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Seismic risk control measure from passive to active through hydraulic fracturing

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Abstract

Significant advancement in seismic hazard understanding and risk management has been made in recent decades through various research projects worldwide. However, rockburst occurrence continues to plague the underground mining industry and remains a significant challenge. As the industry becomes more mature in understanding and quantifying seismic hazard, more effort will be devoted to the development of control measures.

Seismic risk control measures currently applied by the industry tend to be passive in nature and are often associated with significant direct or indirect cost, i.e. ground support, exposure management and mine design changes. Hydraulic fracturing, a technique frequently used in caving operations, has shown promising effectiveness at mitigating large-magnitude seismic events. However, several technical challenges and uncertainties remain which are hindering a wider adoption of the technique within the underground mining industry outside of caving mines.

This paper summarises some of the technical challenges and uncertainties associated with the hydraulic fracturing technique. A solution is then proposed to address these obstacles to explore the full potential of hydraulic fracturing for mitigating large seismic event occurrence and associated hazard.

Keywords: *seismic risk, rockburst mitigation, hydraulic fracturing, rock mass preconditioning*

1 Introduction

Significant contributions have been made in the understanding and management of mining-induced seismicity in the last few decades (Ortlepp 2005; Potvin & Wesseloo 2013a; Counter 2014; Malovichko 2017, among many others). This paper investigates, reviews and discusses the controls with the aim of describing an overall summary of how hydraulic fracturing may impact seismic hazard. Potvin et al. (2019) provided a summary of a generic seismic risk management process (Figure 1) and described each integral component in detail.

Despite the progress achieved so far, the occurrence of large seismic events continues to present significant personnel safety and financial risks to the underground mining industry. This is evident through persistent reports of serious injuries and mining suspension related to rockbursts from the global mining industry (SBS News 2017; MacDonald 2023; Geranios 2011; Lucas 2014, 2020; LKAB 2023). Prolonged production delays, costly rehabilitation work and reserve write-off are still frequent occurrences in seismically active mines. There is a clear need for more effective, and possibly active control measures to be made available to manage seismic risk.

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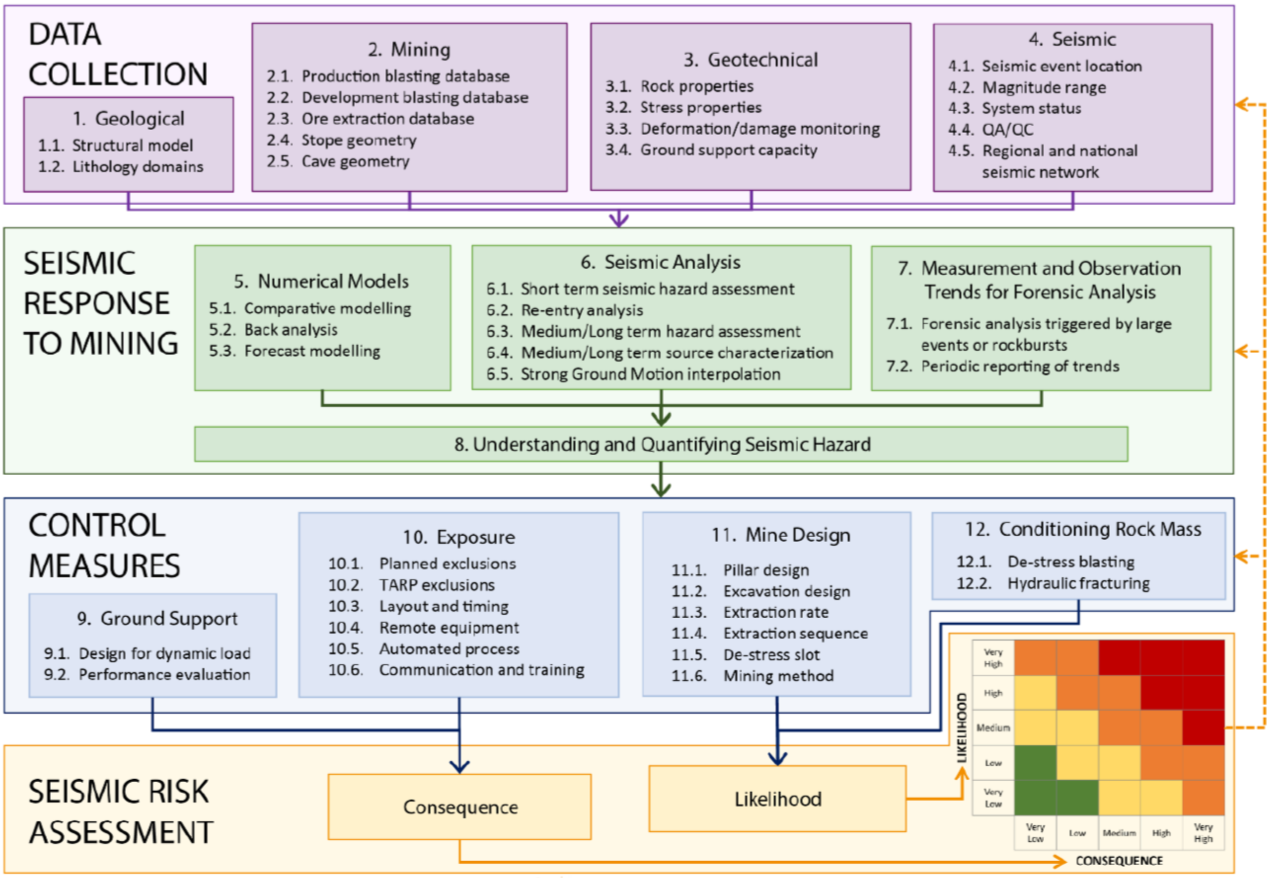

Figure 1 **Seismic risk management plan (Potvin et al. 2019)**

Hydraulic fracturing (HF), a technique commonly used in the oil and gas industry, has been frequently applied at caving mines to improve caveability, fragmentation and drawpoint hang-up frequency. Over the last 20 years, there has been evidence that it could be effective at mitigating large-magnitude seismicity occurrences at caving mines in Chile, Sweden and Australia (Rojas & Landeros 2017; Rojas & Landeros 2022; Jonsson & Martinsson 2018; Lett 2022). However, due to the lack of side-by-side trials in a controlled setting, it remains difficult to quantify its effectiveness at limiting large-magnitude seismicity occurrence and whether reported success is dependent on a seismic source mechanism.

In addition, the HF process itself remains challenging task to perform due to its specialised nature of work, the industry's unfamiliarity with the subject, frequent operational issues, uncertainty regarding fracture geometry and the high upfront costs. All of these factors are preventing more seismically active mines from trialling this technique. These challenges are discussed in more detail in the subsequent sections.

2 Seismic risk control measures and associated costs

The current control measures commonly used by seismically active mines around the world can be broadly classified into four categories according to Potvin et al. (2019). Depending on the risk severity, mines often use multiple controls concurrently to help manage risk, adopting a Swiss cheese model of risk (Reason 2000). Some of these controls are more effective than others due to their hierarchical nature, but all have been routinely applied in various forms around the world. The four categories of controls and their relative hierarchy is shown in Figure 2.

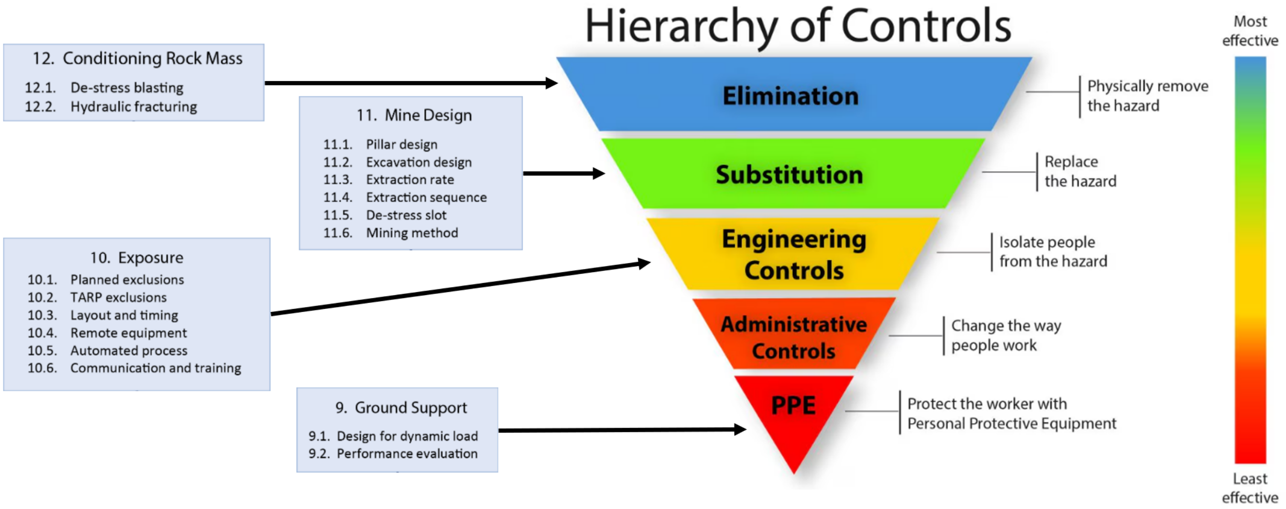

Figure 2 Seismic risk control measures and their relative hierarchy

A dynamic ground support upgrade is a simple and effective control commonly used by seismically active mines to contain rockburst damage. Dynamic ground support, however, cannot eliminate rockburst damage and, despite recent improvements, is still unable to contain large-magnitude rockburst damage (Svartsjaern et al. 2022). The post-rockburst rehabilitation process is even more problematic due to the difficulty of re-supporting damaged ground.

High-capacity dynamic support systems often consist of multiple types of rockbolt and surface support which require multiple passes for installation. This often incurs significant cost with a reduced development advance rate. In Australia, the development cost per metre with dynamic support can triple the cost of standard support (weld mesh and friction bolt). This would result in millions of dollars in additional costs for each level of development for a medium-sized mine.

Exposure management through exclusion zone implementation is another common control used in seismically active mines. Many methods exist to optimise exclusion practice (Tierney & Morkel 2017). Their effectiveness tends to vary across sites and this control, as a whole, can eliminate only a portion of the exposure. The exclusion method introduces a significant amount of reduced productivity into the mining cycle due to, for example, remote bogging/mucking only (slower productivity), and no drilling or charging activities. Depending on the mine layout, the remote bogging process is estimated to be more than 10% less productive than a manual process, and is expected to cost millions of dollars in production loss annually for a small- to medium-sized mine.

Once the seismic behaviour is well understood at a mine, the risk can be managed using higher hierarchy control such as altering the mine design. Many seismically active mines have had success in reducing the seismic hazard level through modifying the mine design (Potvin & Wesseloo 2013b). This is typically achieved through managing stress conditions (modifying pillar size, de-stress slot), optimising the extraction sequence or increasing loading stiffness (moving from shrinking pillar to end access).

Seismic risk management through mine design is a powerful and effective control. It allows mines to apply past learnings to optimise future design by considering factors such as the stand-off distance to known seismic sources, optimised pillar positioning, the effect of various stress levels, and the seismic behaviour of specific geological features. The financial implication of these strategies, however, often equals tens to hundreds of millions of dollars in additional cost due to the additional development required, the lower productivity mining method used and, often, a lower overall recovery. Once a mining method or sequence is implemented, subsequent change is often either impossible or will incur a major financial cost. Beaconsfield mine in Tasmania is a good example.

It is clear that the seismic risk management process has been a major cost to the mining industry. Significant savings and productivity gains can be realised with the availability of additional effective higher hierarchy control.

3 Hydraulic fracturing in mining

HF is the process of injecting pressurised fluid into a rock mass to induce fractures. Although many industries currently apply the technique for various objectives, it is predominately used by the oil and gas industry to extract hydrocarbon resources from low-permeability formations.

Attempts to initiate slip on existing structures in deep mines using pressurised fluid can be traced back to the early 1990s in South Africa (Board et al. 1992). Although the experiment successfully initiated small slips on the target structure, it did conclude that higher-flow rate pumping equipment and better fluid loss control would be required to prop up a larger extent of the target structure so as to achieve a better outcome.

The application of HF has since then gained momentum in cave mines as a tool to promote cave initiation. The first application of such a technique was successfully trialled at Northparkes mine in 1997 (van As & Jeffrey 2000). This work established the basis of applying a HF technique in block and panel cave mines. The pressurised fluid was injected into the rock mass using an inflatable straddle packer tool connected to the end of drill string (as shown in Figure 3).

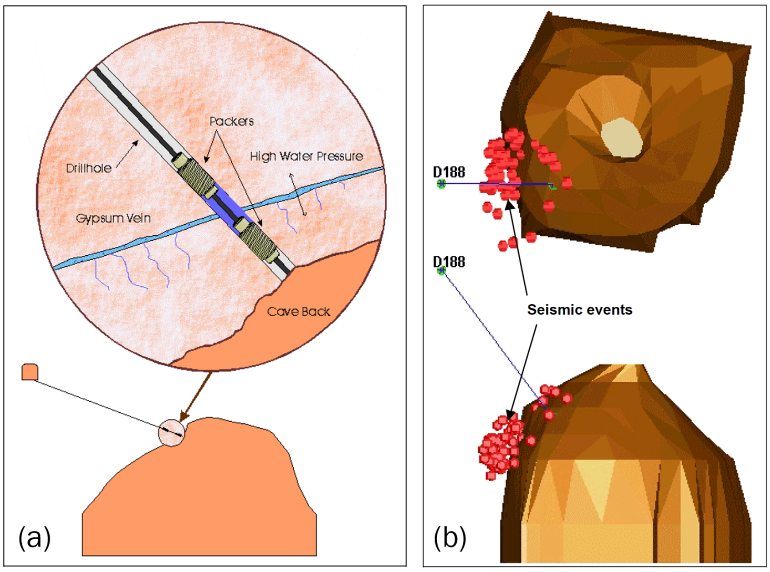

Figure 3 Northparkes mine hydraulic fracturing set-up illustration. Inflatable straddle packer set-up shown in (a) (van As & Jeffrey 2000)

Ridgeway Deeps' block caving operation was the second operation in Australia to apply the HF technique (Jeffrey 2007; Boreham et al. 2009). The primary objective was to improve cave propagation for the eastern block (more competent) and reduce the risk of cave hang-up. The project outcome of promoting caveability was determined to be marginal. However, a notable decrease in maximum event magnitude (ML1.2 versus ML2.3) was observed (Lett 2022).

In South America, Codelco's El Salvador mine conducted trials of HF to promote caveability. The project led to reduced frequency of hang ups, improved secondary fragmentation and reduced drawpoint damage. The Diablo Regimiento sector of the El Teniente mine subsequently applied HF in early 2005 with the primary objective of promoting caveability and evaluating seismic response. The project led to cave connection five months early and demonstrated significantly diminished higher-magnitude seismic events, while smaller-magnitude events increased (Morales et al. 2007; Molina et al. 2008).

Since then, preconditioning using the HF technique has been widely applied in cave operations around the world. In the last decade there has been a shift of focus towards seismic hazard mitigation (Boeg-Jensen et al. 2017; Rojas & Landeros 2017; Amorer et al. 2022). However, such trials have been constrained to caving operations and its adoption in conventional open stoping operations has been very limited.

The HF process is typically carried out using an inflatable straddle packer set-up (shown in Figure 3) with fluid supplied by either an electric- or diesel-driven positive displacement pump (shown in Figure 4). As the equipment is relatively small in size, this set-up can be operated either on the surface or underground. Another novel approach to applying HF has started to appear in mining in recent years, whereby a typical oil and gas approach is used (Amorer et al. 2022). This approach is distinguishable through its use of directional drilling from the surface and a perforate and plug completion technique applied through a cased hole, and its significantly higher pumping capacity. The Cadia surface HF pad set-up using the oil and gas method is shown in Figure 5.

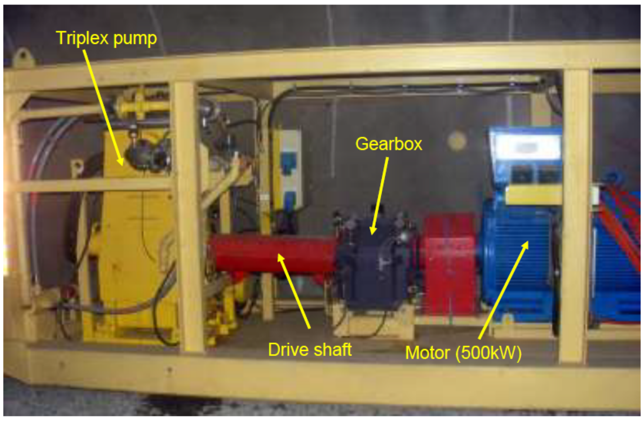

Figure 4 **High-pressure pump used by Newcrest operations (Boreham et al. 2009)**

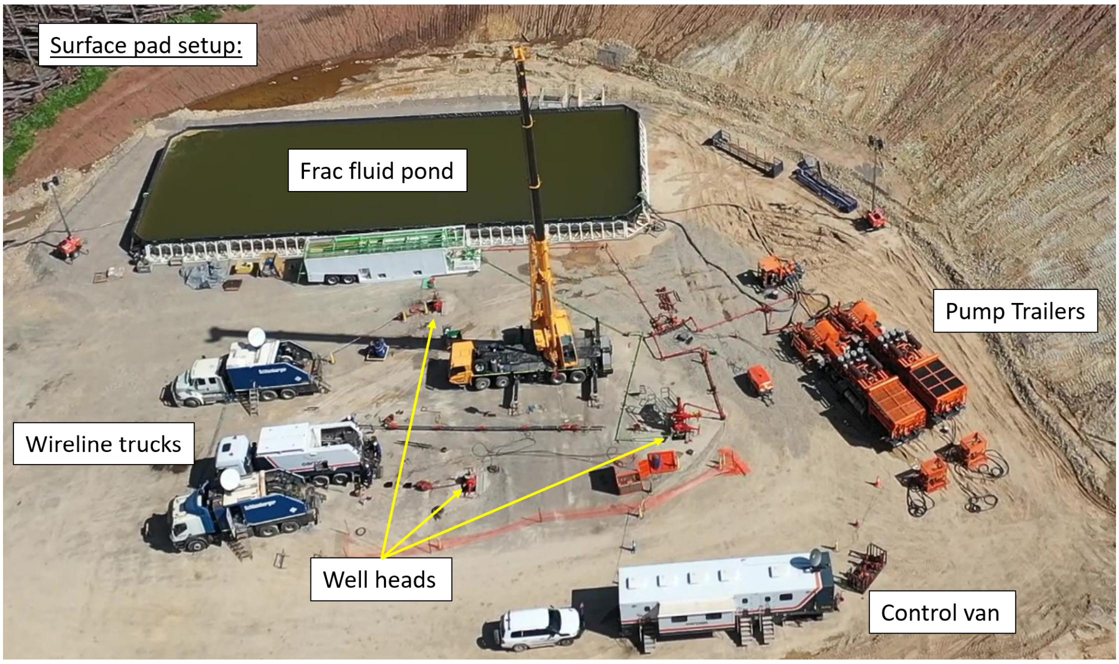

Figure 5 **The Cadia operation hydraulic fracturing surface pad set-up (Amorer et al. 2022)**

4 Seismic source mechanism

Many underground seismic sources can contribute towards observed seismicity, as illustrated in Figure 6a. However, the source mechanism from a seismological perspective can be simplified into two categories: crush type and slip type. Ryder (1988) provided a physical description for both types as follows (also in Figure 6b):

- crush/collapse type events – events associated with the unstable crushing of volumes of rock in close proximity to the mining void, typically governed by the strain weakening of brittle rock in compression, system stiffness, stress drop potential and energy release rate
- slip/shear type events – events associated with the unstable release of shear stress by slip over a planar area (plane of weakness, including intact rock), typically governed by a static/dynamic shear stress drop of sliding surface, system stiffness, stress drop potential and excess shear stress.

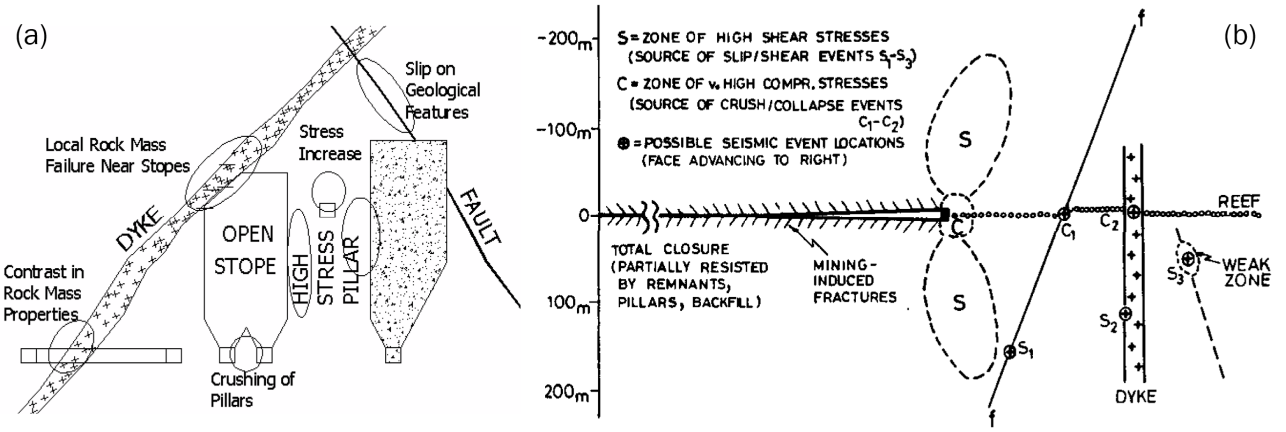

Figure 6 (a) Typical seismic sources in an underground mine (Hudyma et al. 2003); (b) Typical expected crush type and slip type events location in a tabular mining geometry at depth (Ryder 1988)

Historical risk mitigation strategies have been different for the two types of seismic source. For crush type events, de-stress blasting techniques have been trialled as early as the 1950s in South African deep gold mines (Roux et al. 1957). The objective was to weaken the zone of rock mass adjacent to the working face through gas-induced fractures and push stress deeper into the rock mass.

As the HF technique typically induces sparsely spaced fractures on a macro scale, the intact rock property is not significantly altered, as demonstrated by Catalan (2014). One feasible explanation for reduced large crush type seismic events could be due to the induced fractures 'dividing' large competent rock masses into smaller portions, thereby reducing the risk of large volume instantaneous crush failure. The fractured rock mass transforms its behaviour into a more progressive crushing process later in the mining cycle.

For slip type events, the past mitigation technique has focused on modifying the three key parameters governing unstable slip movement: shear stress, friction property along the plane and normal/clamping stress acting on the plane. Board et al. (1992) successfully demonstrated that slip on structures can be initiated by fluid injection, which reduces the normal stress acting on the structure. Kaiser et al. (2013) proposed another hypothesis that slip events can possibly be addressed indirectly through the creation of damage zones around the unstable structure, thereby reducing energy emission levels and rates, which could lead to improved overall outcomes.

Nevertheless, it is likely that each distinct event mechanism will require a fundamentally very different HF treatment design. Crush type event mitigation will need to focus on evenly spaced fracture placement within potential crushing volume. Slip type event mitigation will need to focus on directly managing factors governing unstable slip, such as normal, shear stress or friction properties, or indirectly, as proposed by Kaiser et al. (2013).

5 The impact of hydraulic fracturing on seismic hazard

Several publications have documented the impact of HF application on subsequent seismic hazard (Morales et al. 2007; Catalan 2014; Rojas & Landeros 2017; Jonsson & Martinsson 2018; Ghazvinian et al. 2020; Lett 2022). There was varying degree of effectiveness in seismic hazard reduction observed across reported trials. Some trials reported high effectiveness where the result can be easily quantified, such as Rojas & Landeros (2017). Other trials reported more moderate effectiveness that would require rigorous statistical methods to quantify the difference (example shown in Figure 7). As the occurrence of large seismic events has a stochastic component and is driven by many factors, it is rather difficult to quantify the impact of HF. Despite this, the general consensus of published papers is that HF application indicates a reduced seismic hazard level.

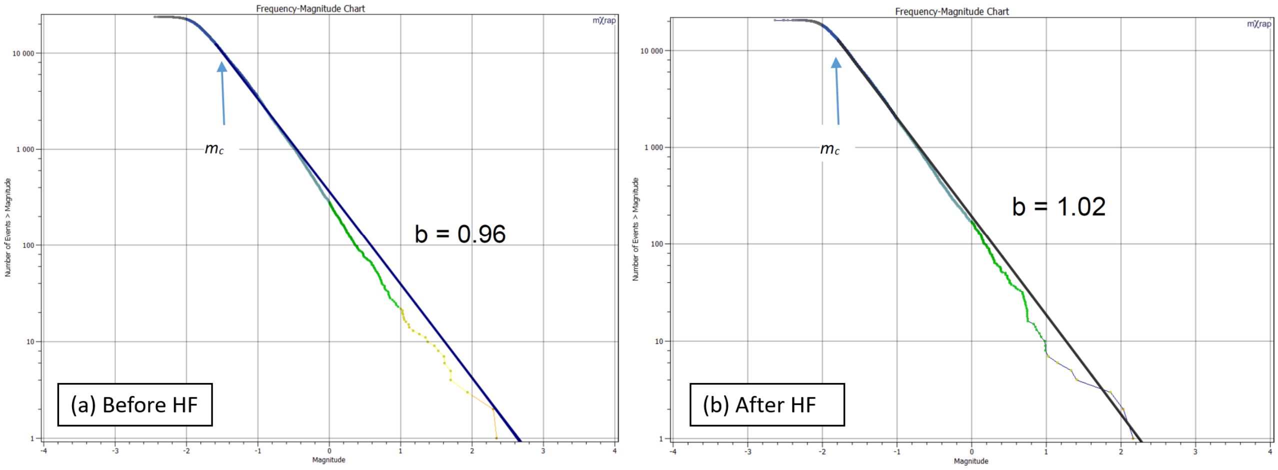

Figure 7 Gutenberg–Richter plot for (a) before hydraulic fracturing application and (b) afterwards. It is notable that more events greater than 1 are observed before the process (Jonsson & Martinsson 2018)

As the impact on seismic hazard is more of a byproduct of HF in caving operations, there have been fewer HF trials specifically aimed at quantifying seismic hazard reduction. Among the few remaining HF trials aimed at quantifying seismic hazard reduction there is a general lack of side-by-side comparative study where other seismic contributing factors such as stress condition, mining geometry and geology remained consistent or comparable.

The Ridgeway Deep HF trial provided a possible example of a comparative study (Lett 2022). Forty percent of the cave footprint at the Ridgeway Deep project was treated with HF as shown in Figure 8. Despite the inconsistency in geology between the western block (untreated) and eastern block (treated), the seismic hazard reduction is evident inside the HF volume through the reduced number and magnitude of large seismic events. However, the hazard quantification was not normalised by volume or over time.

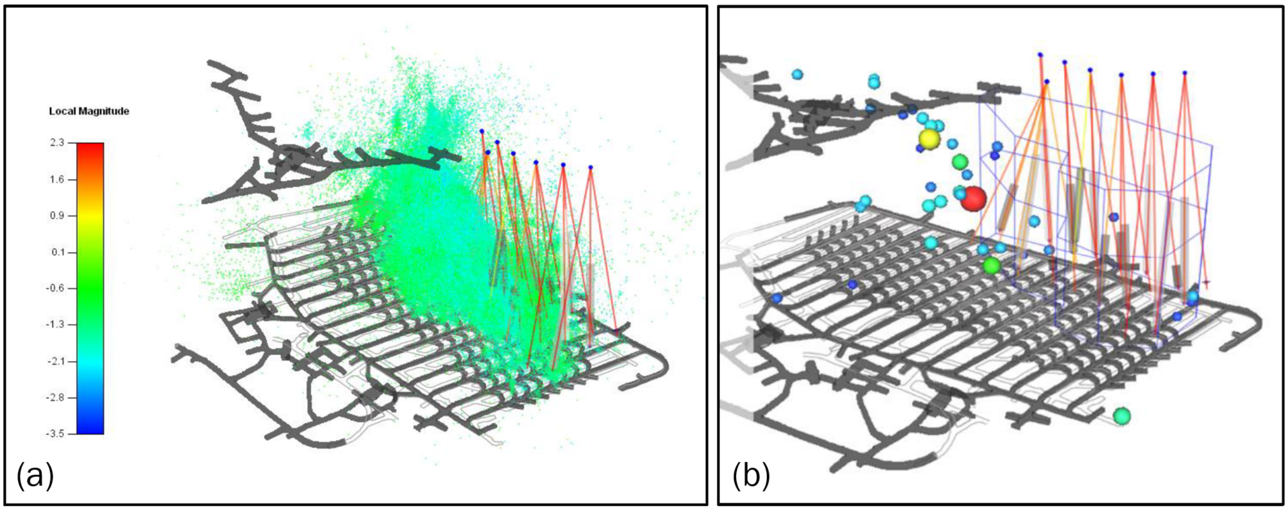

Figure 8 Ridgeway Deep seismic response (Lett 2022). All seismic data and hydraulic fracture holes shown in (a). Significant events observed shown in (b)

The published HF trials so far have reported favourable outcomes in seismic hazard reduction despite the lack of well-controlled side-by-side comparative set-ups. No explicit attempt was made to distinguish the source mechanism type as discussed in the previous chapter. The authors believe that it is critical to identify the dominant event mechanism type prior to designing the HF trial as the same treatment design will likely produce different results for each type of source mechanism. This is the due to the inherent complexity around the facture network creation process and the strong influence of geological structures such as fault, which is explained in the next section.

6 The complexity of fracture network creation

As the HF process is centred on creating and propagating tensile fractures using pressurised fluid, the fundamental focus on key rock mechanic properties has been vastly different than mining rock mechanics. Warpinski (2020) provided an updated summary of key rock mechanic aspects concerning HF and their recent development.

Mine-back exercises which directly expose rock surfaces with induced fractures is perhaps the most valuable opportunity to reconcile fracture geometry forecasts. However, such opportunity is typically rare in oil and gas settings and more practically achieved in mining settings. Warpinski & Teufel (1987) demonstrated the complexity of fracture growth in a mine-back exercise where natural fractures (bedding, joint and fault) had a dominant impact on induced fracture geometry, as shown in Figure 9.

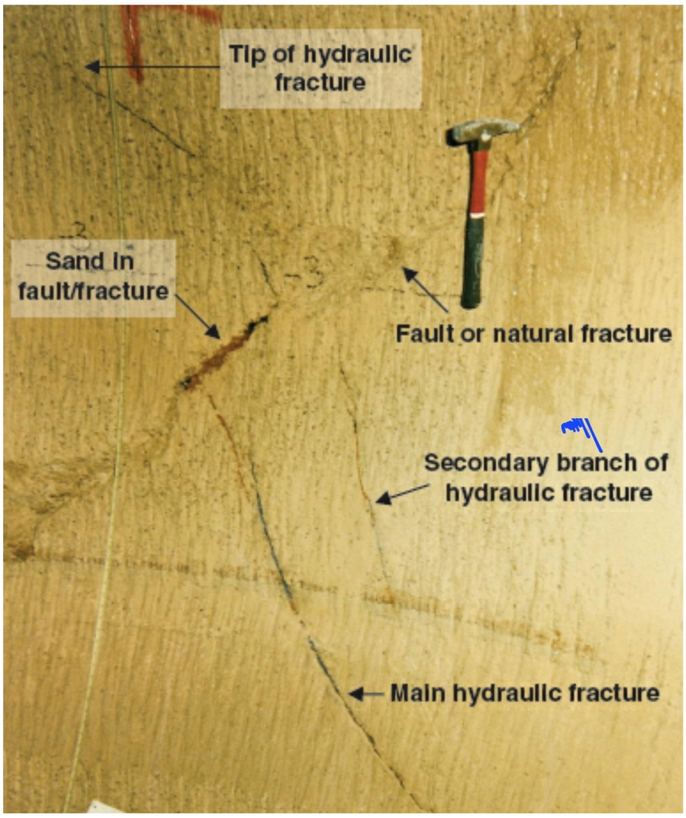

Figure 9 A mine-back exercise showing complex fracture geometry including parallel fracture, fracture offset by a fault and potential proppant marker screen-out (high concentration of red sand along fault)

The fracture complexity due to interaction with natural fractures was demonstrated in another mine-back exercise shown by van As & Jeffrey (2002), shown in Figure 10. Although the overall fracture orientation is consistent with expected minor principle stress direction in the area, significant offset occurred at several locations as the hydraulic fractures grew through natural fractures. It was also observed that the fracture was able to cut through dominant joint set with minimum offset and propagate in subparallel branches.

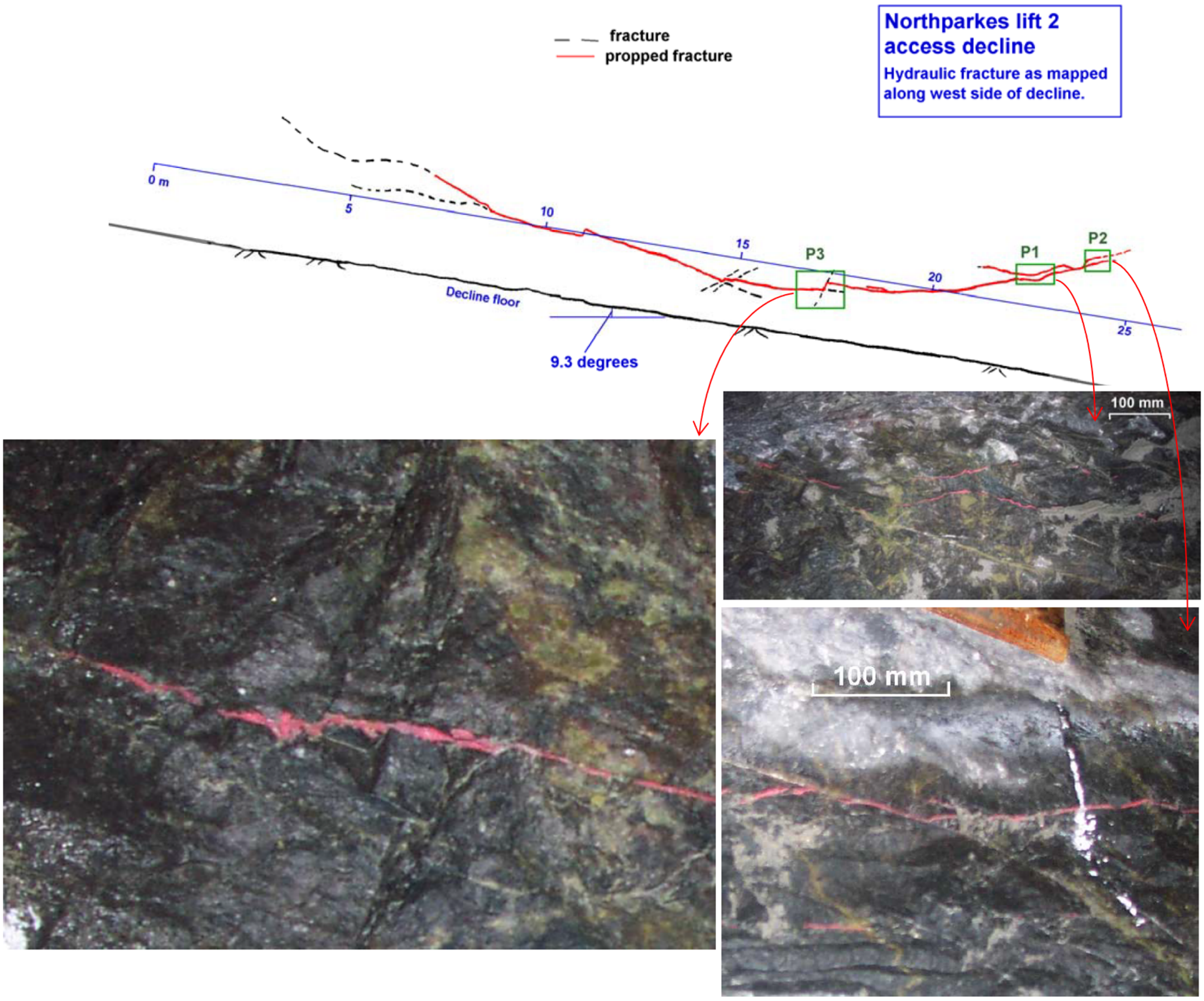

Figure 10 Northparkes lift 2 access decline mine-back exercise

Another mine-back exercise was carried out and documented in Jeffrey et al. (2009), as shown in Figure 11. The project aimed to enhance understanding of fracture propagation behaviour and assess fracture imaging tool performance. The fracture mapping result demonstrated again the complex behaviour of fracture propagation in a non-homogeneous rock mass condition. It also highlighted the importance of fracture imaging application in the HF process to provide critical information on fracture geometry.

Fracture propagation and its inherent complexity appear to be consistently observed in both the oil and gas and mining industries in recent decades (Diamond & Oyler 1987; Jeffrey et al. 1992; Warpinski et al. 1993; Branagan et al. 1996; Fisher et al. 2002; Zhang et al. 2007). Much of the understanding is gained through advancement in fracture imaging technology, which undoubtably sheds light on otherwise unknown fracture network geometry.

For the purposes of cave inducement over a footprint of several hundreds of metres, a small unfractured zone of 10 metres may not be a significant problem. For the purpose of seismic hazard mitigation, however, such an unfractured zone would be sufficient to result in a large-magnitude seismic event which could potentially lead to a substantial amount of damage. High-precision fracture imaging implementation is likely paramount in ensuring that the target rock mass is sufficiently fractured and that ongoing fracturing quality is guaranteed over the entire trial.

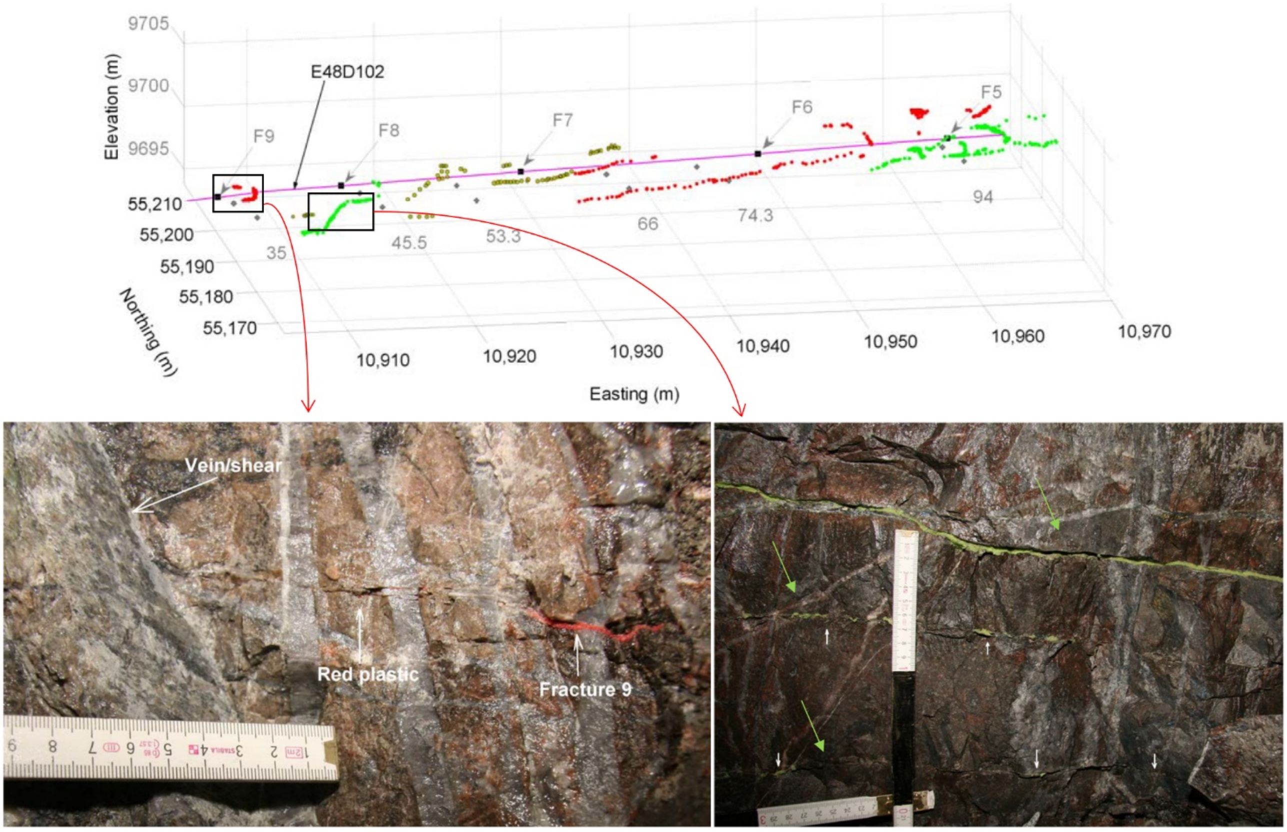

Figure 11 Northparkes ED4 tunnel mine-back exercise

7 Fracture imaging technologies

Unlike the mining industry, where physical and visual inspection can quite often be carried out practically, the oil and gas industry had to rely heavily on geophysical tools to acquire the critical information required to aid in well construction and optimise treatment design. Fracture imaging can be broadly classified into two categories based on their objective: near-field and far-field.

Near-field imaging is focused on the immediate vicinity of the wellbore typically associated with the fracture initiation process (often referred to as the breakdown process). Far-field imaging is typically focused on fracture propagation away from the wellbore; in particular on subjects such as fracture length, height, azimuth and complexity. The remainder of this section will focus on existing far-field fracture imaging technology commonly used in the oil and gas industry to monitor fracturing treatment.

7.1 Microseismic monitoring

Microseismic monitoring was introduced into fracturing operations in the 1970s as a diagnostic tool for geothermal hot-dry-rock stimulation (Warpinski 2020). Its application in HF experienced rapid expansion in the last two decades due to advancement in acquisition hardware and computing power. The fundamentals of microseismic monitoring for HF is well covered in van der Baan et al. (2013) and will not be explained further here.

Microseismic monitoring can provide two crucial sources of information regarding the HF process: the fracture geometry and fracture source mechanism. Fracture geometry can often be inferred from the event cluster geometry, with an oil and gas example shown in Figure 12. It is clear that seismic event location accuracy plays an important role in quantifying fracture geometry.

For HF processes completed in mining, additional sensors had to be deployed in close proximity to the HF volume to improve location accuracy. An example of such an exercise is well documented in Dahner et al. (2022), where a final location accuracy of 3 m was achieved.

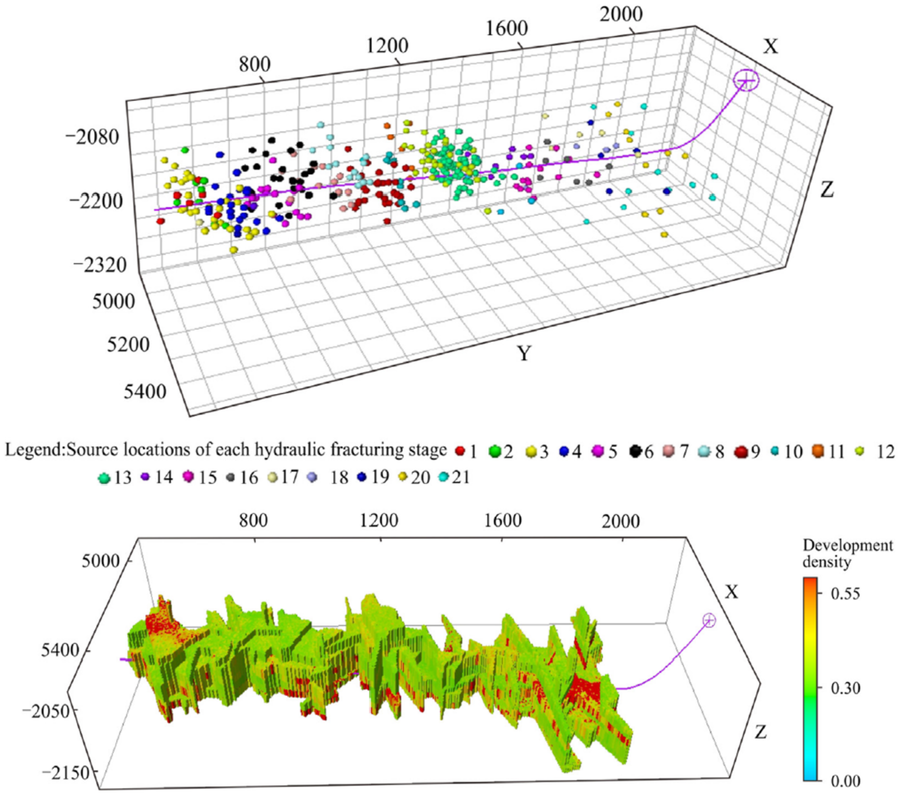

Figure 12 Hydraulic fracture stimulation volume estimation based on microseismic data (Ou et al. 2022)

There is some uncertainty regarding the use of microseismic data to infer fracture geometry as discussed by Warpinski (2020). In the oil and gas industry it is believed that the increase in pore pressure from fluid injection is the cause of most of the seismic events observed. The penetration of injected fluid into natural fractures and general pressurisation of liquid-saturated media can extend the influence far beyond its surface, resulting in seismicity at some distance away from the actual propped fracture. This, coupled with less than desirable location accuracy, add further uncertainty to the practice of inferring fracture extent using microseismic data in mining, as fracture half-length is typically 20 to 30 m from the wellbore (injection hole).

Nevertheless, microseismic monitoring still offers ample of valuable data which will aid in the imaging of fracture network geometry and the understanding of source mechanisms.

7.2 Tiltmeter monitoring

A tiltmeter is an extremely accurate measuring device that detects the angular position change (or tilt) of the surrounding environment (Wright 1998). An array of tiltmeters is typically deployed on the surface to monitor the deformation caused by subsurface activity. The interpretation of tiltmeter data typically requires an inversion with respect to a prescribed deformation model. An example is shown in Figure 13.

Tiltmeter application has been widely accepted in the oil and gas industry and often allows cross data validation, such as in the case presented in Estrada et al. (2009). In the mining industry, tiltmeter monitoring has also been frequently applied and its results verified. Jeffrey et al. (2009) demonstrated the reliability of tiltmeter inversion against mapped fractures (fracture 6 shown in Figure 14) during a mine-back exercise. Overall, the inverted and mapped fracture orientation shared a remarkably small misfit.

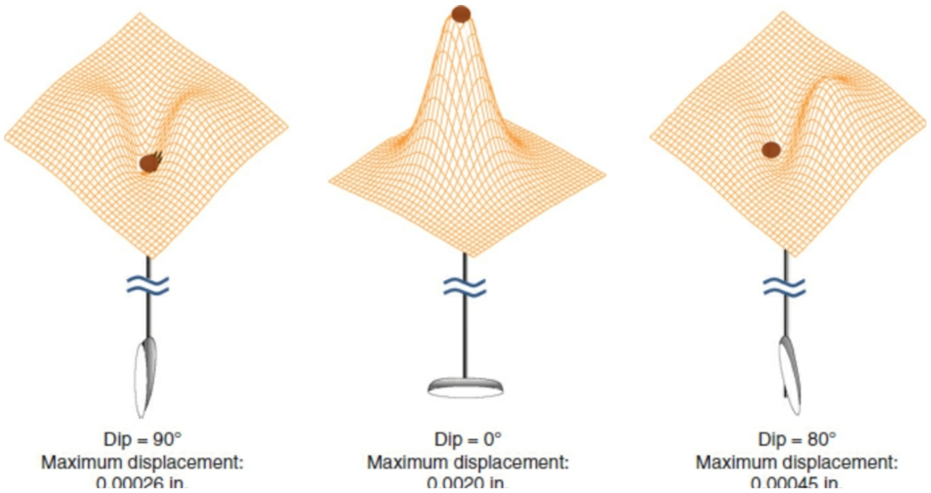

Figure 13 Theoretical tilt distribution for various geometry fractures (Wright 1998)

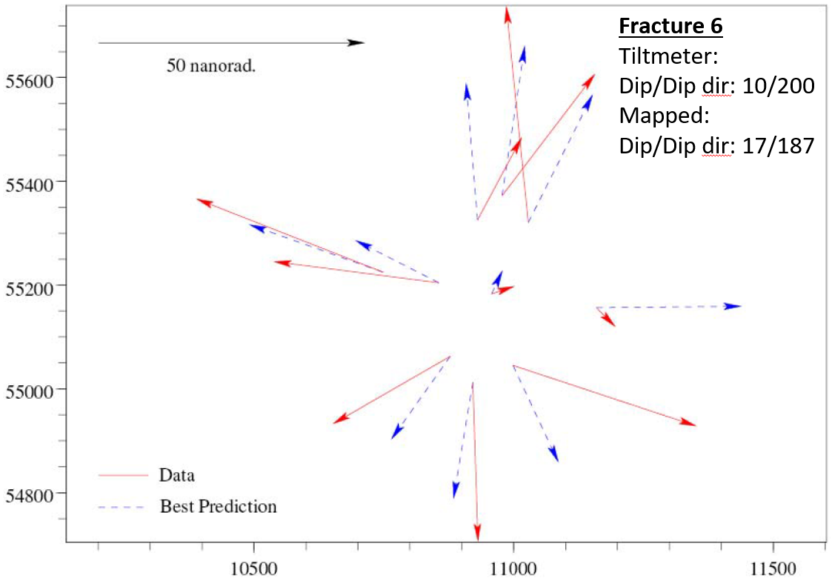

Figure 14 Northparkes mine-back exercise fracture 6 tiltmeter versus mapped fracture orientation (Jeffrey et al. 2009)

As shown, a tiltmeter is a consistent and reliable monitoring technique which can provide critical information on fracture geometry. The authors believe that with additional geometrical constraints included and underground deployment closer to the fracture volume, more accurate data is likely possible than what has been achieved so far.

7.3 Distributed acoustic sensing

Distributed acoustic sensing (DAS) technology, which is mainly based on Rayleigh, Brillouin or Raman backscattering along optical fibre cable, has gained tremendous popularity in the oil and gas industry. Ashry et al. (2022) provide a good summary of the fundamental principles of DAS technology and its current applications in this sector.

Unlike the oil and gas industry, where DAS application for a range of monitoring objectives is relatively common, the underground mining industry has been slow to embrace this technology. At the time of publication, DAS in mining has only been trialled for seismicity monitoring (du Toit et al. 2022) and some ongoing cave propagation monitoring.

For the objective of monitoring HF in mining, DAS application offers two key advantages. The first is its ability to monitor change in strain or strain rate in real time at 1 m accuracy (Furlong & Anderson 2022). This can be used to pinpoint the fracture (tensile) opening in real time. Both distributed strain sensing (DSS) or DAS can be used to achieve such an objective. A recent field trial example is shown in Figure 15.

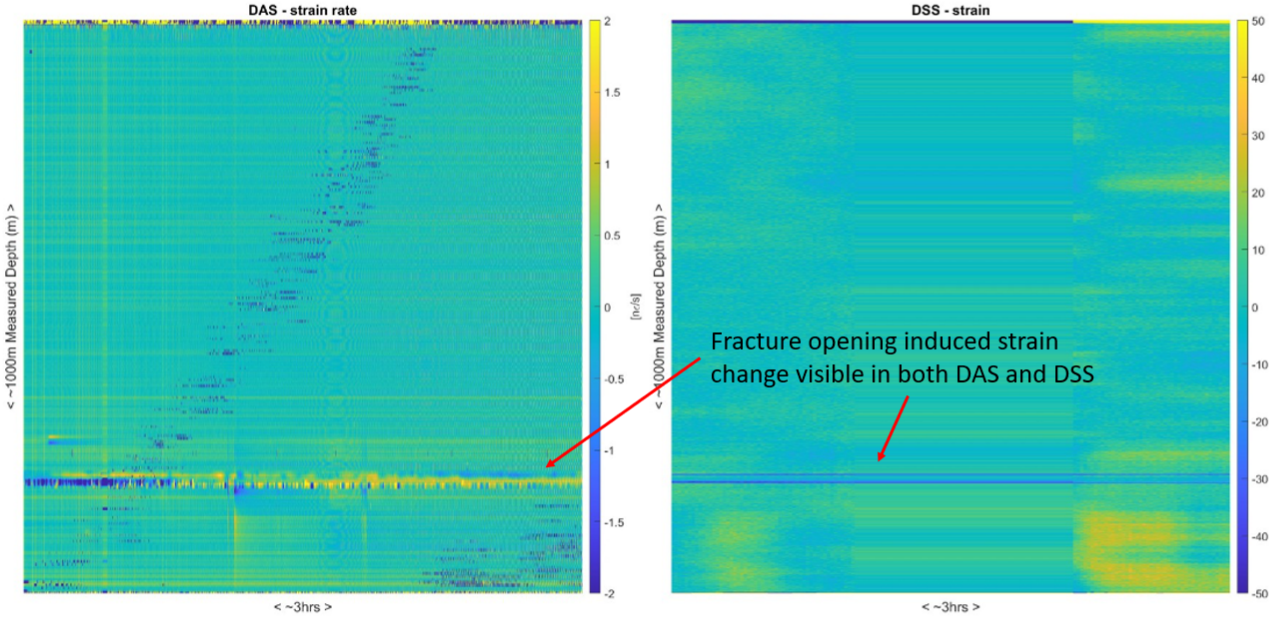

Figure 15 Distributed acoustic sensing and distributed strain sensing monitoring of hydraulic fracturing. Both approaches were able to identify the tensile opening at the fracture location (courtesy of Silixia)

The second advantage of DAS application is its ability to assist in seismic monitoring. This will not only improve the general location accuracy of events within the fracture volume as demonstrated in both mining (du Toit et al. 2022) and oil and gas scenarios (Ma et al. 2023), but it could also allow a propped fracture plane to be imaged through seismic wave reflection, as demonstrated by Staněk et al. (2022) and shown in Figure 16.

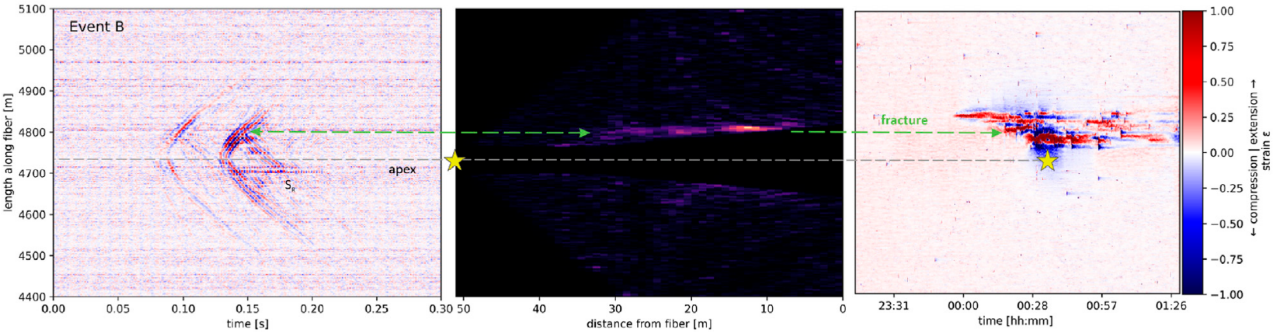

Figure 16 Induced fracture geometry inversion using a reflected seismic wave (Staněk et al. 2022)

The high-precision and real-time nature of the DAS monitoring is likely to be valuable for monitoring the mining HF process. This is particularly important as the fracture spacing used in mining is commonly between 1.5 to 2.5 m. Its ability to pinpoint fracture opening with 1 m accuracy will provide critical information to help optimise fracture design such as fracture and well spacing, locate fracture initiation, understand fracture interaction and, lastly, provide constraint data for tiltmeter inversion.

8 Future of hydraulic fracturing in mining

HF in cave mines has demonstrated that such a technique can be practically applied in both underground and surface mining environments. The technique has been proven to be effective at promoting caveability and has shown circumstantial evidence of the potential to mitigate seismic hazard. However, its effectiveness in mitigating seismic hazard still requires further verification through well-designed trials that focus on the following aspects:

- tailored fracture treatment design targeting specific seismic source mechanisms
- side-by-side trials in seismic hazard areas with comparable geotechnical settings
- high-accuracy imaging of fracture network geometry and optimised fracture placement.

Until now, HF has been mostly limited to caving operations due to its high associated cost and industry's unfamiliarity with the process involved. This, coupled with some uncertainty in its effectiveness, has prohibited wider adoption and trial of the practice in the wider underground mining industry.

One possible solution to overcome these challenges is through an industry-wide HF trial with a shared equipment fleet led by a research organisation. This will allow individual sites to receive a well-designed HF plan reviewed by industry experts.

9 Conclusion

The HF technique can be practically applied in underground mining operations other than cave mines. Although still associated with some uncertainty, it has shown promising potential in mitigating large seismic event occurrences. A statistical analysis to address these uncertainties would require access to the databases from the papers presented. Unfortunately this is not currently possible as databases are not available for public access. Through addressing these uncertainties, the HF technique could make a significant contribution towards seismic risk management and allow control measures to shift from passive to active.

If proven effective, the HF technique could significantly alter the way industry mines deep and high-stress deposits. The impact could range from immediate benefits such as reduced re-entry time and rehabilitation to longer-term benefits such as the adoption of lower-capacity ground support, higher recovery rates, reduced reserve write-off and the use of more productive mining methods that were previously not feasible.

Acknowledgement

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