3 Data Collection for Modelling

The subduction of the Nazca tectonic plate beneath the South American continent cause areas of volcanism in the Andes (Figure 2) [3]. Colombia is home to many active volcanoes, which gives the country significant geothermal potential. Occupying central Colombia is the "Ruiz-Tolima Volcanic Massif" (RTVM) and it is comprised of at least eleven eruptive centers [3]. The region is influenced by two stress regimes [3]. Overall, the stress regime in the region is transpressive, resulting from at least three major collision events. Evidence of these stress regimes can be seen in the fault systems to the west to northwest of the NRV, which occur within the study area for this work.

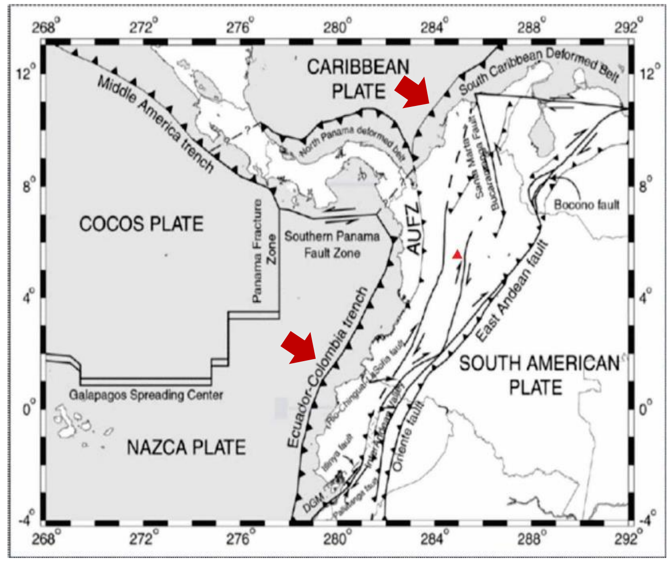

Figure 2. The relationship of the tectonic plates in creating the Andes mountain range. The red triangle is the NRV, and the red arrows indicate the direction of subduction of the Caribbean and Nazca plates. Taken and modified from Trenkamp et al. (2002).

The Cajamarca unit is the oldest unit in the area, situated below the most recent lava deposits [4]. It is regarded as the pre-volcanism, basement rock. In terms of geothermal potential, the Cajamarca Complex is predicted to be the best suited to host the geothermal reservoir [3] [5]. A large proportion of this pre-volcanic basement consists of impermeable plastic rock from metamorphism due to the high temperature and pressure of a subduction environment. However, the complex hosts the inferred granitoid plutons which present high rigidity and exert brittle behavior and are the most likely to house fracture networks that are imperative for permeability [3] [5].

Other major lithological units in the study area are the Quebradagrande Complex and the overlying Quaternary deposits. The Quebradagrande Complex is unique as it consists of two alternating sub-units, one that is a volcanic member, and the other, sedimentary [3]. The most recent deposits of the NRV are a product of the volcano's activity during the quaternary period. They are surficial deposits comprised of pyroclastic rocks, volcanic mud flow deposits, glacial deposits and recent alluvial deposits [6].

3.1 Faulting

Three-dimensional modelling of the faulting present in the north west area of the NRV is a focus of this work. There are sixteen major recognized faults in the area of interest; the collection of fault characterization data showed that specific dip data is often not available, and where this was the case, the dip of the fault was assumed and modelled to be sub-vertical (~85˚). The modelled faults include: Cauca-Almaguer, Silvia-Pijao, Manizales, San Jerónimo (The Romeral Fault System), Santa Rosa, Samaná Sur, Nereidas, Rio-Claro, El Billar, Quebrada Negra, Tosca-El Descanso, Pico Terrible, Olleta-Nereidas, Villamaria-Termales, and Palestina. The purpose of mapping the faults in 3D is to establish a 3D permeability model of the NRV.

3.2 Geophysical Analyses: Seismicity and Magmatic System of NRV

The overall interpretation is that the increased seismicity of the NRV beginning in 2010 is caused by the movement of magma to shallower depths through faulting beneath the NRV [7] [8]. The geothermal significance of this is that the emplacement of magma to shallower depths through the faulting is providing the heat source for geothermal activity.

To visualize the seismic activity occurring beneath the NRV, an earthquake hypocenter dataset with recordings of seismic activity from 2010 – 2018 is incorporated into the 3D model. This dataset is made up of 65,535 different earthquakes all with unique magnitudes and locations within the subsurface of the NRV and was requested for use from Servicio Geológico Colombiano (SGC). The integration of this dataset among all other data will allow the display of seismic activity beneath the volcano and how the location of this activity relates to the faulting and magmatic system of the NRV.

Presently, several studies support a model of multistage magma transport and degassing beneath the NRV, by means of a tripartite magma chamber [5] [9] [10]. There are two main interpretations of the orientation of these intrusive magma bodies in the subsurface, one where the intrusive bodies are trending NW-SE, and in the second interpretation, NE-SW [5] [11]. The shallowest magma chamber is andesitic and thought to reside somewhere between 2-5 km below the surface, the intermediate dacitic chamber between 4-8 km, and the main magma reservoir is basaltic and between 10 to >14 km below the surface [5] [7] [8] [11].

The results of a magnetotelluric survey by the SGC, along with the results of seismic tomography studies will provide a base to shape the magma chambers beneath the NRV [5] [7] [11]. Both opposing orientations of the magma chambers are modelled, providing a way to compare both interpretations with the faulting and seismic data within the rest of the 3D model. This is done to gauge which interpretation is more supported in accordance with the other modelled data.

3.3 Geochemical Analyses

Several thermal features emerge on the flanks of NRV, and the geological configuration of the NRV region suggests strong structural control over the patterns of hydrothermal flow [5]. Surface manifestations are found almost exclusively along fault lines and intersections, specifically the Nereidas, Villamaria-Termales and Santa Rosa faults [5]. This is an indication that fracture

permeability related to faults has a strong influence on hydrothermal fluid flow [12].
Geochemical data is available from geothermal features at Santa Rosa de Cabral (of five thermal springs and three samples from the hot springs of the spa facility) [13]. Further analyses of thermal fluids located in the study area, including from one active fumarole found along the slopes of NRV at an elevation of around 2600 m also contribute to the geochemistry knowledge pool of NRV [14]. Most samples from both studies indicate a meteoric origin, except for the sample taken at Botero Londoño thermal spring which portrayed chemical characteristics expected of hydrothermal fluid (Figure 3) [14]. This sample, along with the sample of the Nereidas fumarole located on the western flank of the volcano, provide significant clues about the deep hydrothermal system of the NRV [14]. The chemical interpretation of both samples suggests a two-phase system, where a vapor-brine envelope surrounds and interacts with the magmatic system [15]. It is further suggested that the Nereidas fumarole is fed by the vapor that separated from a boiling hydrothermal aquifer, while the parent water of the Botero Londoño spring is originally derived from the hydrothermal aquifer [14]. Botero Londoño waters likely represent the brine phase of the local hydrothermal system partially diluted by colder meteoric water as the thermal water made its way to the surface [14]. The chemistry of the Botero Londoño sample, indicates that the temperature of the parent water is 250˚ Celsius, the same temperature that was estimated in the study of the thermal waters of Santa Rosa thermal springs [13] [14].

The collected geochemical data on the NRV and surrounding area, however limited, suggests the presence of a geothermal reservoir beneath the NRV. The available data supports a high-temperature two-phase system, with the possibility of temperature zoning within the reservoir. The conclusions about the geothermal reservoir suggested by the geochemical data will be the foundation for the design of the reservoir system in the conceptual model.

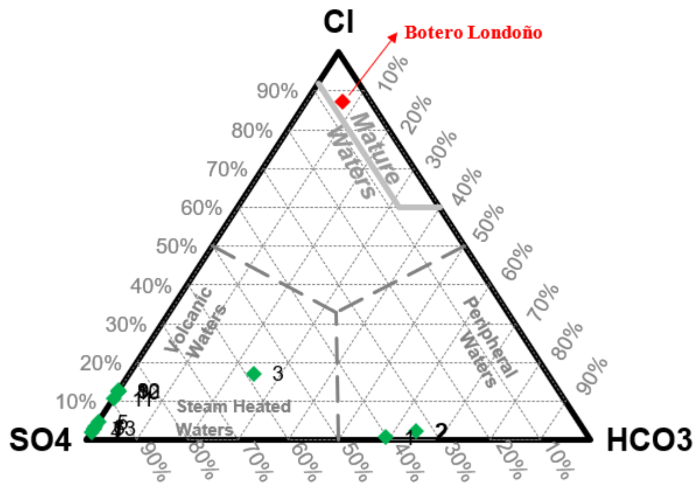

Figure 3. Cl- SO_4-HCO_3 ternary plot of the fourteen thermal fluid samples analyzed by Federico et al. (2017). Majority of the samples plot as peripheral or steam heated waters, except for the sample taken at Botero Londoño which plots as a mature water. [14]

3.4 Well Nereidas-1

Pre-feasibility studies conducted by CHEC in 1983, led to the first geothermal well in Colombia, Nereidas-1. It is located on the western side of NRV and was originally planned to be drilled to a depth of 2000 m but an unplanned deviation of up to 42 degrees resulted in the well being drilled only to 1468 m [16]. Despite the well not reaching its planned depth, much information was derived. At 1466 m in depth, the measured bottom-hole temperature was already 200 ˚C [16]. Taking into consideration the presence of high-temperature alteration minerals such as epidote, indicating temperatures of above 250 ˚C, then there is a likely possibility that the actual temperature of the geothermal reservoir of the NRV is greater than 200 ˚C [16].

The Nereidas-1 well is constructed into the 3D model using the borehole record. The information from the borehole record will assist in determining the thickness of the overlying Quaternary deposits that are abundant in the east of the study area. The contact between the Quaternary and the Cajamarca Complex will be defined by where the units are in contact in the Nereidas-1 well.

4 3D Model Results

Majority of the data gathered was initially compiled in the software ArcGIS by ESRI, a cloud-based mapping platform, and then imported into Leapfrog Geothermal 3.5. The co-ordinate system used was SIRGAS_2000_UTM Zone 18N, and the data set included various forms of shapefiles, digital elevation models, maps, MT and seismic tomography cross-sections, an earthquake hypocenter dataset from the years 2010-2017 and the well-log from the Nereidas-1 well report. The collected data enabled the creation of model features, including topography, fault systems, well(s), stratigraphy, and magmatic intrusions. From this, a 3D model is created of the north west area of the NRV, including the stratovolcano itself and the neighboring SW volcano, Nevado Santa Isabel. Leapfrog Geothermal 3.5 by Seequent was used as the platform for the 3D modelling of the NRV. It was developed to model and visualize geothermal systems in three dimensions, emphasizing its ability to build reliable models out of sparse data which geothermal projects typically have [17].

The surface traces of the lithologic contacts and fault locations are determined with the use of two separate maps, both based from the SGC. The maps are as follows:

1. “Geología del Complejo Volcánico Nevado del Ruiz”, created in 2014

2. Maps 206 and 225 as re-created and made into one map by González (2001) (Figure 4) [18] (“Geología de la Plancha 206 Manizales”, and “Geología de la Plancha 225 Nevado del Ruiz” both created in 1998 by Servicio Geológico Colombiano)

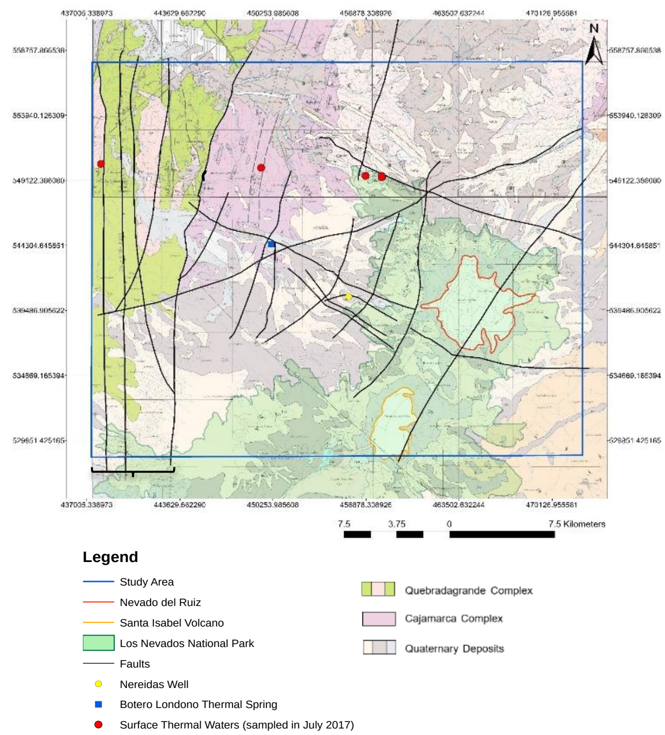

Figure 4. Map 2. Included are the location of thermal manifestations and samples taken by the University of Medellin during the field camp of 2017, the location of a prominent hot spring, Botero Londoño, and the location of Well Nereidas-1. Co-ordinate System: SIRGAS_2000_18N.

Three main lithologies are modelled, being the Quebradagrande complex, the Cajamarca complex, and the overlaying Quaternary-aged deposits. Though all three lithologic groups are comprised of more than one stratigraphy, they are each treated as one single unit according to their overall unique rock type (Figure 5).

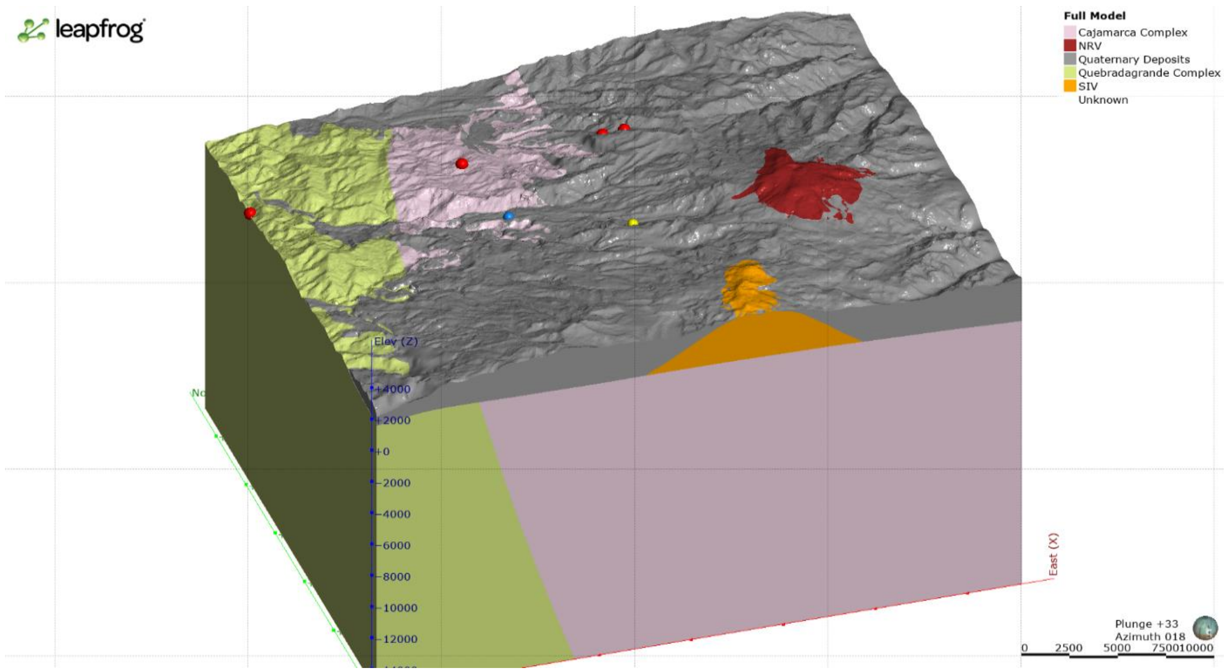

Figure 5. Digitized 3D model of the NRV. Yellow sphere: well Nereidas-1; Blue sphere: Botero Londoño spring; Red spheres: location of thermal spring samples taken in the study area by University of Medellin in 2017 (analysis in process).

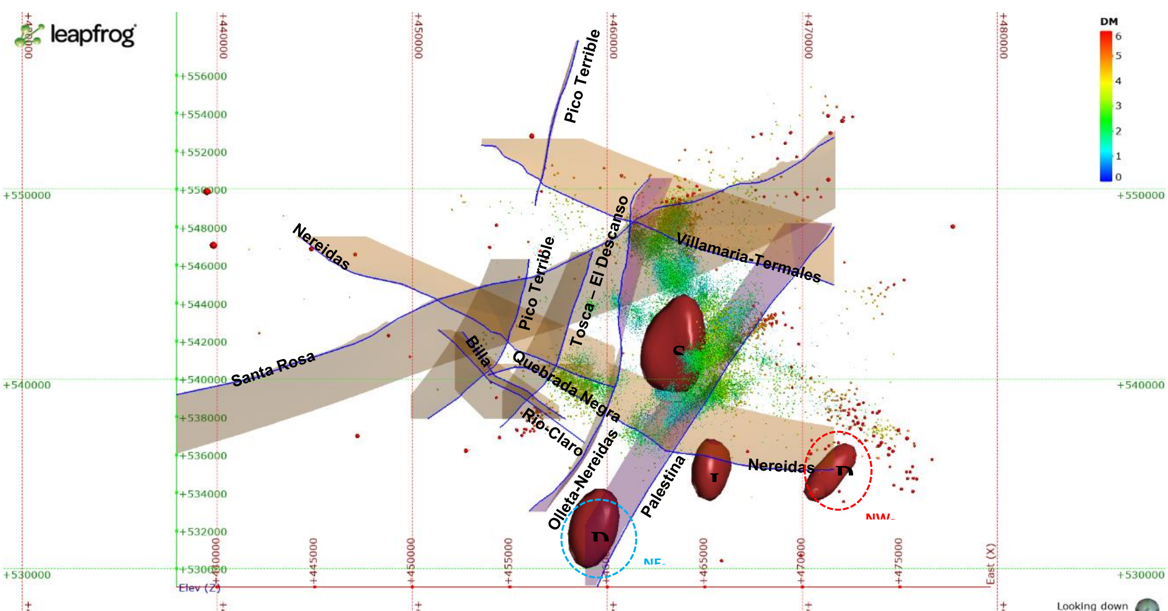

Figure 6. Earthquake hypocenters from 2010-2018 shown with faults that intersect the hypocenter dataset, and both interpretations of magma chamber orientations. View from above. S= shallow chamber, I = intermediate chamber, D = deep chamber(s).

The fault systems are digitized as 3D planes within the proposed study area (Figure 6), which allows the visualization of the behavior of the faults within the subsurface in response to tectonic stress and the indication of the areas where there is higher permeability. The faults were initially digitized in ArcGIS, and then the polylines of the fault traces were exported as .shp files and imported in to Leapfrog Geothermal. Ultimately, fifteen main faults were mapped in 3D, with their surface traces taken from Map 2 when available, and their dips taken from literature where it could be found.

The integration of data into a 3D visualization allows a platform to visualize different working hypotheses against others and determine which interpretation may align more with the given data. Displaying the two interpretations of magma chamber orientation in relation to the whole model will provide a platform to view both interpretations in relation to other related data integrated into the Leapfrog Geothermal 3D modelling platform.

As can be seen in Figure 6, the higher-magnitude hypocenters (red spheres), are abundantly located around the deep magma chamber interpretation of the NW-SE orientation. In comparison, the deep magma chamber of the NW-SW orientation shows almost no traces of seismic activity directly around it. This may indicate that the orientation of the magma chambers is in fact, NW-SE. However, more in-depth subsurface study is required to determine this.

5 Discussion and Conclusion

When looking realistically at subsurface characterization projects it is expected that there will be insufficient direct measurements that are required to create a subsurface model lacking uncertainty. Every model contains assumptions that limit its certainty and thus could limit its usefulness. Both 3D and conceptual models have similar limitations, as they are both ways to portray the subsurface. To get the most out of both subsurface model types, it is of utmost importance to use high-quality, reliable data as the model is only as ‘good’ as the data that it was made with. Reliable, recent data from peer-reviewed studies will decrease uncertainty in the project. Models lacking data, or models using outdated data are quite limited, thus it is important to gather data regularly.
A 3D and conceptual model of the Nevado del Ruiz geothermal system was created by integrating publicly available geological, geophysical and geochemical data. The models provided a platform to view what is currently understood about the NRV’s lithological, structural, magmatic, seismic, and hydrothermal systems. The relationships between these systems facilitate the understanding of the NRV as a prospect from which to produce geothermal energy.

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