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Reconstruction of a "Discrete Fracture Network" in the geothermal reservoir of Rosario de La Frontera (La Candelaria Ridge, Salta province, NW Argentina)

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ABSTRACT

In this contribution we present and discuss the reconstruction of a Discrete Fracture Network model of the reservoir of the geothermal system of *Rosario de La Frontera*, located in Salta province (NW Argentina). This model allows to assess the effective permeability of the reservoir and to obtain input parameters for dynamic reservoir modelling.

Structural studies performed on the outcropping portion of the reservoir, allowed us to define the main fracture system occurring in the structure and to calculate the input parameters for the generation of the DFN in a 3-D volume of the buried geothermal reservoir, using dedicated software (e.g. Move by Midland Valley Ldt.). Faults and fractures were analyzed and quantified by means of scan-lines and scan-area surveys defining diagnostic parameters such as fracture type, orientation, dimension, surface texture and numerical parameters (e.g., density and spacing, length, aperture, etc.). According to the orientation data, the observed discontinuities have been classified in different sets interpreted with respect to the regional structural setting and their density distribution was assessed in different sectors of the reservoir.

In conclusion, several DFN models were generated, one for each fracture set. Furthermore, comparison among the different models provided a preliminary qualitative assessment of reservoir permeability with special regard to the anisotropy due to the secondary permeability.

1. INTRODUCTION

Discrete fracture network (DFN) models are three-dimensional stochastic or combined stochastic/deterministic representations of natural fracture systems. They represent an important tool to investigate pathways for fluid flow in geothermal reservoirs in order to predict their behaviour in prospect evaluation and reservoir management (Dershowitz et al 1988; Cacas et al 1990; Watanabe and Takahashi 1995). In this framework, data uncertainty due to lack of direct observations concerning tectonic features represents one of the major problems in subsurface reservoir analysis. Because of this, in the last years a variety of methodologies for both data acquisition and analysis has been developed, from outcrop/well scale to regional/seismic scale, in order to provide the best criteria for predicting fracture network (Van Dijk 1998). Acquisition techniques are based on characterization of outcropping structures with the aim to use them as analogue for subsurface portions of the reservoirs. They comprise the acquisition of fracture data along scan lines and on scan area, at outcrop scale, in order to elaborate a probabilistic model representing fracture distribution at reservoir scale. We used this modelling approach to study the geothermal reservoir of *Rosario de La Frontera* (NW Argentina) belonging to *La Candelaria Ridge*, one of the positively inverted structures cropping out between the provinces of Salta and Tucuman (NW Argentina).

This active geothermal system is marked by several hot springs, with surface temperatures ranging between 23°C and 99°C, that occur in the suburbs of the town of *Rosario de La Frontera* located at the northern edge of *La Candelaria* mountain ridge. One further hot spring with temperature of about 20°C occurs a few tens of kilometers along the south-western flank of the ridge, in correspondence of the *El Ceibal* area and along a kilometric strike slip fault cross cutting the regional anticline. Fractured sandstones strata belonging to the syn-rift deposits of the Salta Group (Pirgua subgroup) provide the reservoir rocks of this geothermal fluids (Moreno Espelta et al 1975).

Therefore, detailed field measurements of outcropping reservoir deposits were performed to get a qualitative and quantitative description of the DFN. The purpose of this modelling is to create simulation fracture properties (such as porosity, permeability, connectivity) that can contribute to evaluate the productivity potential of this reservoir in terms of the profit volume that enhanced fluid flow. In order to

achieve this purpose, the paper shows the results of the preliminary reservoir simulation studies carried out for the analyzed geothermal system and addressed the reservoir evaluation: reservoir thickness and volume, tectonic features, fractures network features and distribution, and related secondary permeability.

2. GEOLOGICAL SETTING

La Candelaria Ridge lies in the structural province of the Santa Barbara System, in the Sub-Andean foreland thrust belt of northwest Argentina, characterized by a thick-skinned compressive deformation (Allmendiger et al 1983; Jordan et al 1983; Kley and Monaldi 1998; Kley and Monaldi 1999) (Fig.1 and Fig.2). This geological province consists of a basement-involved thrust system resulting from an eastward migrating compression that occurred during Miocene–Quaternary times (Salfity et al 1993; Reynolds et al 2000).

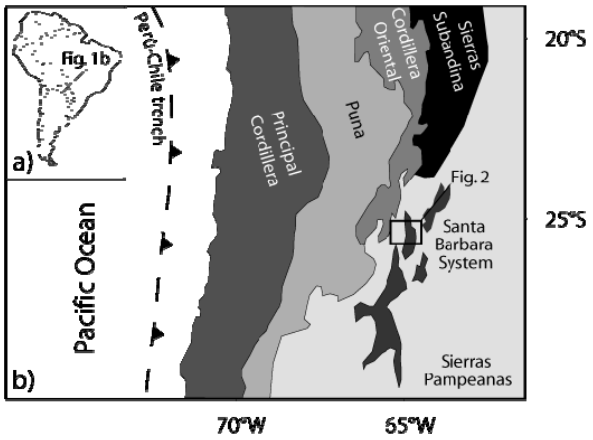

Figure 1: Map illustrating the structural provinces of northwest Argentina, modified from Carrera and Muñoz 2008.

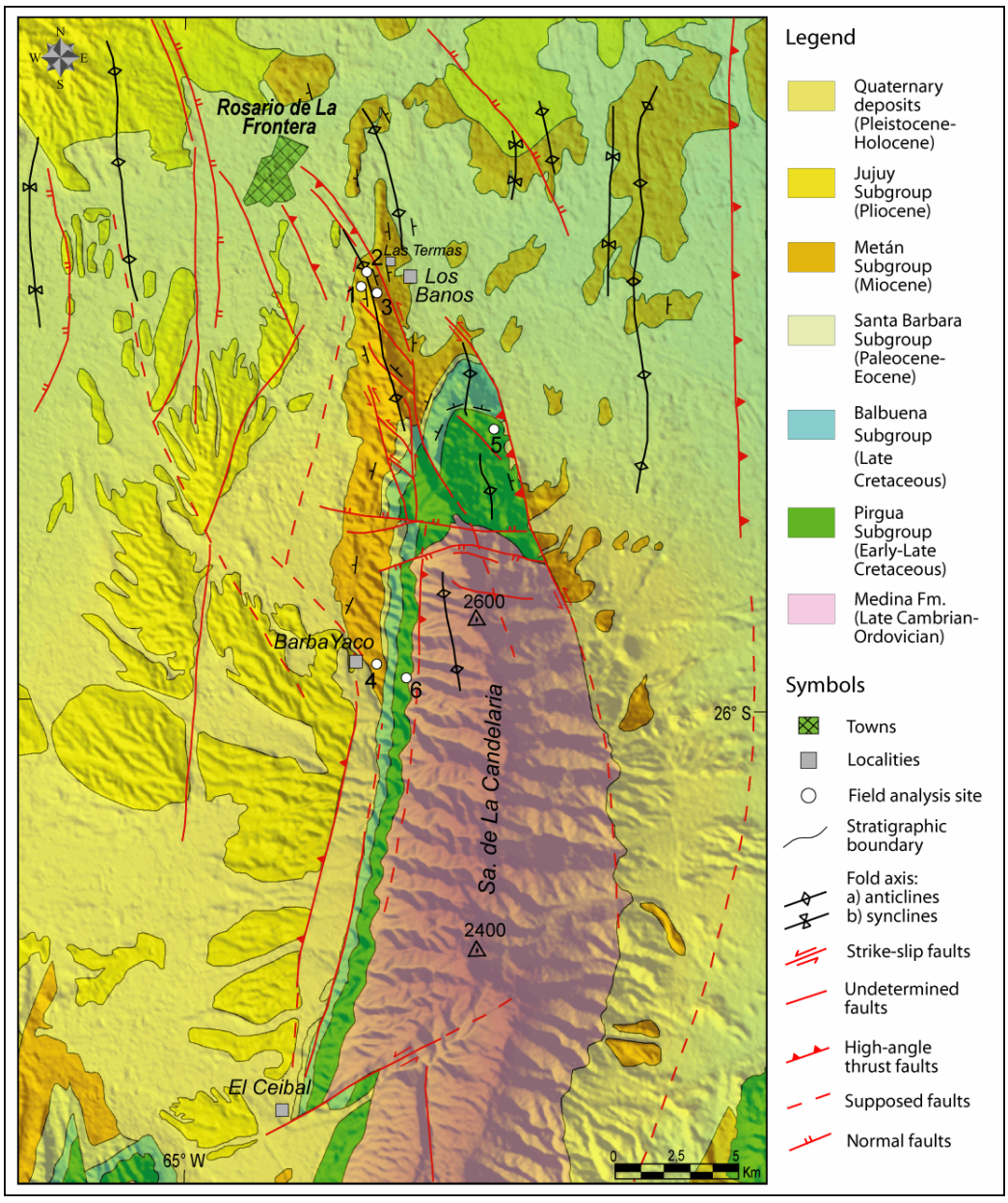

Figure 2: Geological Map of *La Candelaria* ridge

As a result, it is dominated by a stepped fold pattern generated by an imbricate stack of thrust slivers, mainly due to the Andean inversion of pre-existing normal faults generated during regional Cretaceous rifting (Bianucci et al 1982; Grier et al 1991; Salfity et al 1993; Kress 1995; Cristallini et al 1997, Kley and Monaldi, 2002).

La Candelaria Ridge represents one of this broad anticline structures elongated in N-S direction for ca.60 km and strongly plunging (up to 25°) both to the north and south. This anticline is uplifted by high-angle reverse fault planes dipping both to the west and to the east with respectively top-to-the-east and top-to-the west sense of transport. Low grade metasedimentary Precambrian rocks widely crop out at its core and are unconformably overlain by a thick sequence of predominantly continental Cretaceous to Paleogene strata (Salta Group) related to the Cretaceous rift stage (Salfity and Marquillas 1982, 1994). The permeable levels of the syn-rift strata belonging to the Pirgua subgroup (Salta Group) are the reservoir of the active geothermal system (Moreno Espelta et al 1975).

The post-rift (Balbuena and Santa Barbara subgroups) and syn-orogenic impermeable strata (Metán subgroup), that are related to an inversion tectonic phase, provide the cap rock to the geothermal system (Bianucci et al 1982; Cominguez and Ramos 1995; Gebhard et al 1974). In correspondence of the northern plunge, where syn-orogenic clastic sediments extensively crop out, the well-known hot springs and the thermal spa of *Las Termas* are located. Instead, the hot spring of the *El Ceibal* area occurs in the southwestern sector of the ridge where the syn-rift deposits crop out.

3. RESULTS

3.1 FRACTURE FEATURES AND FREQUENCY

Field work observations were concentrated along the limbs and in the northern plunge area of *La Candelaria* anticline. We identified different kinds of structural discontinuities including generic fractures (e.g. with small aperture not sufficient to exclude a shear component during the opening; isolated weathered fracture), gypsum and calcite-filled veins, shear fractures and shear bands (Fig.3).

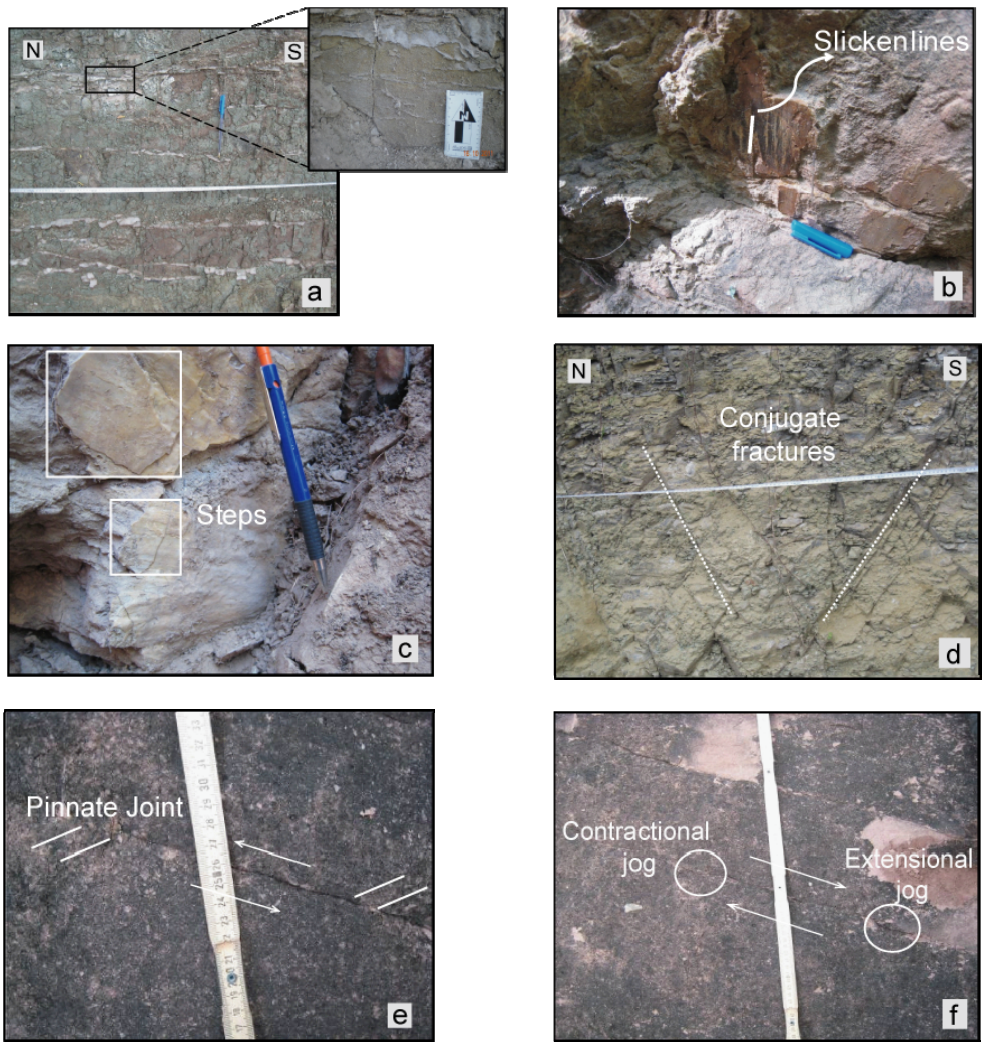

Figure 3: Examples of fractures characterizing the cap rock (Metán Subgroup) and the reservoir (Pirgua Subgroup) of the studied geothermal system. (a) Gypsum veins at field site 1 and (b) (c) (d) shear fractures in the outcrops of Metán Subgroup at different sites; (e) (f) Shear fractures in the reservoir rocks.

According to the orientation data, the observed discontinuities have been classified as longitudinal, transverse and oblique with respect to the regional fold axis (e.g. Stearns 1968, Hancock 1985, Cooper 1992; Tavani et al 2008). They have been grouped into six sets:

• Set 1 includes generic fractures, shear fractures and shear bands striking sub parallel to the fold axis (N30°W ±10°). They have been classified as longitudinal;

• A second (Set 1A) and a third (Set 1B) sets of oblique fractures are observed at an angle of 30° with respect to set 1, and the fold axis. They include generic fractures, calcite veins and shear fractures;

• Set 2, classified as transverse structures with a strike perpendicular to the fold axis (N60°E ±10°), includes generic and shear fractures;

• Set 2A and Set 2B occur at an angle of 30° with respect to set 2. Gypsum veins, generic fractures and shear fractures belong to this fractures set.

Fracture frequency distribution within the anticline was obtained by the acquisition of spacing data derived from scan-lines and scan-areas analysis. Figure 4 shows high values of fracture frequency occurring mainly along the northern periclinal termination and along the western limb of the anticline where Metán subgroup crops out.

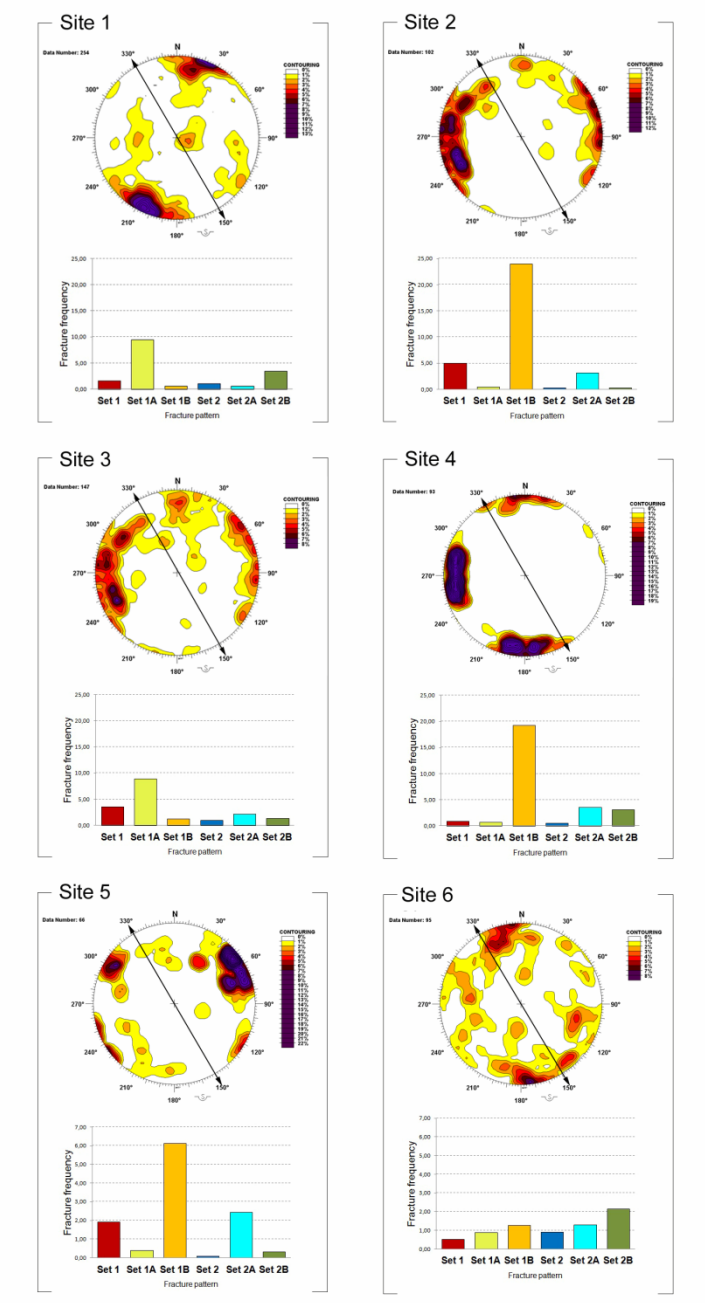

Figure 4: Orientations and frequency analysis after Terzaghi correction of fractures measured at different sites of the studied anticline. Black arrows indicate the fold axial trend. See text for details.

The lowest values occur where reservoir rocks (Pirgua subgroup) crop out. In correspondence of the reservoir outcrops, the highest value of fracture frequency occur along the western limb of the anticline. In this framework, fracture sets 1, 1A and 1B are more frequent along the western limb, whereas sets 2, 2A and 2B occur mainly along the eastern flank. The observed higher frequency on the backlimb can be related to the curvature of stratigraphic surfaces (Hennings et al 2000).

3.2 RESERVOIR RECONSTRUCTION

A three-dimensional reconstruction of the reservoir has been performed on the base of the available geological data using the software Move (Midland Valley Ltd.). The reconstruction is based on a series of thirty geological profiles crossing the anticline, perpendicular and parallel to the fold axes. The 3D surfaces corresponding to the top and to the base of the target formation, Pirgua sandstones, have been modelled using the horizons reconstructed in a series of parallel geological cross sections. Bottom and top surfaces of Pirgua Formation were used to build the tetra volume and the geocellular volume showed in Fig.5. The 3D volume represents the buried portion of the Pirgua Formation, whereas no volumes were considered for the outcropping portion of the same formation.

The accurate geological data allowed to represent in detail the asymmetric shape of the *La Candelaria* anticline which has a gently dipping front limb and a steeply westward dipping back limb. Its general trend is N-S but further to the north it has a NW-SE orientation in the axial plunging *Las Termas* area. The eastern limb of the anticline is bounded by high-angle reverse faults striking NS with a top-to-the-west sense of transport. Along the western fold limb in the southern reconstructed sector, a kilometric NE-SW strike-slip fault borders the reservoir and is marked by *El Ceibal* hot spring. Furthermore, the anticline results to be offset by several minor faults. To the north, the anticline core is truncated by a minor NNW–SSE trending high angle fault with a left lateral strike-slip component; in the western area, the backlimb is affected by several minor reverse NW-SE trending faults.

Nevertheless, it can be assumed that the Cretaceous sandstones, that form the main geothermal reservoir, consist of a single and continuous hydrogeothermal body with an estimated volume of about 53 km^3 and a mean thickness of about 450m. The maximum depths reached by the top and bottom surfaces of Pirgua Formation are 2,000m and 2,400m, respectively, calculated in the northern sector of the anticline, in correspondence to the axial plunge.

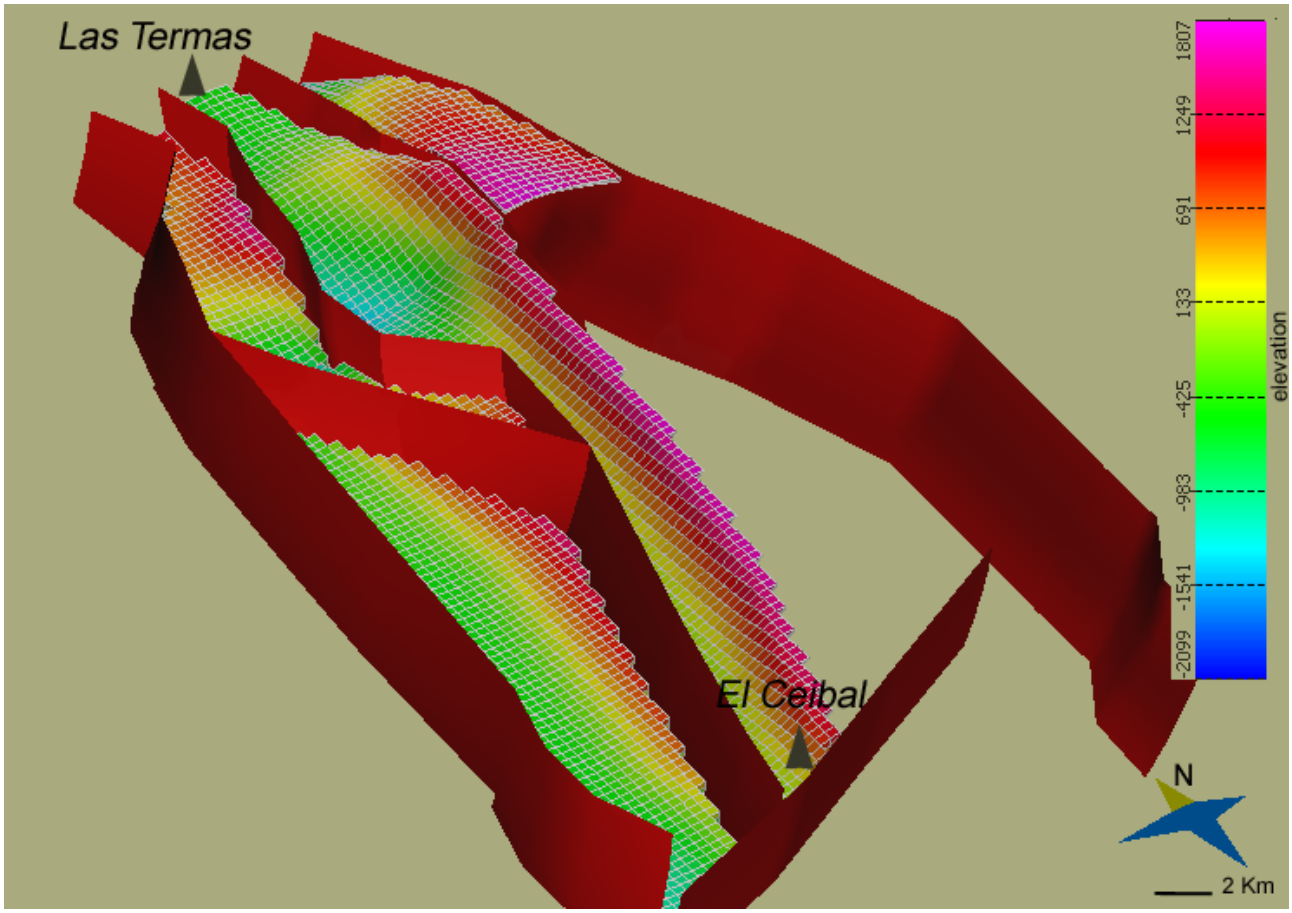

Figure 5: Three-dimensional model of the Pirgua subgroup deposits in *Rosario de La Frontera* area.

3.3 DFN MODEL

We have generated six stochastic DFN models in the 3-D geocellular volume of the geothermal reservoir, using the software Move (Midland Valley Ltd.). These models allowed to calculate the fractured volume affecting the reservoir and a secondary permeability tensor due to the fracture network calculated for each grid cell from orientations, area, and aperture data of the fractures intersecting the cells (Fig.6 and Fig.7).

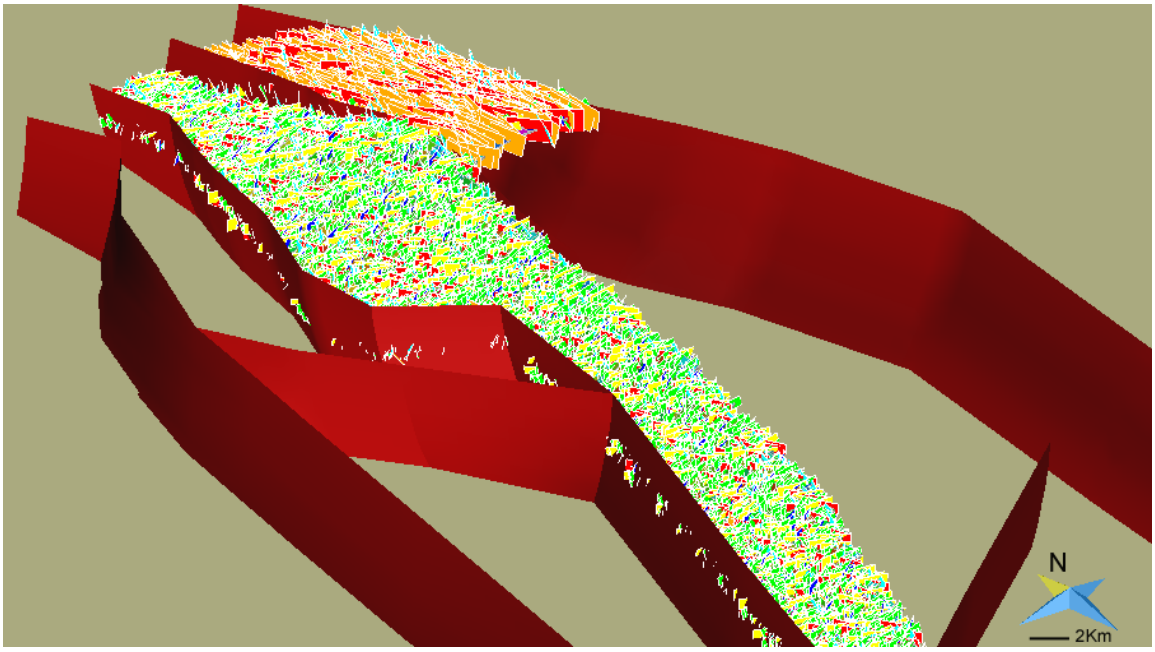

Figure 6: DFN model reconstructed in the profit reservoir volume of the active geothermal system.

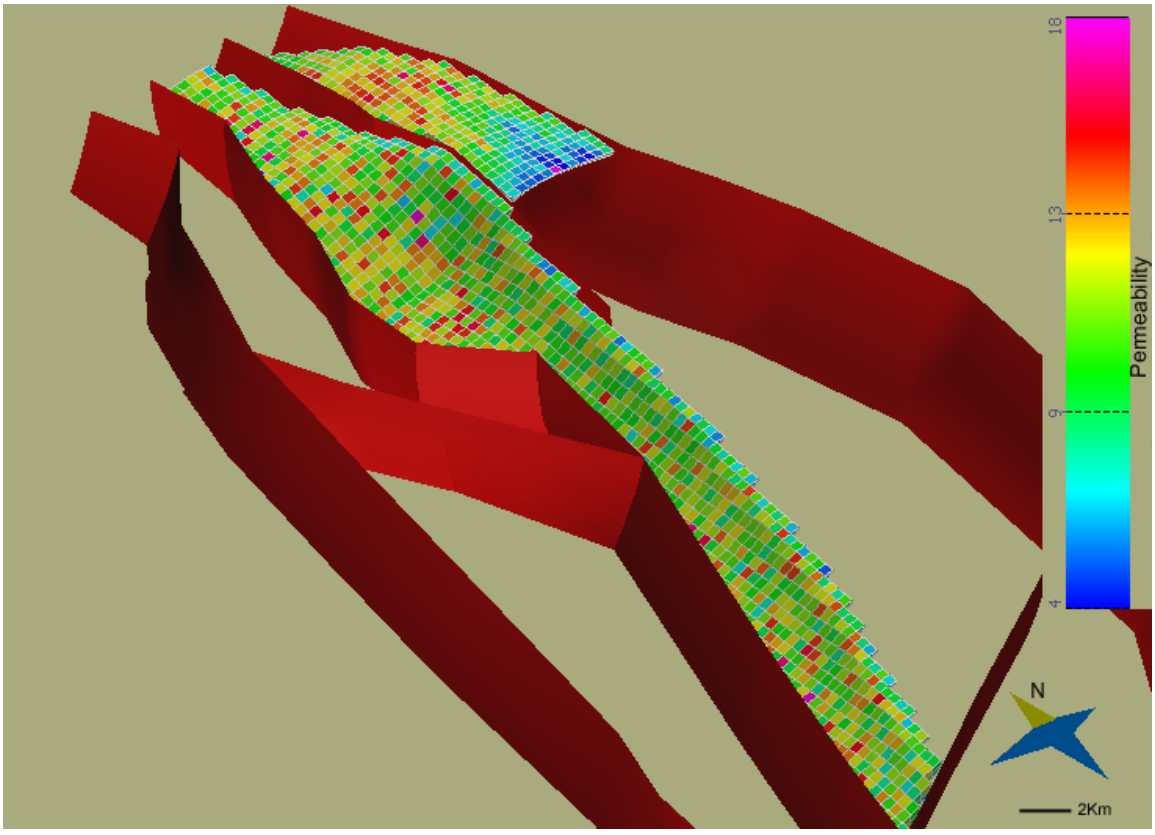

Figure 7: The colour map shows the variations of permeability values (mD) provided by the most frequent fracture sets.

As a result, the fractured volume elaborated by the software on the base of fracture length and aperture is of 5,840,660m^3. It is considered as the profit volume that enhances fluid flow. In this framework, permeability shows the highest values in the backlimb where fractures are characterized by high values of aperture. The comparison among permeability values due to the different fracture sets shows that in this area the highest values of permeability are due to the oblique fractures belonging to set 2A and 2B characterized by high values of frequency. Instead, in the hinge and forelimb zones, permeability values are lower than that in the backlimb, and the highest values of permeability are due to the oblique (set1B and 2A) and longitudinal sets (set 1) that are the most frequent. Changes in the different directions (i.e. xx, yy, xy, xz, yz, zz) are in agreement with the anisotropy of the distribution of the fractures orientation.

4. CONCLUSIONS

In this contribution we present the preliminary results of a series of Discrete Fracture Network models carried out in order to evaluate the potentialities of the reservoir of the geothermal system of *Rosario de La Frontera*, in the Salta province (NW Argentina). On the base of structural analysis performed on the outcropping reservoir rocks, and of the modelling conducted with the aid of dedicated software (e.g. Move by Midland Valley Ldt.), following conclusions can be withdrawn:

1. fieldwork analysis performed on outcropping stratigraphic units as well as on structural discontinuities allowed to consider the Creatceous sandstones of the Pirgua subgroup as the main reservoir of this geothermal system, according to Moreno Espelta et al (1975);

2. the three-dimensional reconstruction of the whole structure of *La Candelaria Ridge* describes an asymmetric anticline trending N-S with a gently dipping front limb and a steeply westward dipping backlimb. It is bounded by high-angle reverse faults striking NS with a top-to-the-west and top-to-the-east sense of transport. In the hanging wall of these faults the reservoir deposits crop out and along the whole anticline they are affected by several minor faults trending NW-SE and NNW–SSE that consist of reverse faults, often with a left lateral strike-slip component. Along the western fold limb, in the southern sector, a kilometric NE-SW strike-slip fault confines the reservoir;

3. the estimated volume of the reservoir is of about 53 km^3 with a mean thickness of about 450m. In the northern sector of the anticline, in correspondence to the axial plunge, it reaches a maximum depth of 2,400m;

4. quantitative and qualitative analysis performed on reservoir outcrops allowed to identify different kinds of structural discontinuities: generic fractures (e.g. with small aperture not sufficient to exclude a shear component during the opening; isolated weathered fracture), shear fractures and shear bands. Fracture frequency distribution shows high values of fracture sets 1, 1B and 2A occurring mainly along the eastern flank of the anticline and in the hinge zone, whereas sets 2A, 2B and 1B occur mainly along the western limb. These distribution can be related to the folding kinematics of the regional structure and are compatible with the curvature of stratigraphic surfaces;

5. the secondary permeability provided by the most frequent fracture sets in the western limb is in the range of 12 and 15mD, whereas the values ranging from 3 to 5mD in the eastern one. The higher values on the western limb are related to the major values of aperture of the fractures analyzed. As a whole, the detected fracture systems affecting the principal reservoir enhances its permeability;

6. the total fractured volume considered as the profit volume that enhanced fluid flow is of about 5,840,000m^3.

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