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Hydraulic Fracturing Mine Back Trials — Design Rationale and Project Status

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Abstract

Last year, a joint Mining and Oil & Gas industry consortium was established in Canada to conduct hydraulic fracturing (HF) tests accompanied by a mine-back of fractured regions to assess HF models and microseismic monitoring data during controlled experiments. Details about the displacement field, fracture aperture and extent, and micro-seismic parameters could then be verified and used as calibration data for modeling of HF processes in igneous and dense sedimentary rocks.

Various injection experiments are planned and they will include pre-fracturing rock mass characterisation using best available current techniques, dense arrays of multi-parameter wall and borehole-mounted instruments, and the treated volume will be mined through to assess fracturing effectiveness, existing fractures and new fracture interactions, and to determine if pathways can be identified for improving currently available numerical and fracture network modeling tools.

In this paper we present the results of the experimental design and planning phase, outlining objectives and justifications for planned experimental layouts. Preliminary plans for a first mine-through trial at Newcrest Mining's Cadia East mine in New South Wales, Australia are described. The hypotheses advanced in this experimental design, supported by evidence from the literature, are that activation and development of a fracture network by hydraulic stimulation is possible if the injection procedure is designed such that injection pressures and rates are maintained within an optimal window, thereby producing conditions under which effective stress management for risk mitigation in deep mining can best

be achieved. The evaluation of these hypotheses is the focus of the current high level experimental plan presented in the paper.

Keywords stress management, stiffness modification, shale gas analogue, mine-back experiments, model calibration, hydraulic fracture, naturally fractured rocks

1. Introduction

Hydraulic fracturing (HF) has been widely used in the oil & gas (O&G) and mining industry: in O&G to stimulate reservoirs [1] and in mining, primarily to initiate caving and to improve fragmentation (e.g. [2-4]). Attempts have also been made to initiate slip on faults or shears [5] and research including mine-backs of hydraulically fractured zones has been conducted [6,7] in order to better understand the characteristics of the propagated hydraulic fractures. However, to the authors' knowledge, although there are many anecdotal indications of hydraulically induced changes to rock mass properties and stress, hydraulic fracturing has so far not been successful in inducing sufficient changes in the in situ or mining-induced stress field to be of practical value for risk mitigation related to violent seismic energy release in deep and high stress mining. It is speculated that the latter can only be achieved by the stimulation, mobilisation and enhancement of a natural fracture network rather than by solely generating a new system of induced hydraulic fractures. Hence, an innovative testing program, focussed on natural fracture network stimulation and the development of these techniques for stress management purposes is pursued. The mobilisation and development of a fracture network is also relevant for the optimal exploitation of tight gas or oil shale reservoirs, which closely resemble hard-rock situations (low permeability block, naturally fractured, stiff, low to moderate Poisson's ratio, etc.). The success of the proposed hydraulic injection program will be investigated during a mine-back test, and the results applied to mining and O&G applications.

In this paper, the results of the experimental design phase, outlining objectives and justifications for planned experimental layouts, are presented. Preliminary plans for the first mine-through trial at Newcrest Mining's Cadia East mine in New South Wales, Australia are described.

2. Project objectives

The practical justification for the overall HF project is different for the mining and O&G sector consortium sponsors. However, both sectors are interested in advancing the state of knowledge in three broad areas: (a) fracture network stimulation and development, (b) stress field modification, and (c) micro-seismic data interpretation during hydraulic fracturing and reservoir stimulation. Hence, the broad objectives of the program meets the primary needs of both sectors and will advance the understanding of hydraulic fracture network stimulation

based on experiments permitting near-field monitoring followed by investigation of the treated volume via mapping and monitoring during mine-through.

2.1. Mining perspective

Various hydraulic fracturing (HF) experiments have been undertaken in mines, some with mine-through experiments (e.g. [6]) for various purposes: to better understand fracture propagation, fracture interaction with natural joints, fragmentation changes, penetration of proppants, etc. Successes have been reported with respect to the use of HF for rock mass preconditioning, for rock fragmentation and cave initiation (e.g. [2]) but unanswered questions remain about its effectiveness in affecting stress redistribution and in controlling energy release from critically stressed rock mass structures. There are much anecdotal but little scientifically proven evidence that HF can help manage stresses, or not. The authors suggest that it may be the methodology of fracturing that may be the source of the apparent contradictions reported in the literature. As mines progress to greater depth stress management for the control of seismically releasable energy becomes of strategic importance. Furthermore, with the introduction of mechanized excavation techniques for rapid mine development (e.g., by Rio Tinto, AngloGold Ashanti, and others), new risks related to strain-bursting are introduced because of the less-damaging nature of these excavation techniques.

For the mining sector the motivations are to broaden the application of hydraulic fracturing and rock mass stimulation beyond cave initiation, propagation and fragmentation management by introducing methodologies for hydraulic stress and rock mass stiffness management that will eventually find introduction for risk mitigation in deep and high stress mining operations. In particular, the problem of fault-slip rockbursting is perplexing and, it is thought, can possibly be addressed through the creation of “damage zones” around potentially unstable structures, thereby reducing the energy emission levels and rates and improving constructability in highly stressed ground.

It is hypothesised that current hydraulic injection techniques deployed in cave mine applications are predominantly propagating hydraulic fractures and that shear dilation is a secondary process. Indeed, opening Mode I fractures develop within a narrow (almost planar) zone normal to σ_3 , and their irregular nature promotes asperity locking resulting in little final net shear strength or stiffness reduction. It is recognised that as fluids are lost in the rock mass surrounding the hydraulic fracture some distributed shearing of critically oriented natural fractures will also occur (e.g. [3]), however in order to enable stress management, one must promote volumetrically distributed irreversible changes to the rock mass and the development of injection techniques that achieve this objective is at the core of the planned research. Section 3 presents the output of a review of current injection practices for various applications and their effect on the rock mass. It served as background for the development of the experimental approach presented in Section 4.

2.2. O&G perspective

The advent of numerous staged HF stimulations along the lengths of deep horizontal wells [8] has unlocked huge quantities of natural gas and oil in low permeability formations that had heretofore been considered non-commercial. Typically, a 1 to 2 km long horizontal well (Fig. 1) is drilled parallel to σ_3 , and a series of hydraulic fractures are installed along the length of the well, injecting into one or several perforated or open sites each time, until from 10 to 40 sites are fracture-stimulated. The optimum design of each stage is still the subject of considerable debate, in part because existing mathematical models of fracturing, founded on single-plane Sneddon crack type assumptions in unjointed continua, are inadequate to predict fracture length, stimulated volume, or surface contact area in naturally fractured rock and more complex approaches using fracture network models are difficult to calibrate. Thus, design is largely empirical, based on remote field measurements that may be inadequate or difficult to interpret (tilt measurements, microseismic measurements and post-fracture well tests). For each new field, there is an extensive period of experimentation with different sequences of fluids and proppants, using different rates and materials, along with limited field measurements (generally microseismic monitoring) to try and optimize the stimulation process to achieve a maximum contacted volume without wasteful fracture propagation into non-productive overlying strata. Each stimulated well may cost 5-10 million dollars, and the eastern United States Marcellus Shale alone may require over 500,000 wells for complete development, as the deposit covers over 95,000 square miles, and at least 6 horizontal wells are needed for each square mile (100 acre spacing). Furthermore, the deeper lying Utica Shale, which also extends into Canada, will eventually be developed, requiring a similar number of wells [9, 10]. Sub-optimal fracture design because of incomplete understanding and inadequate predictive tools quickly becomes a costly luxury.

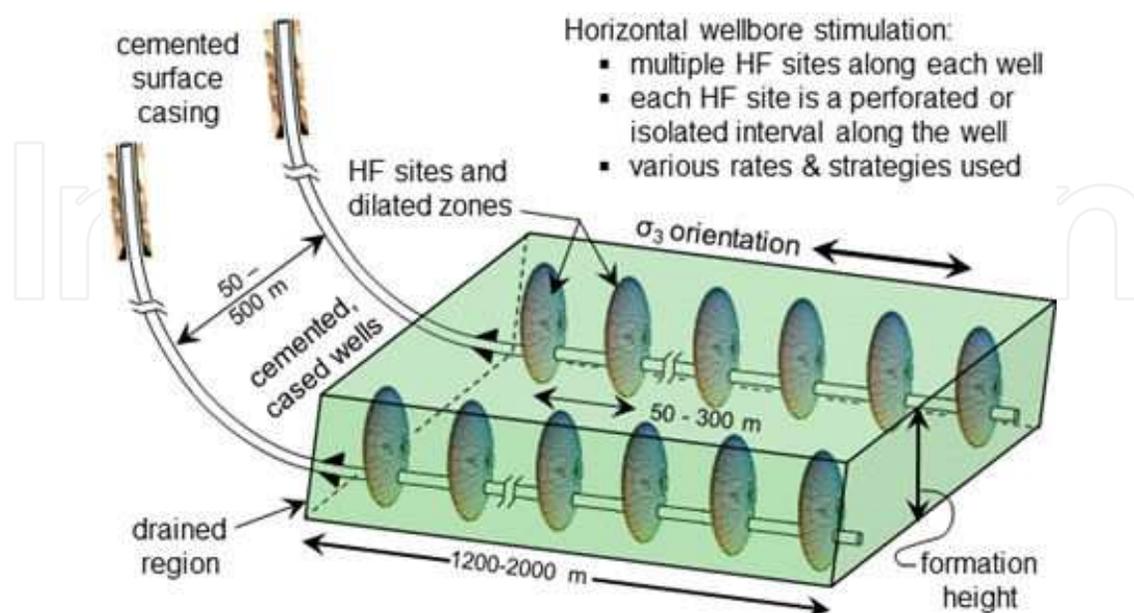


Figure 1. Staged hydraulic fracturing along a horizontal well axis for shale gas stimulation.

These low permeability strata that contain natural gas or low-viscosity oil are often called “shales”, although many of them are better classified as siltstones or even argillaceous limestones (marls). The rock matrix is a stiff (30 to 110 GPa), low-porosity (0.04-0.10), low permeability (microDarcy to nanoDarcy) material. The rock mass is naturally fractured, generally with one dominant set orthogonal to bedding, and one or two minor sets, also orthogonal to the bedding planes. Interestingly, these properties are substantially more similar to those of igneous and metamorphic rocks encountered in “hard rock” mines than they are to typical sedimentary rocks such as heavy oil-rich sandstones, or conventional higher porosity (0.15-0.25) limestones and sandstones. Hence, it is attractive for improving O&G reservoir stimulation techniques to perform tests in a deep mining context.

The O&G dimension of a HF mine-back experiment is to provide an experimental platform for testing predictive models and stimulation procedures suitable for the oil industry. Fracturing igneous rock at depth in a mining context is therefore of interest because the rocks are similar (naturally fractured, stiff, low Poisson’s ratio, anisotropic, almost impermeable matrix blocks...), because the deep mine provides access to a high stress environment (1.5 to 3 km deep) at one tenth the cost of a vertical oilfield borehole, and because a direct mine-back of a fracture-stimulated region can verify assumptions about stimulated volumes, fracture aperture, relationship to microseismic emissions, and the rock mass strains [11].

The concept of a stimulated volume that is far larger than the sand-filled fracture propagation volume (Fig. 2) is fundamental to understanding shale oil or shale gas stimulation, but cannot be easily verified directly, nor can it be predicted by design models that are commonly available. The calibration and validation of advanced model permitting complex behaviour including branching needs data rarely available and the proposed experimental work will contribute to provide such validation data. Fig. 2 presents a 2-D simplification of a complex, 3-D process involving many natural fractures near a wellbore that have been propped, and a large zone surrounding the sand zone where block rotation and shear have created open fractures and self-propped dilated fractures [8]. In mining, this process is called rock mass *bulking* due to geometric incompatibilities between, displaced and rotated, strong blocks of rock. These bulking induced fractures are favored through high-rate injection, and they are thought to be the primary source of microseismic emissions, whereas the zone into which sand is transported, the propped aperture, and the number of near-wellbore propped natural fractures are favored by injection of a highly viscous fluid. Remote displacement measurements (i.e. tilt measurements) cannot distinguish amongst individual fractures, only suitable local instrumentation and a mine-back test can give confidence in the actual geometry and disposition of the dilated or propped regions.

Thus, the motivation for the O&G industry is to optimize HF treatment in tight reservoirs by calibrating design software and hydraulic fracturing propagation monitoring techniques, that is to relate the geophysical observables from fracture initiation and propagation, particularly in the case of microseismic monitoring, and to better understand the development of hydraulic fractures in tight and low permeability naturally fractured lithologies. These objectives can be achieved by performing experiments in deep mines, in which the rock properties are similar to the O&G lithological context because of their stiff, fractured, low permeability characteristics.

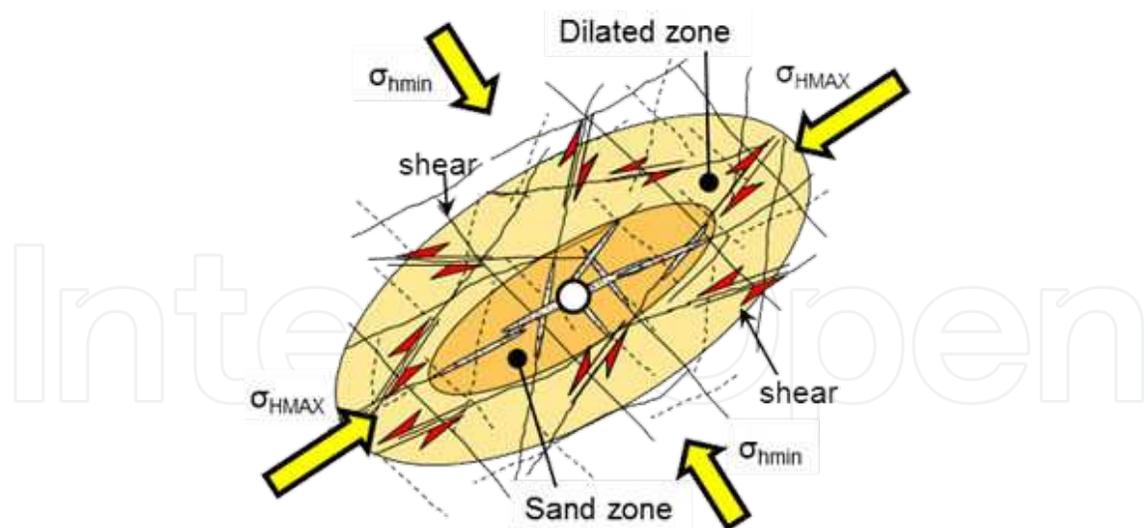


Figure 2. The sand zone and the dilated zone (the stimulated volume).

3. Review of injection practices and their effect on the rock mass

The generic term “hydraulic injection” covers a spectrum of practices with distinct objectives. With the contribution of Itasca, we conducted a literature survey to capture current injection practices in three sectors: mining, deep geothermal and O&G. A case study database, including 14 mining cases, 46 deep geothermal cases, and 4 O&G cases (to be expanded), includes information on the geomechanics context (stress state, rock strength,...), the injection metrics (flow rate, pressure record, injection volume and duration,...), the monitoring program and the measured or observed effect on the rock masses (main activated mechanisms, stimulated volume, fracture extent...).

Fig. 3 illustrates the breadth of injection practices. At the low end of the spectrum, we included some metrics from the ISRM suggested method for hydraulic fracturing stress measurements [12] where a short interval is injected at a very low rate (2 – 3 l/min) for a short time (1 – 3 min). The mechanism in this case is borehole wall failure in tension, captured by the breakdown pressure in the pressure record followed by a limited extension of the hydraulic fracture and its closure after well shut-in (instantaneous shut-in pressure, ISIP) which is used as an indicator of the σ_{hmin} magnitude, assuming that the borehole is vertical and that the fracture has propagated beyond the near-wellbore region.

An up-scaled version of the stress measurement method is used in cave mining operations to pre-condition the rock for improved caveability or fragmentation. A short packed interval is injected to initiate and propagate fractures, and rates, duration and volumes are about two to three orders of magnitude larger than for stress measurements. This propagates fractures typically several tens of meters from the borehole and injections are repeated to generate a zone of fractured rock. Observed fractures typically grow perpendicular to the minimum principal stress and their trajectory is relatively little influenced by natural features (e.g., joints) unless the later makes a sharp angle with the growing hydraulic fracture path.

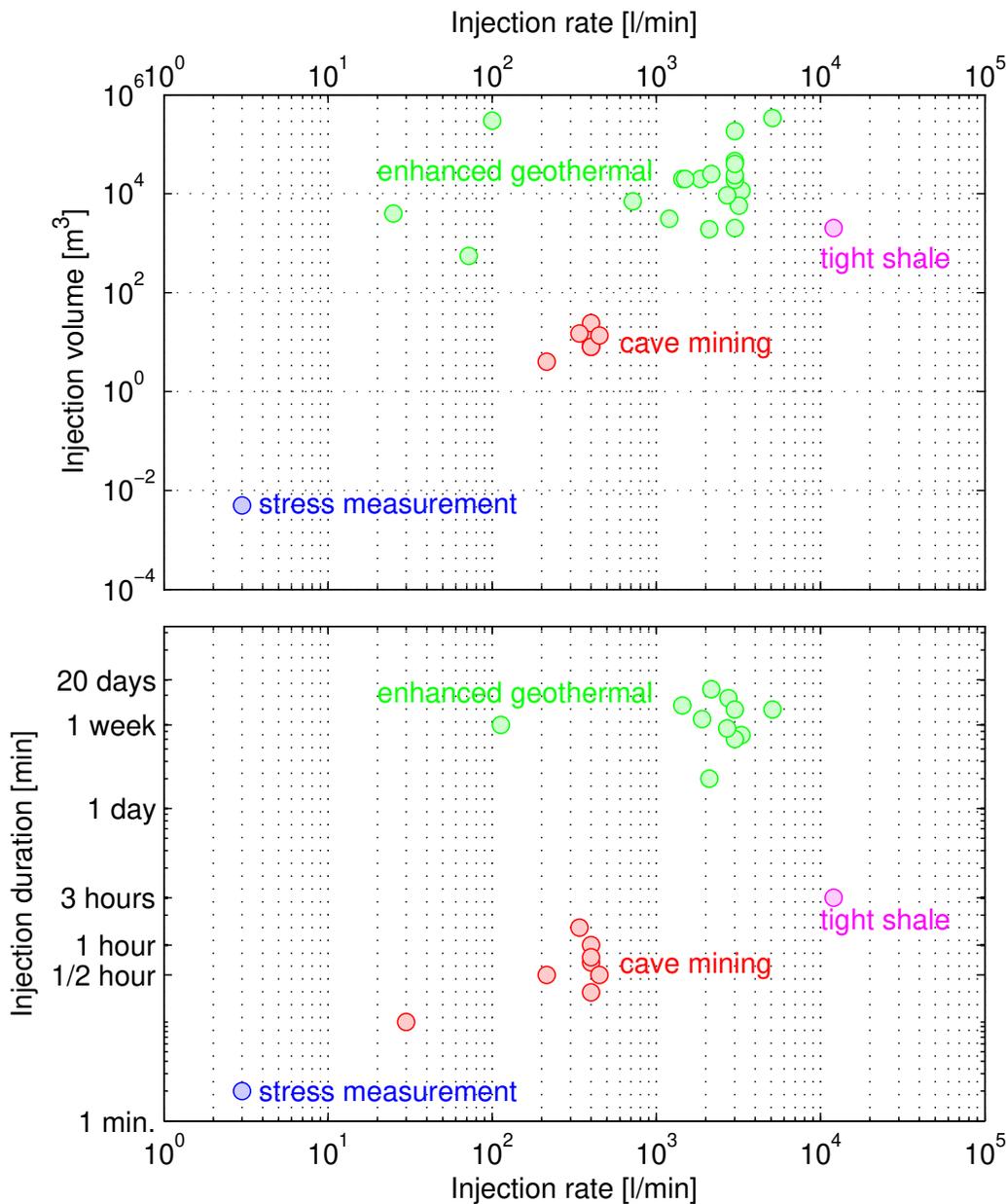


Figure 3. A broad spectrum of injection practices with specific injection metrics for each industry; related objectives are demonstrated by this cross plot of injection volume and injection durations vs. maximum injection rate.

A different situation is encountered in deep geothermal projects with high rate, long duration injections performed in long open-hole sections for reservoir stimulation. The injection metrics are one to two orders of magnitude higher than for cave pre-conditioning cases and extensive monitoring is used to understand fracture activation and propagation, permeability enhancement and fluid penetration [13, 14]. The predominant mechanisms stem from natural fracture system activation [15] leading to fracture self-propping by shear displacement, causing permanent permeability increases. Critically stressed fractures, oriented optimally to the deviatoric stress field for shear failure are the most prone to activation (see Fig. 2), and slip is accompanied by microseismicity.

At the upper end, shale gas well practices involve high rate injection at a number of sites along the well; injections that are carefully sequenced at each stage with massive injection (up to 3000 m³ per site) of fluids of different viscosity at elevated rates (typical rates of 12 m³/min are reported) to optimize proppant penetration and the generation of shear dilated zone volume.

Insights into the role of variable injection metrics on rock mass response is gained in Fig. 4 where the maximum pressure reached during an injection is plotted against the local estimate of the minimum principal stress magnitude as well as the predominantly activated mechanism (Mode I opening fracture propagation vs. shear re-activation). The dominant activated mechanisms on this plot are clearly partitioned by the unit slope line: Mode I propagation cases plot above the unit slope while shear activation cases plot on or below the line.

This partition can in part be explained by considering the simple stability model of a cohesionless pressurized fracture in extension (opening) and shear (Fig. 5). The normal (σ_n) and shear stress (τ) resolved on a fracture can be expressed by the following expressions:

$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3)\cos 2\theta \tag{1}$$

$$\tau = \frac{1}{2}(\sigma_1 - \sigma_3)\sin 2\theta \tag{2}$$

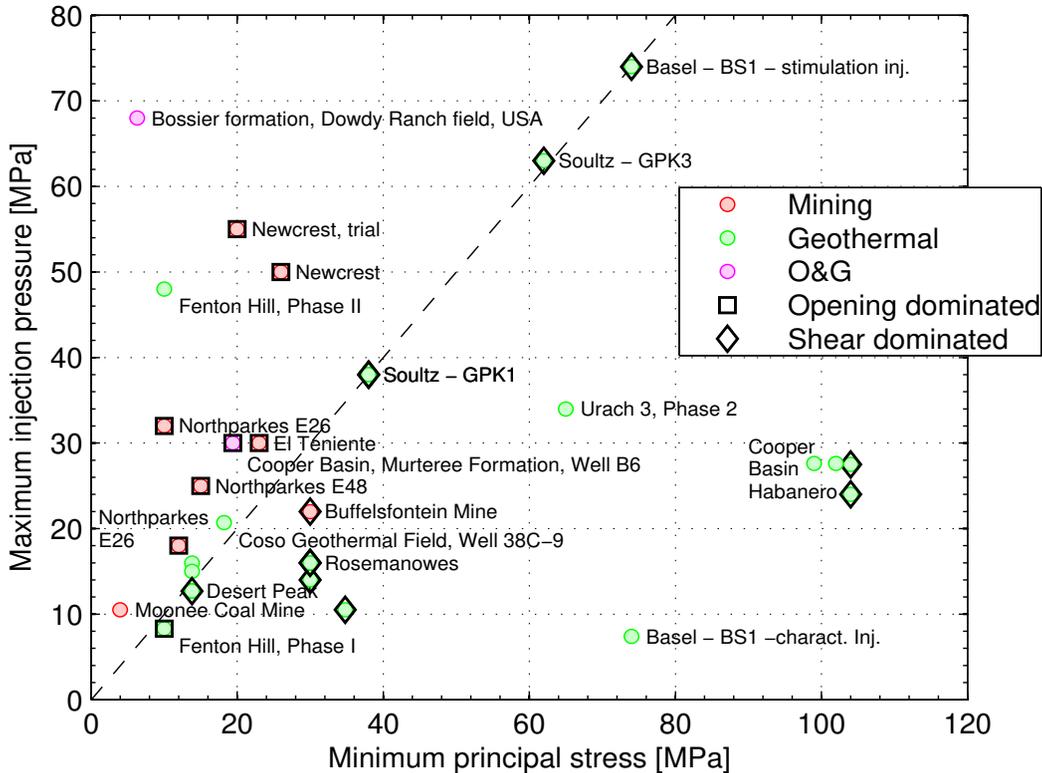


Figure 4. Cross plot of minimum principal stress and maximum injection pressure.

with σ_1 and σ_3 , the maximum and minimum principal stress magnitude, respectively and θ , the angle between the fracture normal and the maximum principal stress direction. The criterion for opening is $P_f \geq \sigma_n$ which, if substituted in Eq. 1 and re-arranged, leads to (blue curve on Fig. 5):

$$R \geq \cos 2\theta \tag{3}$$

with

$$R = \frac{P_f - 1/2(\sigma_1 + \sigma_3)}{1/2(\sigma_1 - \sigma_3)} \tag{4}$$

The minimum pressure to generate jacking is $P_f = \sigma_3$, if the fracture is favorably oriented (perpendicular to σ_3 , i.e. $\theta=90^\circ$). The initiation of the hydraulic fracture at the borehole wall will require a larger pressure (the breakdown pressure, P_b on Fig. 5) that depends on the principal stress ratio. Thus, to initiate and propagate a fracture from the borehole wall where the fracture opening mode dominates requires a pressure larger than $P_f = \sigma_3$ (above the unit slope on Fig. 4). Also a fracture that propagates exactly perpendicular to σ_3 , as a Mode I hydraulic fracture does, will not shear since the resolved shear stress on the fracture plane for such an orientation is 0 (Eq. 2 for $\theta=90^\circ$).

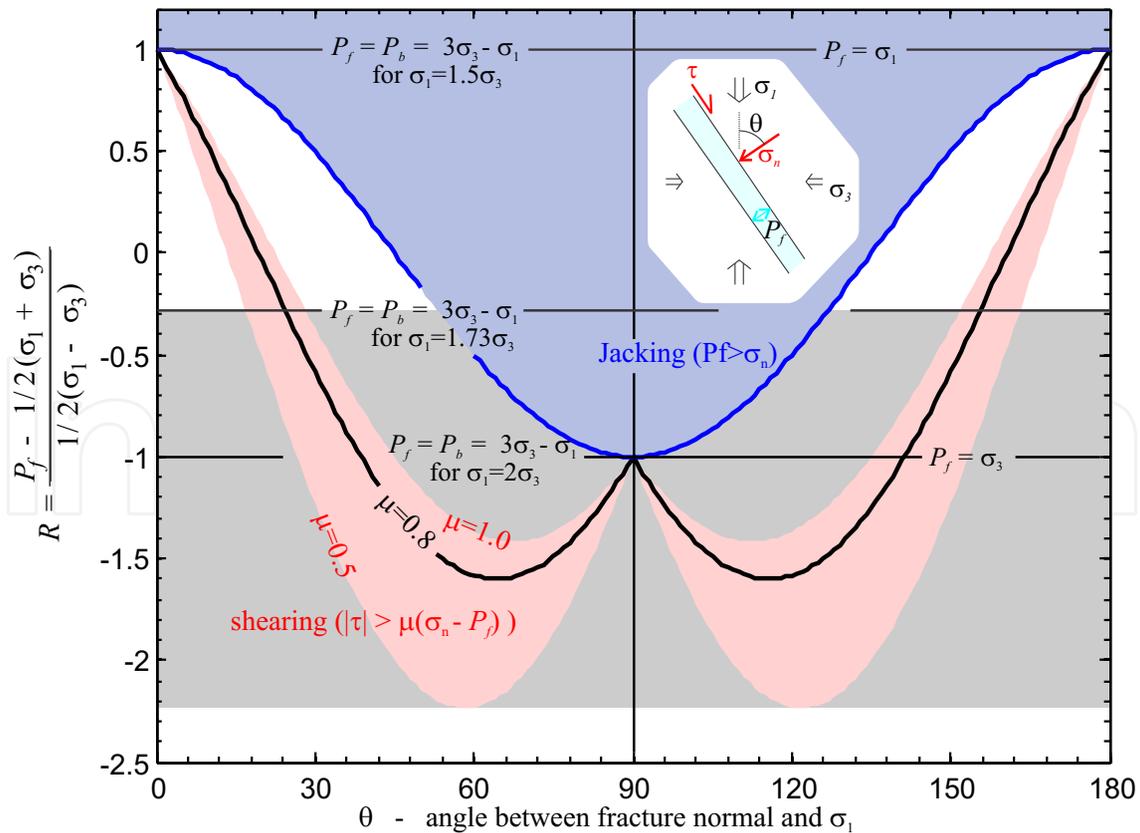


Figure 5. Stability in opening and shear of a cohesionless pressurised fracture.

The criterion for shearing of a cohesionless fracture is $|\tau| \geq \mu (\sigma_n - P_f)$ which, if combined with Eq. 1 and 2 and rearranged (see also [16]), lead to (red area on Fig. 5):

$$R \geq \cos 2\theta - \frac{1}{\mu} \sin 2\theta \quad (5)$$

with μ the coefficient of friction of the fracture. It can be seen from Fig. 5 that fractures optimally oriented ($\theta \cong 40^\circ - 80^\circ$ and $100^\circ - 130^\circ$) will shear at a pressure P_f lower than the minimum jacking pressure (unless locking asperities give a high apparent cohesion). Thus, for injection with connectivity to the natural fracture network where the pressure is raised progressively so that the Mode I breakdown pressure at the borehole wall is not reached, shear mechanisms on critically oriented fractures will be the dominant mechanism and the maximum injection pressure will remain close to or below the minimum jacking pressure $P_f = \sigma_3$ (below the unit slope on Fig. 4).

There is thus the opportunity to generate stress and rock mass properties change through shearing mechanisms if injection is carried out such that pressure is kept in the gray area of Fig. 5, i.e. below the breakdown pressure but above the minimum pressure required for shearing of critically oriented fractures. This situation is called *hydraulic stimulation* in the remainder of this article in contrast with the *hydraulic fracturing* that results in the initiation and propagation of a Mode I fracture. Of course, since Mode I fracture requires a larger pressure than Mode II shearing in rock masses with cohesionless joints, aggressive injection leads to Mode I-dominated fracturing closer to the wellbore, and this zone is surrounded by a pressurized volume within which stimulative Mode II shearing occurs (Fig. 2), and shear displacement also occurs within the Mode I volume.

Based on these theoretical considerations and supported by the compiled literature, an experiment to be conducted at Cadia East mine (Newcrest Mining Ltd) in New South Wales, Australia, is being designed to focus on activating shear mechanisms to generate volumetrically distributed fractures and permanent rock mass change. The high level experimental design that will guide detailed experimental design to fit local site conditions is presented in the next section.

4. Planned experimental approach

4.1. Site conditions summary

The HF experiment will be integrated with a cave conditioning operation using hydraulic injection in the Cadia East mine, PC2-S1 block. The borehole layout for the cave conditioning operation (Fig. 6) will comprise a borehole array with centres at 60 m to 80 m. Two holes will be extended to the undercut level for this experiment, allowing a subsequent mine-through of the stimulated volume.

The local geology consists of a faulted monzonite body intruded into a volcanoclastic series. Typical uniaxial rock strength ranges from 130-170 MPa, and the rock mass quality is fair to

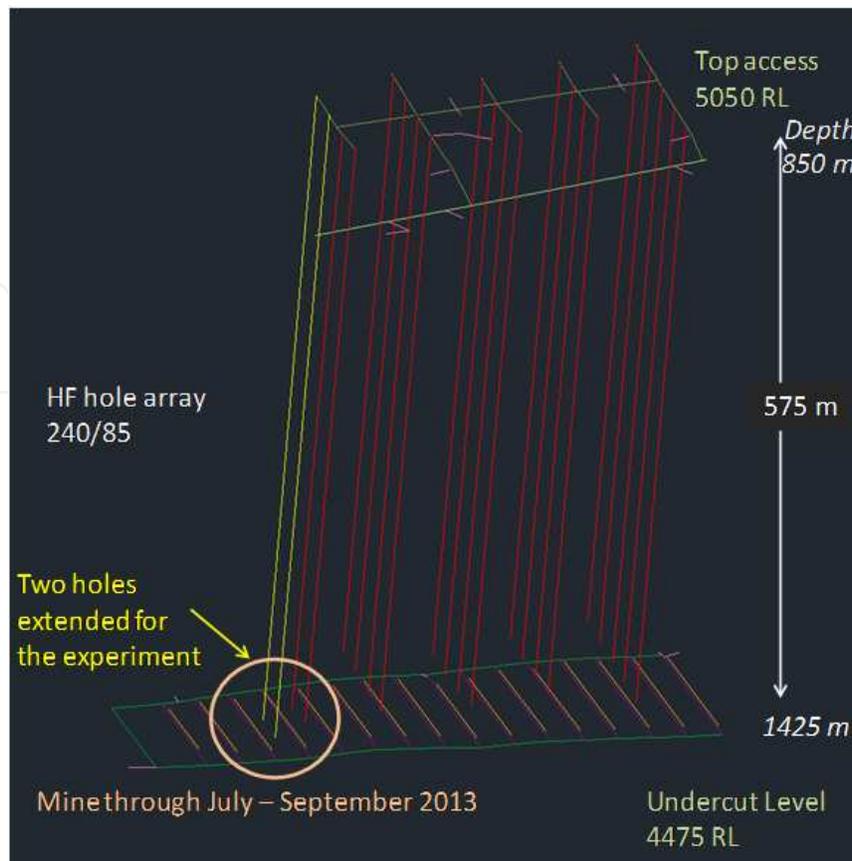


Figure 6. Layout for the experiment to be conducted at Cadia East mine, Newcrest Ltd.

good with two plus random, non-persistent discontinuity sets resulting in a partially connected natural fracture network.

The boreholes will extend from 850 m depth to 1425 m depth, with the experiment taking place at the greater depth. The in-situ stress condition, estimated from an extensive stress measurement program above 1250 m, and then extrapolated to the depth of interest, is on average $\sigma_1 = 73$ MPa (~horizontal E-W), $\sigma_2 = 49$ MPa (~horizontal N-S) and $\sigma_3 = 42$ MPa (~vertical). This places the stresses in the thrust fault condition (future experiments at other mines may be situated in strike-slip and normal fault conditions).

The experimental design is constrained by logistical factors; particularly, the current pumping capacity available and water supply permits to pump 75,000 l of water per 12 hours shift at a maximum flow rate of 400 l/min and maximum pressure of about 70 MPa.

4.2. High level experimental design

The suggested test sequence involves five stages (see Table 1). Stage I will focus on establishing a base line dataset and will involve geological and rock mass parameter characterisation, borehole televiwers and formation testing as well as using standard oil and gas sector pre-fracture treatment modeling routines in order to fine tune the injection procedure.

Stage I	Establishing base line
Stage II	Stimulation injection in virgin rock mass
Stage III	Connect fracture network using hydraulic fracturing to enhance stimulation potential
Stage IV	Solids injection
Stage V	Mine-through

Table 1. Proposed experimental stages.

Stage II will comprise a stimulation of the lower section of the experimental holes. The length of the stimulated section will be determined based on televiewer data and formation testing in order to ensure connectivity with the natural fracture network. It is expected, since the natural fracture network is probably poorly connected (below the percolation threshold), that the borehole injectivity (the capacity of the formation to accept flow for a given pressure increase or reciprocally the pressure increase at a given flow rate) will be so low that it will be difficult not to exceed the optimal pressure for stimulation.

At Stage III, the low borehole injectivity will be remediated through increasing fracture network connectivity by creating an array of hydraulic fractures before performing a second stimulation of the borehole. A final injection stage (Stage IV) will focus on the placement of solids in the fractured rock mass in order to better understand proppant penetration, to modify its properties, and to enhance shear slip.

The final stage of the experiment (Stage V) will be a diagnostic exercise where the injected volume will be mined-through in small increments to evaluate the impact of the injection treatments on the fracturing, the rock mass behaviour and the stress state in stimulated volume.

Characterisation will be repeated between stages in order to evaluate changes to the base line data collected in Stage I, including change of rock mass permeability induced by the applied hydraulic injection treatments.

5. Conclusion

Hydraulic fracturing (HF) currently has found current applications in mining environments in the promotion of rock caving and fragmentation control and has potential for stress and stiffness modification and rock mass pre-conditioning. In the O&G industry, HF in tight oil or gas shales, rocks of similar properties (low k , high E , naturally fractured...), is a vital technology used to develop unconventional oil and gas resources with long horizontal wells and numerous fracture stages at sites distributed along the axis of the horizontal well. We note that the properties of the rocks involved are quite similar in both industries, and the economical need for better HF predictive tools in the O&G industry is large, given the huge development costs predicted for the upcoming decades in North America.

Experiments in deep mines, one planned for 2013 in Australia, and two to follow later in Canada, will be based on extensive pre-characterization, intensive monitoring, staged

hydraulic fracturing and stimulation, and post-fracture characterization, including, where possible, mine-through of fractured zones. Type A predictions (before the event – [17]) based on the detailed ground characterization can be tested in practice, and implications for MS emission interpretation can be ground-truthed.

Specifically, the hypothesis that stress management is best achieved by *hydraulic stimulation*, i.e. activation and development of a fracture network through Mode II shear dilation in contrast to *hydraulic fracturing*, i.e. initiation and propagation of Mode I hydraulic fractures, will be tested. Theoretically there are injection pressure windows favourable for rock mass stimulation and activation in shear of critically stressed fractures, a notion supported by a review of the current practices in the O&G, mining and geothermal industries. Of course, aggressive Mode I fracturing in a strongly deviatoric stress field in naturally fractured rock masses will always be accompanied by shear within and around the Mode I dominated zone. The proposed experimental setup aims at quantifying the changes in the rock mass permeability and stiffness associated with hydraulic stimulation.

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