

Delineation of concealed structures in block caving environments using seismic response to hydraulic fracturing: A methodology

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Abstract

Delineating structures can be problematic in the block caving environment due to a lack of tunnel development. Most mining methods require sub-levels at typically 20-50 m intervals, allowing for closely spaced mapping that can be interpolated with a high degree of confidence. Conversely, block caving mines generally have two effective levels – closely-spaced extraction and undercut levels, and a cave engineering level several hundred metres above. To add further uncertainty, critical infrastructures are usually located in waste rock and not within the orebody or footprint. This can result in speculative interpolations of mapped structures between levels and within waste rock. Recently, hydraulic fracturing of geological structures to reduce associated seismic risk has become industry best-practice. Installation of an accelerometer seismic array can detect smaller (high frequency) seismic events generated from a hydraulic fracturing program, whereas a mine's typical geophone network is unable to detect these micro-seismic events. Analysis of the seismic data during and after the hydraulic fracturing program can reveal thousands of micro-seismic events, and in special circumstances, these events plot on clearly defined planes in a geometric pattern consistent with the known structural framework. When coupled with focal mechanism data from a robust geophone network, faults and lithological contacts can be accurately delineated. Because most drilling campaigns focus primarily on the orebody, very little information is available regarding structure in the country rock where most of a mine's critical infrastructure is usually located. Although the intention for the installation of an accelerometer array in a hydraulic fracturing program is to identify the extent and orientation of hydraulic fractures, the identification and delineation of concealed geological structures can also be realized. The seismic response associated with structures due to hydraulic fracturing in a highly stressed rockmass also provides key insights as to which structures may pose a seismic hazard during cave establishment and growth, an extremely valuable input for geotechnical and mine design. A case study from Cadia East Mine in New South Wales, Australia, provides a methodology for structural modelling in highly stressed rockmasses as well as a proactive approach to identify structures which are prone to slip.

1 Introduction

In the minerals and metals industry, drilling programs primarily target orebodies. Consequently, only a small percentage of this drillhole information is recovered from surrounding waste rock. Underground developments and critical infrastructures (such as crusher chambers, access and conveyor declines, ventilation raises, workshops, offices, main electrical substations, etc) are mostly located in waste rock where there is an inherent lack of data which can lead to major oversights in mine design especially when managing risk associated with seismicity.

Cadia East has an extensive seismic sensor array, and arguably has some of the most well constrained seismicity worldwide. In recent years, analysis of Cadia East's seismicity has revealed multiple trends and has also provided a means to delineate large faults, dykes and lithological contacts. Although this is not unique to Cadia East, the quality of data has provided geologists and engineers with a better understanding of the dominant structural sets in the rockmass, especially those which are prone to slip.

During 2017/2018 a structure of significant continuity revealed itself with a multitude of mid-size events occurring over a short timeframe and concentrated on a single plane (Figure 1). The structure, known as the Southern Seismic Plane (SSP), was approximately 400 m south of the panel cave and was identified using the mine-wide geophone network. Because of prior damaging seismic events at Cadia East, a hydraulic fracturing campaign was designed to fracture the hangingwall and footwall of the structure, a technique that has been successfully employed at El Teniente for similar purposes (Zepeda 2017). At the time, very little data existed in the volume of interest, but as drilling commenced, a few key pieces of information were revealed from drill core. The structure presented as a tightly healed porphyry dyke. It's postulated that movement along this lithological contact was related either to the strength contrast between the porphyry dyke and the surrounding volcanoclastic rocks, or to internal zoning (mineralogical/alteration) within the dyke itself.

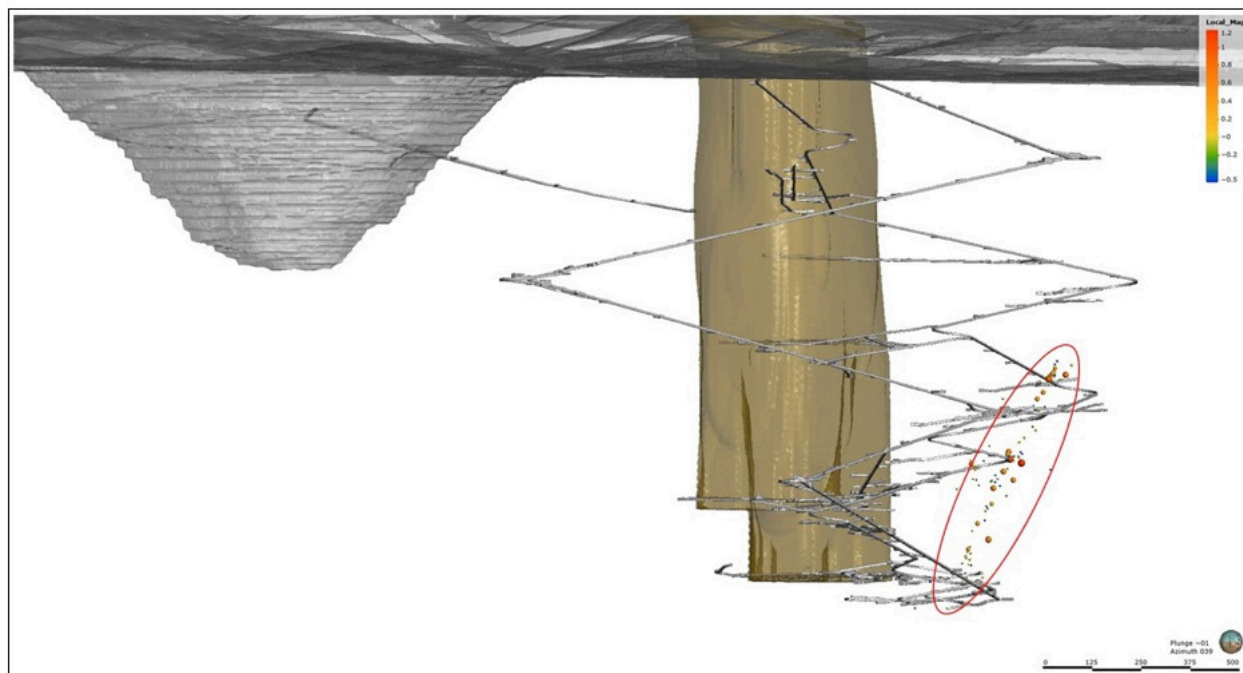


Figure 1 Looking NE, seismicity is filtered to show events in 2017 and 2018 in the volume where the Southern Seismic Plane (porphyry dyke) was discovered. The dyke is considerably continuous with approximate dimensions of 600 m × 450 m

To monitor the effects of hydraulic fracturing of what was assumed to be a single discrete structure, 14 additional seismic sensors (accelerometers) were installed in the adjacent rockmass to measure high frequency events generated from propagating fractures. This paper discusses these results and the subsequent methodology used to constrain the porphyry dyke contact as well as delineate additional structures that would otherwise have remained concealed.

2 Methodology

The initial objective of installing high frequency accelerometers around the SSP was to determine stress orientations, extent and efficacy of fractures from the hydraulic fracturing. However, this volume of rock is interpreted to be in an extremely stressed state where core diskings was identified in drill core. Upon hydraulic fracturing of the first two drillholes, thousands of micro-seismic events were recorded, and while it was still possible to pick the extent of some of the fractures themselves, seismicity along faults and lithological contacts dominated. As fracturing operations continued, it became very apparent that there were two additional structures that were previously unidentified. This marked the beginning of the identification of at least 8 concealed structures covering a large volume within which critical infrastructure is located.

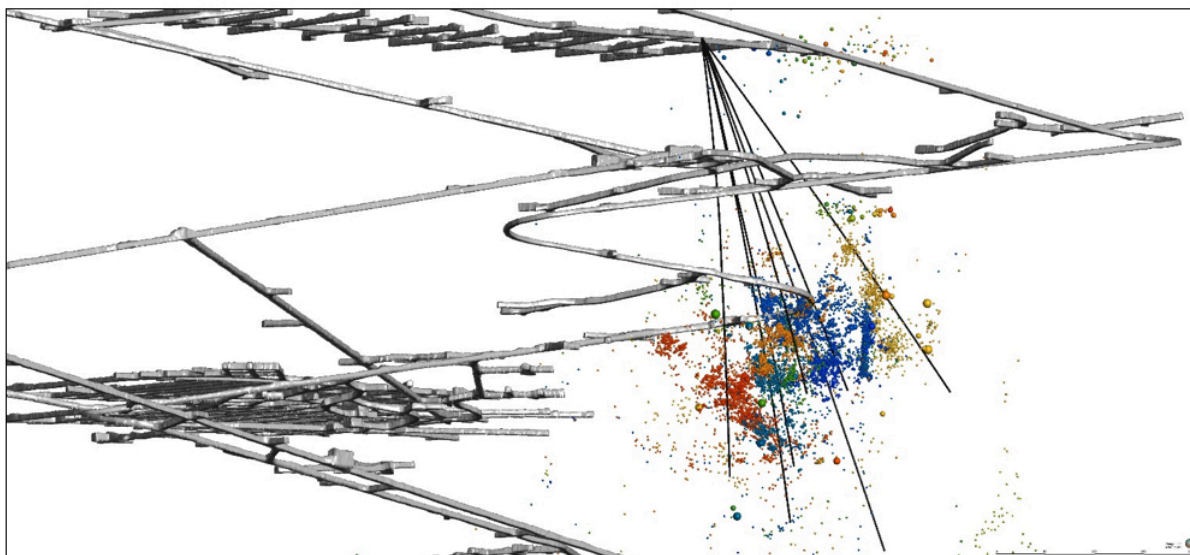


Figure 2 Looking NE, hydraulic fracture drillholes and all associated micro-seismic events during hydraulic fracturing of the Southern seismic plane. Spheres are sized according to local magnitude and coloured according to time, blue (earliest) to red (latest)

Delineating and subsequent modelling of these structures involved the following methodology:

1. Filtering of the accelerometer seismic dataset to capture events which occurred during hydraulic fracturing operations.

Seismicity associated with hydraulic fracturing is thought to be representative of the stimulation of the fracture network within the rockmass. Because accelerometers respond to high frequency events, any minor movement in the rockmass such as blasting or raise-boring will be recorded resulting in thousands of non-fracture-related events which can create noise in the database (Figure 2). Filtering these events to specific time windows during hydraulic fracturing operations provides a far more concise means to spatially detect any trends or planes with significant continuity.

2. Coupling of an identified trend of micro-seismic events detected by the accelerometer array with historical and spatially related focal mechanisms from the geophone network.

Once trends were identified (from the step above), moment tensors were filtered to capture events with high double couple components (i.e. events which are more likely related to slip on geological structures), with the nodal planes from these events considered to test correlation with accelerometer data trends. These focal mechanisms provide additional constraints for the orientation and continuation of structures.

3. Grouping of relevant nodal planes coherent with known geology at Cadia East (Figure 3).

A moment tensor solution provides two possible nodal planes, each with a strike, dip and rake. Using the known geology, orientation of the stress field and downhole and mapping structural data usually allows for the elimination of one of the nodal plane orientations.

4. Wireframing of structures (Figure 4) using geological modelling software (in this case Leapfrog Geo).
5. Examination of mapping (Figure 5) and drilling (Figure 6) data when available to characterise the structure.

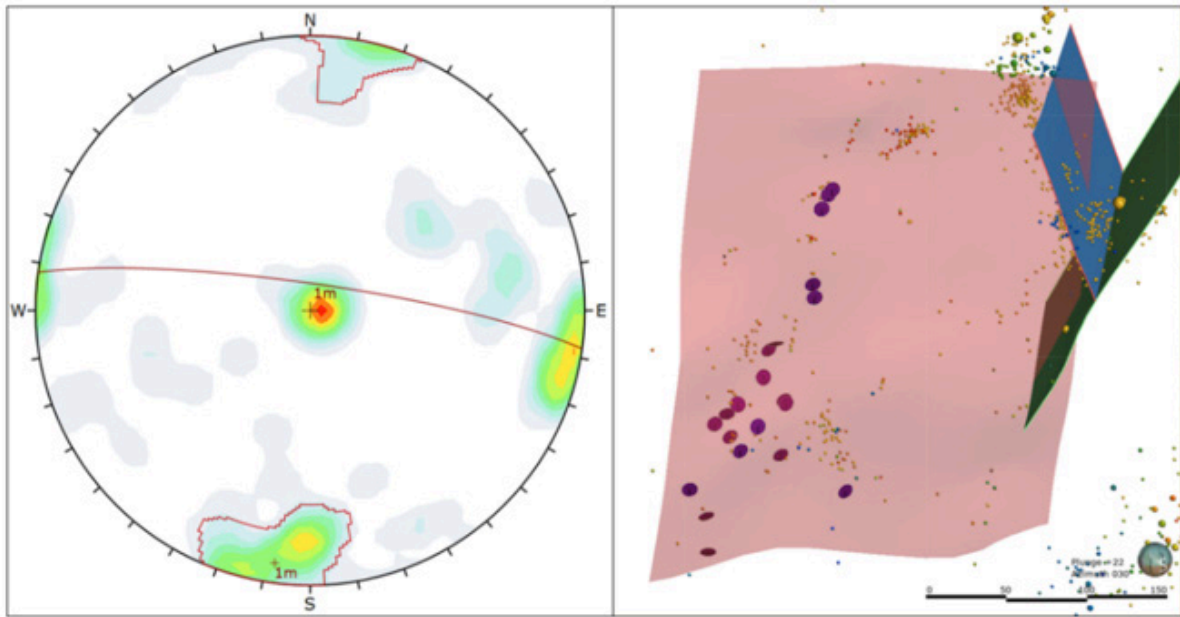


Figure 3 A structure revealed through a Stereonet analysis of focal mechanisms coupled with micro-seismicity. The Stereonet on the left shows a plot of all nodal planes extracted from focal mechanisms in the zone of interest. The image on the right shows an oblique view of the interpreted structure in pink, micro-seismicity coloured by event time, and focal mechanisms that align with the previously concealed structure

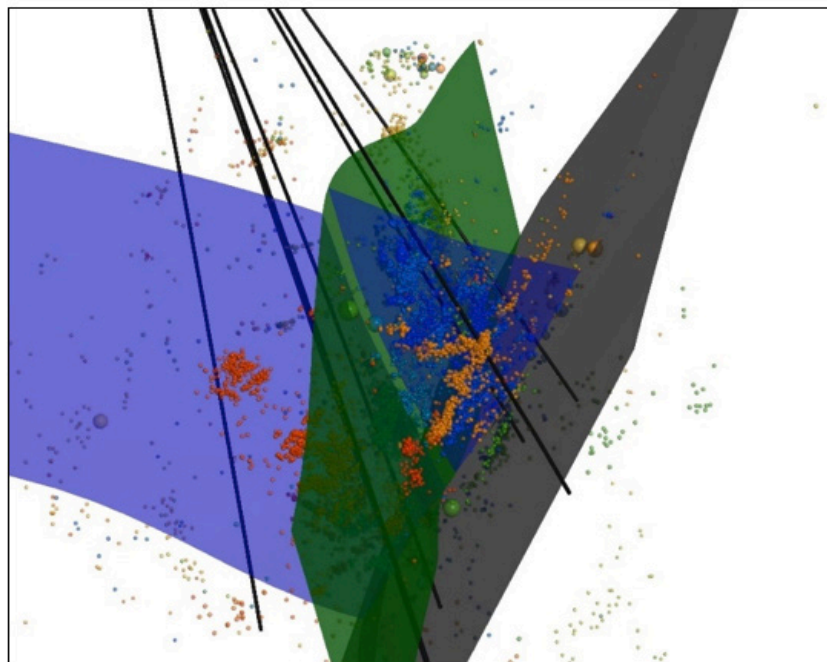


Figure 4 An example of wireframed structures in the region of interest constrained by seismic and drilling data



Figure 5 The image above is from a development drive which intersected a fault. Using photogrammetry, it was revealed that this was the extension of the same fault that was initially identified using micro-seismicity as depicted in Figure 3

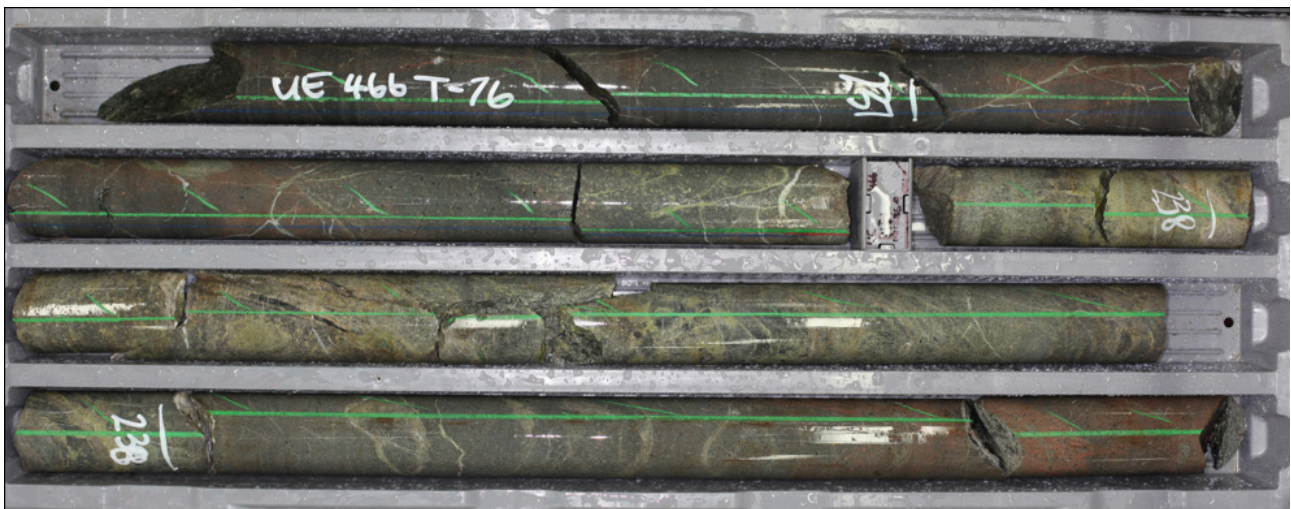


Figure 6 Core photo from a hydraulic fracturing drillhole showing an epidote-rich shear coincident with the structure identified through micro-seismicity in Figure 3 and development photogrammetry in Figure 5

3 Results

The coupling of the accelerometer data with historic and contemporaneous geophone data (focal mechanisms) identified at least 8 new structures that were unrecognised prior to the hydraulic fracturing program (Figure 7).

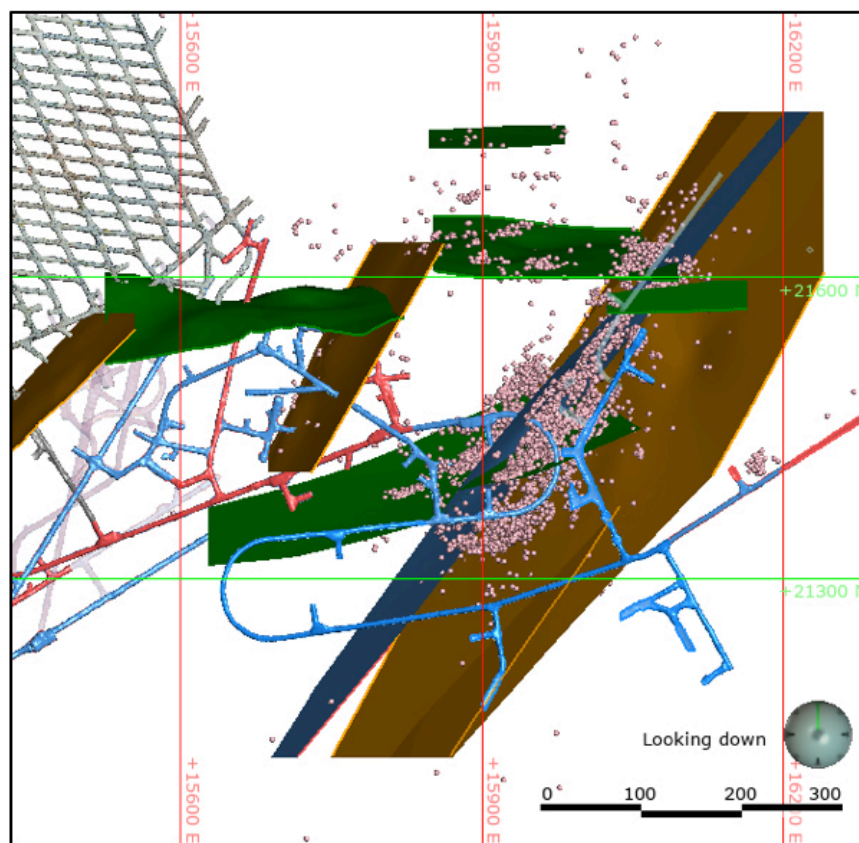


Figure 7 Plan view of micro-seismic response to hydraulic fracturing and structures identified

These were the structures that demonstrated micro-seismic responses and were sufficiently planar, extensive and numerous to engender confidence in their interpretations. The orientations of the planes delineated through micro-seismicity were consistent with the most common structural orientations observed at Cadia East, as defined by the structural understanding of the deposit and mine-wide stereonet analysis. Consequently, the micro-seismic response to hydraulic fracturing has helped to reinforce confidence in the deposit structural model.

4 Discussion

4.1 Importance of structural chronology and extent

This methodology provides information regarding deformation history and timing of structures. Because structural information in block cave mines is often limited due to a lack of underground development and exposure, especially during the studies phases and execution, it can be extremely difficult to determine the continuation and conversely, the termination of structures. By stimulating the fracture network during hydraulic fracturing, the resulting micro-seismicity provides the resolution to determine these timing relationships with a certain level of confidence. By using focal mechanisms, it can be demonstrated that structures of a certain orientation are truncated by structures of another orientation, therefore the uncertainty surrounding their extent is somewhat diminished. This is important for subsequent numerical modelling analysis which may need to determine the potential for a structure to slip and the associated impact, all the while constrained to the given extent of a surface. The extent of a structure may be greater than the area defined by the micro-seismic response, which is constrained by the proximity of the hydraulic fracturing and the prevailing stress conditions. When the structural chronology is understood, those structures not constrained by later structures can be investigated along strike or dip to determine their true extents and better understand the associated impact that a seismic slip event may have.

4.2 Identification of relevant structural orientations

Fracture networks within any given volume of rock are typically more complex than what can be conceived in models. During hydraulic fracturing, the rockmass's fracture network is being stimulated through the injection of water into joints/fractures/faults/contacts. The fact that only certain structural orientations are being stimulated can be considered a tool for calibration during stress modelling, at least for the existing stress conditions in the rockmass at the time of hydraulic fracturing. The importance of focussing on these relevant orientations can save time during interpretation. While faults are always the obvious culprits for large seismic events, lithological contacts may be of greater concern due to these features being unfavourably oriented to mining excavations and the potential for them to be activated due to mining-induced stress changes. There is currently a misconception in the mining industry where conducting structural analyses outside of the orebody will be impractical and provide no value, especially during the studies phases and execution (Carter et al. 2015). In this case, the southern seismic plane was located 400 m south of the panel cave in waste rock. The proximity of this plane and the potential for it to yield a large seismic event and subsequently damage critical infrastructure was of greater concern than the structures internal to the orebody. While numerical modelling is a fantastic tool to identify problematic trends within the rockmass, sometimes geological context can be lost. The methodology presented here provides a means with which to identify structural orientations of concern without losing geological context, albeit limited by the existing stress conditions at the time.

4.3 Structure characterisation

While the seismic response of a concealed structure to hydraulic fracturing can reveal its orientation and minimum extents, it gives no information about its lithological or mineralogical characterisation. Pre-characterised structures on similar orientations within the deposit's structural model may help predict its nature, but true characterisation must be done through direct observation (i.e. drilling or mapping). Cadia East has different fault types and planar intrusive volcanic units (all with different infill mineralogy). Understanding the difference between these features is important for quantifying input parameters for fault slip analysis and comparison with similar features that have displayed a historic seismic response.

5 Conclusion

Engineering around unknown structures in highly stressed rockmasses will become a well-documented topic. Hydraulic fracturing in block caving environments is gaining popularity, whether it be to reduce the risk of large seismic events or to precondition the rockmass prior to extraction.

If possible, installing accelerometers to assess micro-seismicity during hydraulic fracturing can reveal geotechnically relevant structures which can have a material impact on safety and design. The identification of concealed structures through the micro-seismic response to hydraulic fracturing has given impetus to consideration of further accelerometer installation at Cadia East, particularly in areas of known structural complexity or areas proximal to critical infrastructure.

The value of conducting a structural analysis within and surrounding the orebody can be derived by avoiding significant interruptions to business through the early identification of structures and consequent mitigation of the seismic hazard using hydraulic fracturing techniques. Monitoring seismic activity related to hydraulic fracturing provides a positive feedback loop into the understanding of the structural chronology, extent and orientation of hazardous structures which in turn provide important constraints for fault slip analysis.

Acknowledgements

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References

- Carter, TG, Rogers, SF, Taylor, JLL & Smith, J 2015, 'Unravelling structural fabric — a necessity for realistic rock mass characterisation for deep mine design', in Y Potvin (ed.), Proceedings of the International Seminar on Design Methods in Underground Mining, Australian Centre for Geomechanics, Perth, pp. 317-338.
- Zepeda A, R 2017, 'Fault G - Reserva Norte, Pre-conditioning by hydraulic fracturing in El Teniente division, SEG-DGD-GRMD', Unpublished Presentation, CODELCO (internal), in Spanish.