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Determination of the Stress State in the Andean Cordillera Frontal near the Border between Argentina and Chile

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Abstract. The initial state of stress is an important parameter in underground excavations. From its knowledge, it is possible to calculate the stresses induced around the excavation and the necessary support for stabilization. This task becomes critical when the excavations have great dimensions such as caverns and when rock overburden is significant. Different methodologies are discussed, including simple regional stress maps, the survey of surface paleostress and hydraulic fracturing executed in borehole between 500 and 800 m deph. These methodologies have been applied in the Andean Cordillera Frontal, where the Agua Negra tunnel will be built between Argentina and Chile. This area is affected by the subduction of the Nazca plate beneath the South American plate. This setting generates that the greatest principal stress σ_1 has a W-E orientation and relationship with the vertical stress (σ_2) reaches about 1.4.

Keywords. Stress, hydraulic fracturing, Andean Cordillera Frontal, paleostress, Agua Negra Tunnel

1. Introduction

The Agua Negra Tunnel (TAN) site is located between El Elqui (Chile) and San Juan Province (Argentina), under the Andean Cordillera. The tunnel will pass through volcanic massifs mainly composed of andesites and rhyolites [1]. This region is characterized by its high seismic activity due to the stresses induced by the subduction of the Nazca Plate under the South American plate (Figure 1).

The 13.9 km long tunnels will substitute the existing pass road, avoiding the difference in altitude between 4085 m asl and 4765 m asl and shortening the distance by more than 40 km. The tunnel system is formed by two nearly parallel single tubes, W-E oriented, containing 2 lanes each, with a constant longitudinal slope of 3.36 %, falling towards West, from Argentina to Chile [2].

Starting at the West portal there is a rather steep ascent of the overburden. Below the Chilean/Argentinian border which occurs approximately at km 4, there is 1750 m of overburden. The Eastern branch of the tunnel runs almost parallel to the Quebrada de San Lorenzo with overburden between 300 and 600 meters. The tunnels will cross the San Lorenzo fault that is a major structural feature (Figure 3).

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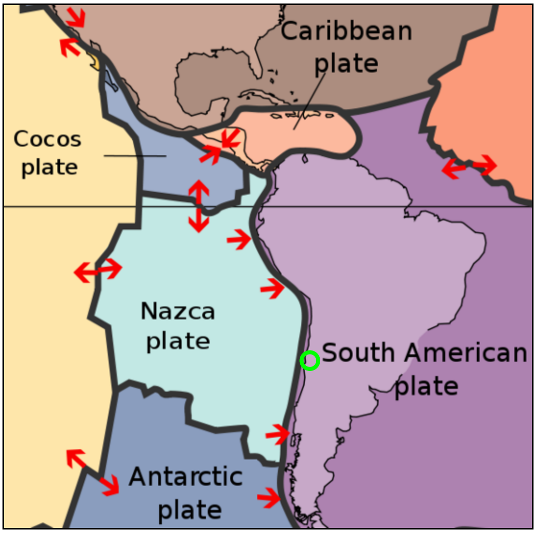

Figure 1. Location of the Agua Negra Tunnel (circle).

Among the accessory works there are two ventilation caverns, situated at one third, respectively two thirds of the tunnel length (Figure 2).

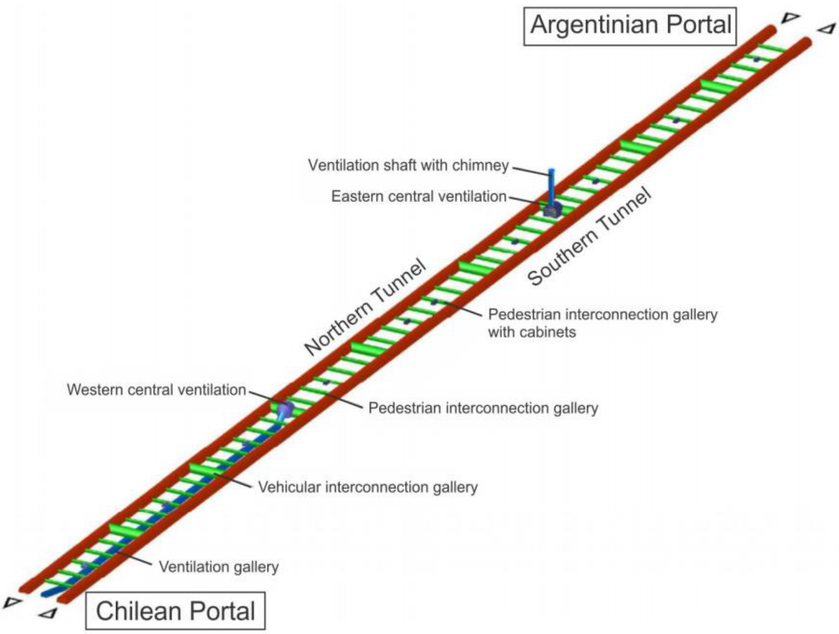

Figure 2. Scheme of the W (Chile) – E (Argentina) tunnel system.

The Western ventilation cavern is linked to the Western portal by a parallel ventilation gallery, while the Eastern cavern is situated at the base of a vertical shaft, which is 509 m high. There are regular pedestrian by-passes between the two tubes and at greater distances special rooms for electromechanical equipment. The cross section of the running tubes contains a traffic space of 7.50 m in width and 4.80 m in height. There are lateral sidewalks of at least 1.00 m width and 2.20 m in clearing height.

The initial state of stress is an important fact in underground excavations. From its knowledge, it is possible to calculate the stresses induced by excavation and the necessary support for its stabilization.

2. Tectonic Setting

The stress state can be interpreted by analyzing the geological arrangement of existing structures and mechanisms of uplift of the range, according to the conceptual model shown in Figure 3 [3].

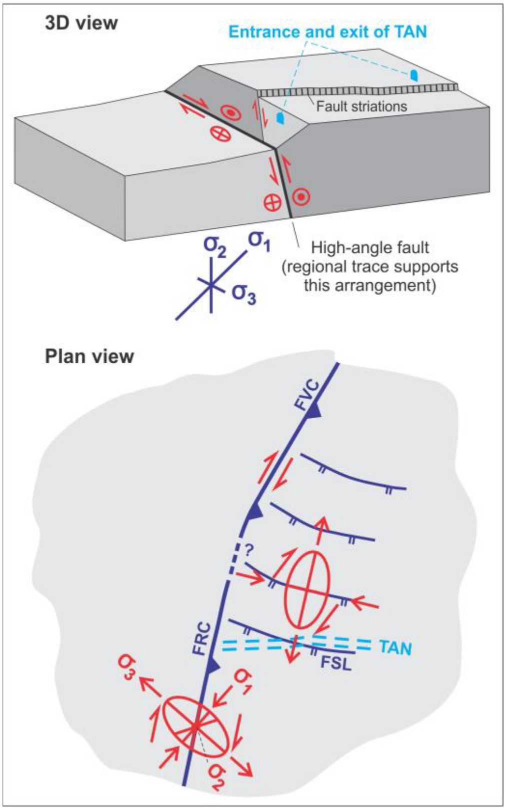

Figure 3. Preliminary diagram showing the regional stress state. FRC: Río Colorado Fault, FVC: Valle del Cura Fault, FSL: San Lorenzo Fault [3].

2.1. Geometric Definitions

In this model, integrating the regional and continental faulting analysis, reverse movements and dextral strike slip along the Río Colorado fault (FRC) and its continuation to the north in the Valle del Cura fault (FVC) are postulated. The regional trace of the FRC-FVC fault indicates that it dips to the east with strong angle, reinforcing the concept of a reverse fault. The model of Figure 3 is transpressive, i.e., it is a convergent oblique shear.

The convergence vector of the Nazca plate is ENE, which together with the regional and continental faulting analysis would indicate an essentially compressive regime but with strike slip (= transpressive = oblique convergent shear). These considerations imply that the average stress tensor would have an orientation as follows: σ_1 horizontal (NE-SW), σ_2 vertical and σ_3 horizontal (NW-SE).

2.2. Surface Survey

The objective of the survey was to analyze the deformational structures recognized and studied in the field, mainly joints, faults and associated minor striations, outcropping in the area where it will be located the TAN. These structures are correlated with the regional tectonic model and used to make a first approach to the determination of the paleostress state of the area.

2.3. Methodological Treatment of Data

Data were collected in a series of structural stations shown in Figure 4. Structural schemes were made and planar and linear orientation data was measured. Data were processed using the Klaus Röller's Stereonett software of the Ruhr University (Bochum, Germany).

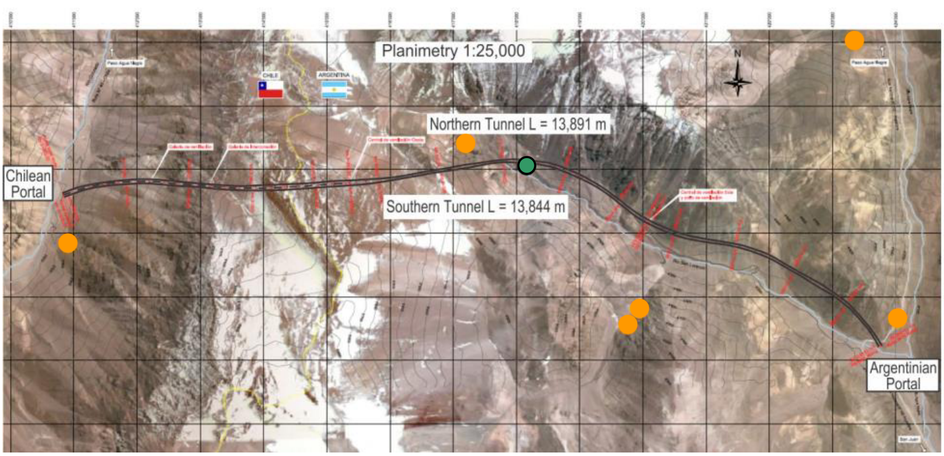

Figure 4. Location of surface surveys (yellow) and borehole P02 (green).

The results plotted in three areas are shown in Figure 5, from West to East:

- Chilean Portal: it has been put under a compressive state with strike slip faulting and a stress state with normal faulting. The first of these has two mutually perpendicular directions, with σ_1-σ_3 subhorizontal and σ_2 subvertical, while in the second, σ_2-σ_3 are subhorizontal and σ_1 is subvertical. In the field survey, it was not possible to find relative chronological evidence between these events.

- Quebrada Olivares: this area has a compressive state with reverse faulting, with σ_1-σ_2 subhorizontal and σ_3 subvertical.
- Quebrada Sarmiento: shows a general compressive state with two faulting, reverse and strike slip. σ_1 is rather inclined in both cases, with a permutation by rotation about σ_1, σ_2 being horizontally during reverse stage and subvertical during the strike slip stage.

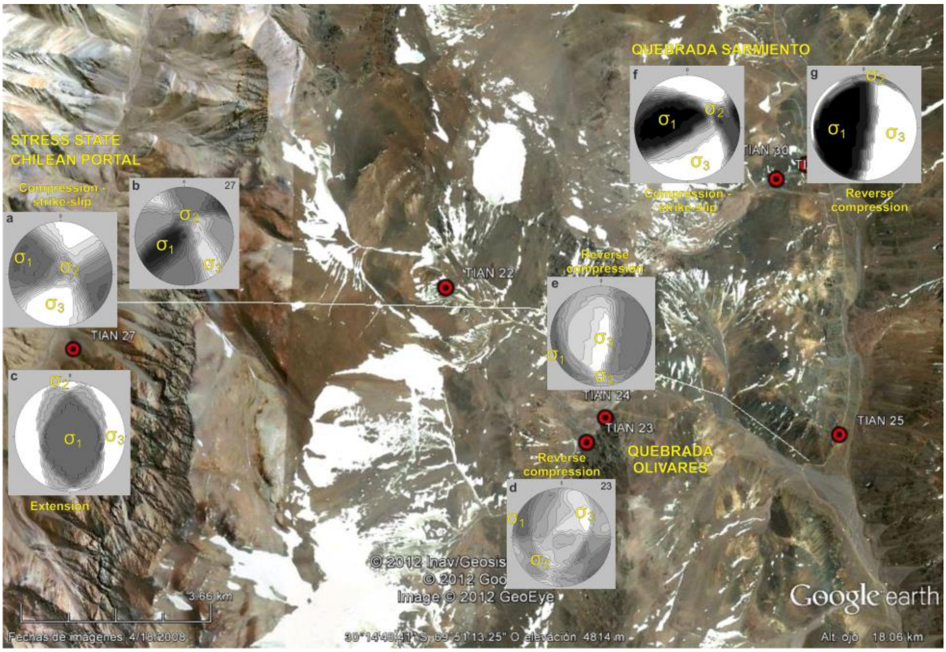

Figure 5. Results of the surface paleostress survey.

3. Stress Measurements in a Borehole

3.1. Methodology

A series of 8 hydraulic-fracturing / hydraulic injection tests including 8 impression packer tests were conducted in a borehole P-02 between 507.6 m and 817.6 m [4]. The main objective of the tests was to determine the magnitude and the orientation of the in-situ stress regime acting in the rock mass for tunnel design purposes. The in-situ tests were carried out by using the MeSy-Solexperts wireline technique to move the hydrofrac and impression packer unit PERFRAC-II within the 76 mm and 96 mm diameter borehole sections.

3.2. Results of Hydrofracture Measurements

The detailed analysis of the tests yields, reliable breakdown-pressure, fracture re-opening pressure as well as shut-in pressure values. Since the impression packer tests showed that fractures with different spatial orientation were initiated or stimulated, the in-situ stress profiles were calculated on the basis of the Psi-method. The results of the inversion calculations can be summarized by the following stress - depth relations within the depth range tested between 507 - 818 m (Figure 6):

$$Sh\ [MPa] = (8.5 \pm 0.5) + (0.022 \pm 0.003) \cdot (z\ [m] - 507)$$

$$SH\ [MPa] = (17.0 \pm 1.9) + (0.037 \pm 0.013) \cdot (z\ [m] - 507)$$

where Sh and SH are the minor and major horizontal principal stresses and z is the depth (Figure 7).

The vertical principal stress Sv was calculated assuming a mean overburden rock mass density of 2.65 g/cm3:

$$Sv\ [MPa] = 0.026 \cdot z\ [m]$$

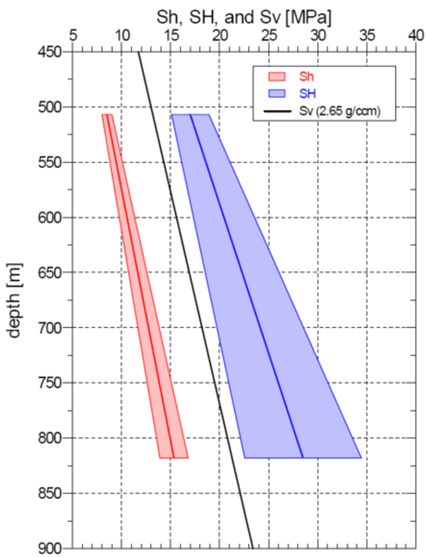

Figure 6. Stress profiles along depth (dash areas represent the scatter of measurements).

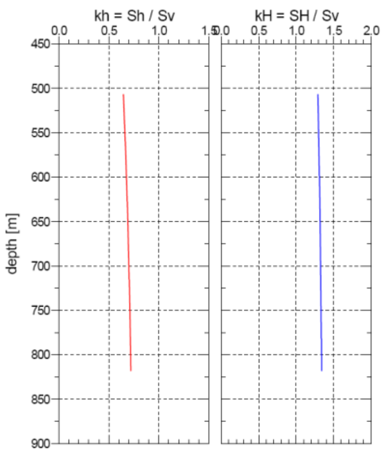

Figure 7. Stress ratios: $k_h = S_h/S_v$ (red) and $k_H = S_H/S_v$ (blue).

The stress measurements in boreholes P-02 yield an approximately W-E orientation of the major horizontal principal stress SH (N 91° ± 2° with respect to magnetic North).

The analysis of the pressure pulse test cycles conducted prior to the hydrofrac tests suggests near wellbore hydraulic conductivity values of $<10^{-11}$ m/s. The interpretation of the step-rate injection cycles conducted at the end of the hydrofrac tests similar to classical Lugeon tests yield hydraulic conductivity data ranging from $5 \cdot 10^{-9}$ m/s to $5 \cdot 10^{-8}$ m/s for the stimulated fractures.

4. Comparison of Results of Survey and Measurements

The results of surface surveys are not strictly comparable with the measured stress state in boreholes. This is because the surface measurements mirrored the stress state at the time when the striations occurred (paleostress).

Nevertheless, the stress tensor obtained by both methods is essentially equivalent. In addition, the stress direction is in agreement with existing stress data of the World Stress Map (Figure 8).

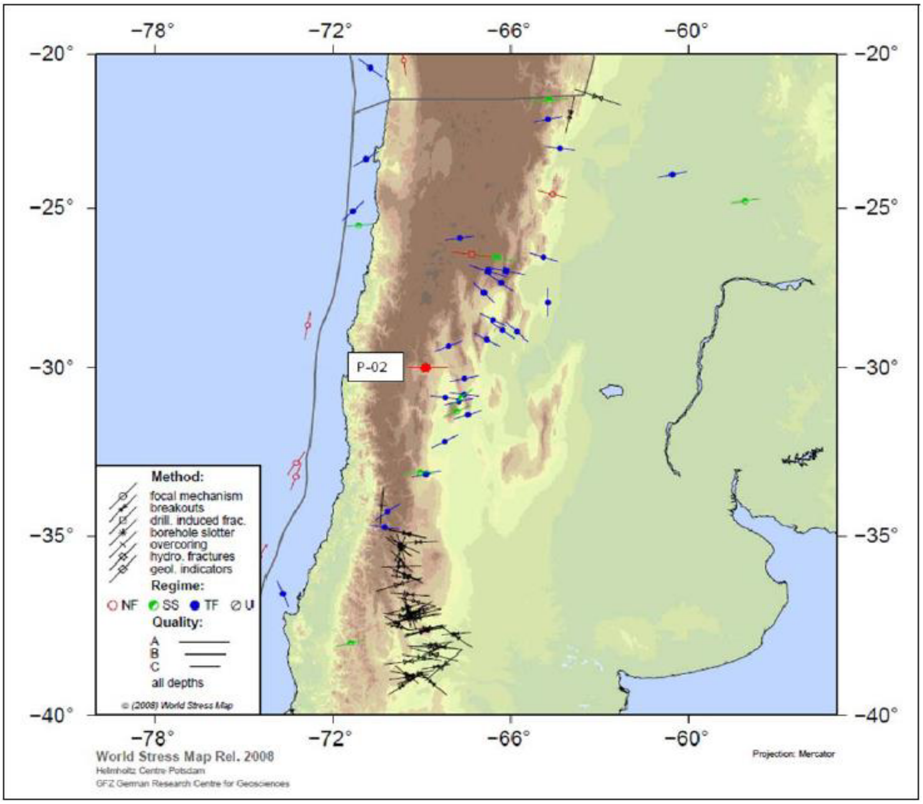

Figure 8. Location of borehole P-02 (red) and other measurement within the World Stress Map.

5. Relevance to the Project

Knowledge of initial stress state becomes critical when the excavations have great dimensions such as caves and when rocky cover is significant.

The general orientation of the tunnels is W-E coinciding with the direction of SH. This situation is favorable for the stability of the tunnels.

Instead, ventilation caverns are located transversely to the axis of tunnels and caverns sides may result in more stress. To remedy this situation, it should be optimized the shape and orientation within the constraints of the equipment.

6. Conclusions

- The stress state measured in the Cordillera Frontal is consistent with the condition defined by the Andean tectonics, where Nazca plate subducts beneath the South American plate.
- The survey indicated that surface paleostresses show the same regional trend. In addition, they are similar to those identified in the World Stress Map.
- Measurements made with hydraulic fracturing in a borehole between 500 and 800 meters deep, have confirmed that background.
- The orientation of the tunnels, essentially W-E, is favorable to the stability of excavations. However, ventilation caverns are in an unfavorable position and the design should be adequate to contemplate this situation.

Acknowledgements

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