Caving 2022 - Y Potvin (ed.)

doi:10.36487/ACG_repo/2205_85

Hydraulic fracturing in the construction of Andes Norte Project

R Navarrete *Codelco, Chile*

C Soto *Codelco, Chile*

F Henriquez *Codelco, Chile*

H Godoy *RyQ, Chile*

Abstract

After 117 years of existence, Codelco's flagship El Teniente mine aims to expand its service life by more than 50 years, increasing the deposit taking advantage of Andes Norte Project (PAN, in Spanish). The Project amounts to 2,020 billion tons of reserves, with an average copper grade of 0.86% and an average molybdenum grade of 0.022%, which is translated – within a period of operation through 50 years beginning in 2018 – into more than 17 million tons of fine copper. The Project configuration considers mining through the panel caving, with 100% of the area preconditioned with hydraulic fracturing (HF) and a levels scheme, typical of El Teniente mine site: undercutting level (UCL), production level, ventilation level, haulage level and crushing level.

This document provides a foundation from the results obtained in the preconditioning activities carried out through HF in the PAN, run by the Project's Vice-presidency (VP), in El Teniente Division, Codelco Chile. The scope of this work considers the development of ascending and descending drillholes and their subsequent preconditioning through HF, applied to the footprint zone. The objective was initiating caving and its propagation. It includes a description of the HF operation development, the stresses resulting from its development, as well as lessons learned and some problems solved during its application. This paper has been written by the construction engineering team that led the development.

Keywords: *hydraulic fracturing, Andes Norte Project*

1 Introduction

Andes Norte Project (PAN, in Spanish), which is due to start operating in 2023, has defined the implementation of ascending and descending hydraulic fracturing (HF) in a systematic manner in the mining polygon (Cifuentes at al. 2019).

"Massive implementation of HF of the rock column to be mined (at least 100 m) as well as in selected areas of the rock mass volume under the production level with the conventional devaluation variant. The abutment stress has the same characteristics as for the conventional variant. HF reduces the seismic hazard risk and, in turn, lowers the impact of seismically-driven dynamic stresses on the pillars. Seismicity is almost exclusively triggered and controlled by the area commissioning in production (drawbell commissioning and undercut blasting), which facilitates the implementation of efficient post-blast re-entry criteria" (Pardo & Rojas 2016), as seen in Figure 1.

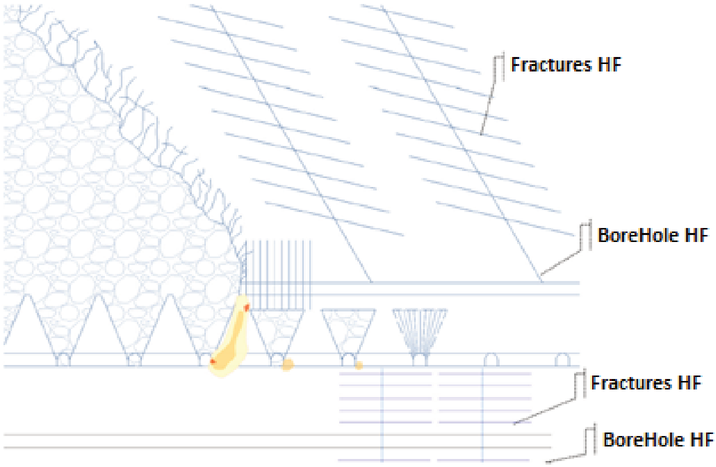


Figure 1 Panel caving conventional undercutting with HF (2010–2015) (Pardo & Rojas 2016)

It has been demonstrated that the benefits related to the application of this technology are the following: Better seismic response from the solid rock, increase in the low magnitude seismicity; increased caveability, facilitating the caving process; varied tendencies in fragmentation size; and improvement in operational indexes in areas where applied. Furthermore, it has been verified that it enhances caving propagation rate, allowing to increase the draw rate in primary ore, as well as lowering the risk of hang-ups and the probability of air blast generation (Codelco 2017).

"Andes Norte Project has relatively similar geotechnical conditions to those found in the upper levels of El Teniente mine (i.e. Esmeralda), however, the stress levels are higher. These conditions make the application of the crinkle cut variant impractical. The preconditioning strategy of Andes Norte Project needs to include HF, including the current industry best practices. Conventional undercutting with HF has helped to control seismicity and provides the required flexibility to ensure the mining continuity in an area. As a result, the implementation of this process is recommended for the conditions expected to prevail at the PAN to ensure that the production commitments stated in the project are fully met." (Pardo & Rojas 2016). The HF application is the main measure to mitigate seismic hazard for the caving process. The technique must be implemented at high compliance regarding fracturing, within the defined volume, considering the current experience of El Teniente mine site.

The PAN mining variant is a conventional undercutting with HF above the undercutting level and under the production level, as shown in Figure 1 (Acre at al. 2022).

2 HF scope in Andes Norte footprint

Table 1 shows the scope of requested boreholes to start the caving in the PAN footprint. It indicates the amount of boreholes to be fractured to achieve the correct execution of preconditioning through HF, in addition to the average length (m) and the difference in the amount of descending and ascending boreholes.

Table 1 Initial HF scope in PAN

From	Area	Boreholes	Amount of boreholes (units)	Borehole average length (m)
Undercutting level	Footprint	Ascending	68	160
	Footprint	Descending	59	70
Production level	Footprint	Descending	8	54

Among the activities prior to preconditioning through HF, it is required to drill and recover diamond drillholes. Then, in some boreholes, and due to the operation's proper way of underground mining, grouting was required in the boreholes (mainly descending holes), then they were redrilled, and finally preconditioning through HF was applied.

3 Andes Norte footprint HF background

Figure 2 indicates the caving initiation point in the PAN, which has an area of 25,000 m^2 and a growth zone of 60,400 m^2, adding up to a total of 85,500 m^2 of the zone to be preconditioned was defined in the investment stage of the NNM Project. Additionally, there is a borehole fence zone in the east and south boundary of both zones, aiming to create a seismic protection for infrastructure and personnel at the production level.

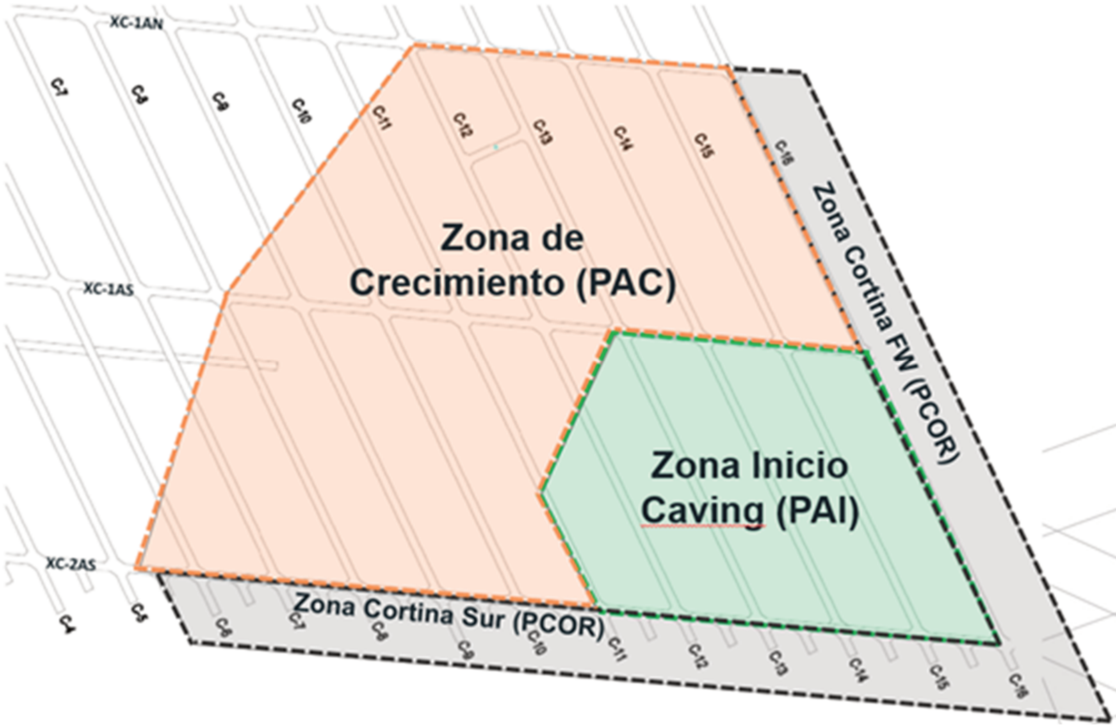


Figure 2 Location of caving initiation point, growth and borehole fences in PAN (Cifuentes at al. 2019)

3.1 Ascending boreholes design

For the PAN, there is a total of 68 ascending boreholes for the caving initiation point, as shown in Figure 3. They are divided into caving initiation point (PAI), growth zone (PAC) and borehole fence zone (PCOR) (Figure 2). Table 2 shows the borehole identification, its length and general characteristics. Figure 2 shows the general layout of ascending boreholes as in Figure 1, with the location of the ascending boreholes.

Table 2 Borehole by zone

Zone	Hole ID	Borehole number	Azimuth (°)	Inclination (°)	Length (m)	Distance between HF (m)	Fracture radius (m)	Number of fractures (m)
Caving zone	PAI	21	77	85	200	1.5	20	130
Growth zone	PAC	32	0	90	140	1.5	30	90
South borehole fence zone	PCOR	15	178.5–191	67–73	140	2.0	30	67
Borehole fence zone FW	PCOR		70–90	76–70	140	2.0	30	67

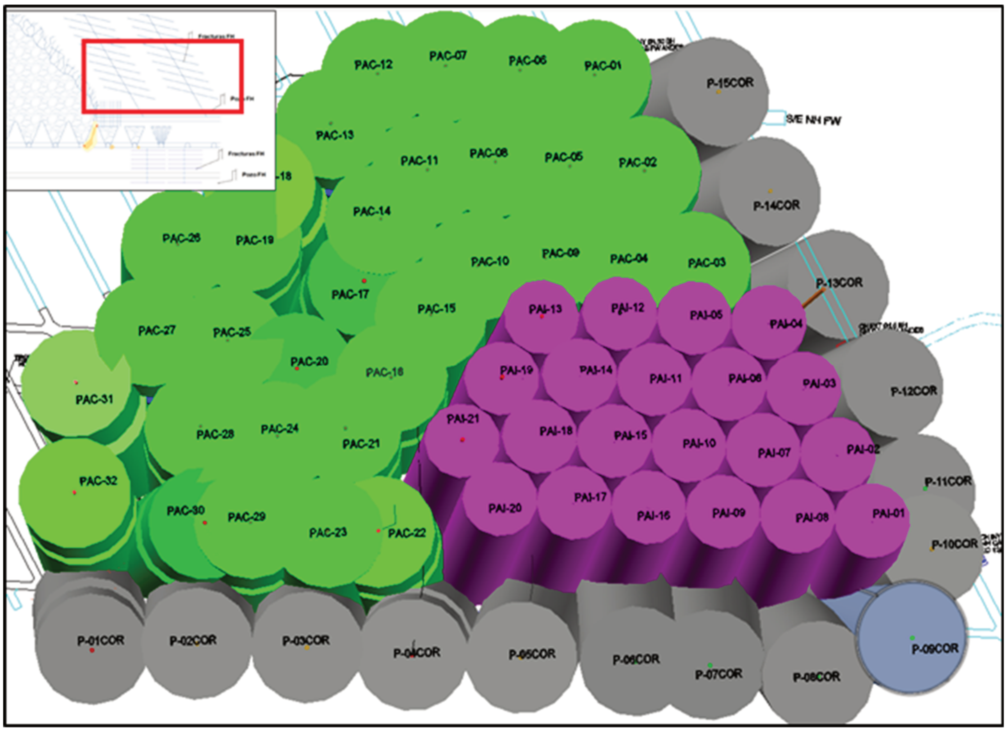


Figure 3 **3D view of ascending boreholes and volume to be fractured as in Figure 1 (DGEOT VP design 2022)**

3.2 Descending boreholes design

In addition to the previous point, the initial design for preconditioning through HF totalled 59 descending boreholes. During the HF execution, a morphology test was carried out on the design of the descending boreholes (VP Internal Note 2016), which resulted in an increase in its fracturing radius from 20–30 m, which in turn was translated into re-designing, as indicated in Figure 4. This figure shows the location of descending boreholes (Figure 1).

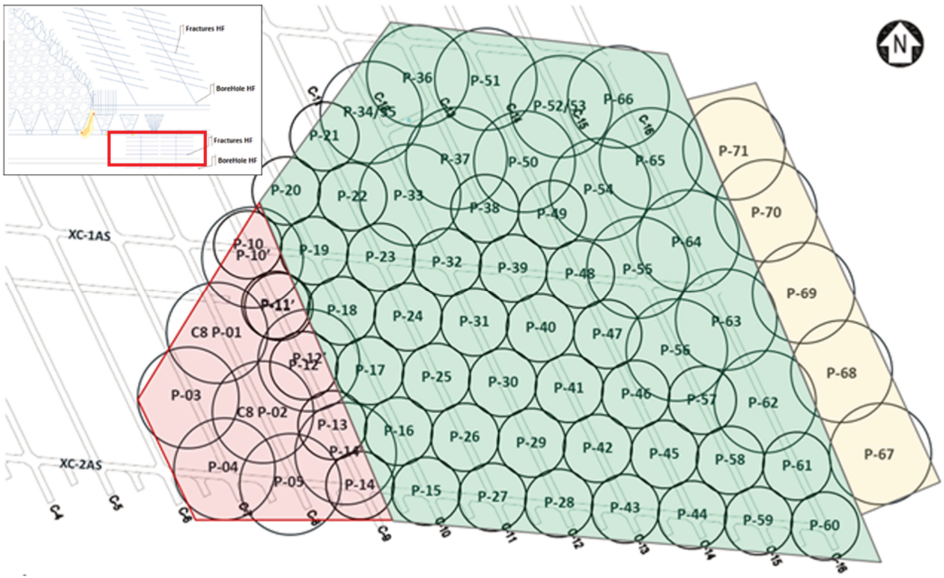


Figure 4 Current design of descending boreholes in PAN, as in Figure 1 (VP Internal Note 2016)

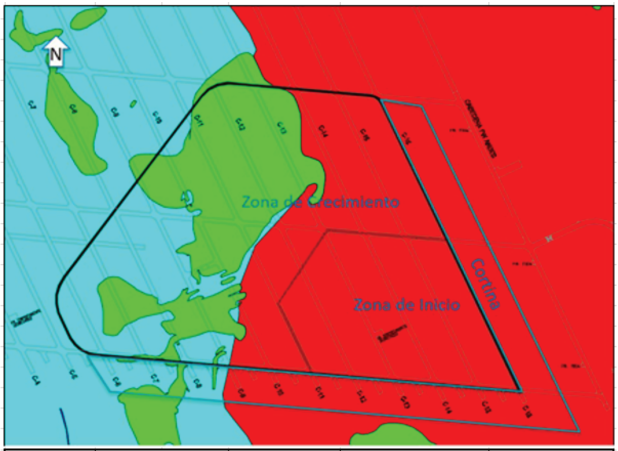
Table 3 shows the current general design of descending boreholes for HF divided in west (HW), east (FW) and central zones.

Table 3 Current design of descending boreholes in PAN

Zone	Azimuth (°)	Inclination (°)	Length (m)	Distance between fractures (m)	Fracture radius (m)	Number of fractures (units)
HW zone	267–287	-71	141	3	20	30
Central zone	245	(-83)–(-90)	91	3	20–30	21
FW zone	78–242	(-32)–(-72)	96–103	3	30	21–23

3.3 Geotechnical characterisation

The Andes Norte geotechnical characterisation has the same characteristics observed in the production sectors of Reservas Norte, Pilar Norte and Esmeralda, located immediately next to Andes Norte area (GRMD Internal Note 2017). Figure 5 shows the geotechnical zoning plan view at elevation 1887, along with the undercutting level layout of Andes Norte sector. From Figure 5, it can be observed that the initiation point area is located in a regular quality geotechnical zone and with a really good drilling quality (VP Internal Note 2016), while the growth zone is located in a regular to good quality geotechnical zone with regular to good caveability characteristics.



Color	Geotechnical Unit		Relative Sinking	Relative Fragmentation	Geotechnical Quality
	Roca Primaria	Zone 1	Very Bad	Very thick	Very Good
		Zone 2	Bad	Thick	Good - Very Good
		Zone 3	Regular	Regular	Good - Very Good
		Zone 4	Regular - Goog	Regular	Regular - Good
		Zone 5	Good	Fine	Regular
	Secondary Rock		Very Good	Very Fine	Very Bad

Figure 5 Geotechnical model at elevation 1887 undercutting level (VP Internal Note 2016)

3.4 Estimated stress state

A pre-mining stress condition has been estimated for the Andes Norte PAN sector (Table 4). For the estimation, stress measurement data have been considered in the PAN footprint and at currently mined levels, with measurements of HF propagation in the alignments of the west side of the pipe, and cavities geometry measurements, in addition to three-dimensional numerical modelling (Arce et al. 2020).

Table 4 Andes Norte Project pre-mining stress condition (VP Internal Note 2016)

Main Sigma	Magnitude (MPa)	Azimuth (°)	Inclination (°)
σ_1	60	320–340	(-5)–(-15)
σ_2	45	50–70	(-10)–(-20)
σ_3	30	77	(-75)–(-90)

3.5 HF technical requirements

For the development of preconditioning through HF in PAN, two sets of rock hydrofracturing equipment or systems are required, with their proper control room, operating at a high pressure and flow rate capacity. Their main characteristics are:

- Flow rate: 377 l/min.
- Maximum pressure: 77 MPa (770 bar).
- Power: 480 kW.
- Voltage: 575 V.
- Frequency: 50 Hz.

3.6 HF process description

The process starts with drilling, from where samples are taken for the HF preconditioning process. It then continues with the installation of the hydraulic pump and then utilities are connected (water, air and electric power), in order to initiate the entry of the steel rod string and packers into the design position for HF, and the HF preconditioning proceeds. After this, the process continues according to Figure 6.

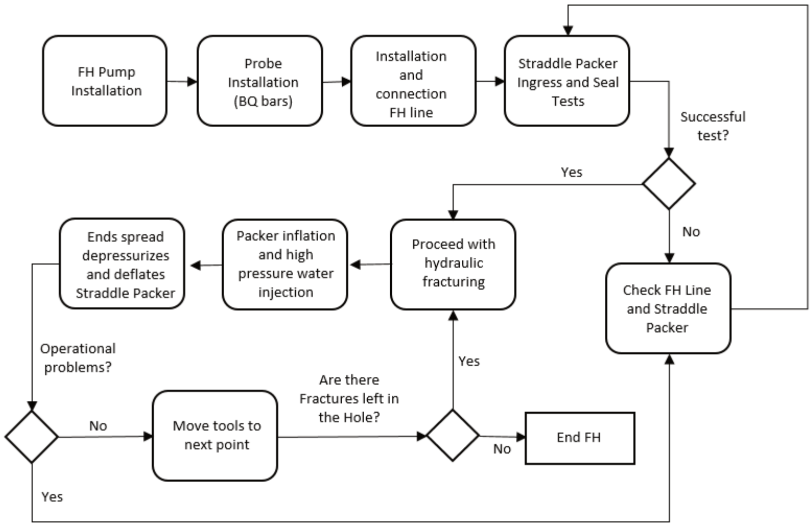


Figure 6 Conceptual map of the hydraulic fracturing process

One of the most important design input parameters is the minor principal stress orientation because HF boreholes must be as parallel as possible in order to achieve a better performance from the fracturing process. The conceptual model indicates that the fracture propagation can be divided into three different stages (Rojas & Landeros 2017), see Figure 7. (i) Hydraulic fracture initiation: A fracture is initiated at two diametrically opposite points on the borehole surface, creating two unconnected fractures, which are independently propagated. These fractures are parallel (or sub-parallel) to the borehole centreline. (ii) Intermediate propagation: After the initiation, fractures rotate to a plane perpendicular to the minor principal stress orientation (σ_3). (iii) Stabilised propagation: Fracture propagation continues until the end of the water injection (Rojas & Landeros 2017).

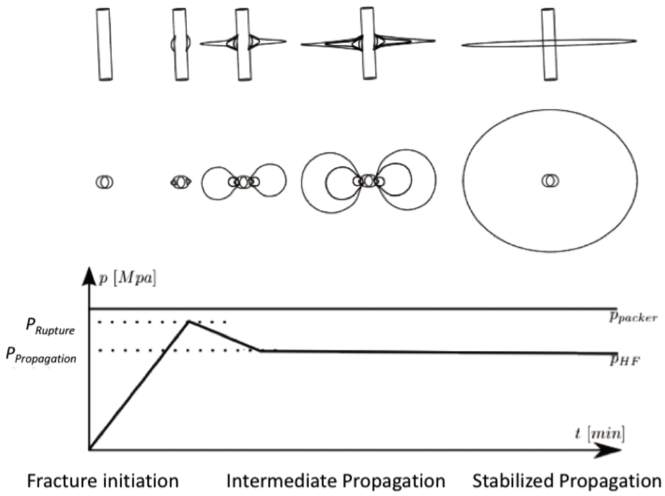


Figure 7 Conceptual stages for hydraulic fracture propagation (Parraguez et al. 2009)

The review of pressure records documenting each HF injection is carried out regularly with the aim of ensuring the preconditioning volume compliance, as well as the validation/rejection of fracturing quality. This is presented for each fracturing injection by the pressure records, as shown in Figure 8. According to the technical bases, it is a must to ensure the compliance of the following parameters: (a) Injected flow rate (lt/min), (b) Time (min), and (c) Pressures (MPa).

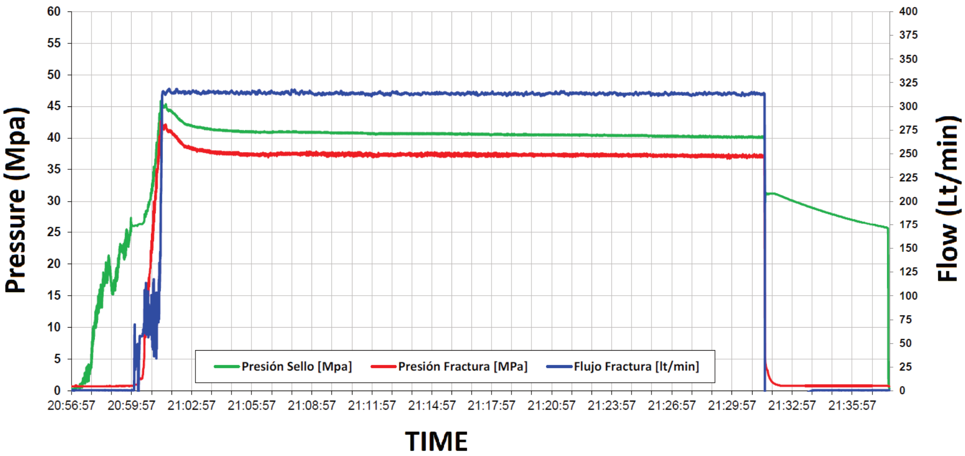


Figure 8 Typical pressure chart depicting packer seal pressure, fracture pressure and fracture flow rate

Due to the induced seismicity produced by energy release of the solid rock, surrounding works are segregated as a protection measure with an isolation halo of 60 m in diameter around the location of each HF location. Additionally, because of high pressures running from the pump to the fracturing point through high pressure hoses, it is necessary to isolate the sectors through which the circuit is routed.

4 Andes Norte HF operational information

4.1 Current state of HF in Andes Norte footprint

The progress was reviewed for the current state of preconditioning through HF in the PAN. The descending boreholes were completed and the ascending boreholes are presented as the ratio between what was requested in the design versus the physical progress. The boreholes for ascending HF show a 36% physical progress.

4.2 Current state of descending HF

The HF sequence in descending boreholes can be observed in the X axis on Figure 9. The Y axis shows the days that it took to carry out the HF operation; the required amount of fracturing by design and the effective fractures are shown on the secondary Y. The first borehole was P14, injected in August 2018, with 35 fractures by design and 14 effective fractures. On the other hand, the last descending borehole was P12’, which started on 26 April 2022 and ended on 29 April 2022, thus concluding the descending HF operation in the PAN. The pumps used for HF were ConMico and Hammelmann dual plunger pumps.

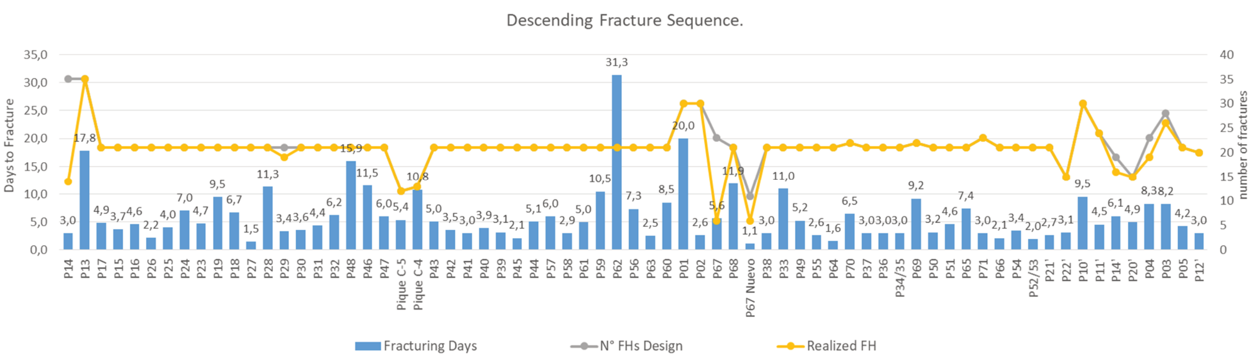


Figure 9 Descending hydraulic fracturing sequence at PAN

4.3 Ascending HF current state

The HF detail for each of the ascending boreholes are indicated in Figure 10. The pumps used for HF were, as with the descending boreholes, ConMico and Hammelmann dual plunger pumps.

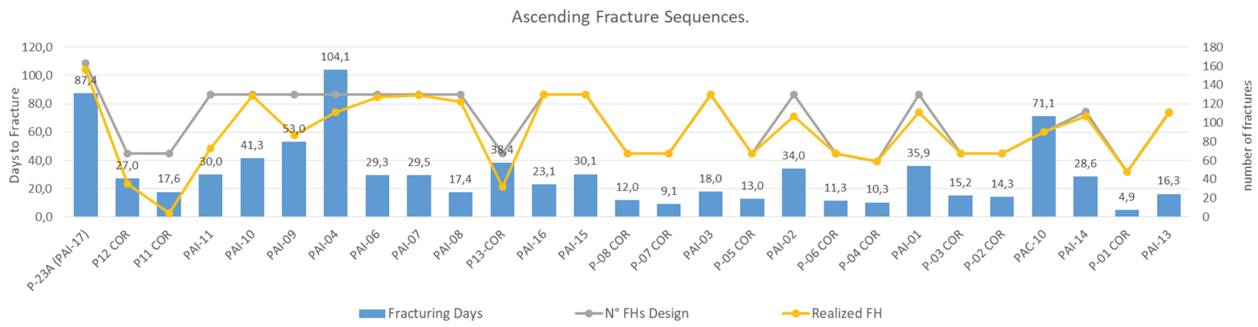


Figure 10 Ascending hydraulic fracturing sequence at PAN

Figure 11 shows the total of boreholes completed in the PAN with each percentage of HF.

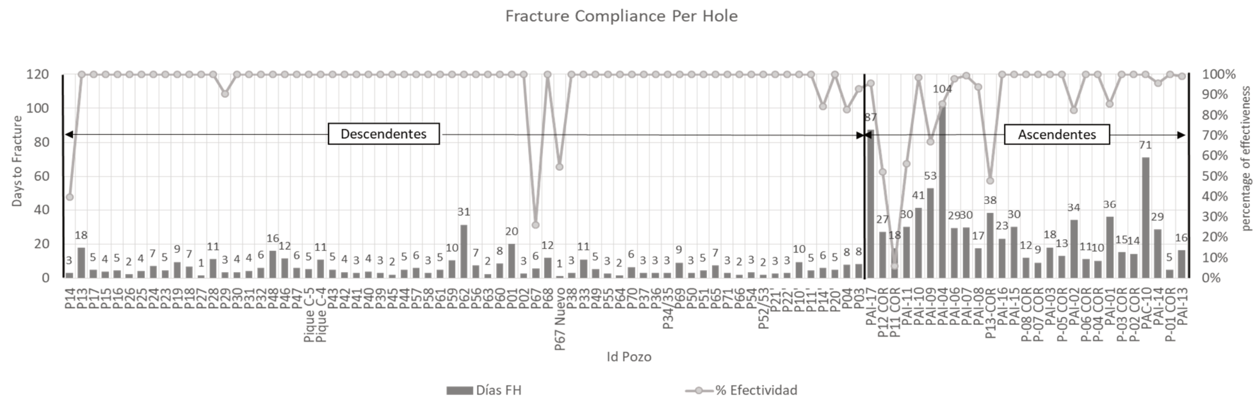


Figure 11 Percentage of fracturing compliance by borehole in Andes Norte Project

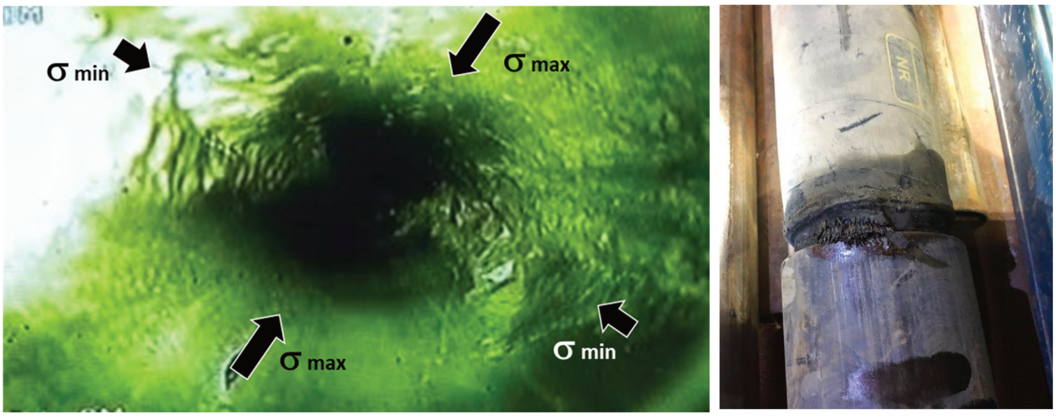
4.4 Operational issues

During the development of preconditioning by HF, a series of operational issues arose, which had an impact on deadlines and thus on development-associated costs. Among these, the following were observed:

- *Packer failure:* Packers are tools for sealing the fracturing section. They require high pressure hoses for inflation. At the operation it is normal to find failures in these elements due to material wear, seal breakage, packer rubber tearing, overbreak in descending boreholes, etc. One of the integrated processes, especially in descending boreholes, was to reduce packer rupture with cement grouting and re-drilling.
- *Packer entrapment:* During the HF operation it is frequent to find cracks in the borehole where the packer gets stuck along with all the injection rods. This event requires a series of activities for recovering all the injection rods before resuming the fracturing process, which entails time to clear the rod system, and the subsequent operational loss.
- *Overbreak in borehole walls:* Due to the borehole characteristics, specifically at areas with presence of veinlets, a major overbreak of borehole walls occurs. In some occasions, given the solid rock characteristics and stress conditions, a specific breakout of the borehole can occur, leaving the section with a 'lemon shape'. In both scenarios, the rod entrapment can take place. An analysis must be carried out in cases that result in any loss of injection rods (Figure 12).
- *Fracturing attempts:* During the fracturing process, certain sections cannot be fractured, and a series of attempts are made in order to achieve fracture initiation. These attempts wear the tools

and occasionally can result in entrapment of packers and rods, resulting in respective time-consuming manoeuvres to recover the tool strings.

This gave place to the implementation of practices within the Hydraulic Fracturing Directorate (HFD), which attempts to control and support the fracturing execution process, such as: defined fracturing sequence in drilling, implementation of packer failure register, HF Attempts Regulations, etc.



(a) (b)

Figure 12 Pictures of operational issues (a) Breakout on the borehole walls; (b) Packer failure

5 Preliminary review of results

The results of the HFD process are presented in function of rupture pressure and propagation.

5.1 Fractioning pressures and propagation in descending boreholes

The breakout pressures obtained from the preconditioning by HF in the descending boreholes are shown in Figure 13, and propagation pressures are shown in Figure 14. In both charts the order is given by the X axis. The boreholes are organised from west to east and by drive (from north to south).

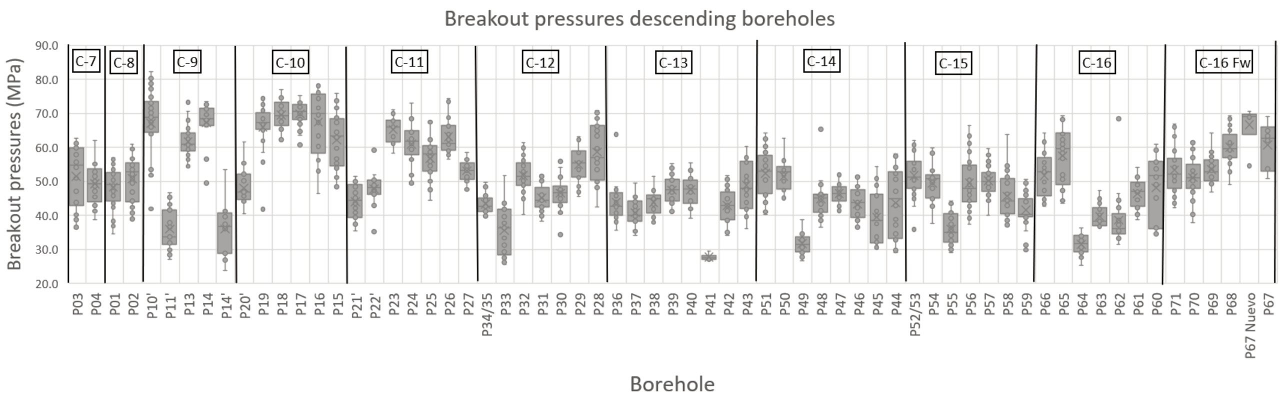


Figure 13 Breakout pressures in descending HF boreholes

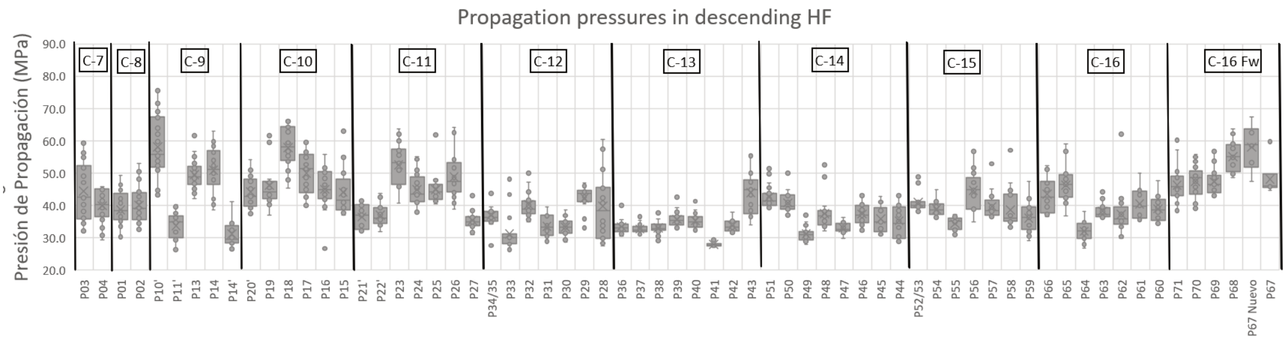
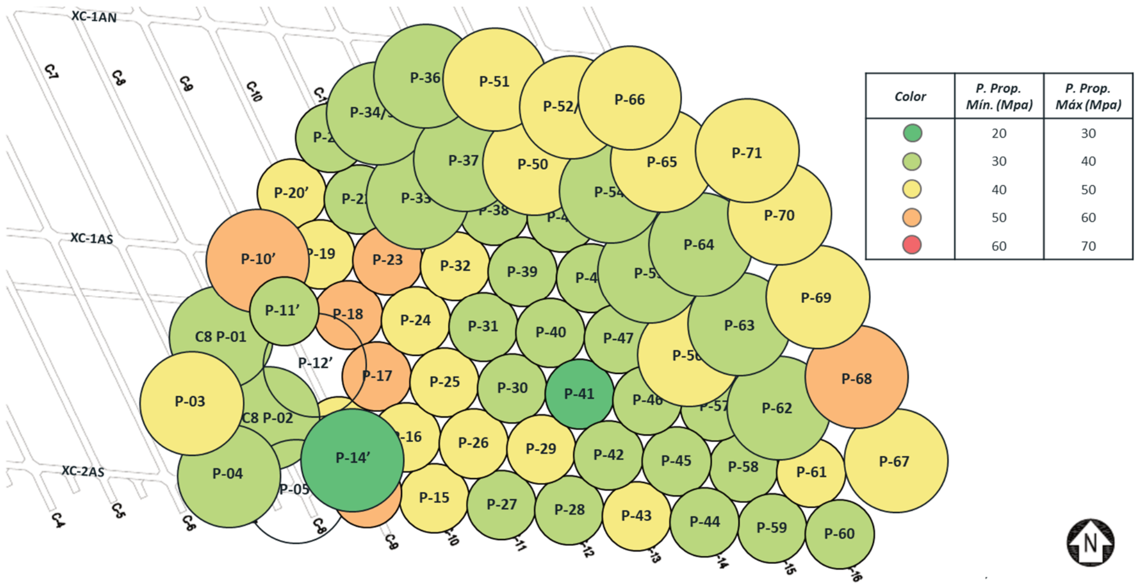
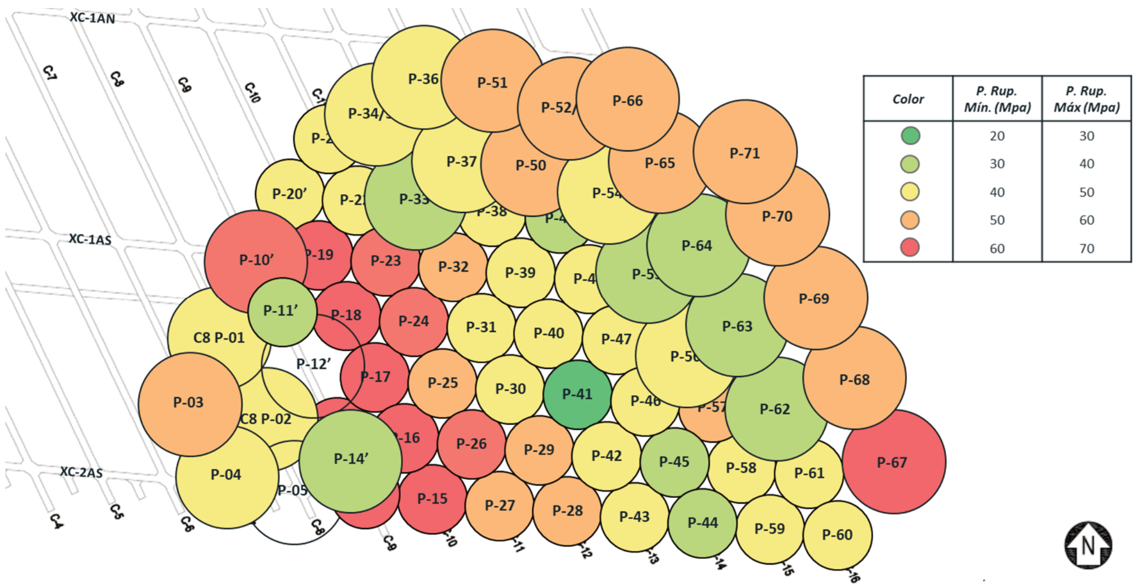


Figure 14 Propagation pressures in descending HF



(a)



(b)

Figure 15 (a) Average breakout pressures; (b) Propagation pressures, UCL descending boreholes

Note that the borehole breakout and propagation pressures present a similar behavior, with a significant decrease on a range of pressures from the breakout to propagation. The range of pressures obtained by borehole during the development of HF is presented in Figure 15.

Regarding the descending HF, two sectors with major pressures arose. The first at C-10' and C-11 boreholes (HW Zone – Central borehole boundary); and the second at C-16 (boreholes with more inclination). These boreholes have an average pressure for breakout and propagation of 50 and 70 MPa. Finally, there is a drop in the range of pressures from the breakout to propagation magnitudes.

5.2 Ascending boreholes fracturing and propagation pressures

Ascending boreholes carried out to date are presented in the following charts. The breakout pressure is displayed in Figure 16, and the propagation pressure is shown in Figure 17. Both have their order in the X-axis, since it shows all the fractured boreholes, organised by drive from west to east and from north to south.

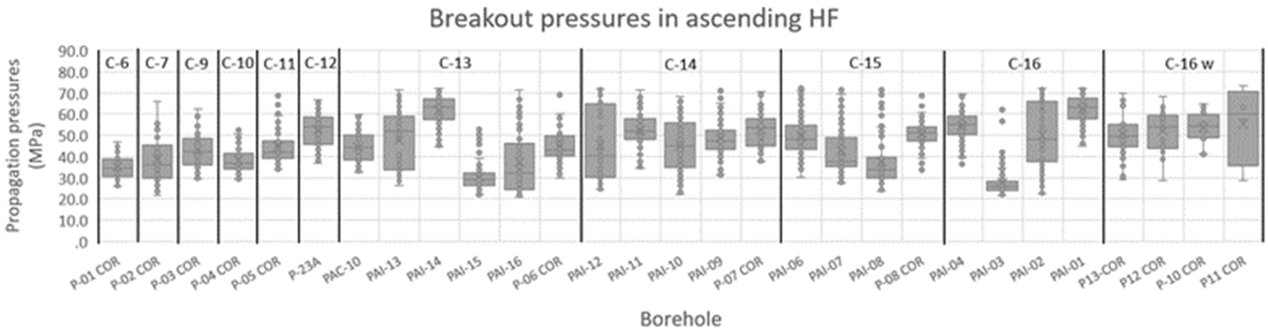


Figure 16 Breakout pressures in ascending HF

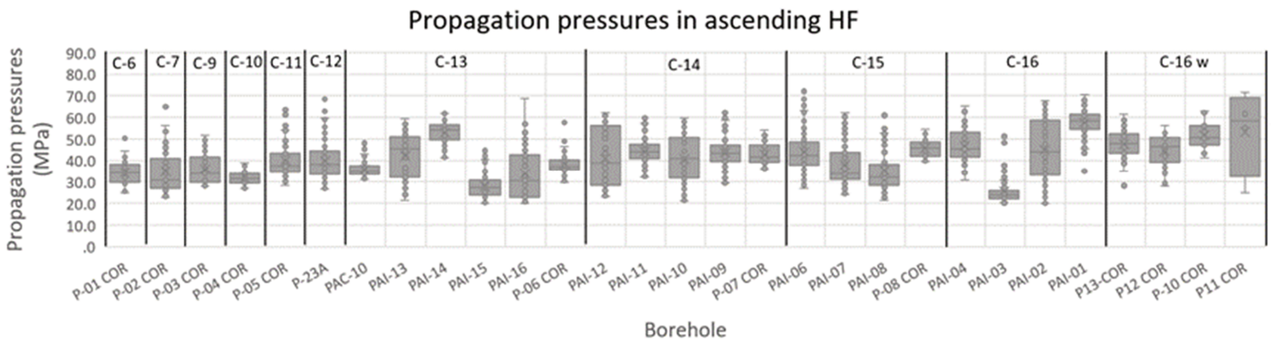
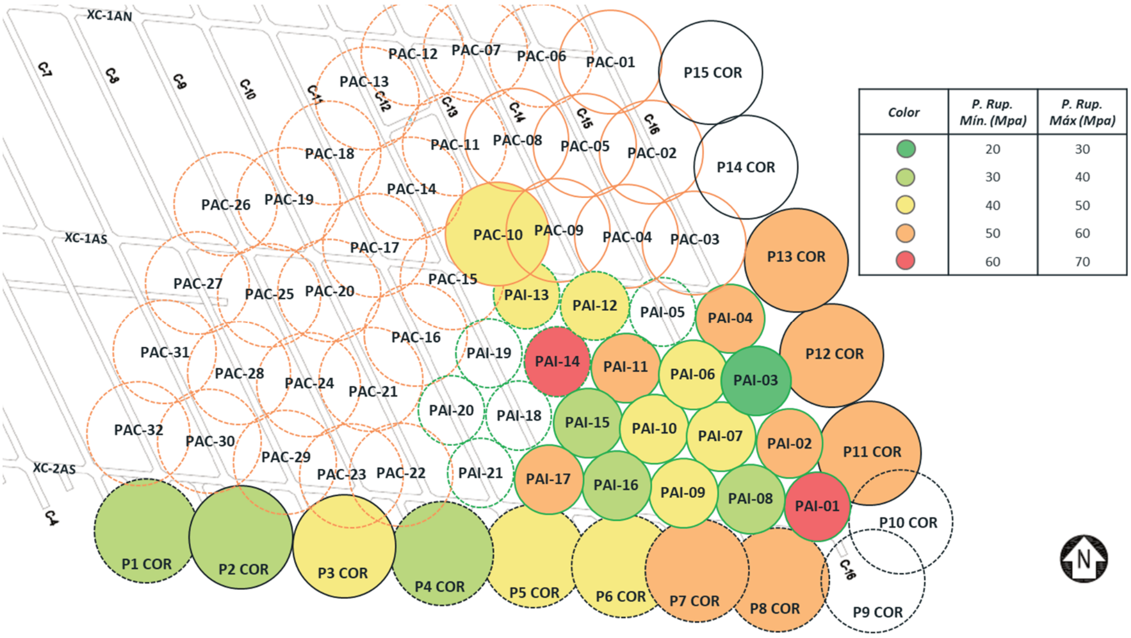


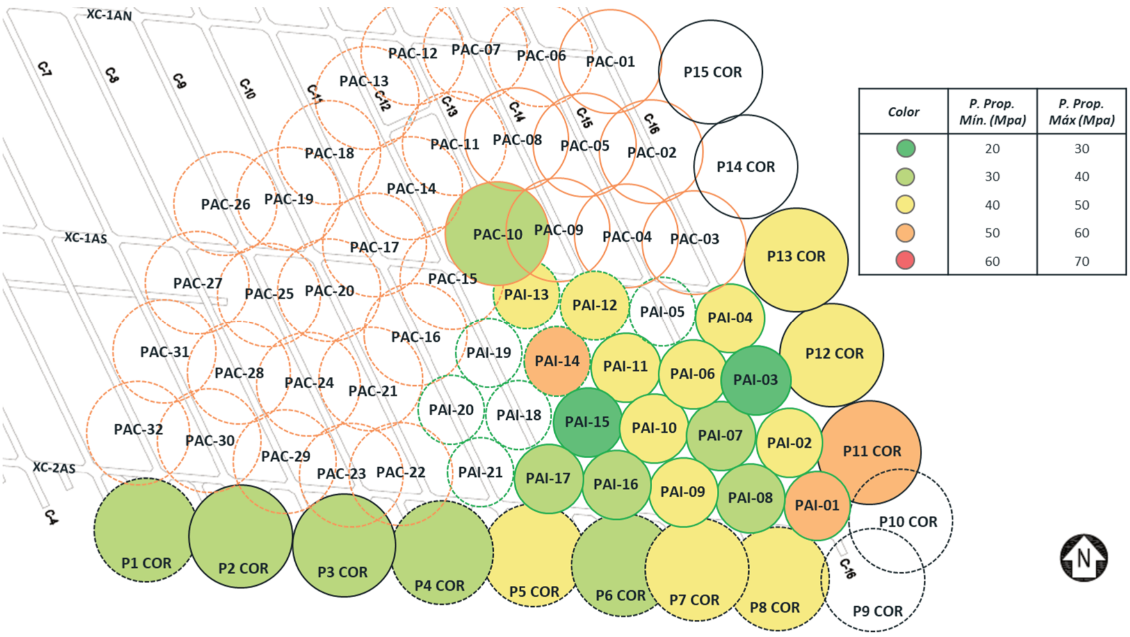
Figure 17 Propagation pressures in ascending HF

It is observed that higher pressures are in boreholes at C-16 and FW fence boreholes, with an average pressure between 50 and 70 MPa (Figure 18).

Additionally, the south fence borehole pressures show a trend of lower pressures towards the west, and higher pressures to the east, as shown in Figure 17.



(a)



(b)

Figure 18 (a) Average breakout pressure; (b) Propagation pressure; UCL ascending boreholes

6 Conclusion

This document presents the development of HF in the PAN. Preconditioning with ascending and descending boreholes through HF leads to conclude the following:

- The HF process requires an onsite monitoring methodology that ensures the proper implementation of the design defined in the mining method. The most relevant parameters are drilling quality, injection pressure records, and execution sequence.

- The PAN design considers the execution of HF in the undercutting level, with a focus on mitigation of seismic hazard associated to the undercutting propagation process at higher elevations. It also considers the inclusion of fractures below the production level at mass scale in order to mitigate seismic hazard in lower levels.
- During the execution and implementation of HF designs, variations have been observed in the injection pressures results (breakout and propagation), which allows identifying zones with different geotechnical behaviours within the volume.
- Additionally, operational issues have been recorded, resulting in interferences and changes that are detailed in this document. The most important ones are borehole damage, packer breakage, water quality, fracturing failed attempts, packer and injection rod string entrapments.
- The success of the PAN – NNM HF is a consequence of a collaborative work between different crosscutting areas with the HF operations, which pursues the compliance of the established design and traceability through an integral follow-up of the process. In view of this, it is worth to mention that a milestone has been set, with the completion of 100% of descending boreholes as per design.

Acknowledgement

The authors thank Codelco Chile for allowing the publication of the information included in this paper. The authors acknowledge the DFH professionals involved in the development of HF in the Project, without whom this paper would not have been possible.

References

Arce, J, Barahona, M & Cifuentes, C 2020, Actualización de Lineamientos Geomecánicos para Fracturamiento Hidráulico Ascendente Proyecto Andes Norte, Reporte interno Codelco (in Spanish). *Update of Geomechanical Guidelines for Ascending Hydraulic Fracturing North Andes Project*, Codelco internal report.

Arce J, Madrid, A, Soto, C, Valdivia, R & Padilla, R 2022, *Consideraciones y Requerimientos Perforación y Fracturamiento Hidráulico* (*Considerations and Requirements Drilling and Hydraulic Fracturing)*, Codelco internal report, in Spanish.

Cifuentes, C, Romero, D & Rojas, E 2019, *Informe Avance N°2, Prueba de Morfología FH Andes Norte* (*Advance Report No. 2, Morphology Test FH Andes Norte)*, internal report.

Pardo, C & Rojas, E 2016, 'Selection of exploitation method based on the experience of hydraulic fracture techniques at the El Teniente Mine', *MassMin 2016, Proceedings Seventh International Conference & Exhibition on Mass Mining,* Australasian Institute of Mining and Metallurgy, Melbourne, pp. 97–103.

Parraguez, R, Zepeda, R & Rojas, E 2009, *Analysis of the Morphology of Hydraulic Fractures*, Codelco internal report.

Rodriguez, W 2021, *Descending FH Wells Design HW and North Side between C-7 to C-11 Sinking Level Footprint North Andes Project*, Codelco internal report.

Rojas, E & Landeros, P 2017, Hydraulic fracturing applied to tunnel development at El Teniente mine', *Proceedings of the 9th International Symposium on Rockbursts and Seismicity in Mines*, University of Chile, Santiago, pp. 236–242.