

Review of Hydraulic Fracturing for Preconditioning in Cave Mining

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Received: 13 March 2016 / Accepted: 17 August 2016 / Published online: 30 August 2016
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Abstract Hydraulic fracturing has been used in cave mining for preconditioning the orebody following its successful application in the oil and gas industries. In this paper, the state of the art of hydraulic fracturing as a preconditioning method in cave mining is presented. Procedures are provided on how to implement prescribed hydraulic fracturing by which effective preconditioning can be realized in any in situ stress condition. Preconditioning is effective in cave mining when an additional fracture set is introduced into the rock mass. Previous studies on cave mining hydraulic fracturing focused on field applications, hydraulic fracture growth measurement and the interaction between hydraulic fractures and natural fractures. The review in this paper reveals that the orientation of the current cave mining hydraulic fractures is dictated by and is perpendicular to the minimum in situ stress orientation. In some geotechnical conditions, these orientation-uncontrollable hydraulic fractures have limited preconditioning efficiency because they do not necessarily result in reduced fragmentation sizes and a blocky orebody through the introduction of an additional fracture set. This implies that if the minimum in situ stress orientation is vertical and favors the creation of horizontal hydraulic fractures, in a rock mass that is already dominated by horizontal joints, no additional fracture set is added to that rock mass to increase its blockiness to enable it cave. Therefore, two approaches that have the potential to create orientation-controllable hydraulic fractures in cave mining with the potential to introduce additional fracture set as

desired are proposed to fill this gap. These approaches take advantage of directional hydraulic fracturing and the stress shadow effect, which can re-orientate the hydraulic fracture propagation trajectory against its theoretical predicted direction. Proppants are suggested to be introduced into the cave mining industry to enhance the induced stress shadow effect if prescribed hydraulic fractures are required. The feasibility of the proposed approaches will be investigated in future studies.

Keywords Preconditioning efficiency · Prescribed hydraulic fractures · Directional hydraulic fracturing · Stress shadow effect · Review

1 Introduction

Cave mining refers to block caving and panel caving in this paper and is an underground mass mining method with high productivity and low operating costs. It is a preferred mining method for extracting large, low-grade orebodies that are at unfavorable depths for the use of open-pit mining. Cave mining is traditionally applied to orebodies that are weak enough to unravel under gravity after undercutting to a specified size based on the rock mass quality. Laubscher (1990, 1994) provided detailed guidelines on rock mass quality assessment and the design of the caving system for optimum extraction. Chitombo (2010) traced the evolution of cave mining to date and stated that it is trending toward what he called super caves in the future. Currently, cave mining is used not only in weak orebodies but also in stronger orebodies with targeted mining block heights of 500–550 m.

In stronger orebodies, artificial weakening of the orebody is required to enable it to cave continuously under

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gravity with desired fragmentation sizes. Artificial weakening is also necessary to reactivate the cave when it stalls, for example, due to arching. Further details of arching can be found in Terzaghi (1943), and its effect on cave propagation was discussed in Laubscher (2000). Artificial weakening of the orebody to induce caving or relieve stress (i.e., de-stressing) is commonly referred to as preconditioning. Preconditioning can be achieved by either blasting or hydraulic fracturing, and the latter is more commonly used in the cave mining industry for the preconditioning purpose mostly because of its much lower cost compared with that of the traditional blasting.

Hydraulic fracturing emerged from the oil industry with its first successful commercial application in 1949 (Clark 1949). In essence, hydraulic fracturing is a process that includes:

- drilling a borehole into the targeted area;
- placing two packers in the borehole for fluid injection and
- creating fractures that initiate from the borehole by injecting fluid into the packer interval to stress levels that fracture the rock mass.

A hydraulic fracture (HF) is called an axial HF (or a longitudinal HF) if the HF is parallel to the borehole orientation as shown in Fig. 1a, or a transverse HF if it is perpendicular to the borehole orientation as shown in Fig. 1b (Valk and Economides 1995; Hossain et al. 2000;

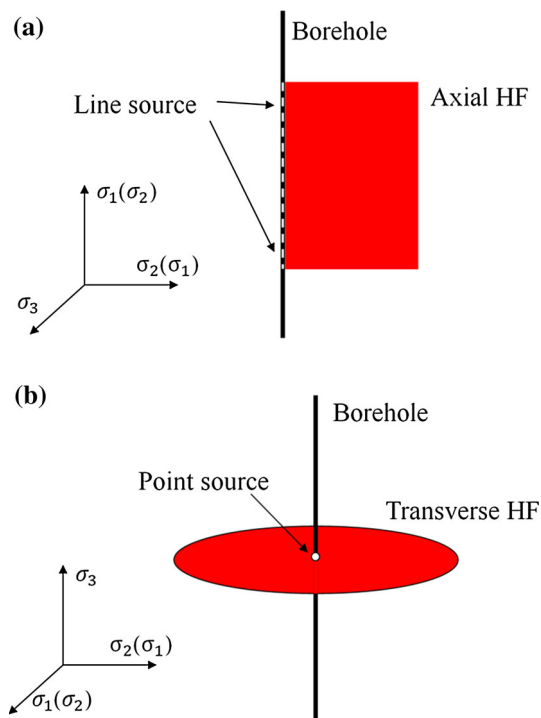


Fig. 1 Hydraulic fractures with different types (Valk and Economides 1995). **a** Axial hydraulic fracture and **b** transverse hydraulic fracture

Abbas et al. 2013). Axial HFs are common in the oil and gas industries. Theoretically, the communication between the borehole and the axial HF is regarded as a line source. Transverse HFs are common in the gas and mining industries. Theoretically, the communication between the borehole and the transverse HF is regarded as a point source. The minimum in situ stress (σ_3) orientation is horizontal in Fig. 1a, while it is vertical in Fig. 1b. In Fig. 1a, b, the induced HF propagation plane is perpendicular to the σ_3 orientation. This is the theoretically predicted orientation (Valk and Economides 1995).

In cave mining, the objective is to create multiple sub-parallel transverse HFs along each borehole to generate additional joint sets in the orebody. The orebody is expected to become blocky with additional joint sets, so that continuous cave propagation and acceptable fragmentation sizes can be achieved.

In this paper, the state of the art of hydraulic fracturing in cave mining is reviewed, and limitations of current applications are identified. Two approaches are proposed to fill this gap, so that the efficiency of the technology in cave mining could be highly improved. The following are the specific objectives of the paper:

- to identify the research gaps in the current knowledge of hydraulic fracturing for preconditioning in cave mining and
- to propose strategic approaches to fill the identified research gaps.

The strategies for achieving these objectives are outlined in detail in the following sections. In the next section, a comprehensive literature review of current hydraulic fracturing applications in cave mining for preconditioning is presented. It is shown that by using the existing techniques, the created HF orientation is not controllable and is strictly governed by the σ_3 orientation. However, creating orientation-uncontrollable HFs does not always necessarily result in additional joint sets that can generate a blocky orebody or achieve better fragmentation sizes as illustrated in Fig. 2. The engineering challenge in generating orientation-controllable HFs, here termed prescribed hydraulic fractures (PHFs), as additional joint sets whose orientations are not dictated by the σ_3 orientation is enormous but desirable.

2 Hydraulic Fracturing in Cave Mining

After being widely applied in the oil and gas industries with much success, hydraulic fracturing was introduced into the mining industry. It has been used in coal mining for improving coal seam permeability (Puri et al. 1991a, b, Wright et al. 1995; Zhai et al. 2012), hard roof control

Fig. 2 Preconditioning with different efficiency. **a** Undesirable preconditioning and **b** desirable preconditioning

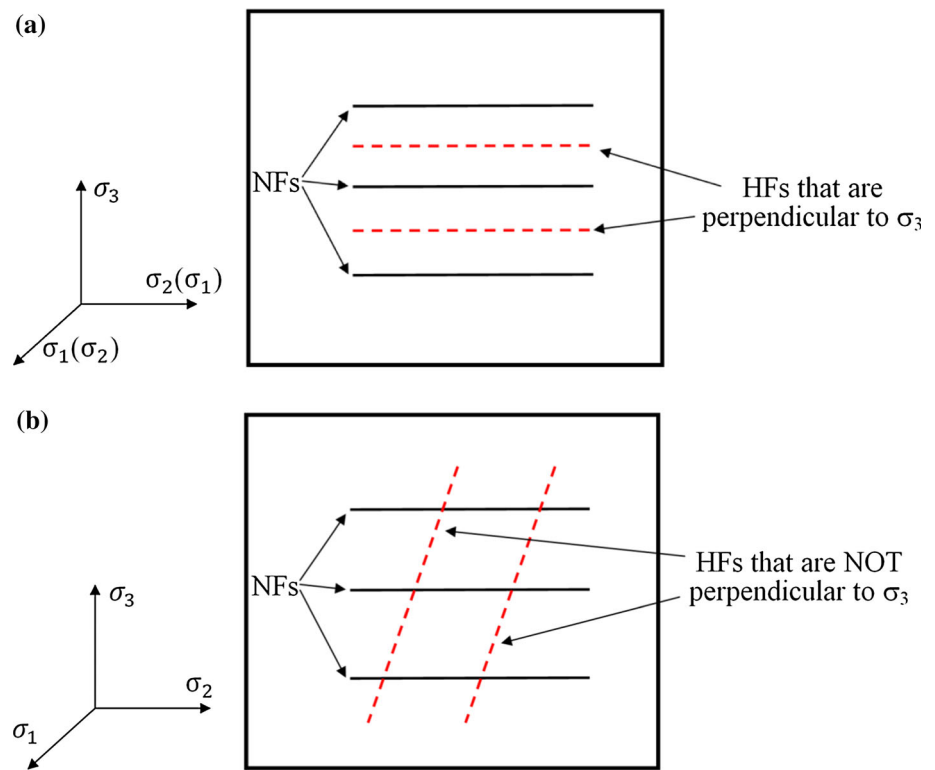


Table 1 Differences between hydraulic fracturing in the cave mining industry and hydraulic fracturing in the shale gas industry, revised by Bunger et al. (2011) and Adams and Rowe (2013)

Application	HF size	Injection volume (m ³)	Injection rate (L/s)	Additive	Proppant	Fracture distance (m)	σ_3 orientation
Cave mining industry	About 30 m in radius	8–20	5–10	No	No	1–2.5	Mostly vertical in Australia
Shale gas industry	Hundreds of meters in half-length	135–1000	75–250	Yes	Yes	About 100	Mostly horizontal

(Chernov 1982; Jeffrey et al. 2000a, b, 2001, 2013; Fan et al. 2012; He et al. 2012; Lekontsev and Sazhin 2015) and enhancing top coal caveability (Huang et al. 2011, 2015).

In cave mining (i.e., hard rock metalliferous environments), hydraulic fracturing has been utilized for either cave reactivation after cave arrests or as a preconditioning measure to initiate caving (Jeffrey 2000a, b; Van As and Jeffrey 2000a, b; van As et al. 2004; Araneda et al. 2007; Catalan et al. 2012). In hard rock cave mining, boreholes are generally drilled from the surface or subsurface excavations, and multiple transverse HFs are produced along the boreholes. This process is similar to hydraulic fracturing in the shale gas industry where multiple transverse HFs are created along a horizontal borehole that is parallel to the σ_3 orientation. As listed in Table 1, the differences between hydraulic fracturing in cave mining and that in the shale gas industry are in the following aspects (Bunger et al. 2011; Adams and Rowe 2013):

- The HF size: Cave mining HFs have radii of about 30 m, while shale gas HFs grow to hundreds of meters.
- The fracturing fluid: In the cave mining industry, no additives and proppants are used. A volume of 8–20 m³ water is injected per fracture at a flow rate of 5–10 l/s. In the shale gas industry, additives and proppants are utilized during or after the hydraulic fracturing operation. A volume of 135–1000 m³ fluid is injected per stage at a flow rate of 75–250 l/s.
- The fracture distance. The multiple transverse HFs in the cave mining industry and those in the shale gas industry are often placed 1–2.5 m apart and around 100 m apart, respectively.

In the following section, current applications of hydraulic fracturing at caving mine sites in Australia and Chile are reviewed and the research and operational gaps identified.

2.1 Hydraulic Fracturing in Australia Block Caving Mines

2.1.1 Northparkes Mines

Northparkes Mines is a copper/gold deposit and is the first block caving mine in Australia. Hydraulic fracturing was initially performed for caving reactivation in the E26 orebody. Continuous caving ceased after the cave back propagated to a maximum height of 95 m above the undercut (Jeffrey and Mills 2000; Jeffrey 2000; Van As and Jeffrey 2000a).

The in situ stress conditions in the orebodies at Northparkes Mines are listed in Table 2. At Northparkes Mines, the in situ stress condition is reverse faulting (i.e., the σ_3 orientation is vertical), which favors the creation of horizontal HFs. In 2002, van As and Jeffrey (2002) conducted hydraulic fracturing trials in the E26 orebody before designing full-scale preconditioning treatments. Mine through mapping was performed after the trials to observe HF trajectories and their interaction with natural fractures (NFs). The study established that HFs were more likely to grow into NFs at acute interaction angles and cross-perpendicular NFs without offsetting. The HF shapes were non-circular due to their interaction with NFs. It was concluded that open-mode fracturing rather than shear-mode fracturing was the dominant fracture growth mechanism.

The HF could be regarded as a flaw with zero tensile strength that can reduce the rock mass quality. Following these observations, van As et al. (2004) carried out a field-scale experiment in the E26 orebody to measure HF growth and assess its capability of inducing caving. The HF size was measured with boreholes and microseismic monitoring systems. The HF orientation was estimated with both tiltmeter monitoring and stress change monitoring. The monitoring results showed that the HF radius extended to 30–50 m from the injection point with a sub-horizontal orientation and was perpendicular to the σ_3 orientation. The hydraulically fractured rock mass quality was assessed by

the post-fracturing P-wave velocity based on the correlation established by Sjøgren et al. (1979), Tanimoto and Ikeda (1983), Palmstrøm (1996) and Barton (2002) as listed in Table 3. The study noted that the effect of hydraulic fracturing for preconditioning was more significant in sparsely fractured rock masses compared with that in highly fractured rock masses, and hence, there should be a critical joint frequency value above which preconditioning is ineffective.

In 2004, Mills and Jeffrey (2004) conducted stress change monitoring with ANZI (Australia New Zealand Inflatable) stress cells (Mills 1997) in the E26 orebody at Northparkes Mines to measure HF growth. The estimation of the HF size and its orientation by stress change monitoring was based on fracture mechanics and was described in detail in Mills et al. (2004). The mechanism and details of this process are presented as follows:

- Due to the newly created HFs, the stress state in the near-fracture region is altered from the in situ stress state. Before hydraulic fracturing, stress cells are installed around the injection point as shown in Fig. 3. These stress cells are located along a single borehole and are capable of measuring both the compressive and the tensile stress change vectors (in both magnitudes and orientations) at each point (i.e., points A, B and C in Fig. 3).
- On the other hand, the induced stress state around an open-mode radial fracture (i.e., a radial fracture sustaining uniform tensile stress on its surfaces) can be calculated by numerical modeling as long as the applied tensile stress magnitude and the fracture radius are known.
- If the HF center is assumed to be always located at the injection point as shown in Fig. 3 and HF propagation is symmetric about its center, by analyzing the recorded injection pressure data and the measured stress change vector at each point at any given time, the HF radius and its orientation at that moment could be deduced.

Table 2 In-situ stress conditions at caving mine sites in Australia (Van As and Jeffrey 2000a, b; Jeffrey et al. 2009; Catalan et al. 2012)

Mine site	σ_1 magnitude (MPa)	σ_1 dip and strike angles (°)	σ_2 magnitude (MPa)	σ_2 dip and strike angles (°)	σ_3 magnitude (MPa)	σ_3 dip and strike angles (°)
E26, Northparkes	22.7	5/141	15.0	15/49	12.1	75/248
E48, Northparkes	39.0	10/102	24.0	10/10	18.0	76/237
Cadia East	73.0	0/74	49.0	0/164	42.0	90/74

Table 3 Relationship between the P-wave velocity change and the rock mass quality change after hydraulic fracturing in the E26 orebody at Northparkes Mine (van As et al. 2004)

Decrease in the P-wave velocity	Increase in fracture frequency	Decrease in RQD	Decrease in the Q value	Decrease in IRMR
15 %	5–8 fractures/m	25–30	1.2–3.8	46–58

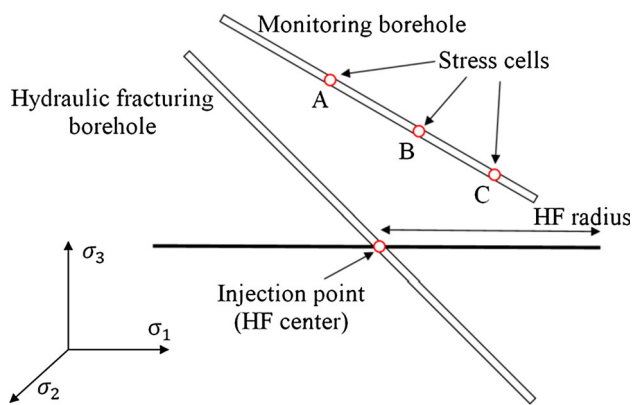


Fig. 3 Stress change monitoring for estimating the HF size and its orientation (Mills et al. 2004)

Mills and Jeffrey (2004) pointed out that stress change monitoring could confine the possible HF orientations in the three-dimensional space in a narrow range and a unique result could be achieved when the monitoring results are combined with other observations. Furthermore, due to the difference between the induced stress state around an open-mode fracture, where the compressive stress vectors are symmetric about the fracture center, and the induced stress state around a shear-mode fracture (i.e., a fracture sustains asymmetric shear stress on its surfaces), where the compressive stress vectors are asymmetric about the fracture center (Valk and Economides 1995), stress change monitoring was capable of discriminating between open-mode HF growth and shear-mode HF growth.

Jeffrey et al. (2009) carried out a hydraulic fracturing experiment in the E48 orebody at Northparkes Mines. After the experiment, mine through mapping was again performed to compare the mapped HF trajectories with that inferred from tiltmeter monitoring and microseismic monitoring. The in situ stress condition in the E48 orebody is listed in Table 2. This study indicated that tiltmeter monitoring was reliable in determining the overall HF orientation and its size (Chen and Jeffrey 2009), while the microseismic monitoring result was mine site dependent and was unsatisfactory in the E48 orebody. On the contrary, microseismic monitoring achieved a successful application at Ridgeway Deeps Block Caving Mine in Australia in estimating the HF orientation, the propagation rate and its size (Joubert 2010). The reasons that cause the different monitoring results are in two aspects:

- The microseismic monitoring system at Northparkes Mines is a so-called trigger mode system that only transmits signal when a triggering criterion for a given sensor is exceeded, and its primary purpose is the monitoring of seismic events associated with mine development and caving rather than hydraulic fracturing.

- Compared with that at Northparkes Mines, the microseismic monitoring system at Ridgeway Mine records data continuously and at significantly higher frequency with sensor density good enough to monitor hydraulic fracturing performance.

2.1.2 Newcrest Cadia East Mine

Newcrest Mining Limited’s Cadia East Mine (a copper/gold deposit) is the first panel caving mine in Australia and is the deepest panel caving mine in the world as well as the largest underground mine in Australia (Catalan et al. 2012). The in situ stress condition at Cadia East Mine is reverse faulting as listed in Table 2. The intensive preconditioning concept that combines hydraulic fracturing and confined blasting was proposed to precondition the orebody (Catalan et al. 2012; Kaiser et al. 2013); Catalan et al. (2012) thought hydraulic fracturing was expected to decrease rock mass strength by introducing additional joint sets, while drilling and blasting aimed at damaging the intact rock so that rock mass mechanical properties (i.e., rock strength and stiffness) could be modified. The intensive preconditioning process involved two steps:

- Firstly, hydraulic fracturing boreholes (down-holes) were drilled from a subsurface excavation that was located in an upper level above the targeted rock mass. Closely located HFs were created along these boreholes to add new joint sets into the rock mass.
- Secondly, drilling and blasting boreholes (up-holes) were drilled from the undercut level in order to further precondition the hydraulically fractured rock mass to modify its mechanical properties.

A series of hydraulic fracturing trials were undertaken from September 2009 to February 2010. According to the acoustic televiewer scanner images collected from the borehole injection interval before, during and after the hydraulic fracturing operation, the HFs had three initiation types that included axial initiation as shown in Fig. 1a, transverse initiation as shown in Fig. 1b and initiation along the existing NF. The damage zone size (i.e., the section of the borehole wall affected by HF initiation) induced by each initiation type is provided in Table 4.

Table 4 HF initiation types and damage zone sizes (Catalan et al. 2012)

Initiation type	Damage zone size (m)
Axial	Up to 2.4
Transverse	0.2
Opening existing NF	0.2

The disadvantages of the HF axial initiation at Cadia East Mine are in two aspects:

- The increase in the damage zone size resulted in a wider spacing between the multiple transverse HFs, which decreased the number of HFs produced along each borehole.
- The HFs sustained serious tortuosity before they re-orientated their trajectories to propagate transversely to the borehole (i.e., propagates perpendicularly to the far-field σ_3 orientation). The near-borehole HF re-orientation process increased the friction loss and formed irregular HF shapes.

In the trials at Cadia East Mine, a special cutting machine was used to create an initial notch around the borehole wall as an artificial weakness for the HF to initiate. The initial notch can not only lower the required breakdown pressure but also prescribe the HF initiation location and its initiation type. This was also confirmed by the hydraulic fracturing application at Narrabri Coal Mine in Australia for preconditioning the hard roof (Jeffrey et al. 2013, 2014). It showed that a low injection rate and high-quality notch cutting are favorable for transverse HF initiation.

2.2 Hydraulic Fracturing in Chile

2.2.1 Salvador Mine

Salvador Mine is a block caving mine (a copper deposit) located in the northern part of Chile. In 2004, a full-scale experiment was carried out to investigate the capability of hydraulic fracturing for preconditioning the orebody and reducing fragmentation sizes (Chacon et al. 2004). Though the in situ stress condition at Salvador Mine was not mentioned in the literature, observation results of HF orientations (Table 5) from monitoring boreholes suggest that the σ_3 orientation is sub-horizontal. Acoustic scans of the fractured borehole revealed that the HF initiated in an axial form and then rotated to a transverse type to become perpendicular to the far-field σ_3 orientation. In the next stage of these trials, a cutting machine was used to create initial notches around the borehole wall in order to introduce weak points that prescribe

Table 5 HF orientations observed from monitoring boreholes (Chacon et al. 2004)

Fracture	Dip (°)	Strike (°)
1	81W	2
2	90	343
3	75W	7
4	75W	7
5	78W	10
6	85E	356
7	82W	2

the HF initiation pattern. Acoustic scan results showed the notching application had satisfactory results.

The HF initiation patterns at Salvador Mine, as well as that observed at Cadia East Mine (Catalan et al. 2012), indicated that the cutting of the initial notch is an important approach to controlling the HF initiation type and avoiding the unfavorable axial initiation. The reliability of stress change monitoring in predicting the HF orientation and its opening mode was validated by comparing with mine through mapping results that showed that the HFs were sub-vertical and dipped at about 75° to the east. The mine through mapping observation also indicated that the HFs at Salvador Mine had little interaction with NFs. Catalan et al. (2012) suggested that the mineral fillings in the NFs increased their shear strength and decreased their permeability, so that HFs tended to cross these NFs rather than terminated at them. On the contrary, the widely distributed shear zones that were more permeable and had lower shear strength at the Salvador Mine had significant influence on HF propagation and acted as barriers that resulted in asymmetric HF propagation.

2.2.2 El Teniente Mine

El Teniente Mine in Chile is the world's biggest underground copper mine. In 2007, hydraulic fracturing was utilized to precondition the competent orebody that was under high stresses in order to eliminate potential rockburst induced by the mining operation (Araneda et al. 2007). The in situ stress condition at El Teniente Mine is provided in Table 6. The effect of hydraulic fracturing was evaluated by the induced seismicity magnitude and the cave propagation rate. Hydraulic fracturing achieved success in rockburst prevention according to the monitoring results. These results showed that the mining-induced seismicity magnitude after preconditioning was lower than 2.1 and the connection time for the cave back to the upper level was 10 months.

2.3 Summary of the State of the art of Hydraulic Fracturing in Cave Mining

From current studies on hydraulic fracturing and its application in cave mining, the following conclusions can be drawn:

Table 6 In-situ stress condition at El Teniente Mine in Chile (Araneda et al. 2007)

	Magnitude (MPa)	Dip (°)	Strike (°)
σ_1	51	76.6	343.5
σ_2	33	42.0	88.9
σ_3	23	51.1	242.5

- Hydraulic fracturing is capable of improving caveability and fragmentation sizes by adding new fractures into the orebody.
- The cutting of an initial notch around the borehole wall before hydraulic fracturing has a notable effect on avoiding HF axial initiation. It does not only favor the desirable HF transverse initiation but also being able to lower the required breakdown pressure.
- Monitoring boreholes, tiltmeter monitoring, stress change monitoring, microseismic monitoring and mine through mapping have been applied in measuring HF growth in cave mining. Monitoring boreholes provide direct measurement of the HF size and its propagation rate (van As et al. 2004). Tiltmeter monitoring is an effective way to estimate the HF orientation and the HF size (van As et al. 2004; Chen and Jeffrey 2009). Stress change monitoring could be used to observe the HF orientation and the HF opening mode (Chacon et al. 2004; Mills and Jeffrey 2004).
- The effect of microseismic monitoring is mine site dependent, and continuous data recording at high frequency improves its accuracy (Jeffrey et al. 2009; Joubert 2010). Mine through mapping is the only direct way to investigate the HF trajectory and its interaction with NFs (van As and Jeffrey 2002; Jeffrey et al. 2009).
- The interaction between HFs and NFs is influenced by many factors. Generally, HFs tend to cross NFs at about 90° interaction angles and grow into NFs at acute interaction angles (van As and Jeffrey 2002). He et al. (2015) carried out theoretical and modeling studies on this interaction process. The study showed that the interaction result is influenced by all the three in situ stresses, NF dip angles and NF strike angles.
- Infillings in NFs are helpful in increasing NF shear strength and decreasing NF permeability so that HFs can cross NFs without offsetting them (Catalan et al. 2012). Meanwhile, shear zones that usually have weaker shear strength and higher permeability (compared with NFs) have significant influence on HF propagation and act as barriers that result in asymmetrical HF propagation.

The above studies are focused on field applications, HF growth measurement and the interaction between HFs and NFs. According to the existing knowledge, the HF orientation is dictated by and is perpendicular to the σ_3 orientation (Hubbert and Willis 1972). In cave mining, hydraulic fracturing operations are designed based on this principle to create orientation-uncontrollable HFs, and their efficiency (i.e., HF generation as an additional joint/fracture set rather than increasing the frequency of an existing joint set) is measured to predict the preconditioning success. In essence, the purpose of hydraulic fracturing as a

preconditioning method in cave mining is to make the orebody become blocky by producing additional joint sets in the orebody, so that continuous cave propagation can be achieved.

As listed in Tables 5 and 6, the σ_3 orientations at Salvador Mine and El Teniente Mine are sub-horizontal, which implies the HF orientation is sub-vertical as dictated by the σ_3 orientation. These additional oblique joint sets are helpful in cave propagation in either a mining block without dominant NFs as shown in Fig. 4a or a mining block that contains NFs with various dip angles as shown in Fig. 4b. The in situ stress conditions at most caving mine sites in Australia are reverse faulting as listed in Table 2. In this scenario, the theoretical HF orientation is horizontal or sub-horizontal. In a mining block dominated by vertical or oblique NFs, these additional horizontal joint sets are effective in making the orebody become blocky as shown in Fig. 5a. The mining blocks illustrated in Fig. 5b, c have no dominant NFs or are dominated by horizontal NFs. The preconditioning efficiency of hydraulic fracturing in these scenarios, however, is limited if the HF is orientation cannot be controlled to form a new joint or fracture set. On one hand, the HF is very likely to propagate into the existing NFs that have small dip angles as shown in Fig. 5c (van As and Jeffrey 2002). This results in the HF having a smaller radius and an asymmetric fracture shape. On the other hand, these additional horizontal joints or fractures do not change the mining block into a blocky one as shown in Fig. 5b, c and only changes the frequency of existing joints

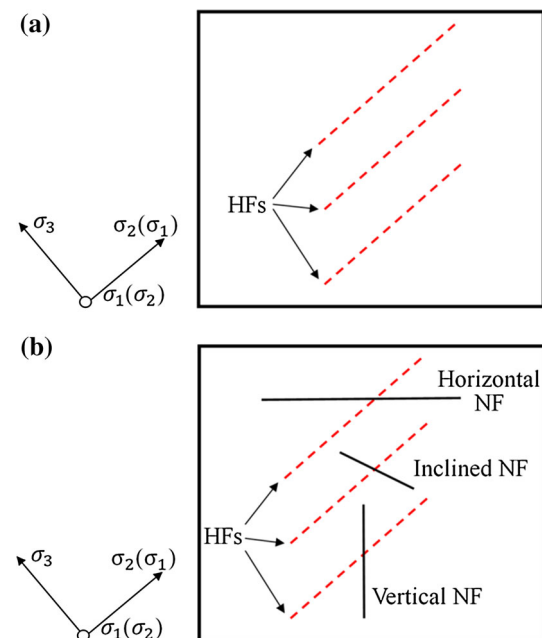


Fig. 4 Hydraulic fracturing in Chile. **a** Hydraulic fracturing in a mining block without dominant NFs and **b** hydraulic fracturing in a mining block containing NFs with various dip angles

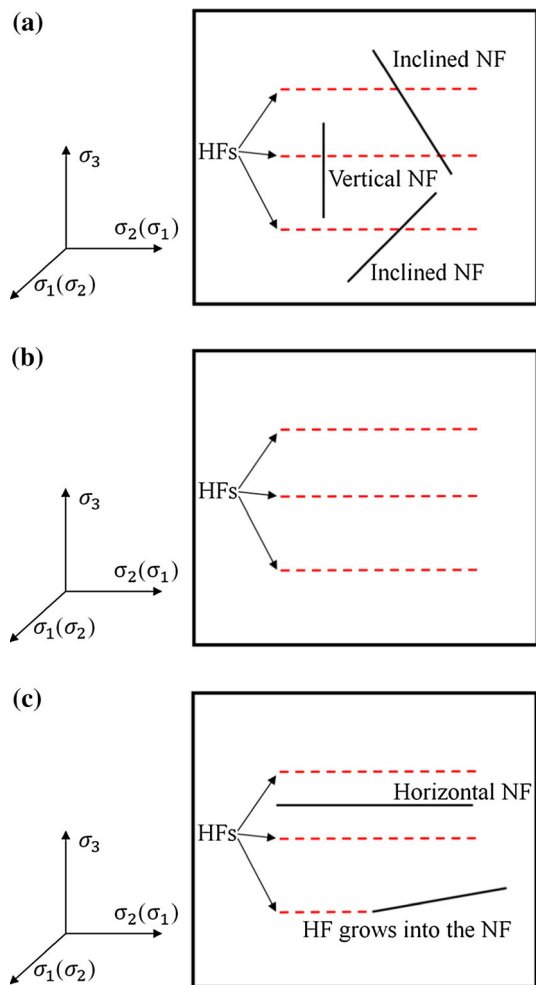


Fig. 5 Hydraulic fracturing in Australia. **a** Hydraulic fracturing in a mining block containing vertical and inclined NFs, **b** hydraulic fracturing in a mining block without dominant NFs and **c** hydraulic fracturing in a mining block containing horizontal NFs

or fractures. In this situation, the creation of horizontal HFs does not necessarily result in reduced fragmentation sizes and the expected continuous cave propagation.

To avoid arching, a blocky rock mass in a relaxed state (i.e., no clamping stresses) is important. In a reverse faulting in situ stress condition, the created HF orientation has to be horizontal by using the existing technique. However, horizontal HFs have limited influence on the existing rock mass structure as shown in Fig. 6a. The horizontal HFs do not favor the unraveling of clamped rock mass fragments, and the cave back maintains an arch shape that hinders caving propagation. On the contrary, if HFs with arbitrary orientations can be created, vertical and oblique HFs have significant influence on the elimination of arching as shown in Fig. 6b, c.

From the above, the creation of PHFs is required so that successful preconditioning could be realized in any

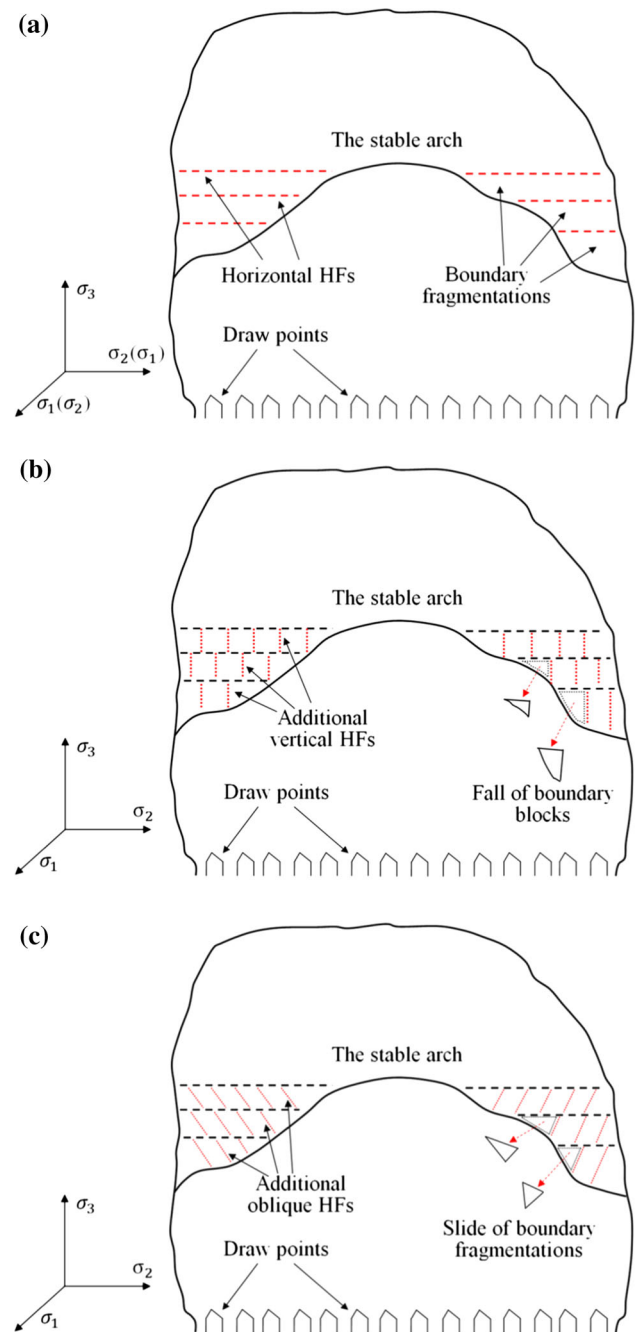


Fig. 6 Effect of hydraulic fracturing on arching. **a** Limited influence of horizontal hydraulic fractures on the stable arch, **b** significant influence of vertical hydraulic fractures on the stable arch and **c** significant influence of oblique hydraulic fractures on the stable arch

in situ stress condition and rock mass structures. To fulfill this objective, HF re-orientation against its theoretically predicted path is needed. In the next section, previous studies on HF re-orientation are reviewed and two approaches that have the potential to create PHFs are proposed.

3 Strategic Approaches to Creating Prescribed Hydraulic Fractures in Cave Mining

In Sect. 2, the state-of-the-art hydraulic fracturing in cave mining is provided, and the necessity for creating prescribed HF is established. To fulfill this objective is a formidable task that needs novelty in HF re-orientation against its preferred propagation plane. In the following section, previous studies on HF re-orientation are briefly summarized and two approaches that are based on directional hydraulic fracturing and the stress shadow effect are proposed to create PHFs.

3.1 Hydraulic Fracture Re-orientation from Oriented Perforations

In the oil and gas industry, cased boreholes are used for hydraulic fracturing. To initiate HF, perforating guns are used to create perforations around the cased borehole wall as initial weaknesses as shown in Fig. 7a. When hydraulic fracturing is performed in a perforated cased borehole, the following scenarios may occur:

- HF may initiate from the top and bottom bases of perforations as starter fractures. These starter fractures

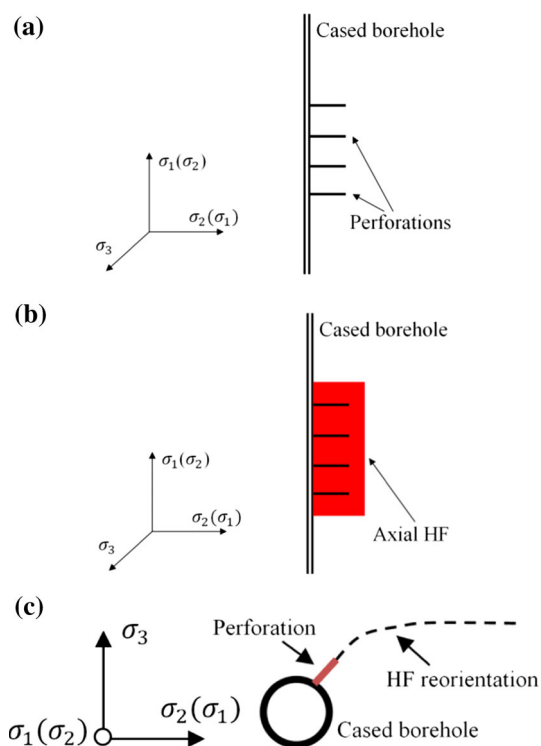


Fig. 7 Hydraulic fracturing through perforations (Behrmann and Elbel 1991). **a** Perforations around a cased borehole, **b** hydraulic fracture initiated from perforations and **c** plan view of hydraulic fracture re-orientation from oriented perforations

may link up to become a single axial HF as shown in Fig. 7b.

- If the perforation orientation is not aligned with the HF preferred propagation plane, the axial HF will experience a re-orientation process before it finally propagates perpendicularly to the σ_3 orientation as shown in Fig. 7c.
- The starter fractures may re-orientate quickly after initiation rather than link up. In this situation, multiple HF are formed instead of a single axial HF.
- T-shape fractures will form when conditions 2 and 3 occur simultaneously.
- The HF may initiate directly from its preferred propagation plane outside of the cased borehole wall rather than initiate from the perforations.

The scenario in condition 2 where a single HF forms and re-orientates its path due to the oriented perforations is of much interest in this paper. In cave mining, the cutting machine is used to create an initial notch around an open borehole wall as an artificial weakness for the HF to initiate. If the notch orientation is not aligned with the HF preferred propagation plane, the HF is expected to deviate from its normal path until the re-orientation process ends.

HF re-orientation from oriented perforations has been widely studied by laboratory experiments (Daneshy 1971, 1973a, b; Behrmann and Elbel 1991; Weijers and De Pater 1992; Abass et al. 1994, 1996; Chen et al. 2010) and numerical modeling (Guangqing and Mian 2009; Sepehri 2014; Sepehri et al. 2015). These studies indicate:

- HF re-orientation from oriented perforations is a near-borehole effect and occurs within one or two borehole diameters. Both tensile failure and shear failure were observed during HF re-orientation.
- The extent of HF re-orientation is determined by many factors that include rock properties, the in situ stress condition, injection parameters (i.e., the flow rate and fluid viscosity), a perforation angle and perforation dimensions.
- A low flow rate favors HF initiation from perforations. The HF could achieve a longer re-orientation distance if the product of the flow rate and fluid viscosity is sufficiently high.

3.2 Directional Hydraulic Fracturing

Directional hydraulic fracturing is similar to the perforation technique used in cased boreholes in the oil and gas industries. In the mining industry, open boreholes are used. The difference between directional hydraulic fracturing and the traditional open borehole hydraulic fracturing is that an initial notch is created with a cutting machine

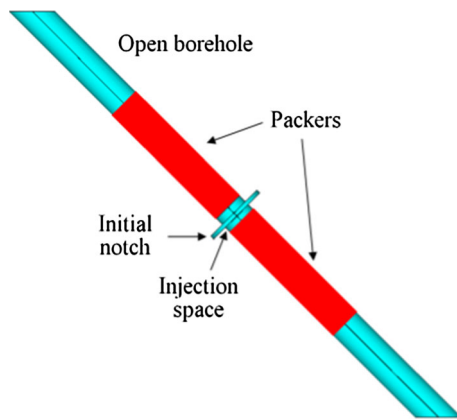


Fig. 8 Directional hydraulic fracturing (He et al. 2016)

around the open borehole wall as an artificial weakness for the HF to initiate as shown in Fig. 8. If the notch orientation is not perpendicular to the σ_3 orientation, the HF is expected to deviate from its preferred propagation plane in the near-borehole area. Directional hydraulic fracturing has been widely applied in the coal mining industry for hard roof control (Chernov 1982; Chernov and Kyu 1996; Chernov et al. 1997; Jeffrey 2000; Fan et al. 2012; He et al. 2012; Jeffrey et al. 2013). Recently, this technique has been used at a longwall top coal caving working face to improve top coal caveability (Huang et al. 2011, 2015).

As mentioned in Sect. 2, directional hydraulic fracturing also has applications in cave mining to lower breakdown pressure and promote HF transverse initiation (Chacon et al. 2004; Catalan et al. 2012). In general, previous studies on directional hydraulic fracturing are focused on field applications. Few studies have been carried out to understand the mechanism of HF re-orientation from an oriented initial notch. HF re-orientation trajectory was investigated by numerical modeling in (He et al. 2016a). He et al. (2016a) concluded that HF re-orientation caused by directional hydraulic fracturing occurred within one or two borehole diameters and was influenced by the in situ stress condition and rock mass heterogeneity.

3.3 Hydraulic Fracture Re-orientation Induced by the Stress Shadow Effect

Besides an oriented artificial weakness, an HF could re-orientate from its preferred propagation plane due to the stress shadow effect. The basic idea of the stress shadow effect is illustrated in Fig. 9. In Fig. 9, the σ_3 orientation is vertical, and σ_2 is perpendicular to σ_3 with σ_1 out of plane. A horizontal transverse HF is created from the vertical borehole (by either creating a new HF or reopening an existing NF). Due to the existence of the created fracture, the stress state in the region around the fracture surfaces is altered as a result of the superimposition of the in situ stress

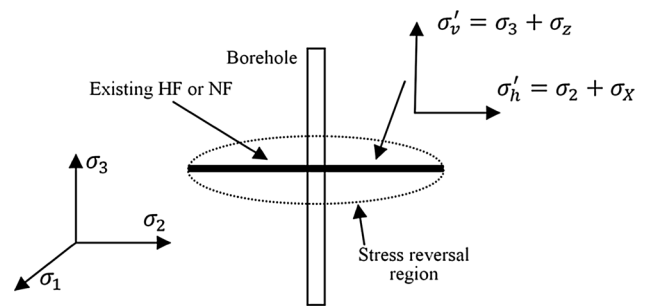


Fig. 9 Stress shadow effect (Roussel and Sharma 2011a, b)

state and the fracture-induced stress state. The fracture-induced stress vector at each point in the near-fracture region can be decomposed into two sub-vectors as σ_z , which is the stress vector in the vertical direction, and σ_x , the stress vector in the horizontal direction. Based on elastic fracture mechanics, both σ_z and σ_x are compressive, and the magnitude of σ_z is larger than that of σ_x in the near-fracture region (Valk and Economides 1995). If the difference between the fracture-induced stresses σ_z and σ_x exceeds the difference between σ_2 and σ_3 , the minimum principal stress orientation in the near-fracture region will rotate by 90° as the component of the superimposed stress vector in the vertical direction, σ'_v , at each point in this region is larger than that in the horizontal direction, σ'_h . This phenomenon described is called the stress shadow effect (Elbel and Mack 1993; Siebrits et al. 1998; Wright and Weijers 2001).

In practice, the stress shadow effect could result in HF re-orientation in the following three scenarios. As shown in Fig. 10a, if the distance between the existing fracture and the newly created HF is too close, the latter one may be influenced by the stress shadow effect induced by the existing fracture and propagate toward the existing fracture (Bunger et al. 2011; Sher and Kolykhalov 2011; Bunger et al. 2012; Kear et al. 2013). As shown in Fig. 10b, if the distance between the existing fractures is close enough to create a stress reversal region between them, the minimum principal stress orientation in this region will rotate by 90° and become out of plane. The newly created HF in this region will re-orientate and propagate as an axial HF (Roussel and Sharma 2011a; Rafiee et al. 2012). As shown in Fig. 10c, after the first hydraulic fracturing operation, a stress reversal region may occur around the existing HF. When refracturing is performed to produce the secondary HF, the newly created HF may experience a re-orientation process before it propagates perpendicularly to the far-field σ_3 orientation (Siebrits et al. 1998; Li et al. 2006; Li 2008).

In essence, HF re-orientation induced by the stress shadow effect depends on whether if a stress reversal region occurs around an existing fracture or between existing fractures and the extent of this stress reversal

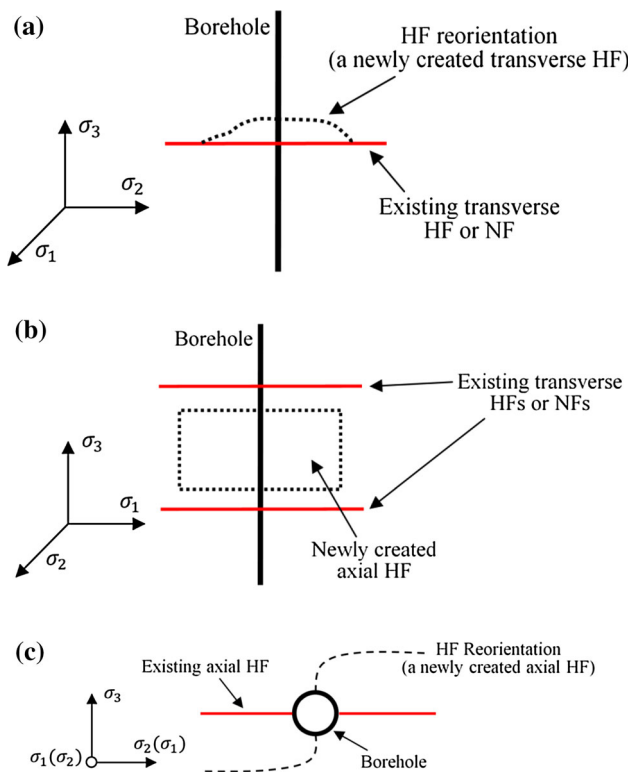


Fig. 10 Hydraulic fracture re-orientation induced by the stress shadow effect. **a** Hydraulic fracture re-orientation induced by a closely located fracture (Bunger et al. 2012), **b** hydraulic fracture re-orientation between two closely located fractures (Roussel and Sharma 2011a, b) and **c** hydraulic fracture re-orientation in refracturing (Wright and Weijers 2001)

region. This subject has been widely studied previously by numerical modeling (Olson 2008; Cheng 2009; Roussel and Sharma 2011a, b; Manchanda and Sharma 2012; Morrill and Miskimins 2012; Rafiee et al. 2012; Roussel et al. 2012; Wu et al. 2012; Geilikman et al. 2013; Wong et al. 2013; Xu 2013). These studies indicate that the extent of the stress reversal region is determined by many factors that include the horizontal differential stress, rock mass properties, fracture dimensions, the fracture propped or residual width and the fracture distance. He et al. (2016b) pointed out that the HF re-orientation process near a

closely located HF was influenced by all the three in situ stresses and rock mass heterogeneity was an important factor that should be accounted for.

3.4 Approaches to Creating Prescribed Hydraulic Fractures in Cave Mining

From the above review of HF re-orientation, it shows that the HF could be forced to re-orientate its path from the theoretical prediction within a certain area by either an oriented artificial weakness or the stress shadow effect. It should be acknowledged that HF re-orientation is a near-borehole effect or only happens in a local space in the oil and gas industry. However, considering the much smaller field size in cave mining, PHFs whose length ranges from about 3–20 m are expected to be created by taking advantage of directional hydraulic fracturing and utilizing the stress shadow effect. Therefore, orientation-control-able HF could be produced in the orebody to ensure successful preconditioning.

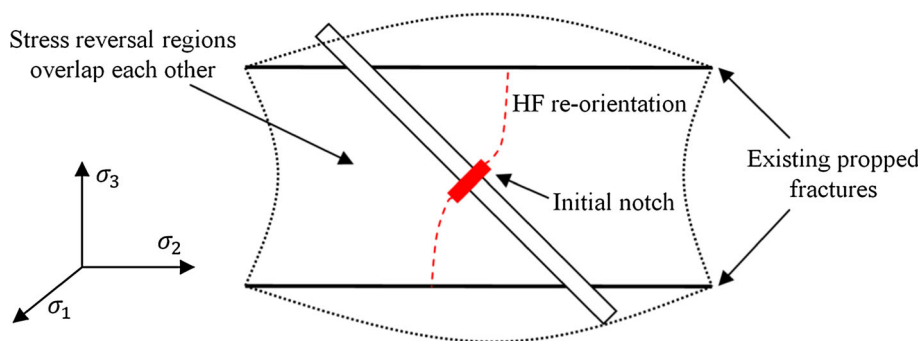
Herein, two potential approaches to creating PHFs are proposed. For demonstration, the in situ stress condition is assumed to be reverse faulting that is common at caving mine sites in Australia. The mining block is dominated by few horizontal NFs. As discussed previously, by using the existing technique to create orientation-uncontrollable HF, the efficiency of hydraulic fracturing for preconditioning in this situation is limited. Our objective here is to create vertical or oblique HF that are not perpendicular to the σ_3 orientation, so that successful preconditioning could be achieved in this condition.

3.4.1 Approach One

As shown in Fig. 11, the first approach includes the following stages:

- Pre-locating two fractures in the targeted orebody by either creating new HF or reopening the existing horizontal NFs. As mentioned previously, horizontal

Fig. 11 Approach One to creating prescribed hydraulic fractures



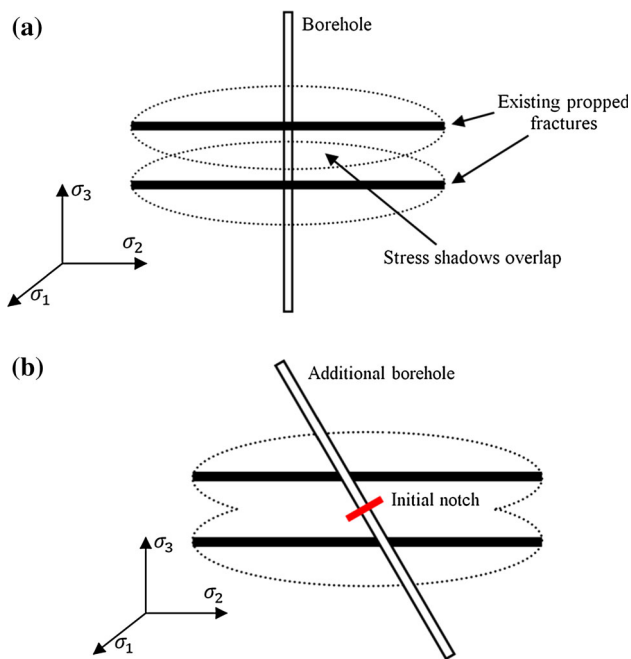


Fig. 12 Stress state and hydraulic fracture initiation in Approach One. **a** Stress shadows overlap each other and **b** hydraulic fracture initiates in the stress reversal region

HFs are easy to create in a reverse faulting in situ stress condition by the existing technique.

- Injecting proppants into the pre-located fractures during or after the hydraulic fracturing process. This is to enhance the stress shadow effect induced by the pre-located fractures, so that the stress shadows of the pre-located fractures overlap each other and the stress reversal region occupies the whole space between these two fractures as shown in Fig. 12a.
- Drilling an additional borehole that passes through the two pre-located fractures from a subsurface excavation and using the cutting machine to create an initial notch around the borehole wall at the middle of the pre-located fractures as shown in Fig. 12b.
- Injecting fluid into the borehole with a low flow rate to ensure HF transverse initiation from the initial notch.

The HF will initiate obliquely due to the oriented initial notch. After that, it will re-orientate its path to propagate in the vertical direction and is perpendicular to the minimum principal stress orientation in the stress reversal region as illustrated by the red dash line in Fig. 11. The overall orientation of the newly created HF is vertical and is parallel to the far-field σ_3 orientation.

3.4.2 Approach Two

In Fig. 13, there are two parallel existing fractures whose separation distance is such that their stress shadows do not overlap. In this case, the normal hydraulic fracturing will result in a fracture parallel to the two existing fractures. This additional fracture will therefore only increase the frequency of the existing fracture set. However, since the objective of hydraulic fracturing in cave mining is to create a blocky rock mass, the hydraulic fractures must result in an additional joint set to achieve this objective. To be able to achieve this, one must make use of directional hydraulic fracturing and also take advantage of the stress shadows of the existing fractures. Both directional hydraulic fracturing and the role of stress shadow effects in re-orienting hydraulic fractures to deviate from their theoretically predicted directions are amply explained in Sects. 3.2 and 3.3 of the paper. Thus, Fig. 13 shows how a combination of directional hydraulic fracturing and stress shadow effect can be used to obtain prescribed hydraulic fractures (PHFs) (i.e., hydraulic fractures that are not perpendicular to the direction of the minor principal stress). A step-by-step procedure in achieving this is as follows:

- Pre-locating two fractures in the targeted orebody by either creating new HFs or reopening the existing horizontal NFs.
- Injecting proppants into the pre-located fractures during or after the hydraulic fracturing process. This is to enhance the stress shadow effect induced by each pre-located fracture.

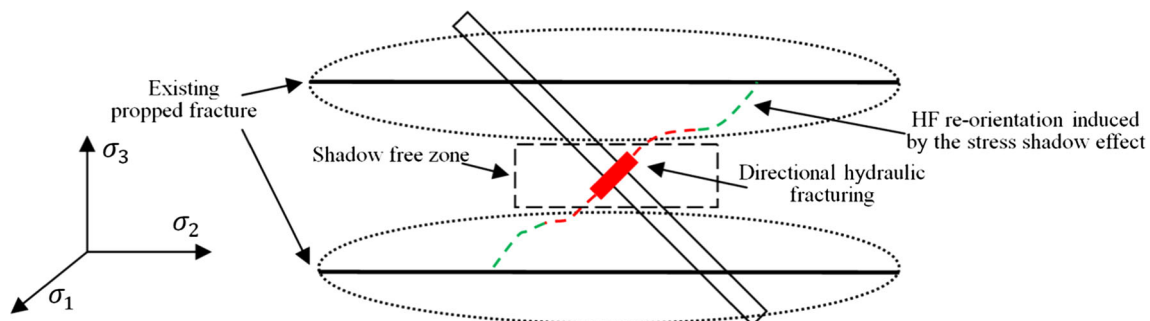


Fig. 13 Approach two to creating prescribed hydraulic fractures

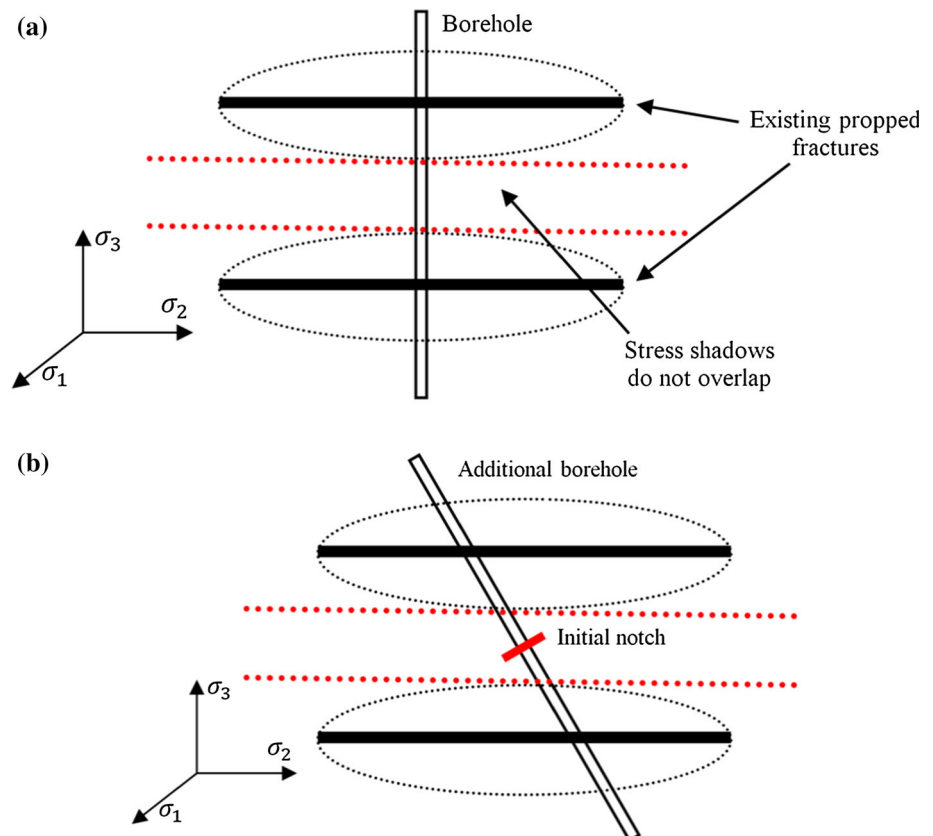
- Different from the stress state in Approach One, a stress shadow-free zone remains between the pre-located fractures in Approach Two as shown in Fig. 14a. In this stress shadow-free zone, the minimum principal stress orientation is still aligned with the far-field σ_3 orientation.
- Drilling an additional borehole that passes through the two pre-located fractures and using the cutting machine to create an initial notch around the borehole wall in the stress shadow-free zone (Fig. 14b).
- Injecting fluid into the borehole with a low flow rate to ensure HF transverse initiation from the initial notch. The HF will initiate obliquely due to the oriented initial notch and experience re-orientation before it propagates horizontally as illustrated in the red dash line in Fig. 13. If the HF re-orientation distance caused by directional hydraulic fracturing is long enough so that the HF could propagate into the stress reversal regions around the pre-located fractures, the HF will experience a secondary re-orientation process caused by the stress shadow effect and propagate toward the pre-located fractures as illustrated by the green dash line in Fig. 13. The overall orientation of the newly created HF is oblique and is not perpendicular to the far-field σ_3 orientation.

The distance between the existing fractures will have impact on whether PHF will be achieved or not. If this distance exceeds a certain length and the stress shadows are very limited, both of these will affect the fracture growth length and the successful generation of PHFs. It should be noted that the stress shadow zone size is dependent on the fracture width, and hence, the use of proppants in this application is suggested as proppants are not currently routinely used in hydraulic fracturing in cave mining applications. Also, the degree of heterogeneity of the rock mass is a governing factor for fracture growth length.

3.5 Discussion

In the field application, the borehole-imaging camera can be used to detect the existing NF around the borehole wall for reopening, locate the position to create PHFs and observe the quality of notch cutting. This technique has been previously applied to the directional hydraulic fracturing process at mine sites in China (Fan et al. 2012; He et al. 2012). The PHF is expected to propagate in the layer divided by the pre-located fractures and terminate when it intersects these fractures. The pumping pressure will drop dramatically if the PHF reaches the pre-located fracture, which provides an opportunity to evaluate PHF growth.

Fig. 14 Stress state and hydraulic fracture initiation in Approach two. **a** Stress shadows do not overlap each other and **b** hydraulic fracture initiates in the shadow-free zone



3.5.1 Feasibility

The functions of directional hydraulic fracturing to create PHFs are in the following three aspects:

- The notch acts as an initial weakness for the HF to initiate, so that the required breakdown pressure could be lowered down.
- The initial notch is helpful in HF transverse initiation, or the unfavorable HF axial initiation may occur.
- It prescribes the HF initiation direction and favors the utilization of directional hydraulic fracturing in Approach Two to create oblique PHFs.

In Approach One, a stress reversal region that occupies the whole space between the pre-located fractures needs to be present. The stress shadow effect between closely located propped fractures has been widely studied previously by various researchers (Roussel and Sharma 2011a, b; Rafiee et al. 2012). These studies show that if pre-located fractures are properly propped, the extent of the stress reversal region is on the order of the fracture radius. For example, if the pre-located fractures have radii of 10 m, the created vertical HF by Approach One may have a length of up to 20 m. To realize Approach One in the field, a numerical simulation could be performed to calculate the stress distribution between the pre-located fractures to ensure that the stress reversal region occupies the whole space between the pre-located fractures under the given operation parameters, such as the pre-located fracture radius, the propped fracture width and the fracture distance.

In Approach Two, a stress shadow-free zone remains between the pre-located fractures. In cave mining, water is normally used as fracturing fluid. This implies that the pre-located fracture width, as well as the induced stress shadow effect, is limited compared with that when more viscous fluid is used. In this situation, a stress shadow-free zone may remain between the pre-located fractures. It should be noted that though the minimum principal stress orientation in this stress shadow-free zone is still consistent with the far-field σ_3 orientation, the differences between the minimum principal stress and the other two principal stresses in this stress shadow-free zone decrease dramatically due to the induced stress of each pre-located fracture (Rafiee et al. 2012).

Rafiee et al. (2012) used the boundary element method to investigate the induced stress change between propped fractures. The selected modeling results where stress shadow-free zones remain between the propped fractures are listed in Table 7, where σ_n is the fracture net pressure (i.e., the difference between the fracture internal pressure induced by the proppant and the in situ stress applied perpendicularly to the fracture surfaces), σ_d is the in situ differential stress (i.e., the difference between σ_3 and σ_2), L_d is the fracture distance and L_h is the fracture half length. The σ_n/σ_d ratio is constant (0.80) in Test 1 and Test 2 and decreases to 0.53 in Test 3. The L_d/L_h ratio is constant (1.00) in Test 1 and Test 3 and increases to 1.25 in Test 2. These results indicate:

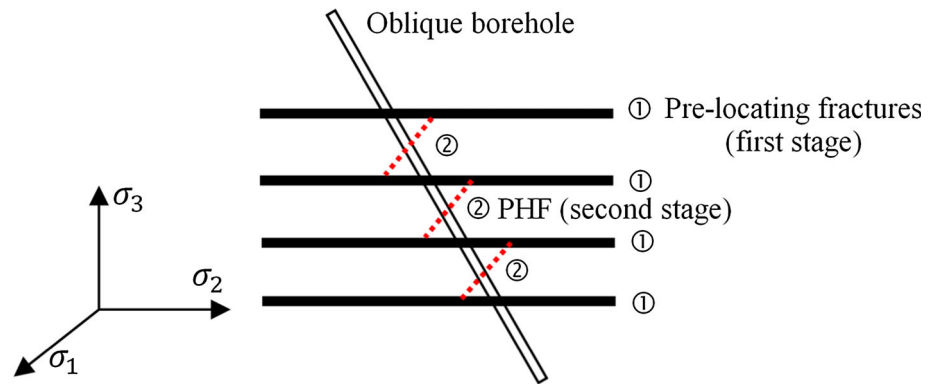
- Although the σ_3 orientation in the shadow-free zone is not altered by the fracture-induced stress, the local differential stress in this zone decreases dramatically. This favors the utilization of directional hydraulic fracturing to prescribe the HF direction in the shadow-free zone as depicted in Fig. 13.
- The induced stress change is determined by both the σ_n/σ_d ratio and the L_d/L_h ratio. A lower L_d/L_h ratio (as indicated by results of Test 1 and Test 2) and a higher σ_n/σ_d ratio (as indicated by results of Test 1 and Test 3) result in a lower local differential stress magnitude.

Behrmann and Elbel (1991) and Abass et al. (1994) pointed out that HF re-orientation from oriented perforations occurred within one or two borehole diameters, which means that Approach Two may not be feasible in the field application because HF re-orientation from the oriented initial notch may be confined in a 20 cm distance (the borehole diameter for cave mining hydraulic fracturing is normally about 10 cm). However, it should be noted that the stress conditions and rock properties in Behrmann et al.'s study and Abass et al.'s study are very different from the potential condition where Approach Two will be applied. In these studies, the differential stresses were 9.65 MPa and 2.4–9.7 MPa, respectively, and trial stress states were simulated. In Approach Two, the stress state around the stress shadow-free zone is much more complicated and has a much lower local differential stress. He et al. (2016a) investigated the HF re-orientation trajectory from a directional hydraulically fractured borehole and

Table 7 Selected modeling results in Rafiee et al. (2012)

Selected result	Net pressure σ_n (MPa)	Differential stress σ_d (MPa)	σ_n/σ_d	Fracture distance L_d (m)	Fracture half length L_h (m)	L_d/L_h	Induced-stress change (MPa)
1	2.07	2.59	0.80	121.92	121.92	1.00	2.07–2.41
2	2.07	2.59	0.80	152.40	121.92	1.25	1.72–2.07
3	1.38	2.59	0.53	121.92	121.92	1.00	1.38–1.72

Fig. 15 Creating prescribed hydraulic fractures without any additional boreholes



noted that the HF trajectory is mainly determined by the initial notch orientation and rock mass heterogeneity in a hydrostatic stress state (i.e., the differential stress magnitude is zero). Bungler et al. (2012) modeled the interaction between closely located HFs and thought that rock strength had influence on the HF re-orientation process. The effect of the differential stress on HF re-orientation could be weakened with strong rock properties. The rock sample used in Behrmann et al.'s study was hydrostone, and the cement blocks used in Abass et al.'s study had Young's modulus of 24 GPa. These experimental tests were based on geotechnical conditions in the oil and gas industries. The orebody in cave mining has much stronger mechanical properties. This implies that the HF may have a long re-orientation distance from the oriented initial notch when the second approach is used to create oblique PHFs.

3.5.2 Operating Cost

In Sect. 3.4, additional boreholes are recommended for creating PHFs between the pre-located fractures as shown in Figs. 11 and 13. While these may be additional costs, successful preconditioning using PHFs eliminates the risk of arching that can delay mine production for months. In such situations additional cost of caving inducement is inevitable. In 1999, an air gap of 95 m occurred at Northparkes Mines due to cave stalling and overdraw (Van As and Jeffrey 2000b). A lot of trials that included boundary weakening blasting and hydraulic fracturing were carried out to reactivate caving. The final cost of caving inducement was around 1.1 million Australian Dollars. Additionally, the cave back stalling and overdraw resulting in the excess air gap caused an airblast leading to four fatalities. Hence, the benefits of the cost of additional boreholes far out way the cost for to not doing so or ineffective hydraulic fracturing.

Furthermore, additional boreholes may not necessarily be required to create PHFs. In some applications, the existing exploration boreholes can be used for creation of PHFs. Exploration boreholes are not always necessarily

vertical but can be oriented at some dip angles (Van As and Jeffrey 2000b; Mills and Jeffrey 2004; van As et al. 2004; Catalan et al. 2012) that can be taken advantage of. These oblique or sub-vertical boreholes can be used for both the traditional hydraulic fracturing and location of preexisting fractures for the planning and creation of PHFs. Figure 15 illustrates the basic idea of creating PHFs without any additional boreholes and also shows how HFs can be created along the same borehole between different layers (pairs of joints).

Sand is suggested as a proppant to maintain the pre-located fracture width. Smith and Montgomery (2015) provided a relationship between the fracture propped width and the closure stress (i.e., the in situ stress applied perpendicularly to the fracture surfaces) when different types of sand are used as proppants and concluded that the fracture propped width decreased linearly with the increase in the closure stress.

In general, the feasibility of Approach One is deducible from previous related studies on the stress shadow effect between closely spaced fractures. Approach Two requires the utilization of directional hydraulic fracturing technique and the stress shadow effect. The stress state in Approach Two and the mechanism of this approach are more complex, but this condition might be more commonly in cave mining due to the utilization of water as fracturing fluid with its limited effect on the fracture width. The feasibility of Approach Two and the influencing factors in this approach will be further investigated in a future study.

4 Conclusions

Hydraulic fracturing originated from the oil industry and has been recently used in cave mining for preconditioning orebodies. According to the theoretical prediction, the HF orientation is uncontrollable and should be perpendicular to the minimum in situ stress orientation. At most caving mine sites in Australia, the in situ stress conditions are reverse faulting type that favors the creation of horizontal

HF. In this situation, the effectiveness of hydraulic fracturing in preconditioning is limited if part of the orebody has no dominant NFs or is dominated by horizontal NFs. In this scenario, additional horizontal HFs will not necessarily result in reduced fragmentation sizes as they will not increase the orebody blockiness. Furthermore, the creation of horizontal HFs has limited contribution in preventing arching that hinders cave propagation. In this paper,

- Previous studies on hydraulic fracturing in cave mining as a preconditioning method have been reviewed. This is a significant review of the evolution of hydraulic fracturing in cave mining. The review shows that previous works have been largely focused on field applications, HF growth measurement and its interaction with NFs.
- A research gap is identified. In some geotechnical conditions, orientation-uncontrollable HFs (i.e., HFs whose orientations are dictated by and are perpendicular to the minimum in situ stress orientation) are unable to improve rock mass caveability and prevent arching. Therefore, the creation of orientation-controllable HFs is required to ensure effective preconditioning in any geotechnical condition.
- To create PHFs, novelty in HF re-orientation is needed. The literature review indicates that PHFs can be achieved by intelligently using knowledge and experience from oriented perforations, directional hydraulic fracturing and HF re-orientation induced by the stress shadow effect.
- Based on the knowledge of HF re-orientation, two approaches that take advantage of directional hydraulic fracturing and the stress shadow effect are proposed to create PHFs with arbitrary orientations in cave mining. The introduction of proppants in cave mining hydraulic fracturing is suggested and may have the benefit of achieving PHFs. The feasibility of the proposed approaches will be further investigated in future studies.

Acknowledgments The first author of this paper would like to appreciate the support from the China Scholarship Council (CSC) for his PhD study.

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