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Surface hydraulic fracturing trial at Cadia East

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Abstract

Historically, preconditioning practice at Newcrest's Cadia Valley Operations has been to conduct the drilling and fracturing activities associated with hydraulic fracturing from underground excavations. In 2020, Newcrest undertook a trial to investigate the application of oil and gas industry techniques from the surface as an alternative to the approach from underground. Prior to this trial, these techniques had not been tested in a hard rock mining environment.

The trial was designed to show that hydraulic preconditioning operations, including drilling, fracturing and monitoring, could be successfully completed solely from surface. The primary objective of the trial was to investigate the potential safety, logistical, schedule and financial benefits that could be realised from executing hydraulic preconditioning from surface. The trial consisted of preparation of the surface drill pad and water supply, the drilling of three boreholes each over 1,520 m deep, collection of detailed geophysical logging, execution of 132 fractures and the monitoring and verification of execution outcomes.

The results of the trial greatly exceeded expectations for hydraulic fracture extents and the volume preconditioned. This paper discusses the Surface Preconditioning Trial stages and summarises the outcomes against the trial objectives.

Keywords: *hydraulic fracturing, preconditioning, block caving, microseismics*

1 Introduction

Traditionally, the primary purpose of hydraulic fracturing at Cadia, and generally in block cave mines, is to precondition a strong orebody column by fracturing the competent rock mass, and thus promoting cave propagation and resource recovery (Catalan et al. 2017; Cuello & Newcombe 2018). Preconditioning the rock mass through hydraulic fracturing is deemed an effective technique to reduce air blast hazard by improving caveability and to reduce seismic hazard during cave propagation and breakthrough (Catalan et al. 2017; Flores-Gonzalez 2019) by reducing the number and magnitude of rockbursts (Catalan et al. 2017).

The current approach at Cadia is to extend the use of hydraulic fracturing to mitigate seismic hazard at all cave stages, as described in Flores-Gonzalez (2019). This is achieved by executing a hydraulic preconditioning programme prior to cave establishment, and by expanding the preconditioned volume to include the footprint and part of the waste volume surrounding the block cave. This current approach incorporates the knowledge and successful outcomes of newly developed hazard management strategies, which are listed and referenced in Flores-Gonzalez (2019).

Cadia has further developed preconditioning to mitigate developing seismic hazards associated with major structures (fault slip events) and managing mine-wide seismic hazards in new caving operations, where the potential for large damaging seismic events exists due to high stresses and hard competent rock masses (Lett 2022). Preconditioning of the rock mass through hydraulic fracturing is seen as one of the most effective techniques to decrease seismic risk during cave operations (Catalan et al. 2017; Cuello & Newcombe 2018). The current practice at Cadia to date is to drill and conduct hydraulic fracturing from underground.

Hydraulic fracturing is routinely used within the oil and gas industry to increase permeability and hence recover more oil or gas from a reservoir (e.g. King 2012). Application of oil and gas techniques from the surface has not been trialled before in a hard rock mining environment. The Surface Preconditioning Trial employed oil and gas industry drilling and hydraulic fracturing techniques to precondition part of the latest caving mine at Cadia, known as PC2–3, as shown in Figure 1.

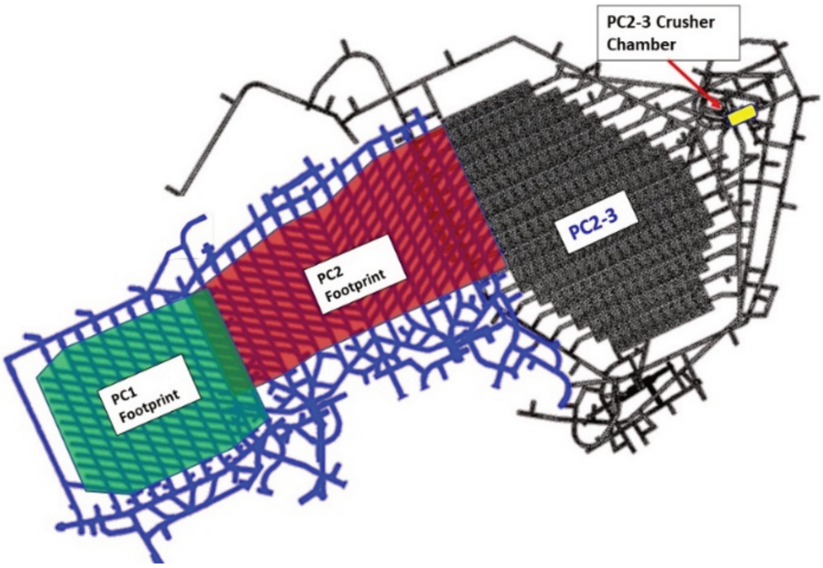
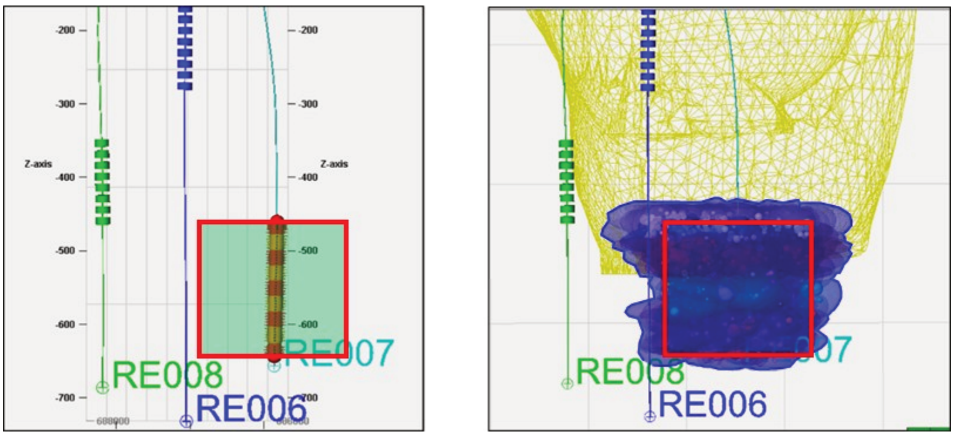


Figure 1 Plan view of existing Cadia East caves and designed PC2–3 footprint

The primary objective of the trial was to investigate the potential logistical, technical, and financial benefits of conducting hydraulic fracturing from surface using oil and gas techniques in place of the existing techniques from underground.

The trial was successfully completed at the end of 2020 and the hydraulic fracturing results exceeded expectations, as shown in the example below of planned versus actual volume preconditioned as indicated in Figure 2.



(a) (b)

Figure 2 Section through drillhole RE007 showing (a) Planned (green box with red outline), and (b) Actual (blue shaded) volume preconditioned

The trial achieved much faster drilling when compared to underground. Cadia Underground (UG) Diamond Drilling operations achieved an average rate of penetration of 1 metre per hour. Using the oil and gas drilling technology, an average rate of 7 metres per hour was achieved. For rate of fracturing, the UG hydraulic fracturing operation at Cadia achieved on average ten hydraulic fractures per day. With the techniques described in this paper, an average of 15 fractures per day was achieved, obtaining a larger preconditioned volume when compared to those obtained with the current underground hydraulic fracturing methods. The actual achieved rates of penetration and the treated volumes are detailed in Section 3.2 and 4.6 of this paper.

2 Trial background and setting

2.1 Trial planning

Preconditioning through hydraulic fracturing is used to decrease seismic risk during the mine development phase and during caving operations. Besides reducing seismicity and hazards associated with large and damaging seismic events, targeted outcomes from preconditioning can also include (Catalan et al. 2017; Cuello & Newcombe 2018; Flores-Gonzalez 2019 and references within):

- Promoting steady rate of cave growth.
- Reducing the risk of cave stall.
- Improving primary fragmentation.

A review of the existing hydraulic fracturing practices at Cadia led to the identification of multiple opportunities to increase operational efficiencies by utilising practices, equipment and engineering techniques routinely used to date within the oil and gas industry. Application of these was expected to successfully enable the relocation of drilling and fracturing preconditioning operations to surface. This was expected to enable several overall improvements including more efficient fracturing, greater control over fracture spacing, safety risk reduction, schedule ramp up (for overall block implementation) and cost reduction.

During the feasibility study for PC2–3 an extensive underground preconditioning programme was designed to be executed from a purpose built monitoring and hydraulic fracturing level at 5050 mRL (800 m below surface).

During the PC2–3 execution stage it was identified that the development of this block offered the opportunity to trial the novel approach of surface oil and gas techniques in a hard rock, caving environment. The plan for PC2–3 was then revised to precondition the PC2–3 cave orebody zone using conventional packer-based fracturing from the dedicated underground level, while concurrently targeting the infrastructure zones on the east side of the footprint using surface techniques from the oil and gas industry as shown in Figure 3.

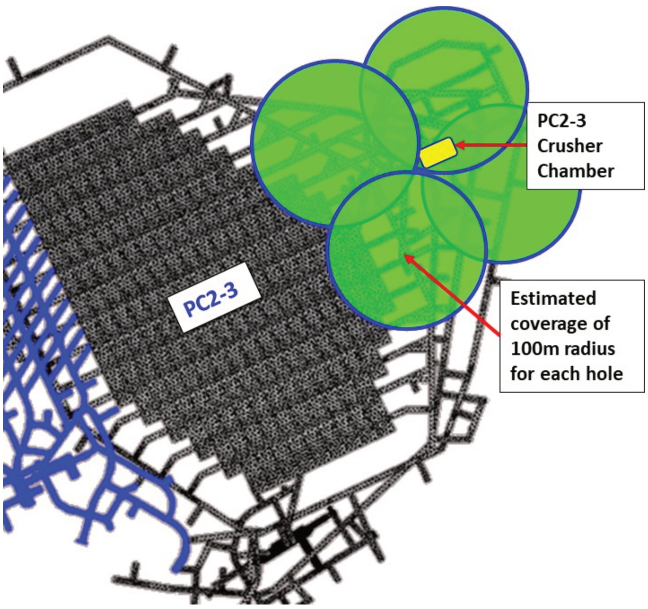


Figure 3 Plan view showing the originally planned surface trial drillholes and estimated coverage

2.2 Trial dimensions and scope

At the time of the original plan in December 2019, the trial consisted of four surface boreholes to be drilled above the PC2–3 Crusher and eastern infrastructure area as shown in Figure 3.

The original scope of the trial included:

- Earthworks and services for drill pad.
- Drill four 1,500 m depth drillholes: two vertical and two directionally drilled.
- Case drillholes with high pressure steel casing and cement in place.
- Hydraulically fracture the bottom 180 m of each drillhole using the 'Plug-and-Perf' technique:
  - Target a minimum 100 m radius and with a 4 m fracture spacing.
  - Trial fracture spacings of 2 m and 1 m in selected sections.
- Real-time monitoring of induced seismicity using a microseismic system.
- Analyse seismic data and evaluate achieved results.

The 'Plug-and-Perf' technique is commonly applied in oil and gas formations to stimulate flows. The Plug-and-Perf process is detailed in Section 4.2.

The long-term purpose of the trial was to assess the potential safety, scheduling, and cost improvements of surface techniques over conventional underground fracturing and evaluate the applicability for future Newcrest caving projects. As such, the trial was treated as a research and development project. However, the trial also provided a more immediate benefit to the PC2–3 Project through preconditioning the crusher and eastern infrastructure zone, replacing part of the planned underground hydraulic fracturing programme.

2.2.1 Geology

The basement rocks in the Cadia district are feldspathic siltstones and lesser sandstones. These are conformably overlain by a sequence of volcanic and volcano-sedimentary rocks ('Cadia Volcanics and Volcaniclastics'). Silurian shale, sandstones and fossiliferous limestone unconformably overlie the eastern part of the district at up to 200 m thickness. The Cadia East lithology consists of Forest Reefs Volcanics, with a large monzonite porphyry intrusion. There are several mine-scale faults associated with this intrusion. These faults include a number of sub-vertical east–west trending faults and thrust faults. At Cadia East, four main structure types have been recognised: pyrite/phyllic/Zn–Pb faults, carbonate faults, calcite–laumontite fracture zones and chlorite faults (Cuello & Newcombe 2018).

The unconfined compressive strength (UCS) of the Cadia volcanics and volcaniclastics averaged 133 MPa, however, ranged up to 269 MPa. The silica content of 60.7% meant that there was a high abrasivity index.

3 Drilling stage

3.1 Drilling stage implementation

The drilling programme was originally designed to be conducted from one drill pad with four directionally drilled holes. However, a further optimisation of the programme considering a different fracture design to cover the entire target, resulted on the reduction of the trial from four to three hydraulic fracturing boreholes. Final drillhole trajectories are shown in Figure 4.

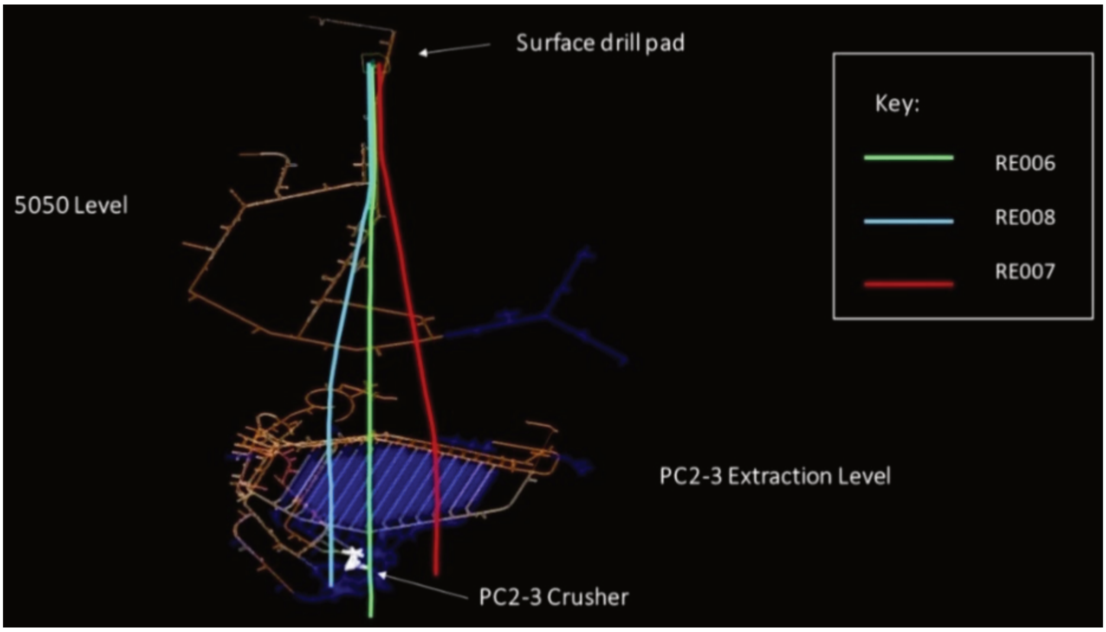


Figure 4 Schematic view showing the three final drillholes and PC2–3 Extraction Level

The three holes were drilled from the dedicated surface drill pad to depths around 1,520 m below surface. Note that the holes were all directionally drilled with a step-out of up to 200 m. The holes were 's-shaped' to divert around the 5050 mRL level and to reach the target zones. The directional drilling of 's-shaped' boreholes was also a key part of the trial as it was considered this would be required for future application at caving operations due to topographic constraints and the influence of surface disturbances such as existing open pits or subsidence zones.

3.1.1 Earthworks

The location for the drill pads was set to overlie the PC2–3 Crusher, however the steep terrain at this location provided challenges through construction. The drill pad location on the side of a gully on the eastern edge of the Mine lease, as shown in Figure 5a, required substantial earthworks to complete the 75 × 70 m pad.

(a) (b)

Figure 5 (a) Drill pad construction in progress (February 2020); (b) Completed drill pad (March 2020)

The scope included excavation of an access road, tree removal, major earthworks and final sheeting for an all-weather work area as shown in Figure 5b.

The pads were constructed in early 2020 coinciding with extremely hot and dry conditions and extensive bushfires throughout NSW. There was an unacceptable risk to operate heavy machinery within the forest area, due to hazards of sparks or hot exhausts causing a fire. This resulted in significant delay to the drill pad preparation works that were eventually completed in early April 2020.

3.1.2 Drill rig mobilisation

At the time of the planned trial in early 2020, there was only one suitable drill rig available in Australia that could meet the schedule and drillhole parameters. This was due to competing oil and coal seam gas projects. The drilling rig selected was a super single rig, with a maximum hook load of 82 tonne (180,000 lbs). Given the target depths to be drilled and the weight of the bottom hole assembly required to conduct the operations, the drilling rig had to be capable of successfully achieving the trial drilling objectives.

The drilling rig selected was provided by an experienced drilling contractor from Queensland, Australia, who had extensive experience from multiple drilling operations across Australia and New Zealand.

Separate contractors and suppliers were engaged for supporting scopes for the drilling stage. All contractors and suppliers worked under the Principal Drilling contractor’s Safety Management System and the Wellsite Permit to Work (WPTW) system. The WPTW system is an international leading practice, risk-based, work authorisation process that is used throughout the Australian onshore oil and gas industry. All contractors’ safe work procedures (SWPs) were reviewed and approved for use by Newcrest.

Drill mobilisation included the drill rig and all associated supporting equipment including generator sets, pipe handling equipment, pipe racks, mud pumps, control room and supporting offices, crib room and self-contained ablutions block, as shown in Figure 6.

Figure 6 Drill rig setting up on first collar at North Drill Pad (April 2020)

3.2 Drilling stage – results

The rock conditions at Cadia are not typically encountered in the oil and gas industry where drilling through low strength sedimentary formations is the norm (Raymond et al. 2012; Peytchev et al. 2013). The only similar hard and abrasive ground conditions appeared to be those encountered by drilling contractors in deep geothermal drilling through rhyolite lavas.

The Cadia conditions were seen as extreme by the drill bit suppliers and the drilling consultant, with some initial estimates of rate of penetration around 2–3 metres per hour in the deeper, harder Volcanics sequence. The trial set a target drilling rate of 5 metres per hour in the 216 mm section of the drillholes. In order to cover various drilling conditions, four drill bit suppliers were engaged and by the end of the trial a total of 24 different drill bits had been used to complete the drilling operation.

3.2.1 Drilling rates

The first drillhole RE006 was used as an initial test to determine which bits may work across the various rock types and depths. The three main types of drill bit used on hole RE006 were:

1. Poly-crystalline diamond composite (PDC).
2. Tungsten Carbide Insert bit arranged as a Tri-cone (TCI).
3. Hybrid: Combination of PDC and TCI.

Although a total of nine bits were used on RE006 and the subsequent tripping times to change bits added around six days to the planned programme, the information gained was invaluable and allowed much better bit selection aligned to hole depth intervals and rock types for the subsequent drillholes.

The entire drilling performance per borehole was measured using a time–depth graph where the drilling operation planned was compared with the actual operation. Figure 7 shows an example of the time-depth curve for drillhole RE008.

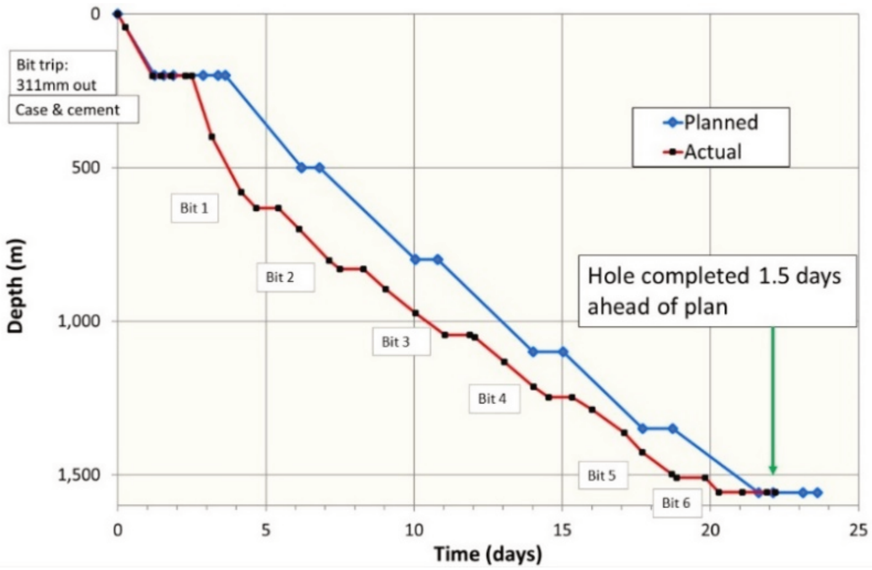


Figure 7 Time–Depth curve for drillhole RE008

After the drilling stage of each borehole was completed, operational lessons learned were identified and applied to the next borehole. This continuous improvement of drilling operations subsequently reduced the number of days required to complete the same scope for each drillhole. The third and final borehole RE007 was completed in only 20.5 days.

The overall drilling rate of penetration (ROP) for the 216 mm diameter section of the drillholes, which comprised 90% of the total drill metres, was 6.1 metres per hour compared to the planned rate of 5.0 metres per hour.

The overall duration for the drilling stage from collaring to final tripping of rods from the completed hole was 20–22 days compared to the originally estimated 16–18 days per hole. Although drilling ROP was faster than planned, overall duration was influenced by the relatively slow rod tripping time of around 24 hours per trip.

3.2.2 Drill stage statistics

Each drillhole was started with a 311 mm diameter drill bit down to between 150 m and 250 m depth, then cased and cemented around the outside of the casing. The main part of the hole was drilled with 216 mm diameter drill bits to final depth as shown in Table 1.

Table 1 Rate of penetration and other drilling parameters

Drillhole parameter	Units	RE006	RE008	RE007
Drilled depth	m	1,546	1,557	1,529
Section from surface at 311 mm diameter	m	0–257	0–202	0–150
Main drillhole section at 216 mm diameter	m	1,289	1,355	1,379
Duration	days	29	22	20.5
Drill bits used	No.	9	6.5	7.5
Rate of penetration in 216 mm section	m/hr	4.7	7.1	6.3
Survey location accuracy (distance from target)	m	4.4	3.3	4.5

3.2.3 Drilling stage summary

To summarise the drilling stage, the utilisation of the oil and gas equipment and specialist techniques to drill boreholes in hard, abrasive rock achieved rates of penetration 2–3 times faster than the rates of penetration reached by typical diamond drilling rigs used in mining. In addition, the ability of the oil and gas equipment to conduct directional drilling, proved very successful. The average True Vertical Depth (TVD) of the three boreholes drilled was 1,544 m and the bottom hole targets were hit within between 3.3–4.5 m of accuracy. This was an important result to support future application of these techniques in caving mines for situations where a step out may be required due to unfavourable topography or existing, open pits, underground workings, or subsidence zones.

4 Preconditioning stage

4.1 Planning for preconditioning stage

Detailed design and planning for the hydraulic fracturing stage was carried out in-house by Newcrest in collaboration with the principal hydraulic fracturing contractor engaged for the trial to conduct the Plug-and-Perf and fracturing services.

There were three additional service providers engaged to support the hydraulic fracturing stage including frac pond construction and fluid management, hydraulic fracturing microseismic monitoring and mapping and frac head services.

A 60-tonne crane with a 20 m coverage was positioned in the centre of the three drillhole collars. By centrally locating the crane, it provided sufficient boom coverage across all three collars such that lowering of both wireline tools and microseismic monitoring tools, plus frac head installation could be carried out easily and efficiently as shown in Figure 8.

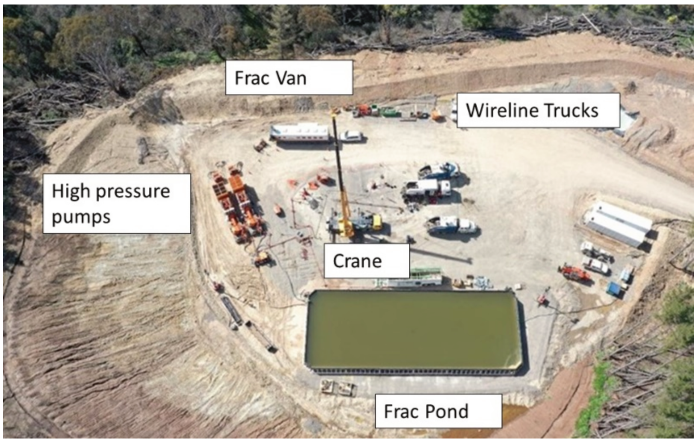


Figure 8 Aerial photo showing surface hydraulic fracturing layout with central crane

4.2 Overview of Plug-and-Perf technique

The fracturing technique used on this trial, called Plug-and-Perf, is commonly used in the oil and gas industry. Perforations are created in the drillhole casing wall using shaped explosive charges. The explosive charges are arranged in a 'perforating gun' on surface then lowered to specific depths on a wireline system. The gun also includes a 69 MPa pressure rated bridge plug which is used to seal off the previously treated section of the hole below, as shown in Figure 9a. In this way, only a 20 m section of drillhole was preconditioned at a time.

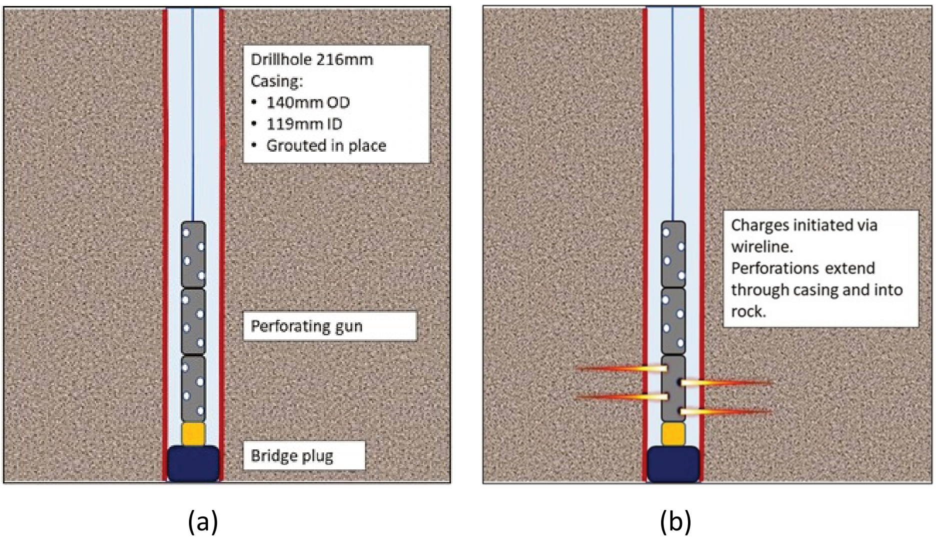


Figure 9 Section showing (a) Plug-and-Perf tool lowered into drillhole, and (b) Perforations created by firing shaped charges

Charges were initiated from surface via the wireline in a set of four, arranged at 90° spacing. The perforations are 10 mm diameter and penetrate the surrounding rock by around 200 mm as shown in Figure 9b. The gun is then raised up 4 m and the next set of perforations fired as shown in Figure 10. The openings created by the shaped charges provide the initial path for the fracturing fluid to follow in the next step, pumping.

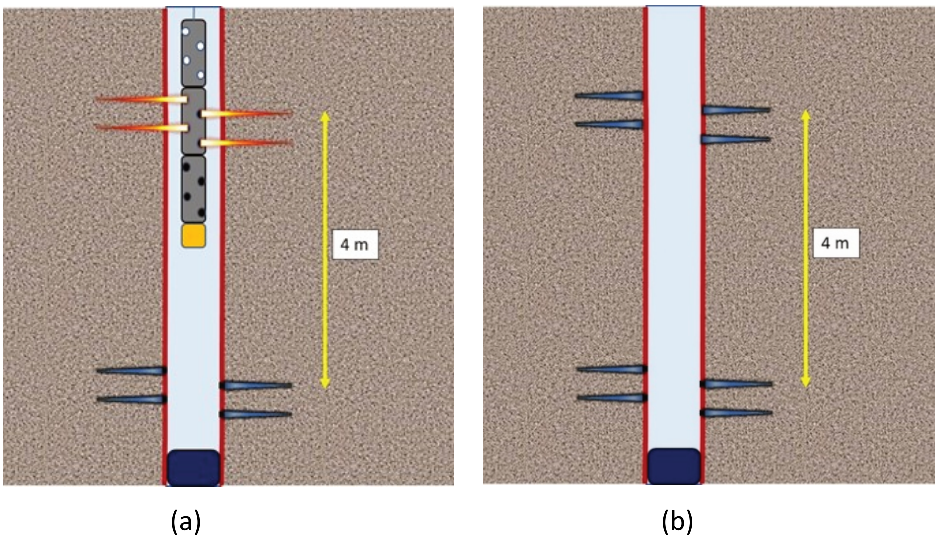


Figure 10 Section showing (a) Raising gun to fire next set of perforations, and (b) Perforations at 4 m spacing ready for pumping

During the pumping stage, the perforating gun is removed to surface and the whole casing is pressurised down to the lowest bridge plug using high pressure pumps. The two 1,600 kW diesel-powered surface pumps were supplied and operated by the fracturing service provider. Each pump could deliver 3,000 litres per minute at up to a maximum 100 MPa pressure at the surface. The 100 MPa rated 'Frac Head' on each drillhole enabled the controlled application of flows and pressures within a contained system.

As the pressure increases, the pumped water finds the weakest opening across a typical 20 m high section and the fractures propagate. As the entire hole is cased, the weakest openings in the system are the perforations created by the perforation guns. However, as the stress contrast is negligible between the perforation clusters across the 20 m section (5 × 4 m spacing), it is very difficult to forecast which interval will break first. The fractures deform the rock and as a result, microseismic events occur as shown in Figure 11a. After a calculated duration at a set flow rate to pump the desired volume to create the designed fracture, plastic 'bio-balls' are released from surface. These bio-balls sink at a set velocity and reach the first frac zone. The flow draws the balls into the 10 mm perforations and hence seal off the holes.

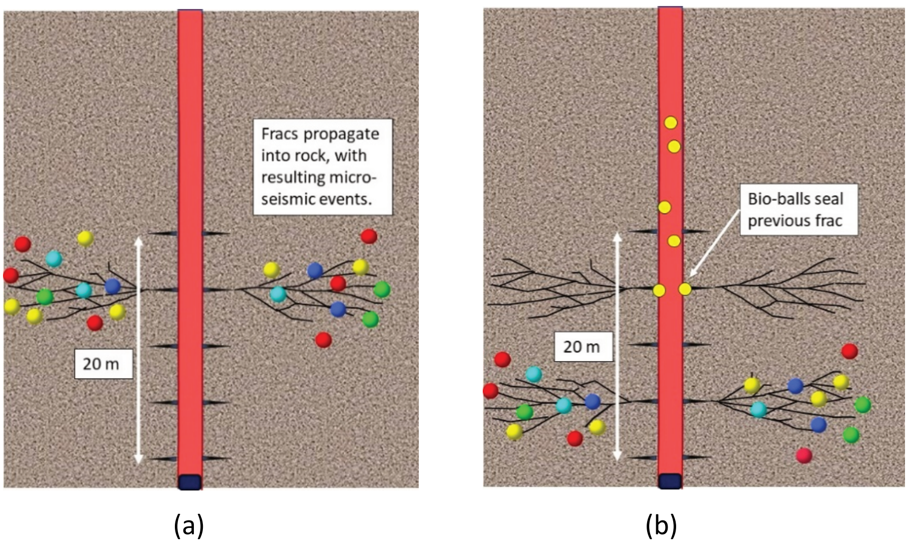


Figure 11 Section showing (a) Raising gun to fire next set of perforations, and (b) Perforations at 4 m spacing ready for pumping

Once the first bio-balls are seated, the pressure finds the next weakest opening and the second set of fractures propagate as shown in Figure 11b. The second set of balls are dropped, and the process repeated until the five fracs in the stage are complete, typically across a 20 m high section.

4.3 Fracturing process and results

The high-pressure pumping part of the frac stage takes around 55–75 minutes and was all controlled and monitored from the Frac Van in real time, allowing full control of the operation at every stage of the pumping. An example of the real time data as displayed in the Frac Van and transmitted online is shown in Figure 12.

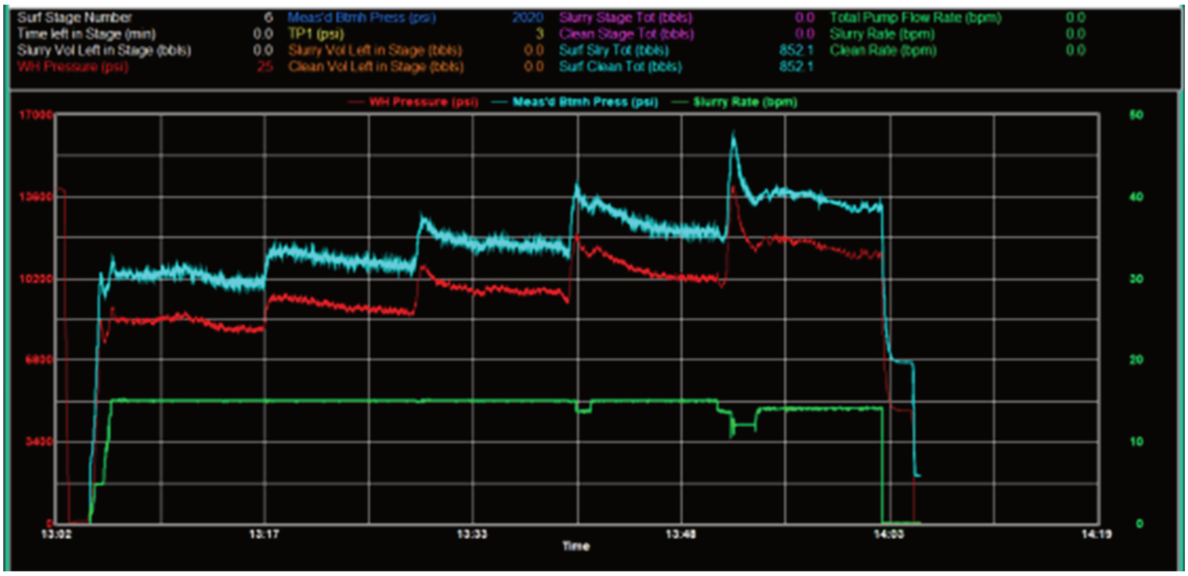


Figure 12 Screenshot showing pumping and flow data against time (RE006, Stage 6)

The green curve shows the flow rate in barrels per minute. In this case, the maximum rate of 15 barrels per minute equates to 40 litres per second. The red curve is the measured pressure at the Frac Head, with this particular fracturing Stage 6 in hole RE006 ranging from 59 to 82 MPa (8,500 to 11,900 psi).

The step changes in the pressure curves represent each individual frac achieved with the jump up in pressure corresponding to the bio-balls hitting the previously open perforation and sealing it off, thus increasing the pressure in the system until the breakout of another perforation cluster at higher stress conditions.

The blue curve is the calculated pressure at fracture depth and is more relevant to the fracture radii achieved and seismicity created. For RE006 Stage 6, the downhole pressure ranged from 72 MPa in the first frac to 94 MPa on the fifth frac with a pressure spike to 115 MPa. It is important to highlight that the boreholes were expected to operate at a pressure of around 103 MPa. However, due to perforation friction and tortuosity during the breakdown, in some stages abnormally high breakdown pressures were experienced. In addition, it is possible that some of these pressure spikes were located in the very hard monzonite layers. Moreover, all the equipment installed at surface was capable of pumping at 138 MPa. The actual downhole pressures achieved during the trial reached around 138 MPa (or 20,000 psi).

4.4 Microseismic process and acquisition geometry

In order to estimate, monitor and hence control the hydraulic fracture extents, oil and gas microseismic technology was utilised. The main activities in the microseismic scope included:

- Cement bond logging and sonic log acquisition of each hole.
- Vertical seismic profile (VSP) surveys.
- Install and run seismic acquisition downhole tools (each tool included eight triaxial accelerometers).

- Record and use perforation shots to calibrate the velocity model.
- Monitor the hydraulic fracturing stimulation of each hole.
- Perform synchronisation using a seismic vibrator truck unit during and at the end of each drillhole.

The purpose of the pre-hydraulic fracturing VSP surveys was to calibrate the sonic log data and derive a log of attenuation, which is required for hydraulic fracturing mapping, as well as to understand the geological structure at each drillhole location. A dual-well hydraulic fracturing monitoring operation was conducted, as shown in Figure 13, to improve microseismic event detectability and location accuracy, and to estimate seismic moment tensors (MT) of the individual fracturing events. Moment tensor solutions provide information about the microseismic events sizes, geometry and relative amplitude of deformation, localised strain axes, failure mechanism and relative contribution of failure modes, and fracture plane orientations of dominant shear events.

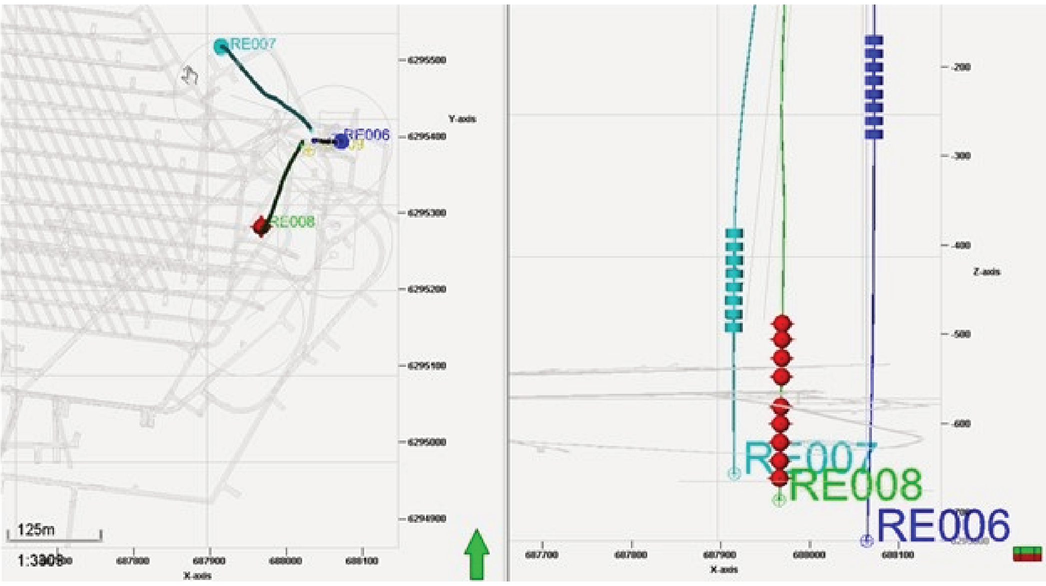


Figure 13 Plan and section views of acquisition geometry around Hole RE008 (red = frac stages, blue and green = seismic tools in RE006 and RE007)

4.5 Detailed microseismic results and analysis

The initial seismicity monitored by the microseismic set up was displayed in real-time. The events underwent processing by geophysical specialists during the monitoring phase, and were classified into good, intermediate or poor location confidence levels by visual inspection of the waveforms and phase arrival adjustments. The visual inspection was necessary during the real-time processing because the classification of different noise sources originating from mine activities required specific filtering which was not available at that particular time. The initial microseismic results gave confidence to the project team that the fracturing process was preconditioning the designed volumes in the Cadia volcanic formations.

More detailed post-processing was undertaken at the end of the trial (September to October 2020) in which the velocity model was calibrated using perforation shots and mine blasts, specific noise filters were designed to detect noise sources related to mining activity, events were reprocessed and quantitatively reclassified based on location signal to noise ratios, and seismic MTs were estimated for good quality events. The noise from jumbo drill rigs, longhole rigs, blasting events including development blasts, and secondary breaking events was identified and removed.

The final results from the microseismic monitoring of the measured fracture radius indicated that the target fracture volumes were able to be achieved and actually exceeded with the process used. The post-processing results from drillholes RE007 and RE008 are presented in the next section as examples to demonstrate that preconditioning of the design volume was exceeded.

4.5.1 RE007 Monitoring results

The monitoring results of two fracturing stages of RE007 are displayed in the following figures, incorporating plan and section views along with a chart of fracturing pump pressures, flow rates, and seismic events plotted against time.

The seismic events picked up by the monitoring system are shown as coloured spheres and have been filtered such that only those with a good location confidence level are presented in Figures 14 and 15, for Stages 2 and 9, respectively. The colour coding of the spheres is related to the time that they appear during the fracturing stage (around 40–55 minutes duration) and the size of the spheres is related to confidence level. NB: The colour coding of the spheres in Figures 14–17 does not use a constant system to represent magnitude or timing across the different stages or drillholes, hence a legend for seismic events is not presented here. In both stages, microseismicity is detected as soon as breakout occurs, event rate is approximate the same over time, and continues for about 30 minutes after shut-in.

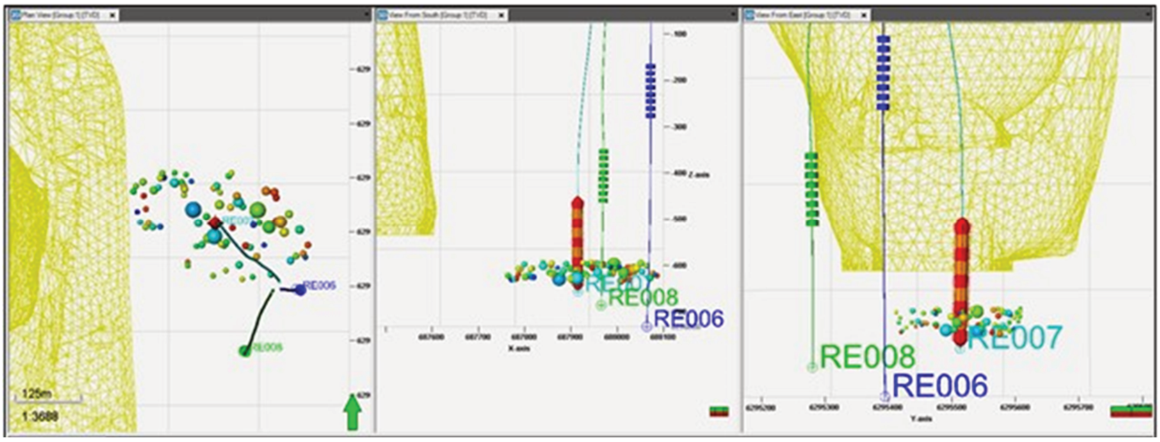


Figure 14 Drillhole RE007 Stage 2

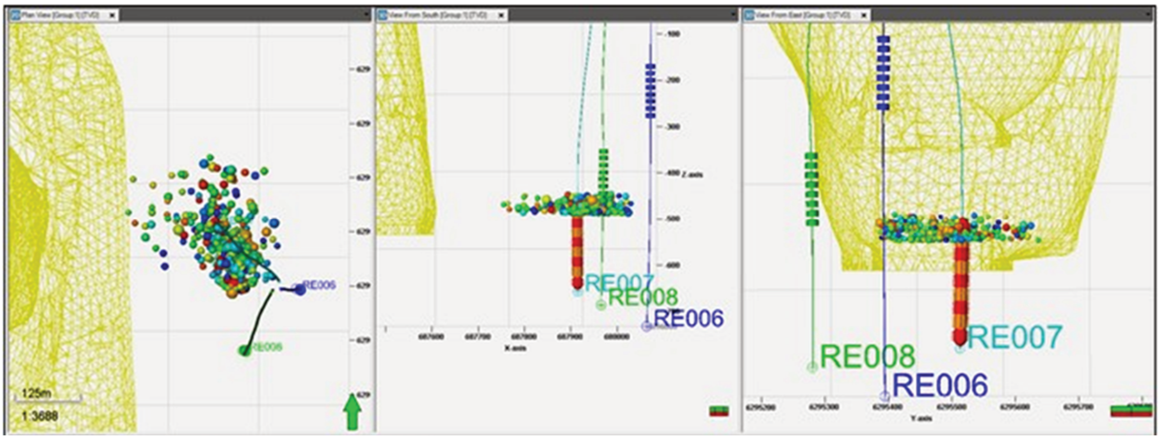
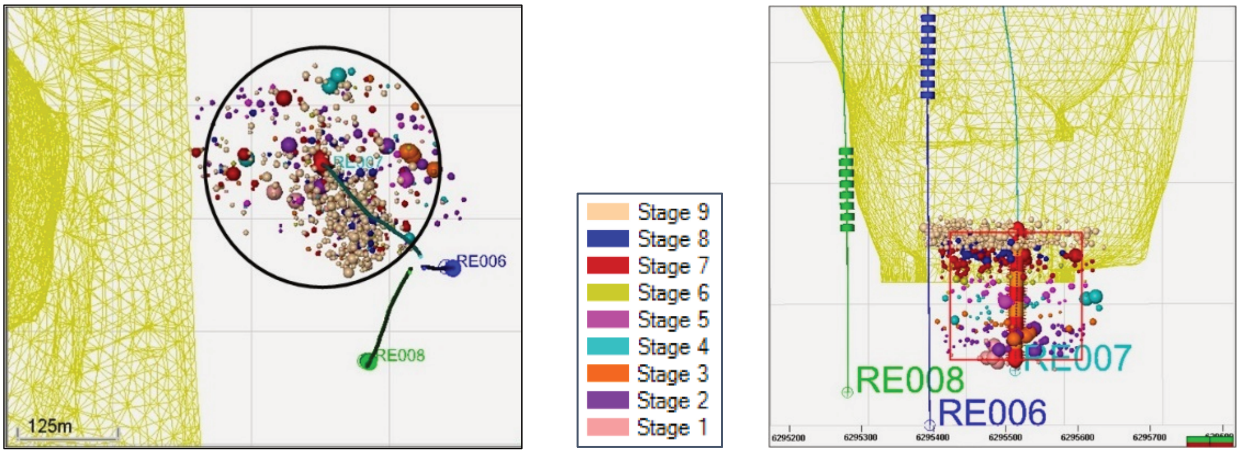


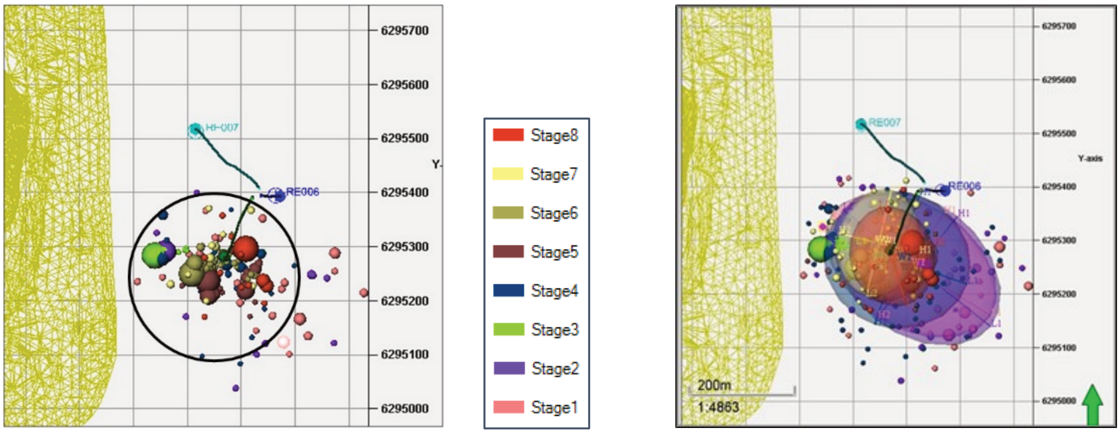
Figure 15 Drillhole RE007 Stage 9

The fracturing of Drillhole RE007 was conducted in nine frac stages. Figure 16 shows the monitoring results for all nine stages combined for the overall volume preconditioned over the 180 m high planned zone. Note a trial of 2 m frac spacings was conducted in the top Stage 9 of RE007. It was observed that with the greater frac density, a greater density of microseismic events was recorded compared with earlier 4 m spacing stages that were lower down in the target volume. Moment magnitudes of RE007 microseismic events range from M-2.2 to M-0.1. The 11 good quality events suitable for MT inversion, show dominant shear component indicating hydroshearing is the preferred failure mechanism. Most of the events have a negative isotropic component indicating fracture closure.



(a) (b)

Figure 16 Combined results for RE007 with (a) Plan view with an interpreted 145 m radius circle, and (b) Section view looking west



(a) (b)

Figure 17 Combined results for RE008 with (a) Plan view with an interpreted 160 m radius circle, and (b) Plan view showing interpreted elliptical extents of seismicity

4.5.2 RE008 monitoring results

The monitoring results for RE008 are displayed in Figure 17, incorporating plan and section views showing high confidence seismic events. Fracturing of Drillhole RE008 was conducted in eight frac stages. Figure 17 shows the monitoring results for all eight stages with interpreted elliptical shapes at each stage with the length of the semi-major axis up to 160 m. Moment magnitudes for RE008 microseismic events ranged from M-1.5 to M0.0. In RE008, 110 good quality events were suitable for MT inversion. Contrary to RE007, only 30% of the events show a dominant double-couple mechanism. The remaining events show primarily shear-tensile closures and openings, and a few have implosive mechanisms.

Subsequent post-processing managed to take the high-confidence seismic events and demonstrate the volume of rock stimulated by the hydraulic fracturing at each pumping stage. The examples above show that high confidence microseismic events associated with the fractures were recorded within and beyond the target volume of 100 m radius from the borehole, indicating that the design requirements had been met. However, the future goal for caving mines is to precondition the maximum volume of rock with the safest, most efficient and cost-effective means. The overall volume preconditioned is the key parameter, rather than measuring individual fracture radius.

Microseismic results indicate that, for the hydraulic fracturing programme applied in a mine setting, a singular flat fracture emanating as a disc from the drillhole was not created. The observations support that, as expected and similarly to oil and gas settings, a cloud of multiple complex and interconnecting fractures was recorded at each frac stage. A singular large bi-wing fracture (zone) exists as a useful representation of a fracture model to use in flow and production models, but is not consistent with microseismic observations (e.g. Urbancic et al. 2017; Viegas et al. 2018). The multiple in situ structures, joints, infills and other discontinuities that are known to exist in the Cadia orebody are stimulated during the hydraulic fracturing programme and generate a hydraulically connected discrete fracture network, even if temporary, covering a wide zone. The different mechanisms retrieved from the MT results indicate that both new fractures (shear-tensile opening) and existing fractures (double-couple and shear-tensile closing) were activated during the hydraulic fracturing programme. As the injected high-pressure fluid penetrates and inflates the rock mass, stress is transferred to adjacent rock volumes, and stress induced fractures are generated away from the perforation zone, which are not hydraulically connected to the fracture zone. The evolution of the microseismic cloud does not show a clear outward propagation from the injection point. Instead, it shows events appearing close and far away at similar times. This may be caused by several physical factors such as the anisotropic nature of the rock mass, the complexity of the fracture network potentially interconnected between stages, and the occurrence of stress transfer events. On the other hand, it can also be a biased spatial evolution of events because of detection limitations of the monitoring system that is not capable to detect potential smaller events that would illuminate the fracture front evolution.

4.6 Summary of hydraulic fracturing stage

The hydraulic fracturing stage of the trial was completed on the 10 September 2020 with the results shown in Table 2 which show that the target volumes were met and exceeded through the execution of the trial. Target volumes are estimated using microseismic event density. Following the standard practice in oil and gas, the stimulated reservoir volume is measured using the closest 85% events to the injection borehole, to avoid the inclusion of stress induced events.

Table 2 Preconditioned zone results – planned versus actual

Drillhole	Planned			Actual			Percentage increase (% over planned)		
	height (m)	radius (m)	volume (m^3)	height (m)	radius (m)	volume (m^3)	Height	Radius	Volume
RE008	180	100	5,655,000	190	160	15,281,000	6%	60%	170%
RE007	180	100	5,655,000	200	145	13,211,000	11%	27%	134%
RE006	180	100	5,655,000	200	127	10,135,000	11%	27%	79%

5 Conclusion

The trial was considered successful in terms of the hydraulic fracture extents achieved and the volume preconditioned.

To measure the success of the trial, key physical parameters were monitored that drive overall feasibility and potential benefits associated with conducting the drilling and fracturing operations from surface using oil and gas techniques. These parameters included the overall drilling penetration rate of 5 metres per hour and the fracture radius >100 m. Both targets were exceeded through the trial, demonstrating the feasibility of this application.

Other benefits that were noted during the trial included: more fractures per shift and much more volume preconditioned can be achieved when compared to current underground hydraulic fracturing methods. All of the works were achieved from a single drill pad on the surface, away from any operational areas and in a self-contained environment. This also allows extra resources to be brought in easily to add capacity. By decoupling drilling and fracturing from the underground environment, hazard exposure and congestion will be reduced. Preparation work for hydraulic fracturing would become independent of underground mine development, utilising civil earthmoving equipment to construct drilling pads on surface rather than develop drilling platforms underground. This would reduce the amount of equipment and personnel underground, reducing the congestion in the workings, exposure manhours, ventilation demand and power requirements. Another major advantage of conducting fracturing from surface is that the whole rock mass can be preconditioned, starting from the planned Extraction Level and continuing right up to the surface.

A drawback associated with conducting the fracturing from surface was being exposed to weather delays. The trial project duration exceeded the original plan with delays due to bushfire risk and wet weather.

The trial was required to precondition a specific target area at PC2–3 by a set milestone date and this objective was met. In contrast, the trial was carried out as a field trial to prove the concept that techniques from oil and gas could be successfully applied in a previously untried and unknown environment, namely underground hard rock mining with high seismicity. For future caving mines, surface preconditioning is forecast to enable several overall improvements, including more efficient fracturing over larger volumes at specific initiation points, fracture spacing, safety risk reduction, faster scheduled ramp up (for overall block cave implementation) and cost reduction.

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