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Assessment of the effect of hydraulic fracturing on overbreaking in horizontal developments, Andes Norte project, El Teniente mine

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Abstract

The Andes Norte project is the deepest project of the El Teniente mine and will extend its life span by adding 50 more years of exploitation. The development is still under construction and the mine design layout is based on a conventional panel caving exploitation method, with preconditioning by hydrofracturing above the caving level (upward) and below the production level (downward) being one of the main measures for the mitigation of seismic hazards and rockburst risk management strategy during production.

The construction plan for the initial sector of the project considered executing hydrofracturing below the production level at early stages of development. Consequently a large number of horizontal and vertical excavations in the eastern zone of the footprint were carried out in a rock mass previously hydrofractured.

This work will describe the methodology used for geotechnical ground control and the identification of hydraulic fractures at the tunnel scale, focusing on conducting a comparative analysis of the levels of overexcavations that have been generated in horizontal tunnels developed both inside and outside the preconditioned volume under similar geotechnical conditions.

Keywords: *overbreaking, geomechanical risks, hydraulic fracturing, tunnelling in high stress*

1 Introduction

The Andes Norte project is the deepest project currently under construction at the El Teniente mine and will begin operations this year (2024). The caving level is at an average elevation of 1,887 m, approximately 330 m below the Esmeralda mine and about 1,200 m below the surface topography.

This project involves a conventional exploitation method (panel caving), with a hydraulic fracturing (HF) process above the caving level (upward) and below the production level (downward) being one of the main measures to mitigate seismic hazards and the risk of rockbursts during the production stages.

One of the initial phase construction strategies of the project included performing HF below the production level before the execution of the initial polygon developments (in the eastern zone of the footprint, as shown in Figure 1). Therefore a significant amount of horizontal and vertical development was carried out in previously hydrofractured rock mass.

The Andes Norte project mining sector is located below Esmeralda, Pilar Norte and Reservas Norte mines, where their current cavities influence the pre-mining stress state. Increasing magnitudes are also consistent with the deepening.

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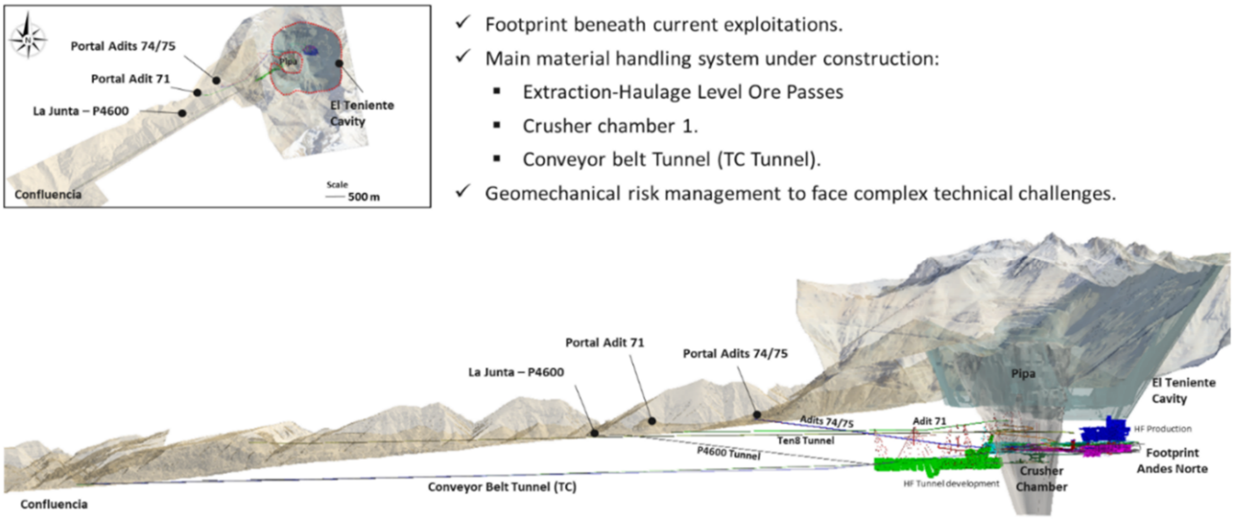


Figure 1 Andes Norte project. The footprint is located beneath current exploitations

In order to improve the understanding of pre-mining stress, the depth of the El Teniente mine numerical model was extended. This model represents results from an iterative process including calibrations against damage conditions, stress measurements, HF pressures, overbreaking and seismicity. Average principal stress magnitudes and orientations are described in Table 1.

Table 1 Pre-mining principal stress magnitudes (Balboa et al. 2017)

Principal stress	Magnitude (MPa)	Azimuth (°)	Plunge (°)
Major – S1	55–60	305–325	7–15
Intermediate – S2	40–46	34–52	5–30
Minor – S3	25–32	Sub-vertical	

This work aims to represent how the geological, geotechnical and structural surveys, and hydrofracture mapping, were conducted at the scale of the tunnels, particularly at the lower levels (ventilation sublevel and intermediate transport level). Subsequently it aims to compare the levels of overexcavation recorded both inside and outside the preconditioned volume, selecting developments with the same geotechnical conditions. These include lithology, the geotechnical zone (geotechnical modelling based on the frequency of veinlets with a majority filling of soft minerals), the shape and size of the excavation, the excavation method and the direction of advance.

2 Conceptual baseline

2.1 Hydraulic fracturing

The El Teniente mine HF conceptual model indicates that fracture propagation can be divided into three different stages, as shown in Figure 2 (Parraguez et al. 2009):

1. Hydraulic fracture initiation – fracture is initiated at two diametrically opposite points on the borehole surface, producing two unconnected fractures which are independently propagated. These fractures are parallel (or subparallel) to the borehole axis.
2. Intermediate propagation – after the initiation, fractures rotate to a plane perpendicular to the minor principal stress orientation (σ_3).
3. Stabilised propagation – fracture propagation tends to be symmetrical and radial around the original point.

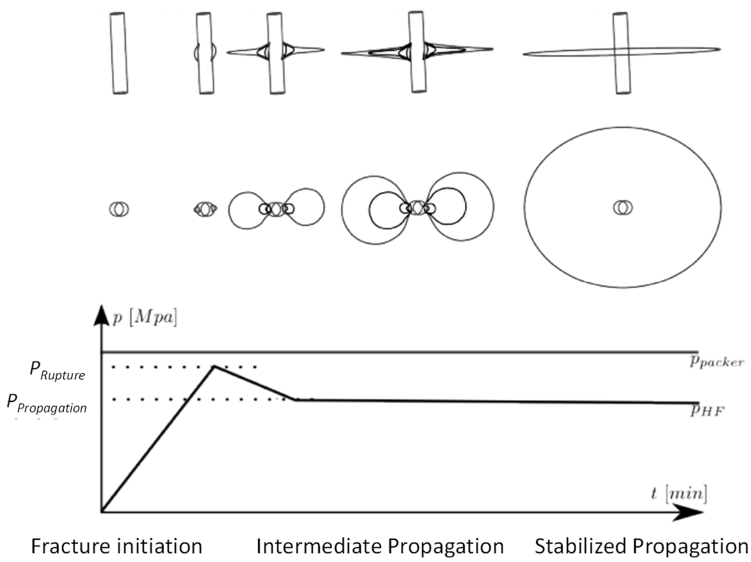
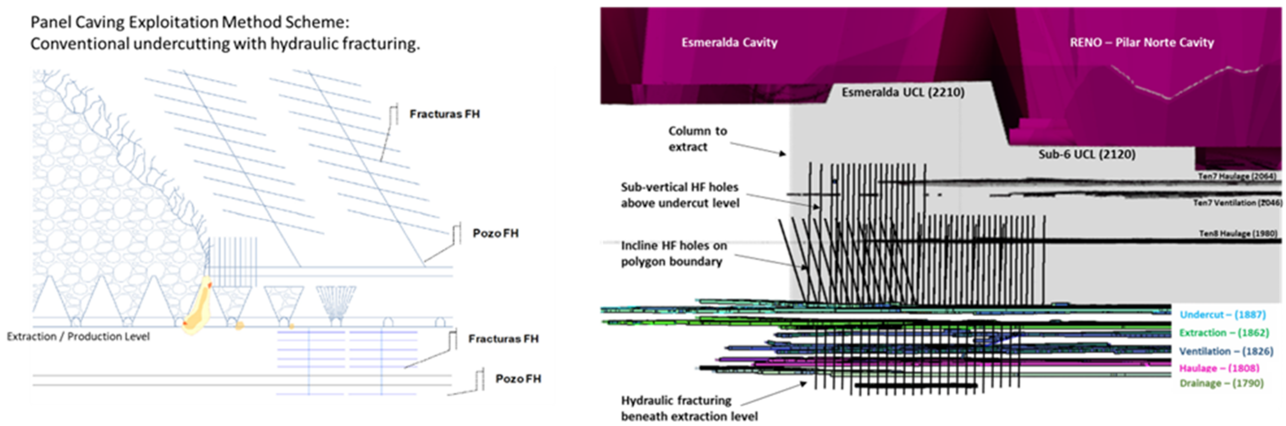


Figure 2 Conceptual stages for hydraulic fracture propagation (Parraguez et al. 2009)

Design considerations must include not only borehole orientations but a precise location for the fracture initiation and its relative position to the planned tunnel.

The use of HF in the exploitation method is defined as one of the main measures to mitigate seismic hazard for the production stage. The exploitation method considers the application of this technique above the caving level and below the production level. In the case of the Andes Norte project, for its initial polygon, its execution was planned early to minimise the interferences inherent to the activity and also to achieve the implementation of a more homogeneous design. The scheme of the exploitation method and the configuration of the initial zone of the Andes Norte project is presented in Figure 3. For this reason, in the initial footprint polygon there are developments that were excavated within volumes preconditioned with hydraulic fracturing.



(a) (b)

Figure 3 (a) A schematic of the exploitation method defined for the Andes Norte project (taken from Pardo & Rojas 2016); (b) The planned application for Andes Norte (taken from Landeros Córdova 2022)

Previous work has been conducted in the main infrastructure tunnel developments having a high risk of rockburst (Rojas & Landeros 2017, 2022), which allowed the identification of hydraulic fractures during tunnel construction and provided the opportunity to deepen the methodologies from a geotechnical perspective.

Inside the footprint area, with the development of tunnels at deeper levels (ventilation and intermediate transport levels) in previously hydrofractured rock mass below the production level, the hydraulic fracture planes begin to be identified. They are then mapped and entered into the project's geological-geotechnical database. Their main characteristics are rock matrix breakage and a sub-horizontal arrangement with dip angles less than 35° and, in some cases, they influence the geometry of the advance contour. Some examples and conditions for identification are provided in Figure 4.

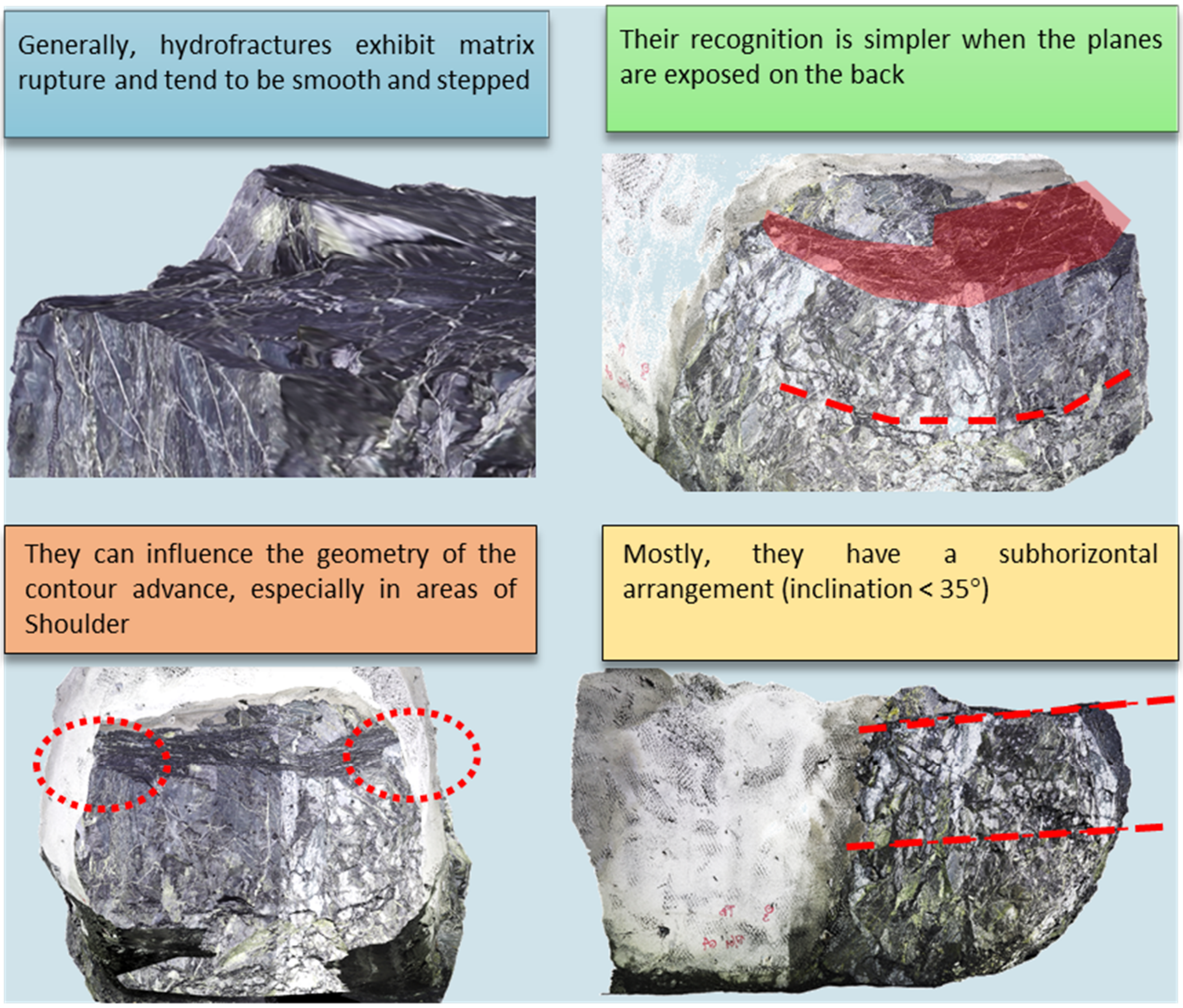


Figure 4 Morphology of hydraulic fractures observed and mapped in horizontal tunnels inside the footprint of the Andes Norte project

2.2 Overbreak

The definition used in this study for the term overbreak relates to the increase in the excavation section compared to the design section. The most common methods to record overbreak are: distance between the designed topographic profile and the measured field profile, areal difference between the design profile and the topographic measurement, and volumetric difference between the blasted volume and the final excavation volume.

Overbreak is a critical issue in any underground excavation, especially in complex geomechanical environments with high stress levels. This phenomenon involves the removal of more material than necessary, which can result in several drawbacks:

1. Increased costs and time – higher levels of overexcavation require additional volumes of fortification. This increases material and labour costs, and extends construction cycles, affecting project efficiency.
2. Threat to stability – overexcavation can compromise the stability of the original design, increasing the risk of collapses and structural failures. This is especially critical in areas with high stress levels, where the strength of the surrounding materials is essential to maintain the integrity of the excavation.
3. Safety issues – the additional instability caused by overexcavation can become a source of danger for workers and equipment, increasing the risk of accidents and damage.

In summary, overexcavation must be minimised through proper design and precise execution using advanced monitoring and control techniques to ensure that the material removed stays within the planned limits.

Overbreak control is carried out by ground control geotechnical teams, based on visual inspections, topographic measurements and photogrammetric surveys. The causes of overbreak are currently classified as follows:

- Operational – in photogrammetry (a 3D model of the advancing face is obtained after each blast), efforts are made to identify and log 'half barrels' in the database, which serve as evidence of the drill shots performed. The location of these half barrels relative to the design section helps to determine if there were any deviations in the drilling process. As a result, overbreak is attributed to operational causes (Figure 5). In the case of the Andes Norte project, deviation is considered when the values exceed 0.4 m.

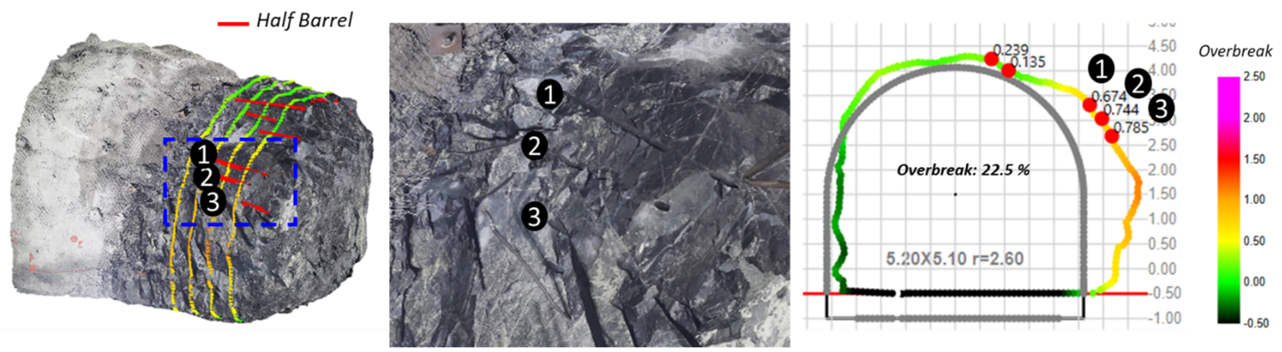


Figure 5 Example of the recognition of half barrels and determination of operational overbreak

- Stress conditions – it is attributed to conditions of greater stress anisotropy and in conditions with higher stress levels. It is complemented by other indicators such as breakouts in drilling and seismicity records, as appropriate (Figure 6).

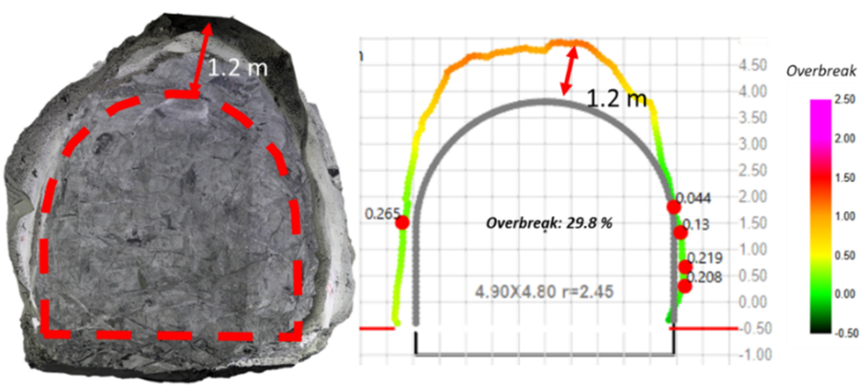


Figure 6 Example of a case of overbreak conditioned by high stress levels

- Geometries controlled by discontinuities – in this case, geometries controlled by geological structures (identifiable by containing fillings) are distinguished, as well as those controlled by mechanical fractures induced by the preconditioning process of HF (Figure 7).

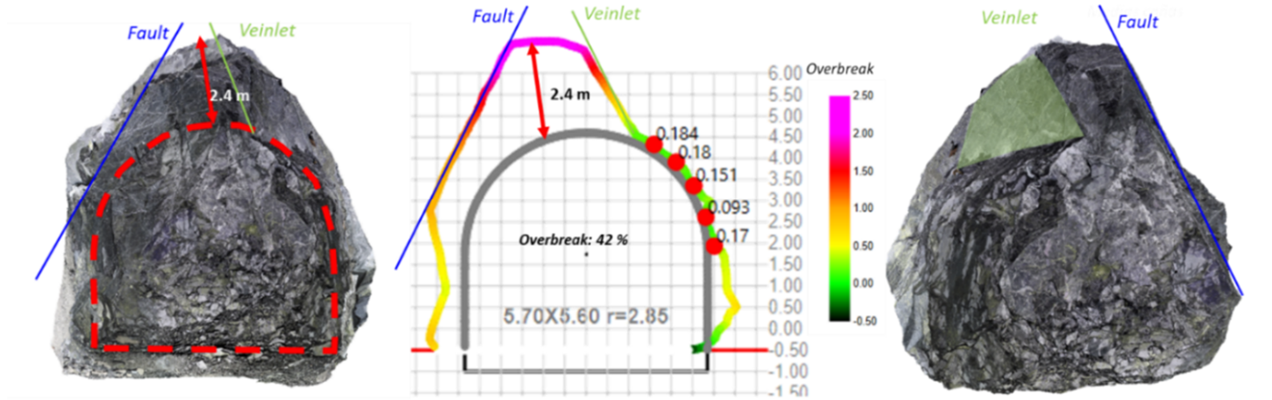


Figure 7 Example of a case of structural overbreak where the presence of faults and veinlets controls the geometry of the excavation

A scheme of the classification used is presented in Figure 8.

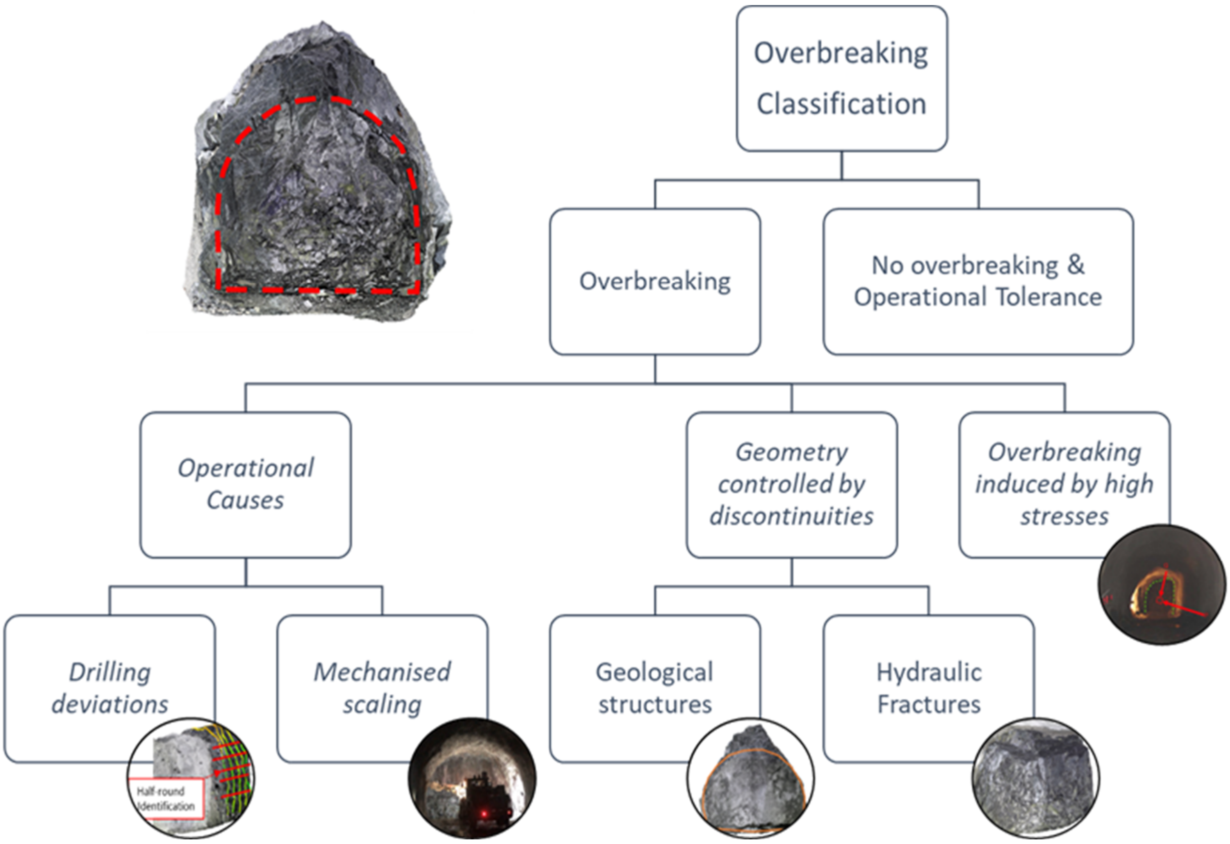


Figure 8 Overbreaking classification based on different most-probable causes

3 Geotechnical characterisation and data

The workings chosen for analysis and comparison of their levels of overbreak are located in the ventilation sublevel (elevation 1825) and intermediate transport level (elevation 1808). In the first case approximately 900 linear metres were developed in a rock mass previously preconditioned with hydraulic fracturing, and a total of 187 hydraulic fracture planes were recognised. In the second case about 1,000 linear metres were developed under the same conditions, with a total of 171 fracture planes observed. Figure 9 shows an overview of the layout of the levels and the galleries selected for analysis. At each level a comparative analysis was conducted between galleries within the preconditioned volume and those outside it.

In relation to the lithological bodies located in the analysis area, the El Teniente Mafic Complex (CMET) predominates. Located east of the dioritic porphyry intrusive bodies, this unit is characterised by abundant veinlets comprised mainly of chalcopyrite, pyrite and anhydrite, which are associated with the main hydrothermal alteration zone.

In the ventilation sublevel, analysis is conducted on a section of dioritic porphyry which corresponds to a series of felsic intrusives located in the central portion of the mining polygon of the Andes Norte project, and also to a section of igneous breccia of dioritic porphyry. This unit is preferably located at the contacts between the dioritic porphyry and the rocks of the CMET. It is characterised by presenting thicknesses ranging from a few centimetres to tens of metres. It regularly consists of a felsic matrix of dioritic porphyry with sub-angular fragments predominantly of mafic rocks belonging to the CMET.

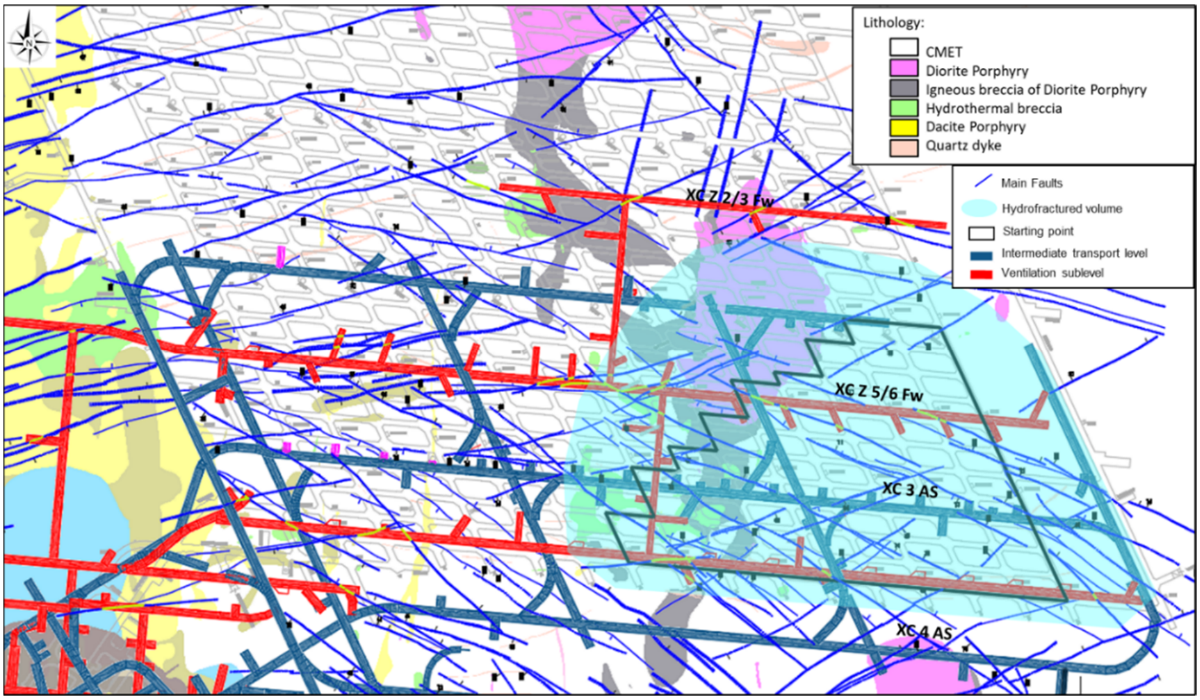


Figure 9 **Layout plan view. All the galleries have the same orientations. Two galleries within the preconditioned volume were compared with two galleries outside the volume**

For the analysis, the data indicated in Table 2 were considered. Additionally it was verified that the advance lengths for each development blast were comparable, as shown in Figure 10.

Table 2 **Summary of datasets used for the analysis**

Level	Excavation ID	Condition	Datasets
Ventilation level	XC Z 2/3 Fw	Outside hydraulic fracturing volume	62
	XC Z 5/6 Fw	Inside hydraulic fracturing volume	57
Haulage level	XC 3 AS	Inside hydraulic fracturing volume	63
	XC 4 AS	Outside hydraulic fracturing volume	69

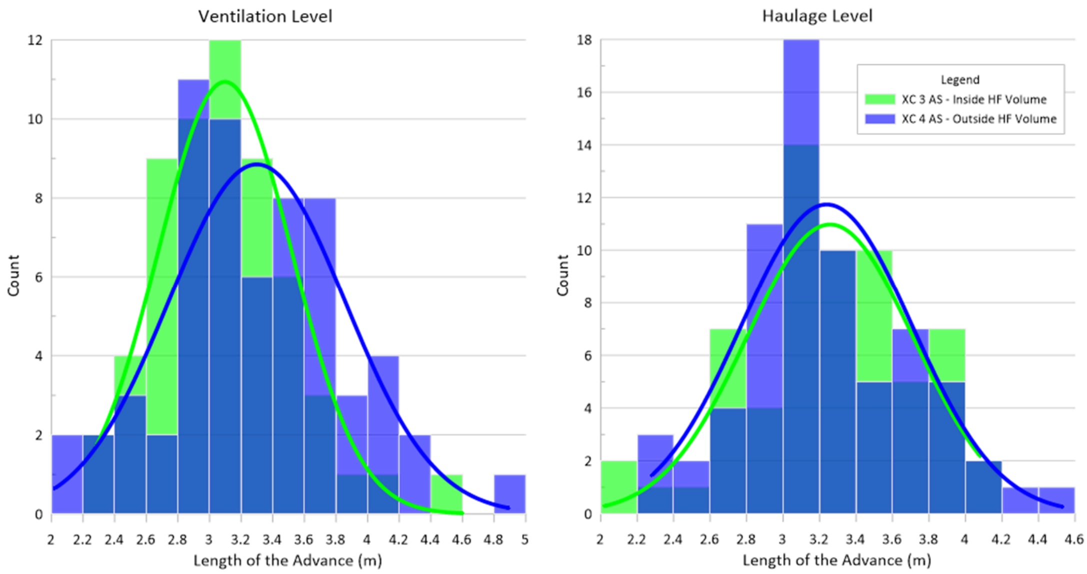
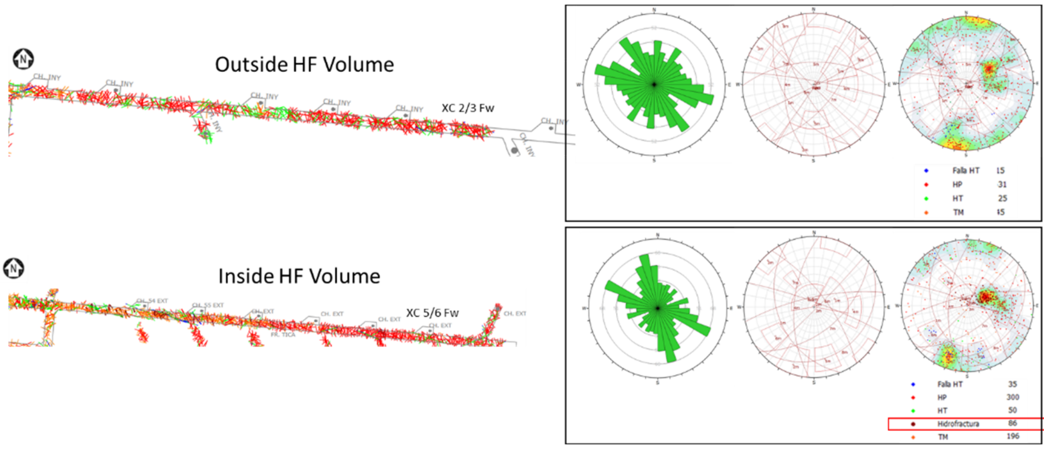


Figure 10 Statistical analysis of the advancement lengths in the datasets used

3.1 Structural analysis

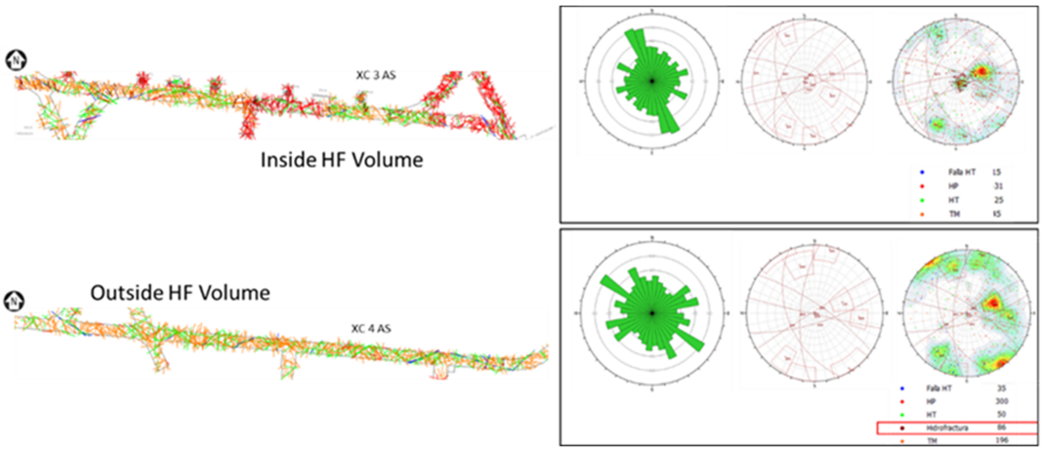
The structural geological mapping is carried out using stereophotogrammetric techniques (Benado 2010) which provide higher precision for the analyses. For the case of the ventilation level, the integrated pole analysis is shown in Figure 11. Figure 12 shows the case for the haulage level.



Sets	Dip	Dip Direction
1	44	238
2	84	10
3	87	124
4	46	274
5	55	359
6	87	224
7	56	127
8	87	153
9	72	239

Sets	Dip	Dip Direction
1	35	248
2	82	20
3	86	135
4	58	274
5	74	348
6	69	53
7	51	141
8	18	147

Figure 11 Pole density plot for the ventilation level. Two sets were classified as hydraulic fractures



Sets	Dip	Dip Direction
1	47	248
2	11	282
3	73	23
4	79	158
5	80	353
6	49	295
7	87	314

Sets	Dip	Dip Direction
1	47	248
3	75	34
4	73	163
5	88	193
6	66	274
7	87	328

Figure 12 Pole density plot for the haulage level. One set was classified as a hydraulic fracture

The recognised hydraulic fracture planes present a sub-horizontal disposition in both levels of the footprint with an inclination less than 35°. It agrees with the dip of the theoretical propagation orientation of 7°/335° (dip/dip direction), but there is a variation when considering the strike of the fracture planes. When conducting detailed tracking of the hydraulic fracture planes, especially those positioned on the tunnel roof, a certain sinuosity is observed, which may affect the variability of the strike while maintaining horizontality.

3.2 Overbreaking results

This study involved a statistical comparative analysis of overbreak levels in tunnel excavation inside and outside HF zones. To ensure a precise comparison and to eliminate absolute differences between datasets, standardisation using z-scores has been employed. This technique normalises the values to fairly assess the distributions under both conditions and highlight differences in data variability and centralisation, providing a clearer and more objective view of the effects of HF under similar excavation conditions.

For the analysis conducted in the ventilation level, overbreak testing was carried out for 62 advances in XC Z 2/3 Fw, which is outside the hydrofractured volume. For XC Z 5/6 Fw, 59 overbreak analyses were performed in previously hydrofractured rock mass. While the overbreak mechanisms are different, in both tunnels the undetermined and operational conditions presented practically the same percentages, with the structural mechanism being the most relevant at over 60%.

The data analysis shows no trend to indicate that tunnelling in previously hydrofractured rock mass presents higher levels of areal overbreak, especially in the CMET lithology. This is summarised in Figure 13.

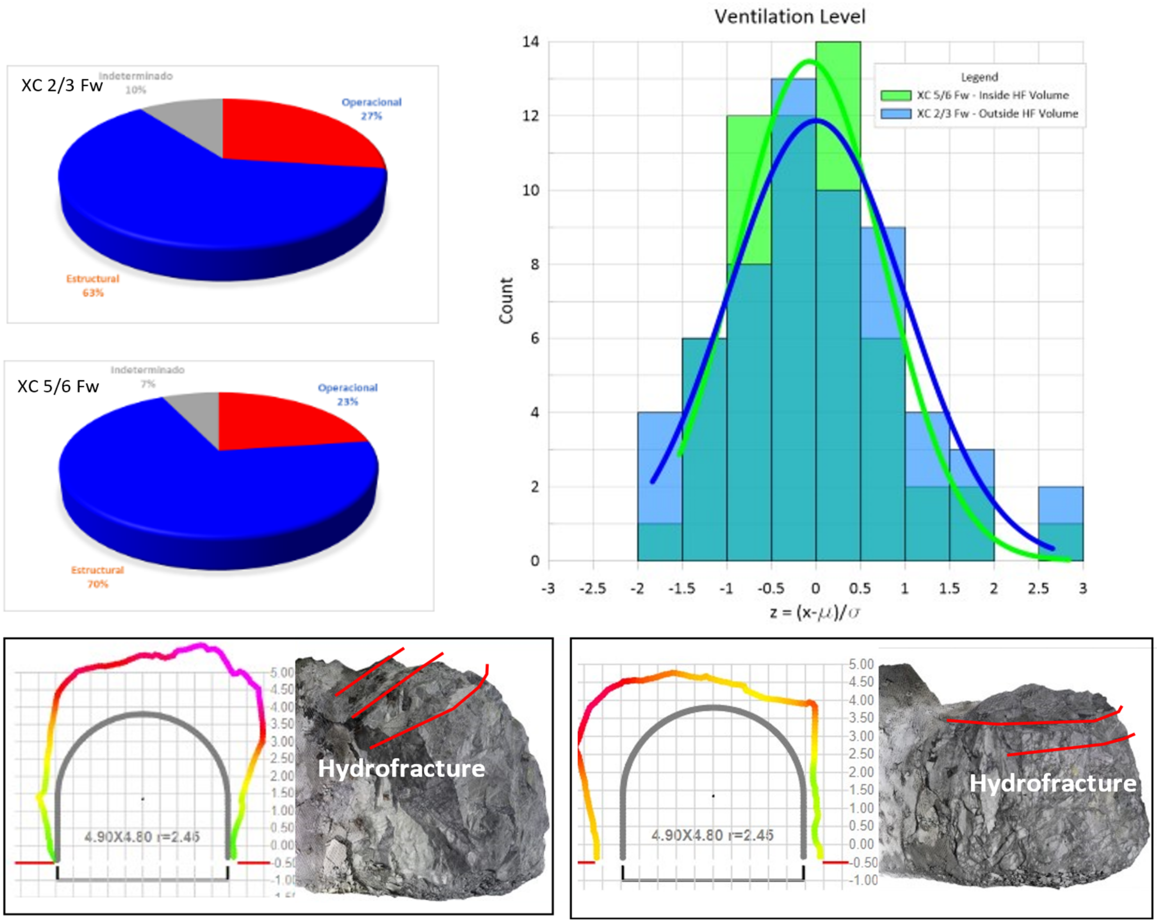


Figure 13 Summary of measured overbreaking for the ventilation level

In the case of the analysis conducted in the intermediate transport level (elevation 1808), overbreak testing was performed for 63 advances in XC 3 AS in previously hydrofractured rock mass, and for 69 advances in XC 4 AS outside this volume. Both excavations are located in the CMET lithology.

Similar to the observations from the ventilation sublevel analysis, the overbreak mechanisms are different but their distribution is similar, with the structural mechanism being the most relevant as accounting for over 66% of the cases. Therefore this is not considered a factor that could affect the comparison. The summary of the results is presented in Figure 14.

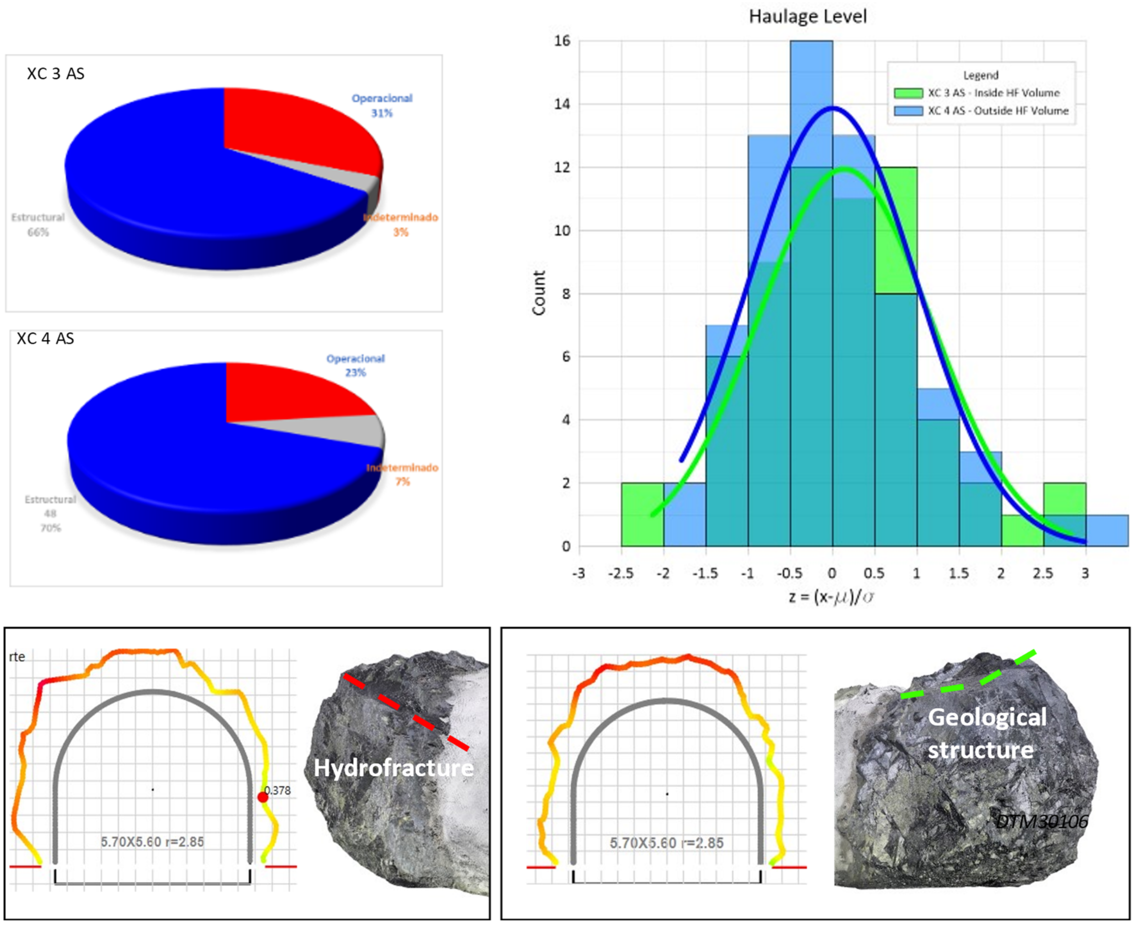


Figure 14 Summary of measured overbreaking for the haulage level. Some examples with relevant overbreaking are shown with both hydrofracture and geological structure conditions

Like the case of the ventilation level, there is no significant difference in overbreak levels between excavations inside and outside HF zones at the haulage level. HF does not appear to increase the overbreak levels in the galleries. Structural overbreak mechanisms are the most relevant in both conditions, suggesting that prior HF is not a determining factor in the increase of overbreaking.

In all cases the operational measures sought to reduce overbreak values include increasing control over drilling deviations in contours with an emphasis on proper drilling parallelism, reviewing the drilling parameters of the equipment, and modifying the blasting diagrams by adjusting the positions of the initial free faces based on the geotechnical and structural geological conditions.

4 Discussion

When comparing tunnels with similar geotechnical conditions in volumes of hydrofractured and non-hydrofractured rock mass, it is possible to determine that this process does not result in increased levels of overbreak. Of all the sectors analysed, only in some specific cases were high overbreak values conditioned by hydraulic fracture planes found.

Furthermore, in some cases a high frequency of hydraulic fractures at a face does not influence the geometry of the advance. This can be seen in the Figure 15 example, where the advance was made in XC Z 5/6 Fw near an HF injection point. The final geometry was not primarily influenced by this situation.

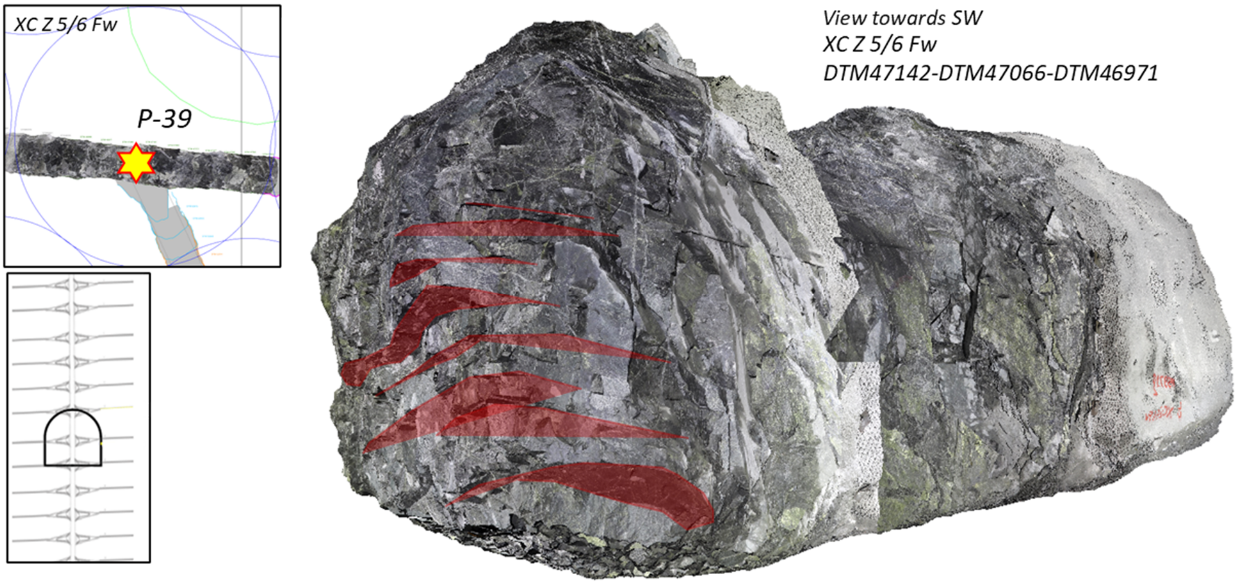


Figure 15 Progress of development along the axis of the hydraulic fracturing well. A large number of hydrofracture planes which did not affect the contour advance geometry are observed

5 Conclusion and remarks

The comparative analysis between tunnels developed within and outside of hydrofractured volumes demonstrated that HF does not lead to a significant increase in overbreak levels. This suggests that the technique is effective for preconditioning the rock mass without compromising structural stability in horizontal developments.

The use of HF in the Andes Norte project is an effective measure for mitigating seismic risk and rockbursts. The identification and mapping of hydraulic fracture planes allow verification of the condition of the rock mass and assurance that the process has been carried out correctly.

The predominant lithology, specifically the CMET, showed that the presence of hydraulic fractures does not significantly affect overbreak. This indicates that the geotechnical characteristics of the rock mass play a crucial role in the response to hydraulic fracturing.

Regarding the impact on the advance geometry, the high frequency of hydraulic fractures in some advance faces did not condition the final tunnel geometry. This suggests that the orientation and disposition of the hydraulic fractures do not decisively influence overbreak, despite the observed orientations allowing for the mobility of blocks near the face. This requires the installation of permanent support near the face, with deeper anchoring depths, early in the construction process. The results obtained support the need to adhere to defined support and operation designs, thus minimising the risks associated with overbreak.

Acknowledgement

The authors wish to thank all the people involved in the HF process at the Andes Norte project, especially the members of the geotechnical team, who have closely monitored the entire process. Finally, thanks go to Codelco for providing the authorisation to publish this paper.

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