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Calibration of structurally controlled caving propagation using 3DEC. The Esmeralda Block 1 case study

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Abstract

In the context of the transition studies from Open Pit to Block Cave mining at the Chuquicamata Underground Project, the validation of Itasca's caving algorithm being used to predict caveability in a structurally controlled environment was deemed necessary. CODELCO proposed application of the caving algorithm to the observed caving behavior of Block 1 case study at Esmeralda Mine, El Teniente Division, which was known to have been influenced by the presence of a few major faults in its development. This paper presents the first successful attempt to calibrate a structurally controlled caving process in 3DEC.Itasca implemented the caving algorithm in 3DEC using all the data provided by CODELCO and successfully matched the observed behavior at El Teniente's Esmeralda mine. From the calibration, it was concluded that the parameters with the most significant influence in the results were the stress field, rock mass properties and faults properties. A good correlation was obtained when compared with the emerging cave shapes from the model and the position of the micro-seismic activity recorded in the period of interest. When comparing the results of the geometric observational modeling developed by CODELCO with the emerging results from the 3DEC model, a reasonable match was observed in terms of geometry and volume of the caves. Additionally, breakthrough to the upper level Teniente 5 and the main propagation mechanism influenced mainly by J and H Faults were captured.

1 Introduction

The caving algorithm developed by Itasca over the last 20 year has been successfully applied to many operations across the world. The algorithm was initially implemented within the three-dimensional, continuum-based program, *FLAC3D* (Itasca 2019 and recently migrated to use with *3DEC* (Itasca 2013). The mining transition studies of Chuquicamata mine require to simultaneously consider open pit and underground mining, with the latter having the chance of influencing structurally controlled mechanisms in the pit given by the presence of a significant number of major faults in the area of the first macroblock. On the other hand, the stability of Chuquicamata pit has been studied by Itasca for more than 15 years, having achieved a good understanding of the failure mechanisms applying the *3DEC* discontinuum analysis code, which allows the implementation of a large number of faults. Given the lack of experience with caving simulations using *3DEC*, the project team agreed first to validate the code with a real caving experience within a similar mining environment strongly influenced by discontinuities but involving fewer faults, which corresponds to the case study described in this paper.

Block 1 is part of Esmeralda sector, belonging to El Teniente mine in central Chile. It has been mined via panel caving since August 2011, and the breakthrough to the upper level (Teniente 5 level) occurred between June and October 2012. Figure 1 illustrates the relative positions of both levels along with the actual breakthrough observed in the upper level, showing the fault influence.

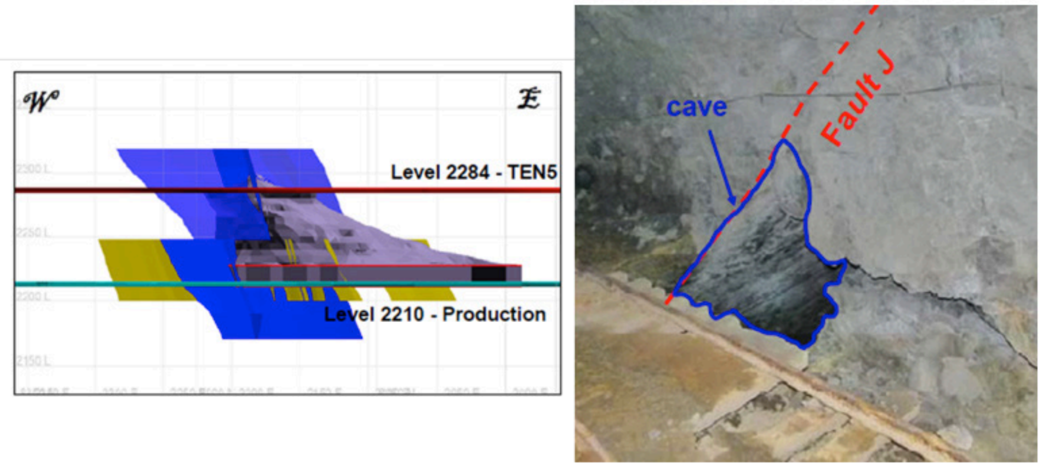

Figure 1 Cross section illustrating the relative position of Block 1 with Teniente Level 5 along with schematic views of faults and idealized cave (Millán & Brzovic 2013a). Actual cave breakthrough is shown on the right, highlighting the fault effect

The calibration period was defined from August 2011 until December 2012 following Block 1 historical draw schedule. Caving was implemented following the caving algorithm developed for *3DEC* by Itasca.

2 Caving numerical modeling

The numerical model attempts to capture many of the important features of caving, which are shown in Figure 2 according to the conceptual model developed by Duplancic & Brady (1999), in terms of five key geomechanical zones.

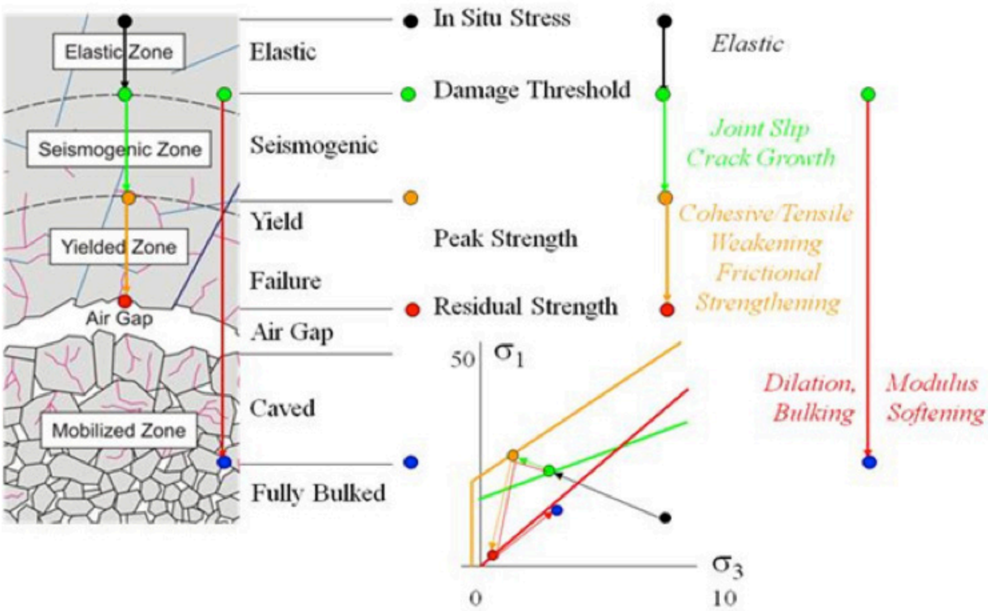

Figure 2 Conceptual model of caving (Duplancic & Brady 1999)

The caving algorithm makes use of the proprietary strain-softening Cave-Hoek constitutive model available in *3DEC*, developed specifically by Itasca for the caving algorithm. This allows for the representation of modulus softening, density adjustment, dilation, dilation shut-off, scaling of properties to zone size, cohesion weakening, tension weakening and frictional strengthening. The GSI, mi and UCS parameters control the shape of the Hoek-Brown envelope (Hoek et al. 2002). The model also requires a definition of the residual strength parameters to which the rock mass softens as a function of plastic shear-strain after reaching peak strength. An estimate of the relation between the critical strain and GSI was determined by a back-analysis of rock mass failure in caves and other openings as part of the MMT project (Lorig & Pierce 2000), namely: critical strain = (12.5 - 0.125*GSI) / (100 * zone size). Lastly, the intact Young's modulus is used to calculate the rock mass Young's modulus, using Hoek & Diederichs (2006) equation, which governs the rock mass elastic behavior.

The caving algorithm follows a rigorous mass-balance routine to ensure that the tons-based production schedule is represented accurately. Undercut advance is simulated by converting the model zones (elements) that represent the undercut to fully fragmented and bulked rock; then the model is run to equilibrium. The undercut volume is deleted and the support to the surrounding rock mass is replaced with equivalent boundary forces that exist after the undercut is replaced by the fragmented, bulked rock. Draw of the ore is then simulated by applying a small downward velocity to all gridpoints in the roof of the undercut. This velocity is set low enough to ensure pseudo-static equilibrium throughout the model. The undercut is advanced, and draw simulated in many small computational steps until achieving the target mass set by the production schedule. As the mass is drawn at the undercut, the yielded zone will spontaneously emerge within the model (controlled mainly by the stress state and yield strength of the rock mass) and may progress upward from the undercut as long as the geomechanics conditions allow it to do so. As draw continues, rock within the yielded zone will have moved enough distance (typically >1m) to be identified as caved (mobilized) material.

3 Geotechnical assumptions

Plan view of Esmeralda mine is shown in Figure 3, depicting Block 1 and Block 2 as independent panels away from the old Esmeralda cavity. The calibration analysis involves only the first mined block, which covers roughly 43,000 m^2. Block 1 is mined with conventional panel caving with preconditioning of the first 100 m. The column height in Block 1 is around 700 m with the first 160 m of virgin rock and then broken rock up to the surface. Mining in the *3DEC* model was simulated on a monthly basis according to the program shown in Figure 4, indicating a total accumulated extraction of 1.7 Mtons by December 2012.

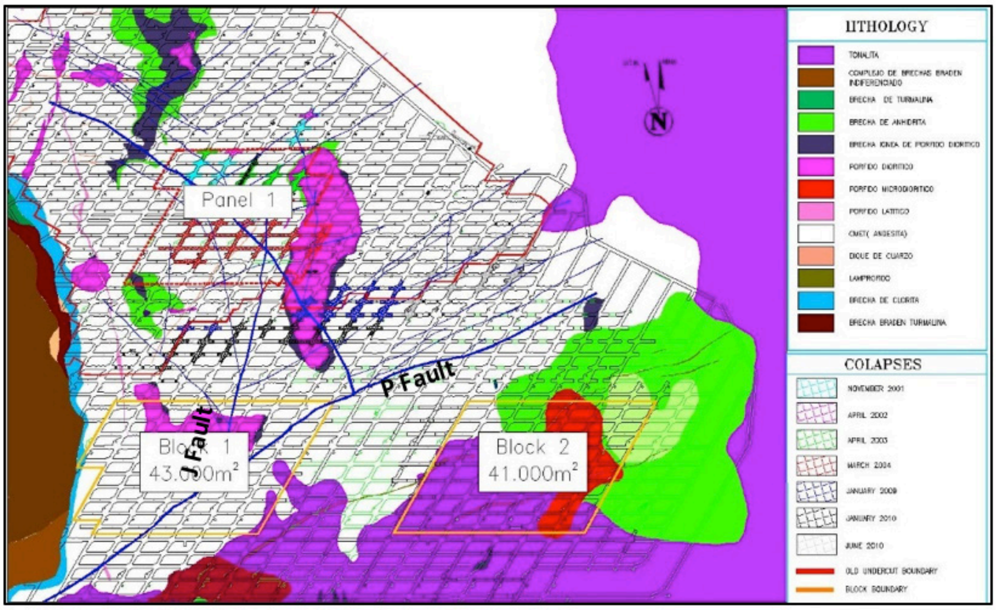

Figure 3 Block 1 and Block 2 locations in Esmeralda mine relative to previous mining and collapses

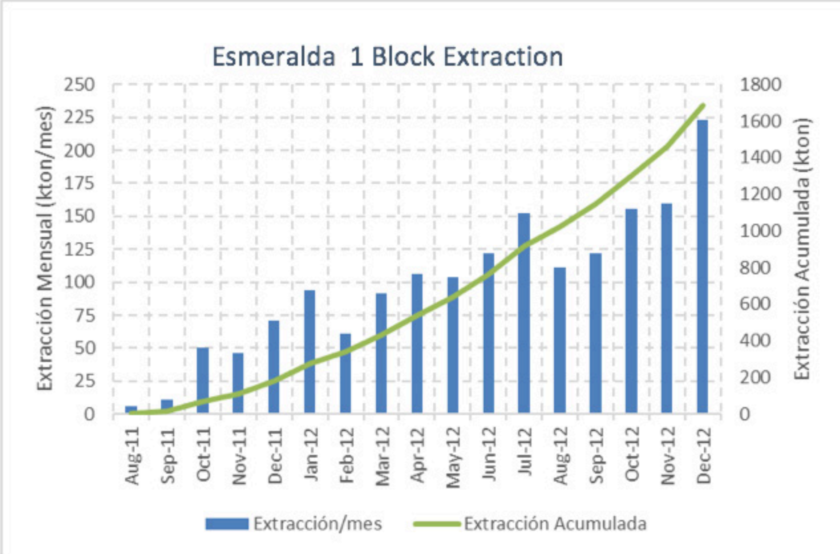

Figure 4 **Block 1 draw schedule on a monthly basis, including accumulated tons**

The lithology of Block 1 is primarily competent rock mass defined mainly by El Teniente Mafic Complex (CMET) and diorite porphyry. The quality of this rock mass is Regular-Good on the IRMR scale. The material properties are shown in Table 1.

Table 1 **Block 1 Rock Mass Properties (Vallejos et al. 2014)**

Rock Unit	σ_{ci}(MPa)	mi	GSI	Em(GPa)
Diorite porphyry.	140	11.3-13.1	45.3-47.3	8.8-9.2
CMET	121	11.0-13.7	48.6-52.2	12.5-16.3

The main structures of Block 1 dip towards NE and NNW; which are P Fault and H and J Faults, respectively. The spacial fault distribution is illustrated in Figure 5, having as reference Block 1 undercutting front of October 2012. Fault´s properties are shown in Table 2

Table 2 **Main structure properties (Millán & Brzovic 2014)**

c(kPa) Peak	c(kPa) Residual	Friction Peak	Friction Residual
120	0	25	25

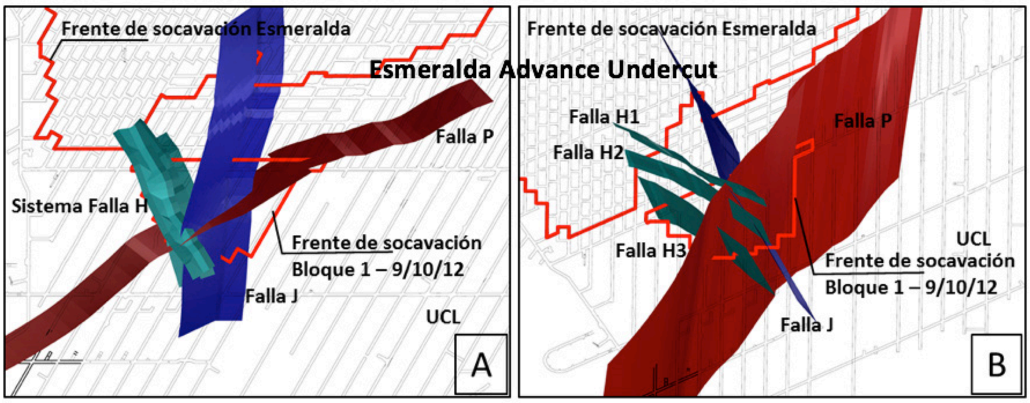

Figure 5 **Faults locations in plan view (A) and isometric view (B). Block 1 mining front as of October 2012 is included relative to previous mining from Esmeralda**

The stress field inside Block 1 is affected by the presence of the existing cave from Esmeralda mine; therefore, an excavation sequence of the previous cave was implemented to capture the mining induced stresses in the area of interest. The *3DEC* model was initialized using the pre-mining stress field, according to Table 3. The in situ minor principal stress is expected to be sub-vertical, while the major and intermediate stresses have a similar magnitude and are oriented NS and EW respectively.

Table 3 Block 1 pre-mining stress field (Quiroz et al. 2010)

Component	Magnitude (MPa)	Trend	Plunge
s1	40	353°	1°
s2	36	257°	5°
s3	21	123°	81°

The Block 1 cave breakthrough to Teniente 5 level (2284 masl) took place between June and October 2012, with cave growth significantly influenced by the main faults, as depicted in Figure 6 (Millán & Brzovic 2013b).

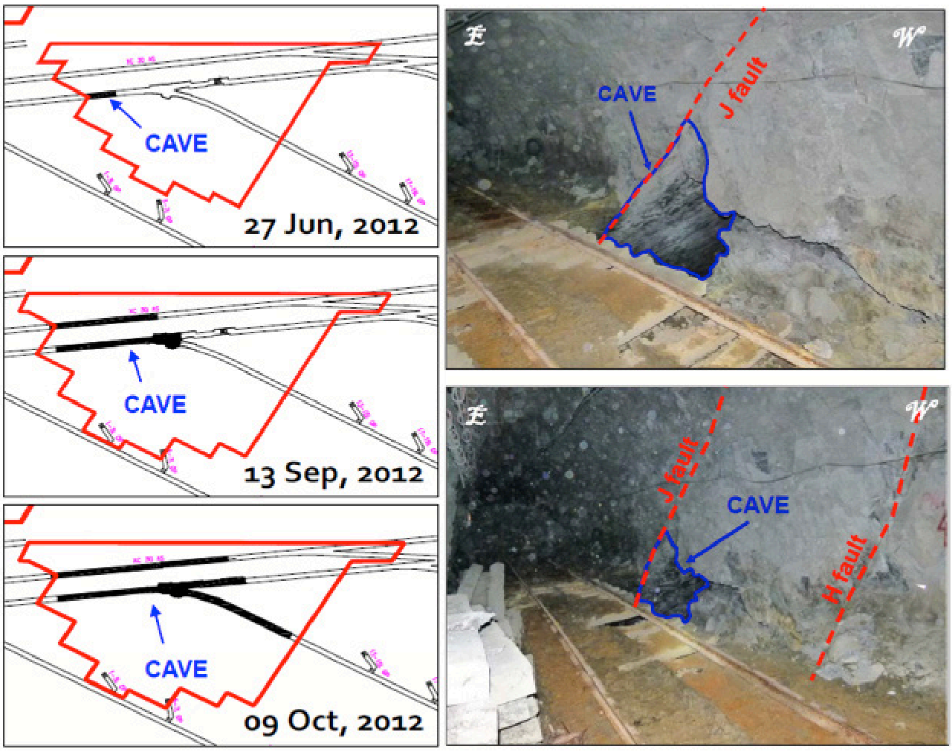

Figure 6 Cave growth evolution as observed in Teniente 5 level showing the relative position of faults (Millán & Brzovic 2013b)

4 3DEC Model

The 3DEC model is shown in Figure 7 and Figure 8, with the main faults implemented as explicit discontinuities. The initial model is run to equilibrium after assign the rock mass properties, the in-situ stresses and install the pre-existing cave. Note that the stresses inside the pre-existing cave are initialized to zero and then cycled until it reached equilibrium, to account for the stresses inside the cave, to represent the broken material.

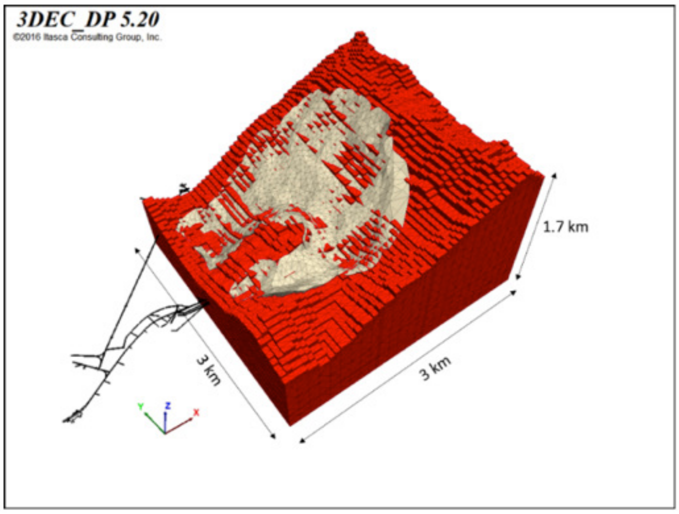

Figure 7 3DEC model showing the presence of the existing cave in Teniente mine (light brown)

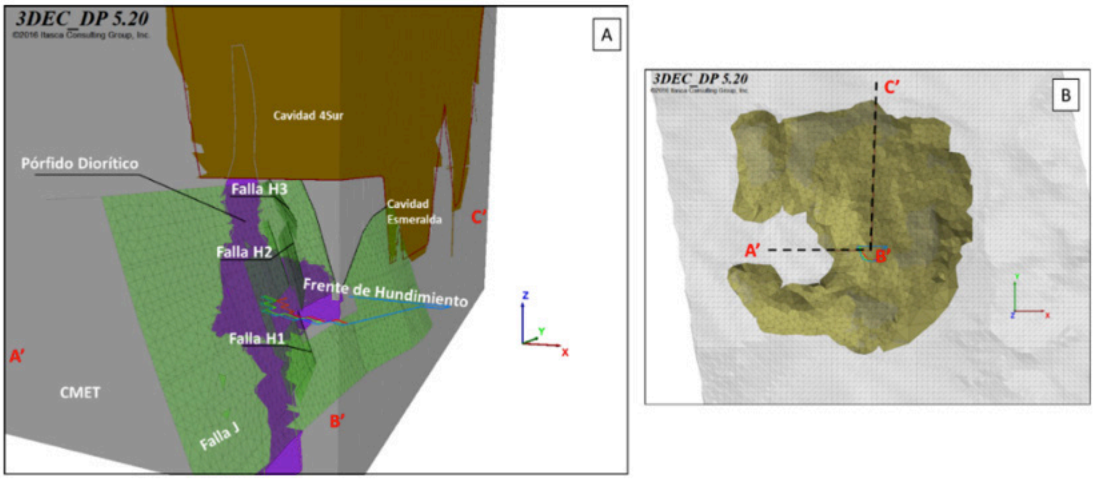

Figure 8 3DEC model describing rock units, fault and existing cave (A) in a clipped box (B)

After the initialization of the model is completed, the Caving algorithm is used to simulate the draw schedule summarized in Figure 4. Considering the location of Block 1 when compares with the previous Esmeralda sector, it was noticed that Esmeralda's cave highly influences the stress field in Block 1. Therefore, the orientation of the minimum principal stress rotates modifying the expected orientation of hydro-fractures, which were implemented to preconditioning the rock mass. Due to this effect and complemented by mine staff observations, the role of the hydro-fracturing in cave propagation (during the timeframe of interest) was minor and hence not included in the model.

5 Caving propagation results

Cave growth is an emerging result from the model, where the cave shape is interpreted using displacement criteria based on empirical data from numerous back-analyses of cave propagation , e.g., Northparkes E26 (Pierce et al. 2006), Palabora (Sainsbury et al. 2008), Grace Mine (Sainsbury et al. 2010), Henderson Mine (Sainsbury et al. 2011). Itasca has found that 1 m downward vertical displacement iso-surface represents the approximate mobilized zone or caved rock mass volume reasonably well.

The model results are presented in a plan and perspective view in Figure 9 for selected dates (July, October and December 2012). The cave back is illustrated by the iso-surface of 1 m settlement. It can be observed that the model capture the cave breakthrough to Teniente 5 level by July 2012 and thereafter continue growing as mining progressed. The large cave growth observed by December is aligned with the drawing increase that month (see Figure 4), which was around 225 ktons/month against 150 ktons/

month from previous periods. In addition, the cave growth towards the east of J fault is consistent with the subsidence mapping carried out by the mine staff, see Figure 6.

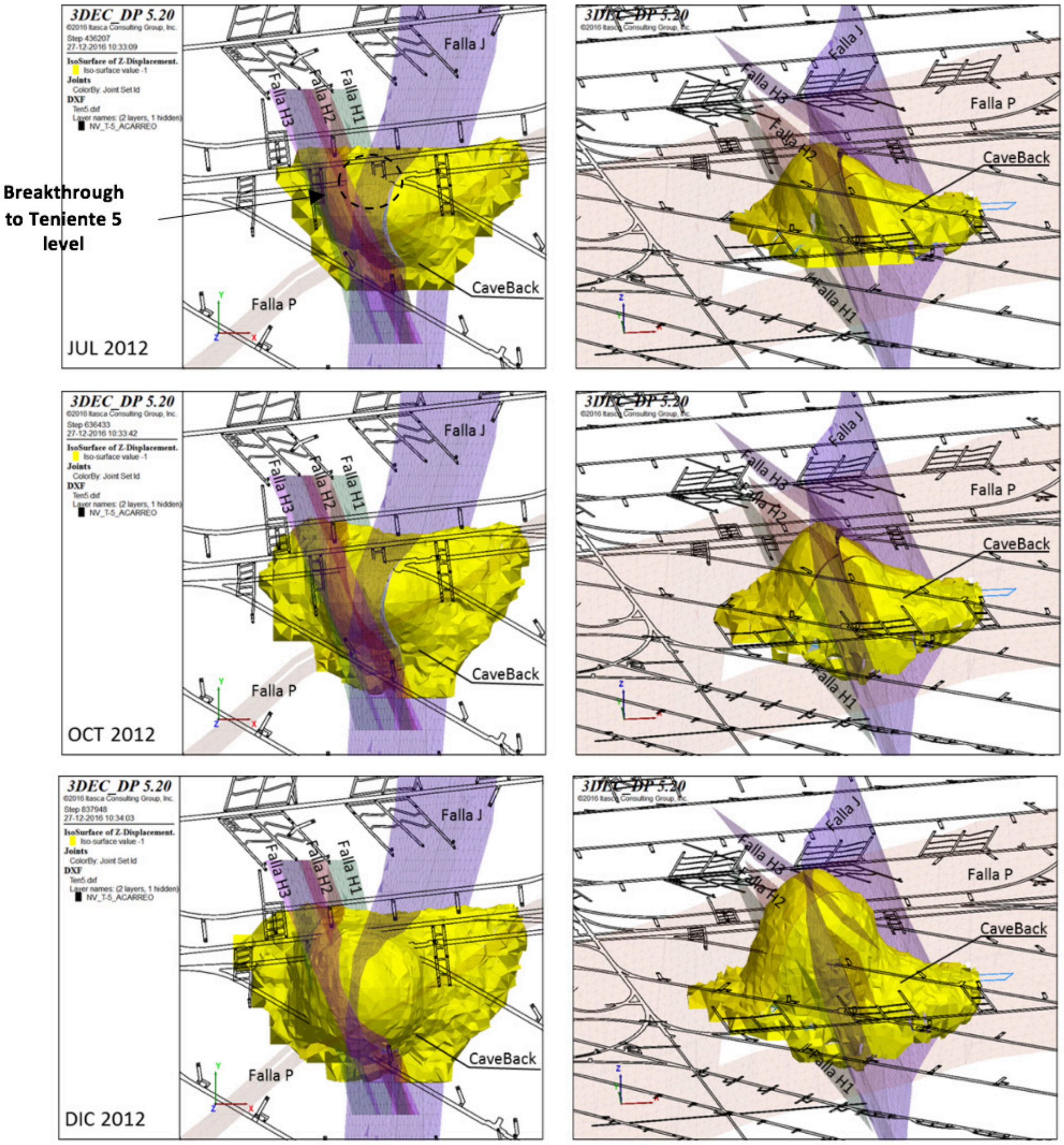

Figure 9 Cave propagation in plan view (left) and isometric view (right) at selected times

The seismic activity recorded during Block 1 establishment is another piece of information that is used to validate the cave-back geometry. Seismic events occur due to the breakage of the rock mass driven by cave induced stresses. The seismogenic zone is where micro-seismicity occurs within the jointed rock via joint slip and fracture extension, is located just above the yielding zone (see Figure 2) preceding the cave-break. The modelled cave back is plotted along with the seismicity recorded during the same month to compare with the cave location, as shown in Figure 10. The seismic events displayed in the cross-section (Figure 10 right) corresponds to those within a 30 m distance from the section. The results show a high concentration of seismic events in the cave crown, which is also influenced by the nearby faults (J and Hs). J and H3 Faults define a seismic corridor that can be observed in the figures. Lastly, the emergent cave shapes compare reasonably well with a geometric model developed by Millán & Brzovic (2013b) based on production data and empirical evidence (seismicity, boreholes, subsidence mapping, etc.), see Figure 1.

It is important to note that the influence of the fault controls the staggered shape of the cave, leaving the rock mass component as less relevant. Several sensitivities were carried out to try to improve the match with subsidence observed in Teniente 5 level (see Figure 6). However, minor differences were obtained as fault properties were changed. Thus, the original set of parameters (Table 2) was maintained as the outcome from the calibration process. The fault slip highlighted in Figure 10 could have been larger if much lower fault residual properties had been used (10°), which was unrealistic. As far as the caving algorithm itself, the dilation assigned by default to the rock mass needed to be reduced from 10° to 8° to counteract the mesh dependency in 3DEC (tetrahedral elements are stiffer than hexahedral elements in FLAC3D).

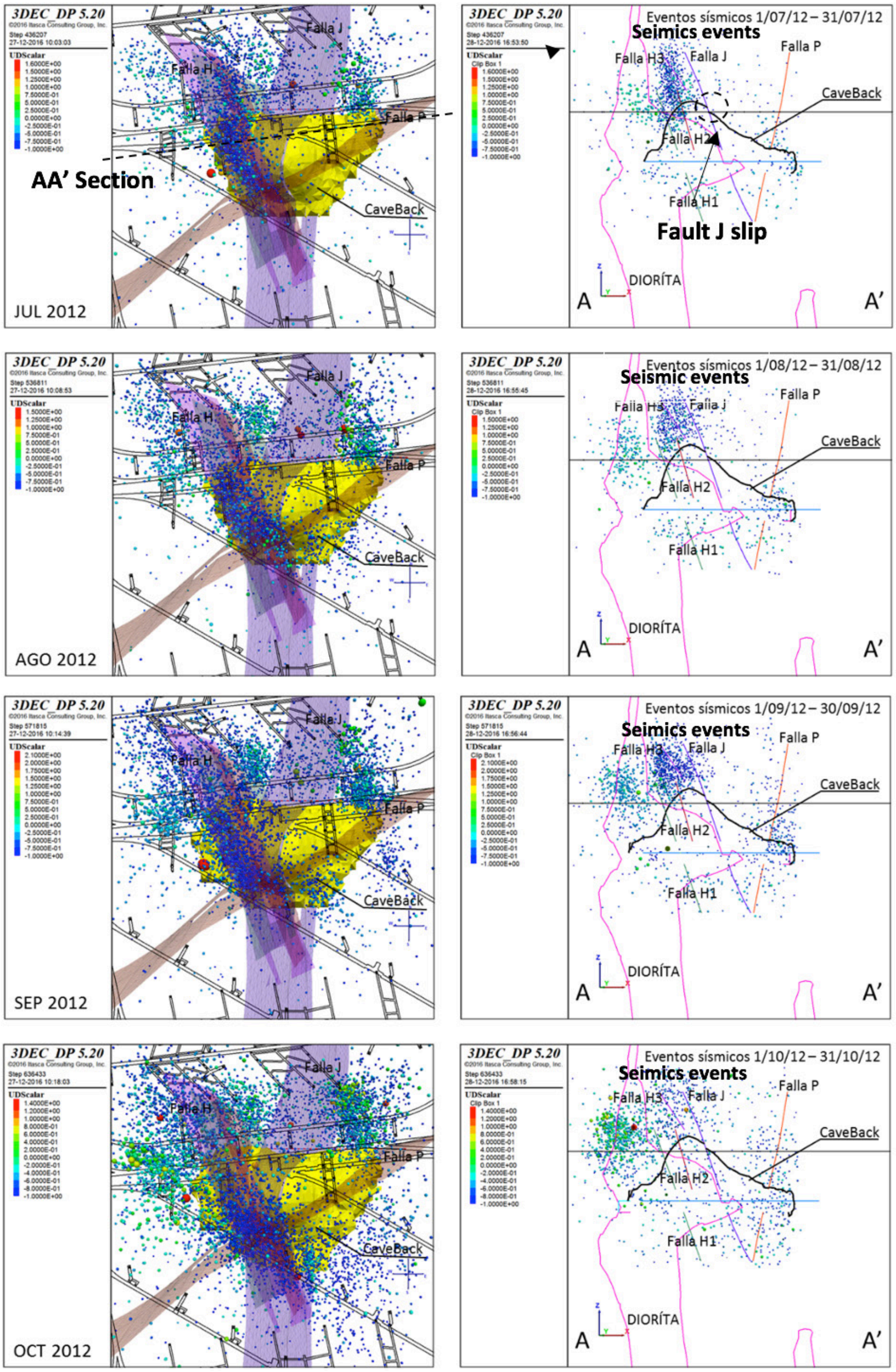

Figure 10 Cave propagation at selected times at plan view (left) and cross section (right) including the seismic events recorded in corresponding months

6 Concluding remarks

In the context of the Chuquicamata OP/UG transition studies, the authors implemented the caving algorithm in 3DEC to successfully match the observed cave propagation behavior at El Teniente´s Esmeralda mine. From the calibration effort, it was concluded that the parameters with the most significant influence on the results correspond to the stress field, rock mass properties and mainly Fault properties. It is important to note that the dislocated shape of the cave is explained only by the influence of the faults, leaving the rock mass component with secondary relevance. A good correlation was observed between the evolution of the cave shapes emerged from the modeling and the location of the micro-seismic activity recorded in the analysis periods. The emerging results of the *3DEC* model reasonable match the geometric observational modeling developed by mine staff, in terms of geometry and volume of the cave backs. Additionally, breakthrough to the upper level Teniente 5 and the main propagation mechanism influenced mainly by J and H Faults were captured.

Esmeralda Block 1 case study allowed to validate the caving algorithm implementation in *3DEC*, providing confidence in the subsequent open pit to underground transition studies performed for Chuquicamata mine, where more complex mechanisms are expected due to the presence of a significant number of major faults in the underground environment, plus the need of assessing the co-existence of open pit and underground operations.

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