Pillar preconditioning using hydraulic fracturing

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Deep Level Gold Mining at Sibanye Stillwater

- The problem:
  - To mine at depth, up to 35% of our orebody is left in dip stabilising pillars
  - We want to mine those pillars, but the seismic risk is considered too great

2500 m

20-25° dip

3200 m

Seismic risk reduction for pillar extraction

- To implement pillar extraction, the potential for seismic events must be reduced
  - The effect of conventional preconditioning tends to be localised, and diminishes over time
  - One potential approach to precondition the rockmass and reduce stress on the pillar is to generate large, open fractures using hydraulic fracturing (fracking)

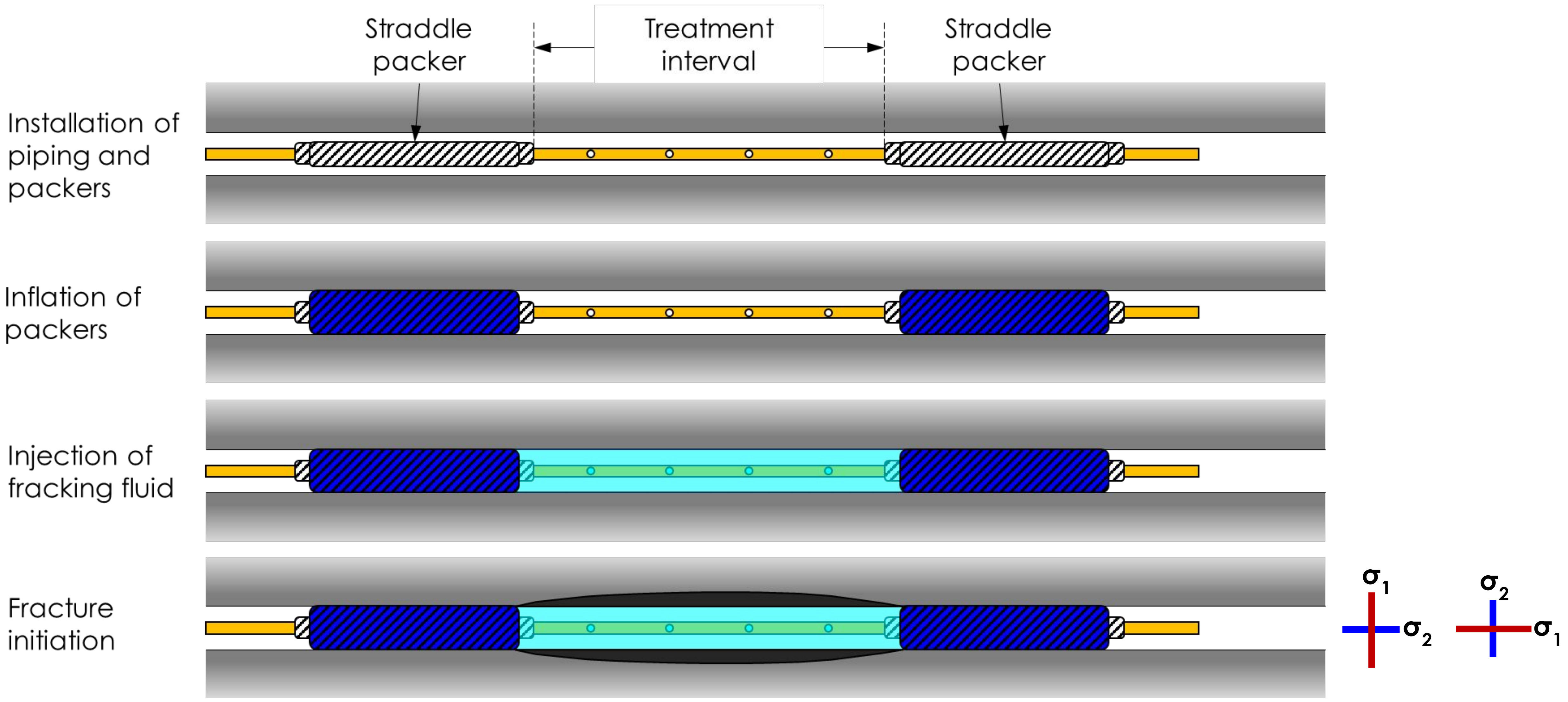
Hydraulic fracturing in practice

Hydraulic fracturing has been successfully employed in preconditioning for block caving operations

Sibanye Stillwater's application is different to those operations:

- The rockmass:
  - The rockmass in block caving operations is low to medium strength, often with extensive jointing and other geological disturbances.
  - The rockmass in a West Wits gold mine is massive, stratified, largely competent with high strength and brittleness.
- The stress field:
  - In previous implementations, the stress field is characterised by low vertical stress, with the major and intermediate stresses oriented approximately sub-horizontally. Depths are less than 2000 m.
  - In our gold mines, depth will be up to 3000 m, with the major principal stress oriented perpendicular to reef (sub-vertical) and k-ratios of 0.5 or less.
- Access:
  - Multiple access points are available in block cave operations, usually above and below the cave front
  - Access opportunities will be limited in gold mining operations.
  - At present, the implementation concept is to drill from nearby haulages or cross-cuts which are actively supplied with electrical, water and transport services.
  - The integrity of the holes will also be affected by the drilling angle, relative to the orientation of the stress field. Ideally, holes should be drilled parallel to the major principal stress (perpendicular to reef). Shallow drill holes may suffer from severe breakout.

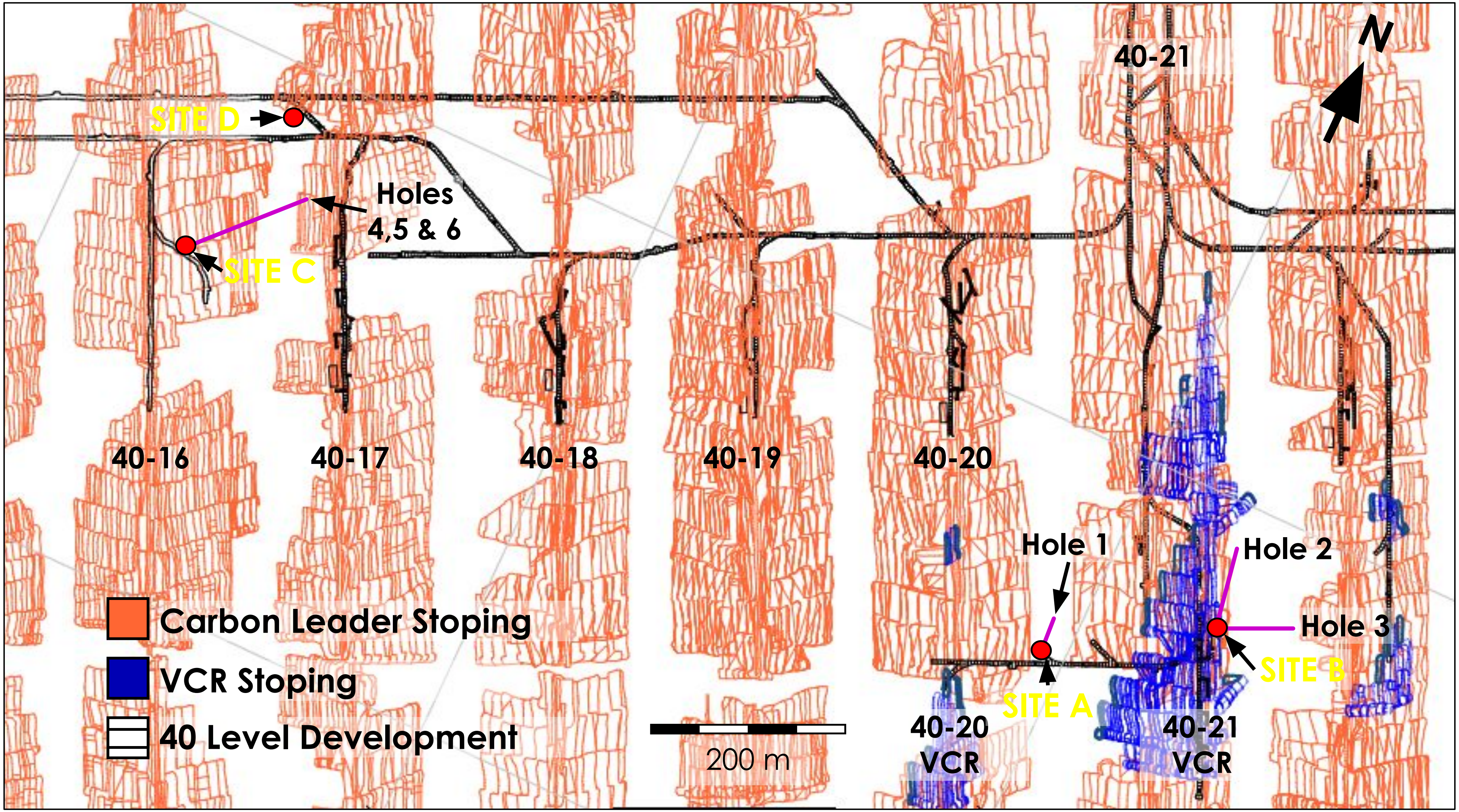
Hydraulic fracturing in practice



Project plan overview

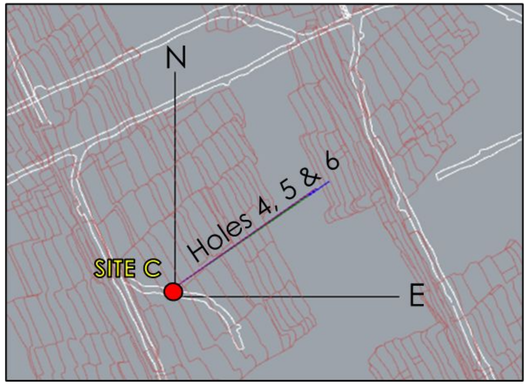
- Technical assessment
  - Literature review
  - Numerical modelling
- Hole profile and quality test
  - Hole parallel to stress field (from haulage above or below the pillar)
  - Hole oblique to stress field (from cross-cut)
  - A set of “fan” holes oriented on similar azimuth and at various dip angles
- Fracking trials
  - Frack Trial 1: mini-frack test in sub-horizontal hole
  - Frack Trial 2: mini-frack test in de-stressed (overstoped) ground
  - Frack Trial 3: mini-frack test in highly stressed ground
- Frack growth trials (2025 onwards)

Site locations

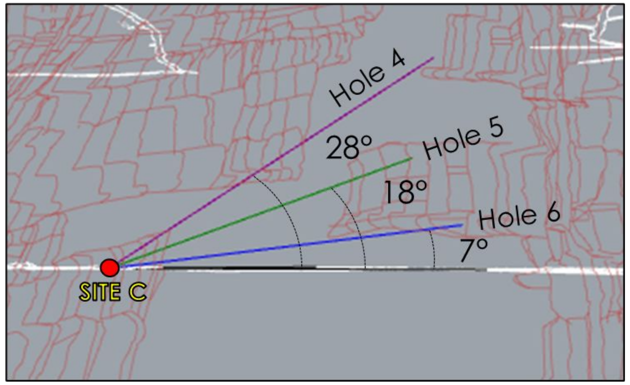


Drilling trials

Site	Hole	Dip [°]	Scenario	Observations
A	1	-63	Parallel to S1. On pillar line. Downwards toward pillar	Hole in good condition up to Green Bar intersection.
B	2	42	Oblique. Parallel to VCR abutment	Breakout and disking from 61 m
	3	-39	Oblique. Downwards toward pillar	Breakout and disking from 60 m
C	4	28	Oblique. From overstoped towards pillar. 5-20 m below pillar.	Breakout and disking from 70 m
	5	18	Oblique. From overstoped towards pillar, 40-45 m below pillar.	Breakout and disking from 70-75 m
	6	7	Parallel to S3. Sub-horizontal. From overstoped towards pillar, 60-65 m below pillar.	Generally good conditions



Plan



Elevation (SE-NW)

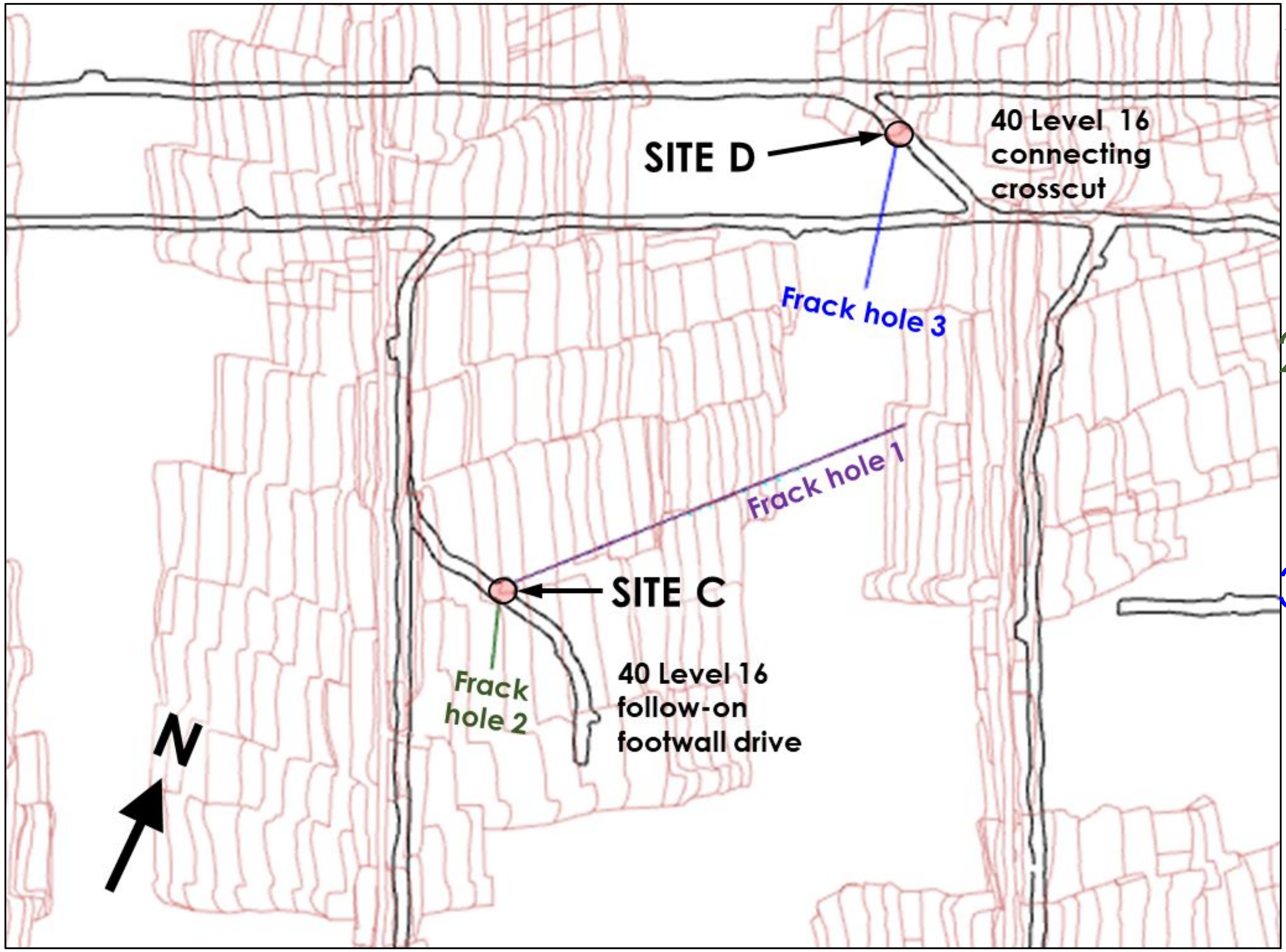
Drilling trial outcomes

- We can drill ~100 m BQ holes with reasonable accuracy
  - The hole parallel to S1 remained accessible (were it not for the seismic event)
  - The oblique down holes could not be controlled from 50-60 m
  - We moved away from active mining to prevent losses due to seismic events

Mini-frack tests

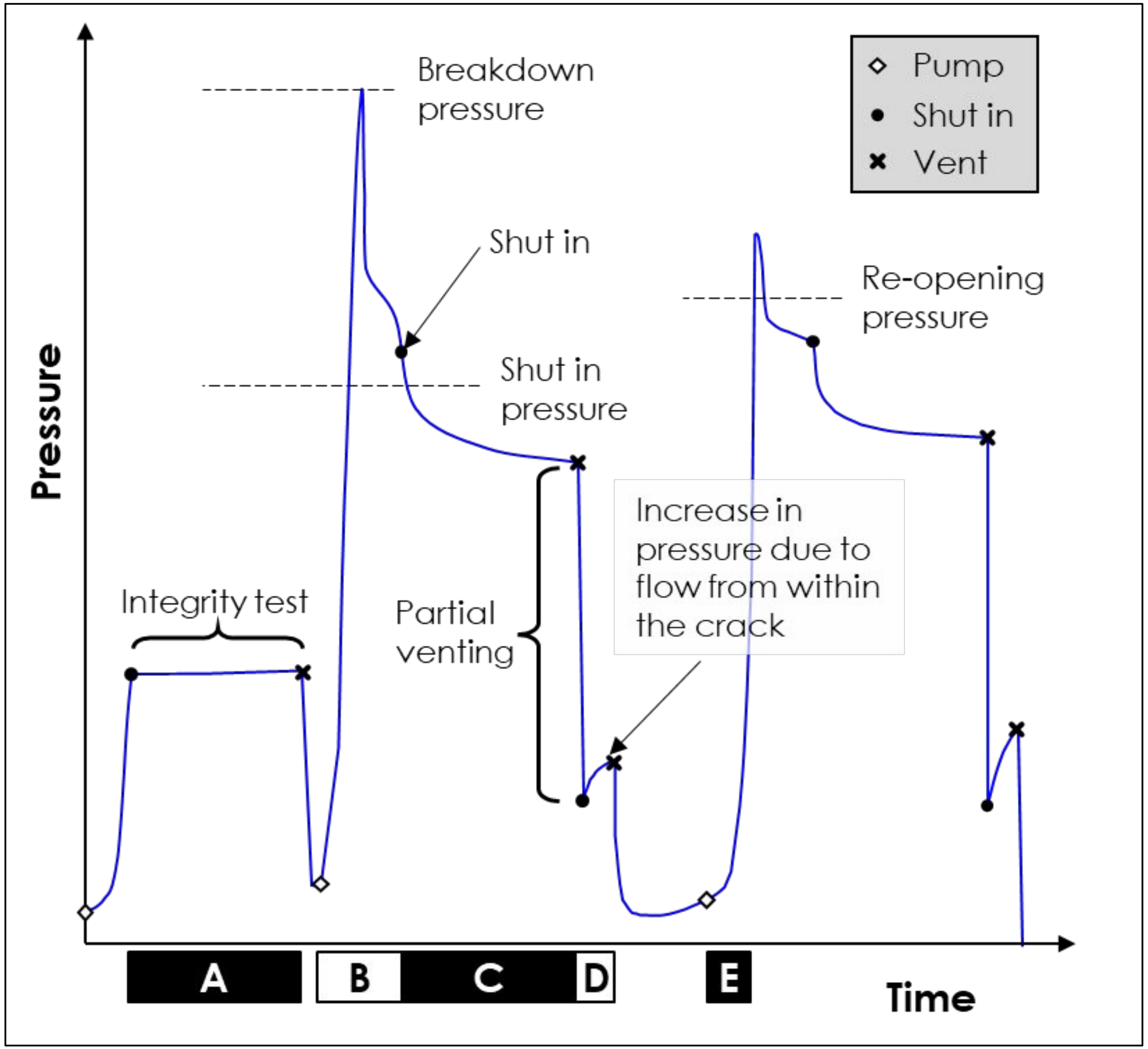
- These tests establishes whether it is possible to create fractures, and determines:
  - Required pressures;
  - Minor stresses perpendicular to the hole; and
  - Rockmass hydraulic tensile strength.
- Equipment is suitable for NQ holes (76 mm)
- A segment of the hole which is not broken out is required for the packers to be inflated safely
- We cannot grow the fractures using mini-frack test equipment

Mini-frack test sites and scenarios



1. Sub-horizontal hole from overstoped to within pillar shadow, approximately parallel to S3. 110 m long, inclined 6° up
2. Overstoped hole, oriented along virgin S1. 45 m to reef, inclined 67° up
3. Hole under pillar, oriented along virgin S1. 105 m to reef, inclined 65° up

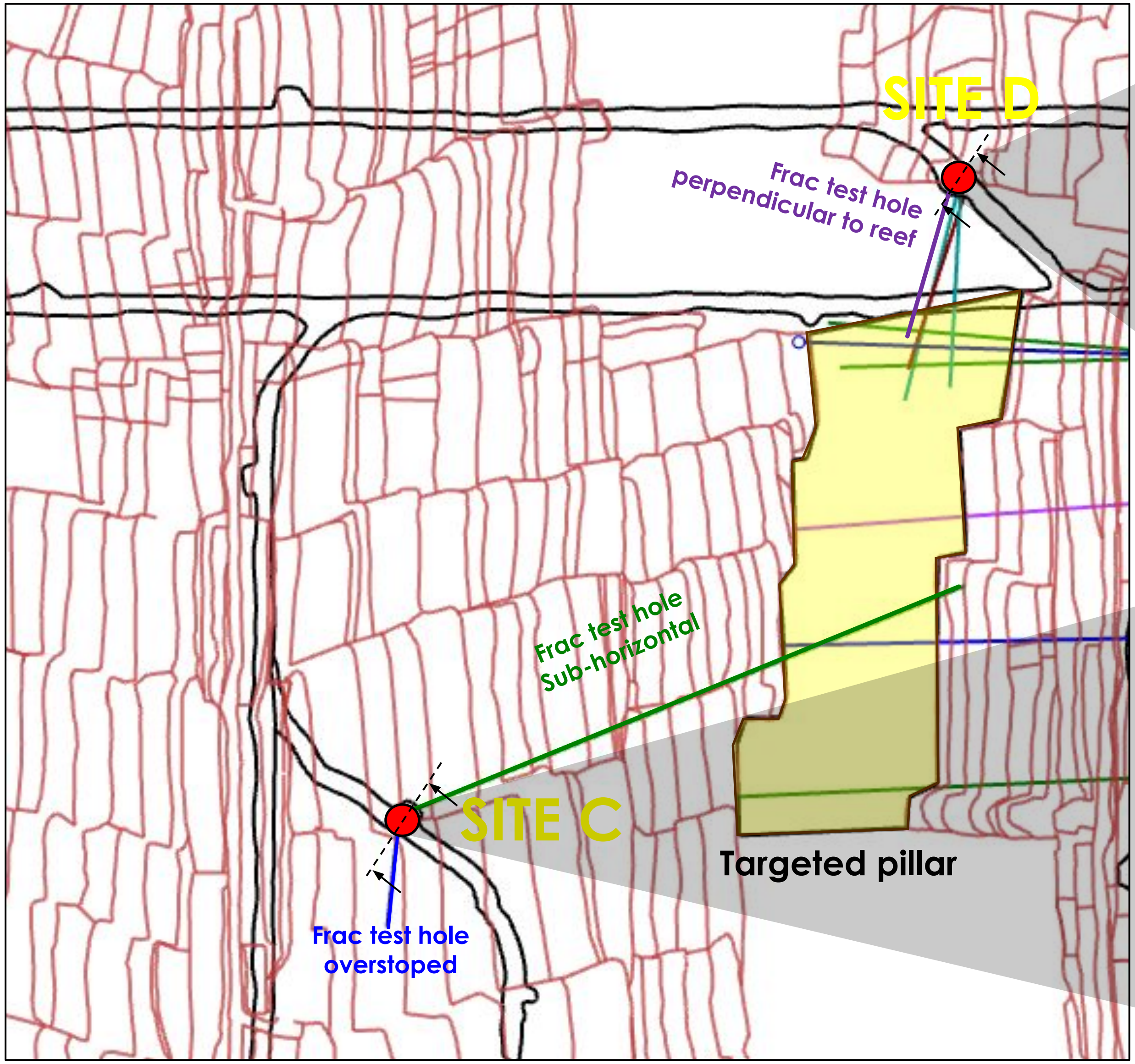
Mini-frack test background

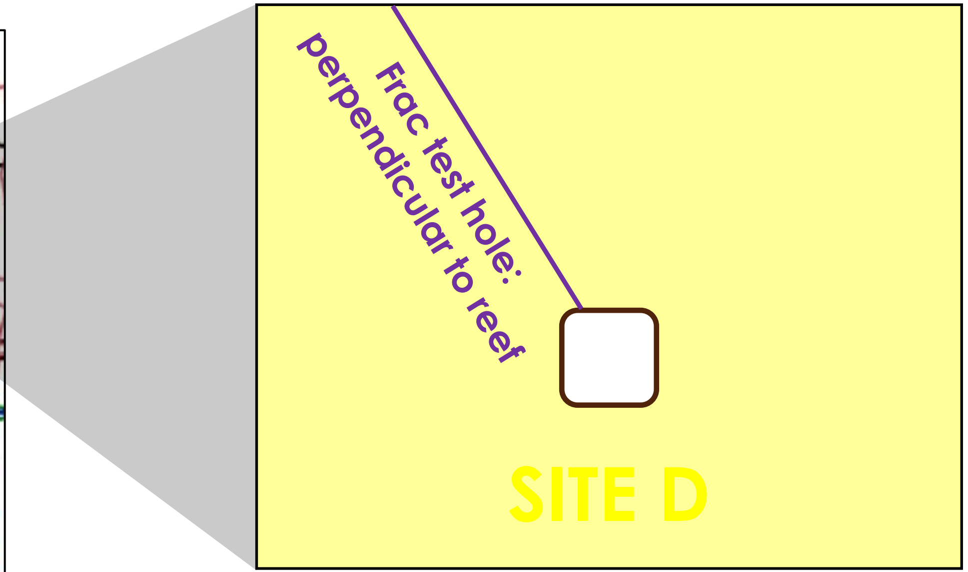


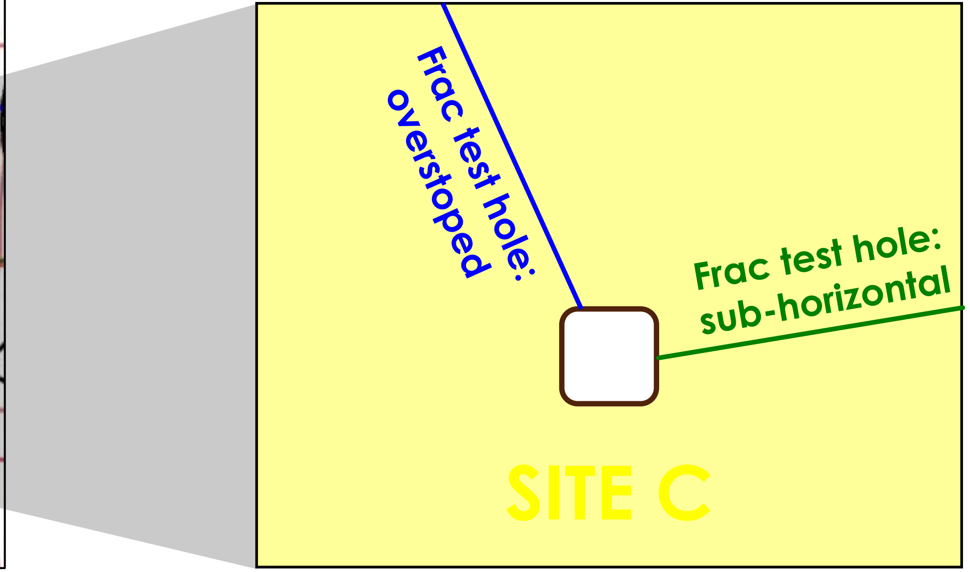
A	Integrity test	The treatment interval is initially pressurised to a nominal pressure expected to be lower than the breakdown pressure (5 – 10 MPa). The pressure is maintained for several minutes to test the ability of the rockmass to sustain a constant pressure. The pressure is then reduced or the system vented.
B	Pressurisation and breakdown	Pressure is increased at a constant flow rate until the breakdown pressure (fracture initiation pressure) is attained.
C	Shut in	Flow is stopped and the fracking fluid is 'shut in' at pressure. The measured pressure now decreases as the fracture stops growing and closes. The pressure at which the fracture closes is termed the 'instantaneous shut-in pressure' (ISIP).
D	Partial/full venting	With partial venting, the system is vented until a nominal pressure is reached, and flow is stopped. A subsequent increase in pressure shows that the fluid within the crack is flowing back into system. Such a response confirms that an opening fracture was created by the frack. The system is then fully vented
E	Re-opening	Pressure is increased at a constant flow rate as before. The pressure required to re-open the fracture (the refrac pressure) is taken as the first significant deviation from linearity of the pressure-volume relationship.

- Outputs
  - Breakdown pressure = frack initiation pressure
  - ISIP ≈ S3 (in-plane)
  - Hydraulic tensile strength = breakdown pressure – re-opening pressure

Site details: mini frack tests

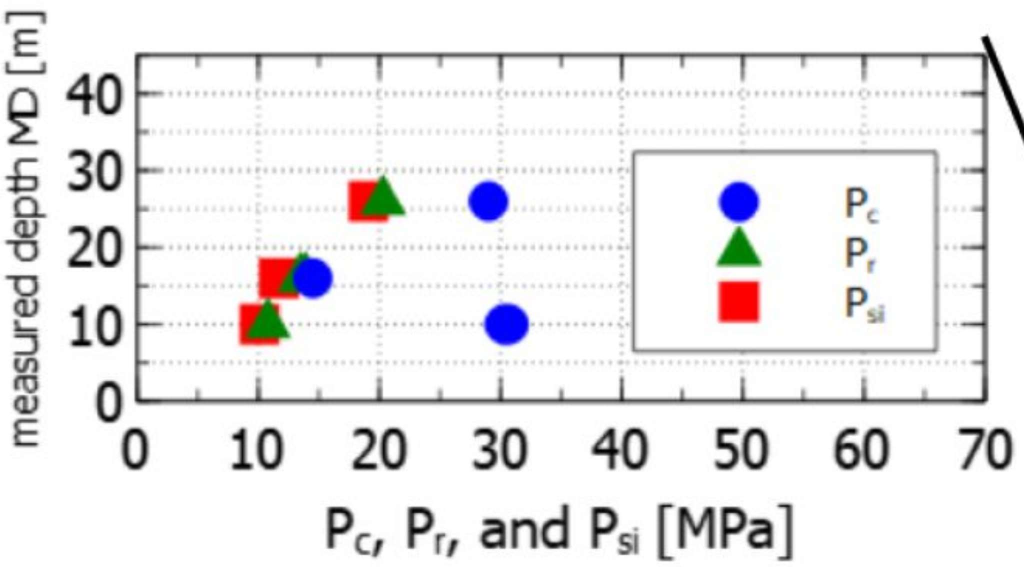




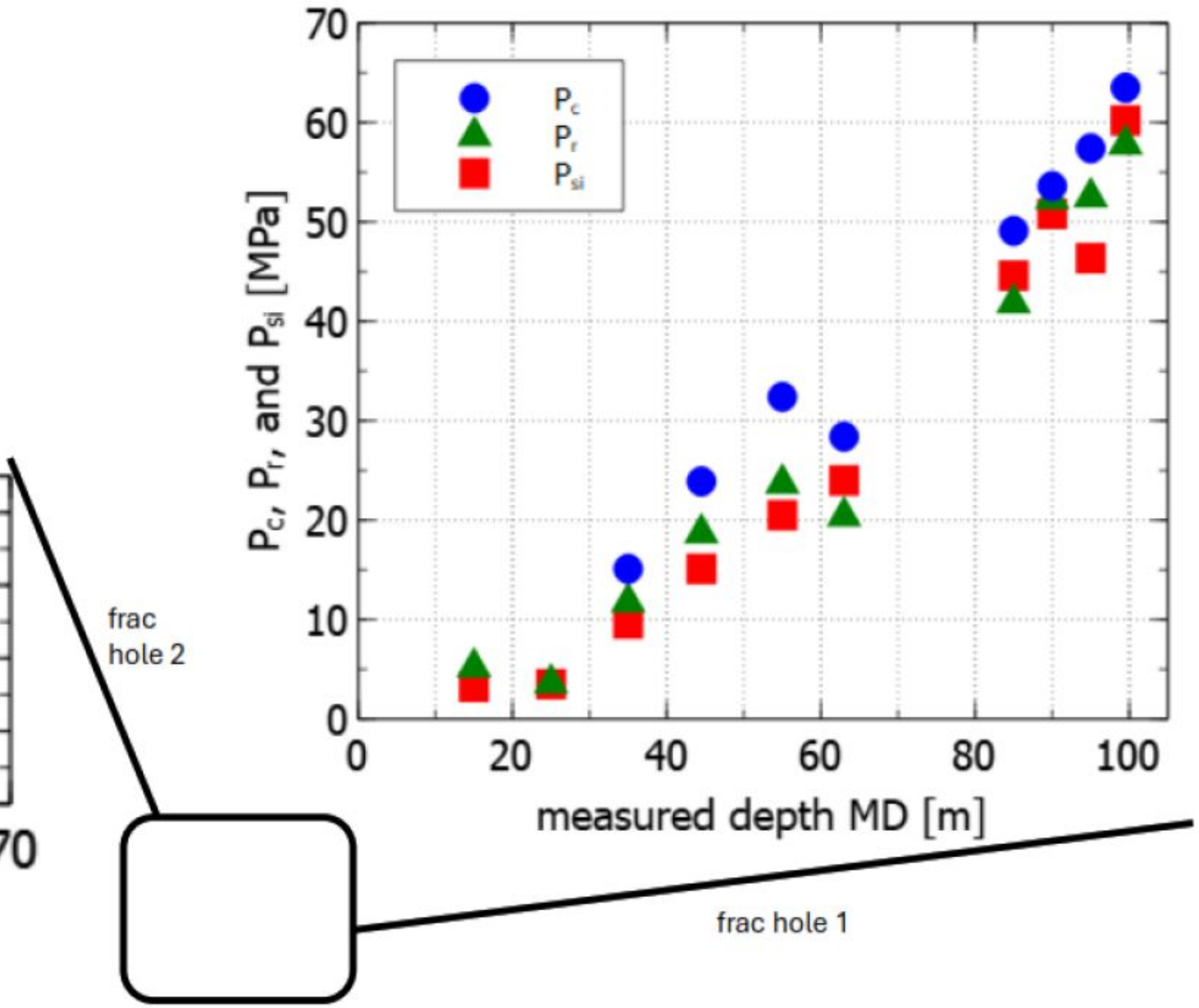


Mini-frack test results: frack holes 1 and 2

● P_c = Fracture initiation pressure
▲ P_r = Re-opening pressure
■ P_{si} = Shut-in pressure ($\approx \sigma_3$)



σ_{ht} = 19.5 – 19.9 MPa



40 Level 16
follow-on footwall drive

σ_{ht} = 3 – 9.9 MPa

Mini-frack test results: frack holes 1 and 2

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▲ P_r = Re-opening pressure
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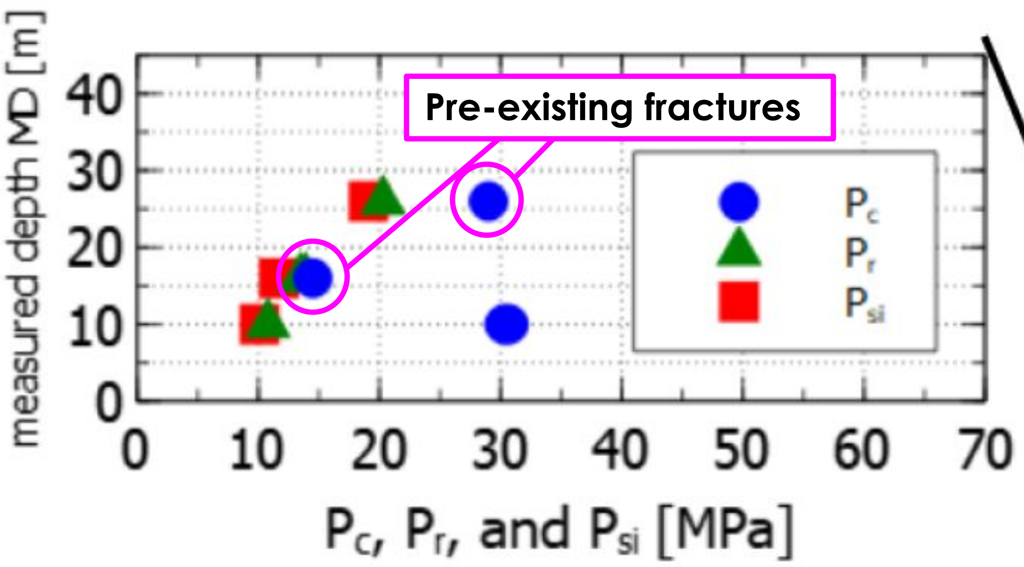

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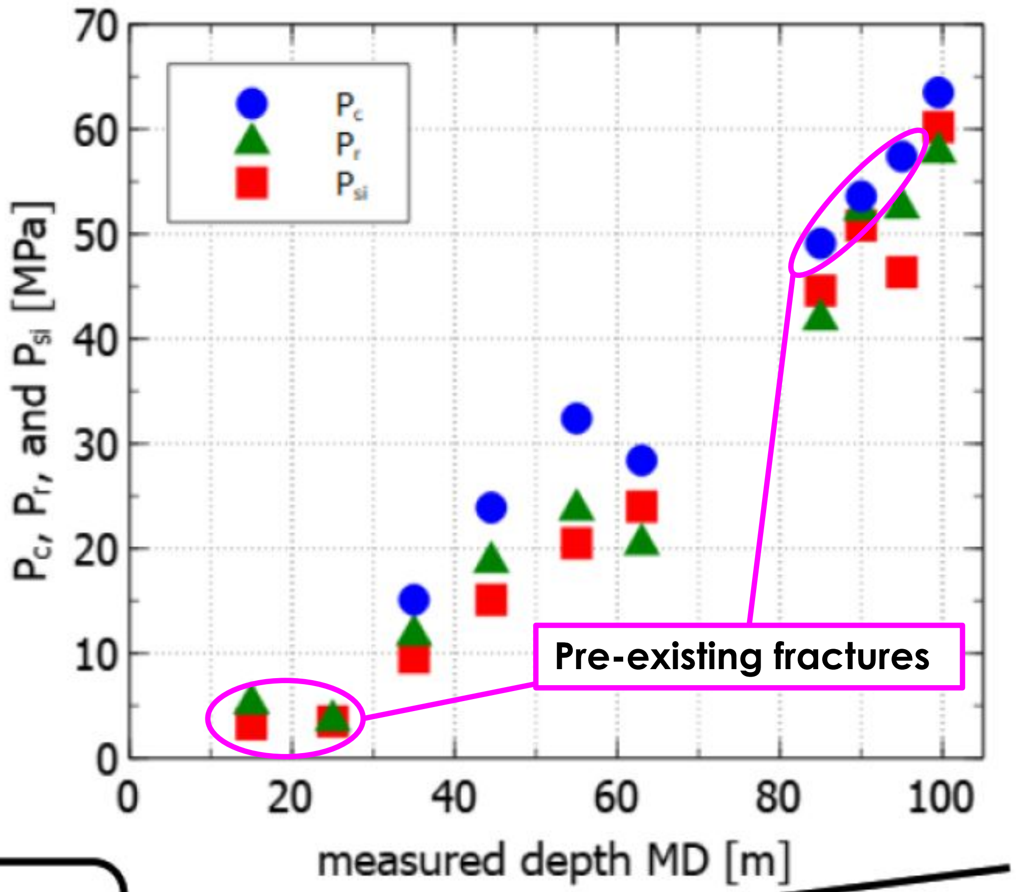
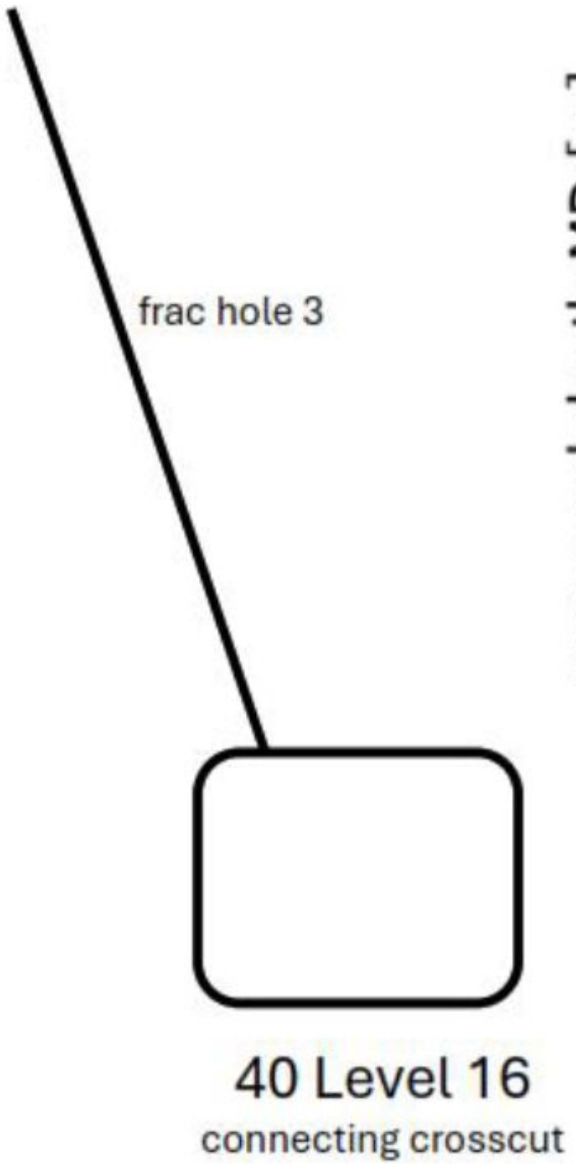
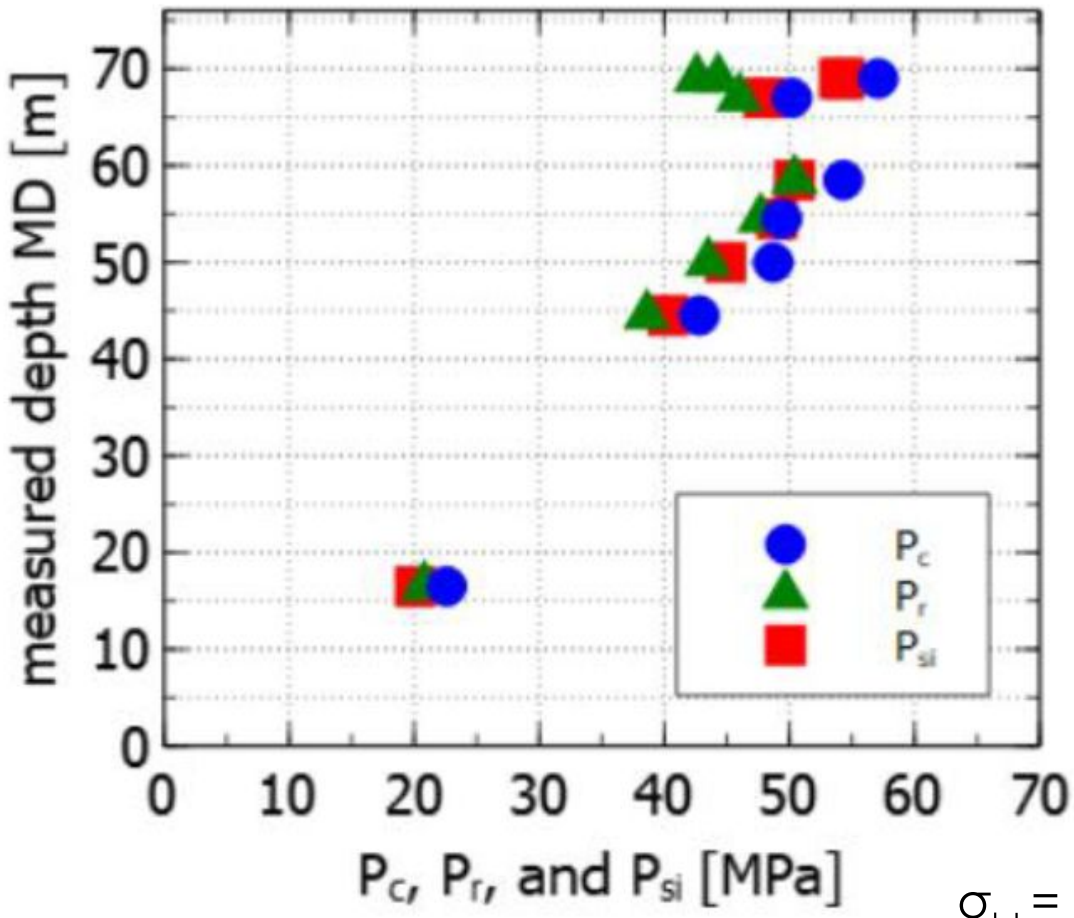


σ_{ht} = 3 – 9.9 MPa

Mini-frack test results: frack hole 3

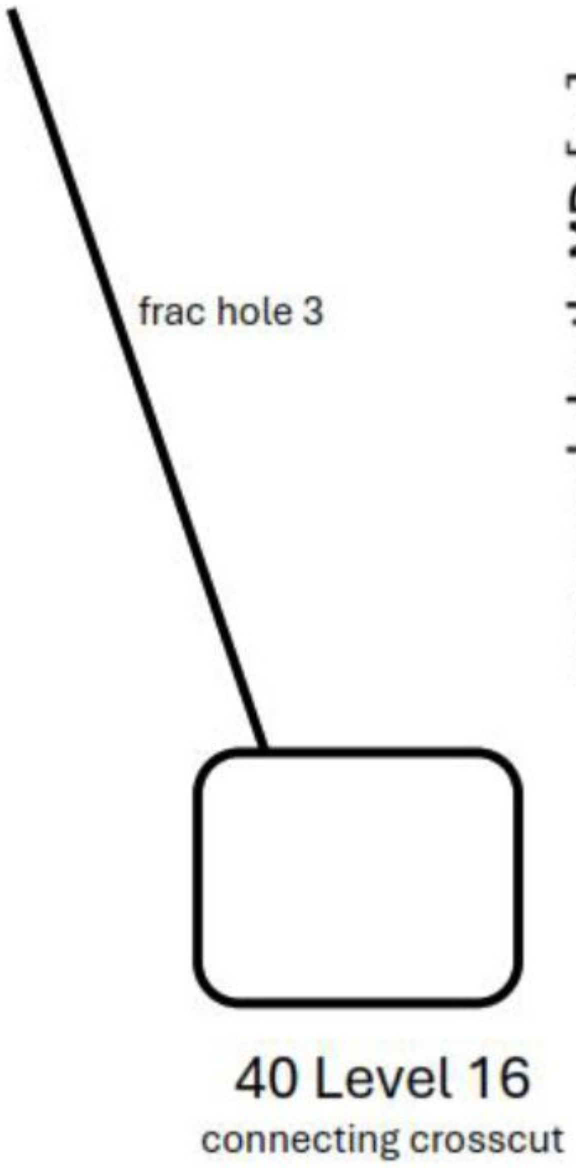


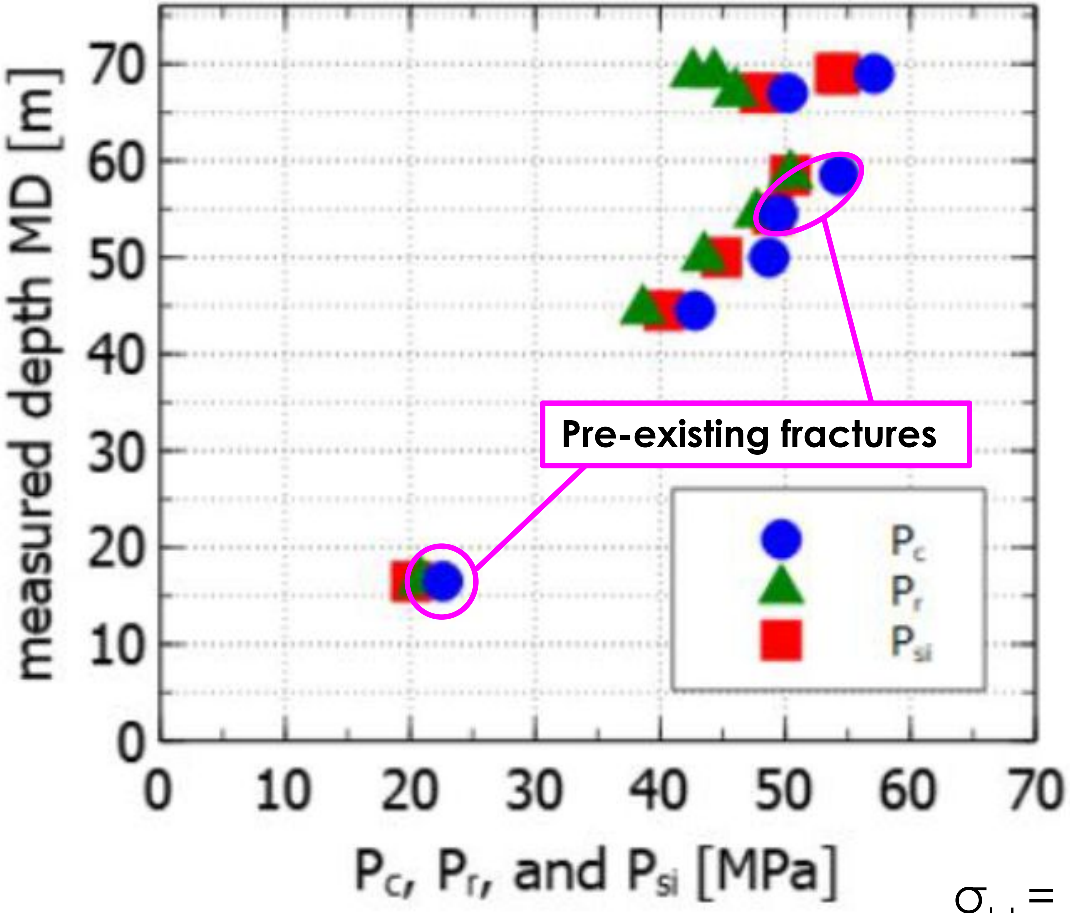


σ_{ht} = 4.2 – 14.5 MPa

- P_c = Fracture initiation pressure
- P_r = Re-opening pressure
- P_{si} = Shut-in pressure ($\approx \sigma_3$)

Mini-frack test results: frack hole 3



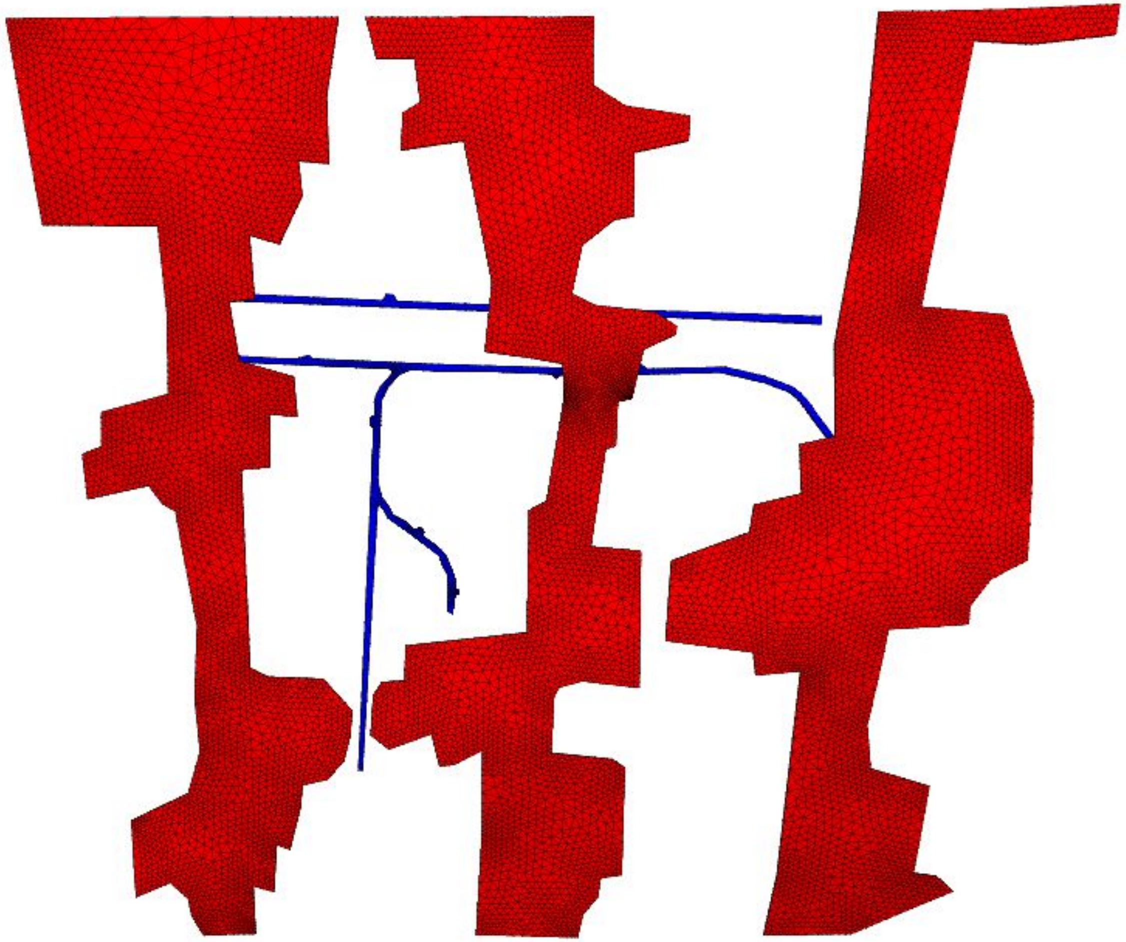


σ_{ht} = 4.2 – 14.5 MPa

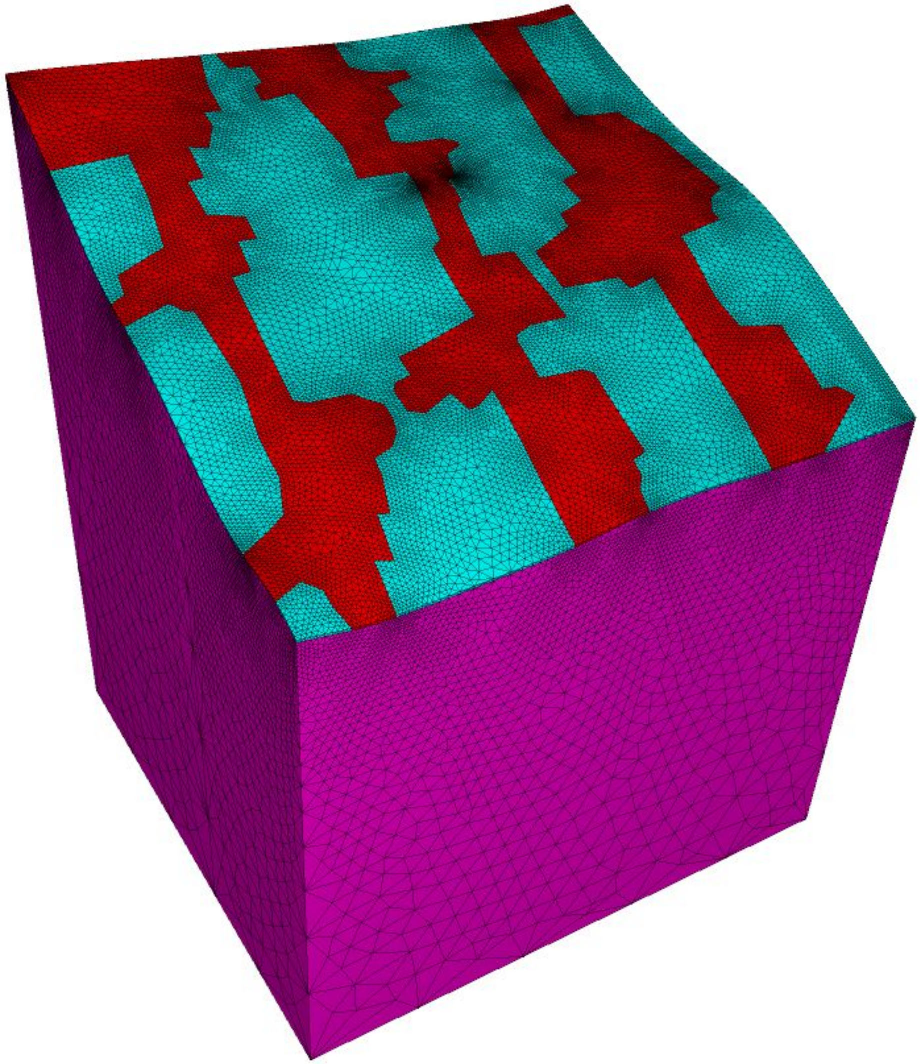
- P_c = Fracture initiation pressure
- P_r = Re-opening pressure
- P_{si} = Shut-in pressure (≈ σ_3)

Comparison with modelling

FLAC3D model of the 40-16 area



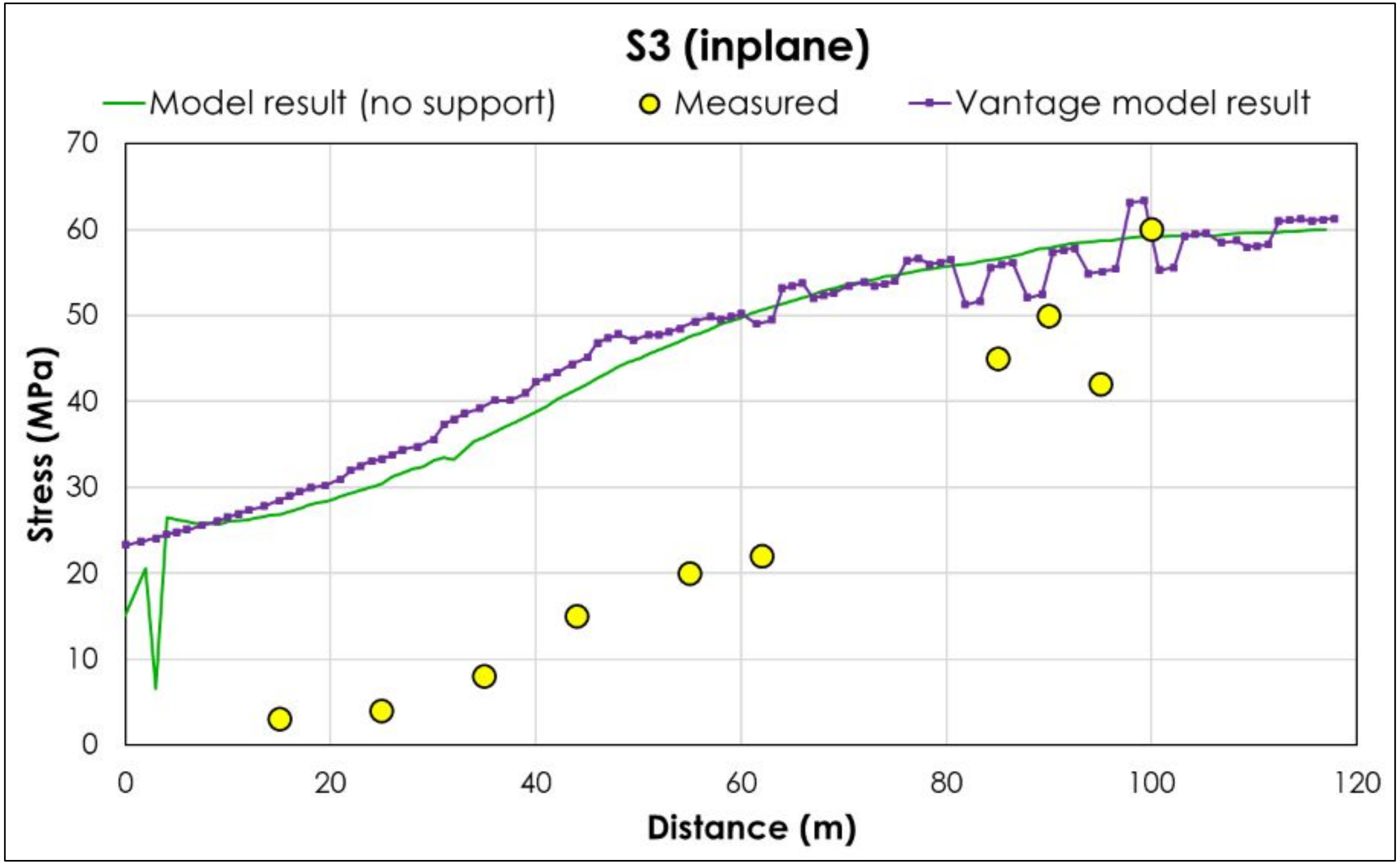
Footwall, hangingwall
and stopes hidden



Hangingwall hidden

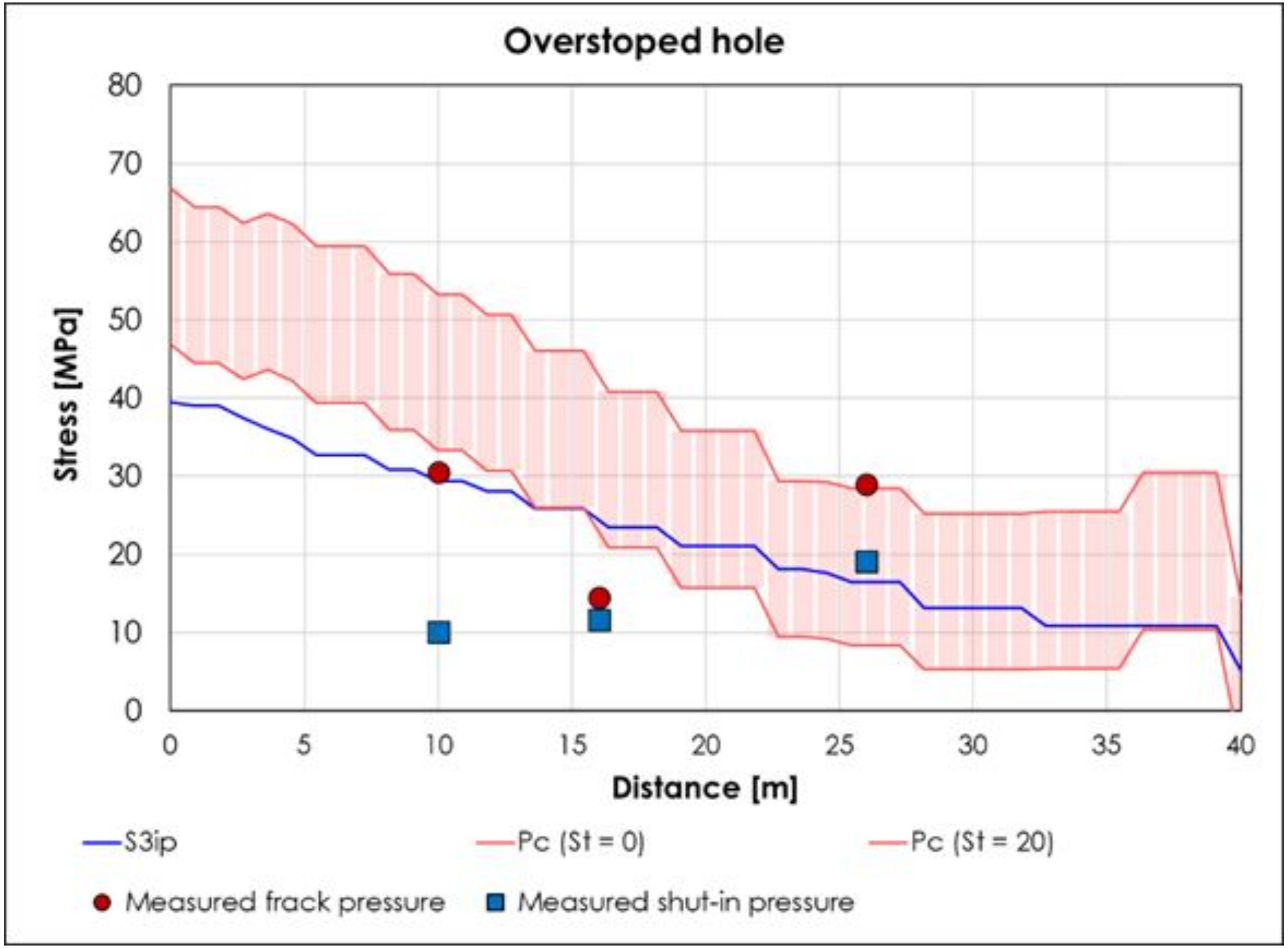
Comparison with modelling

Comparison with frack hole 1 (sub-horizontal) result: “best” FLAC3D result and Vantage result



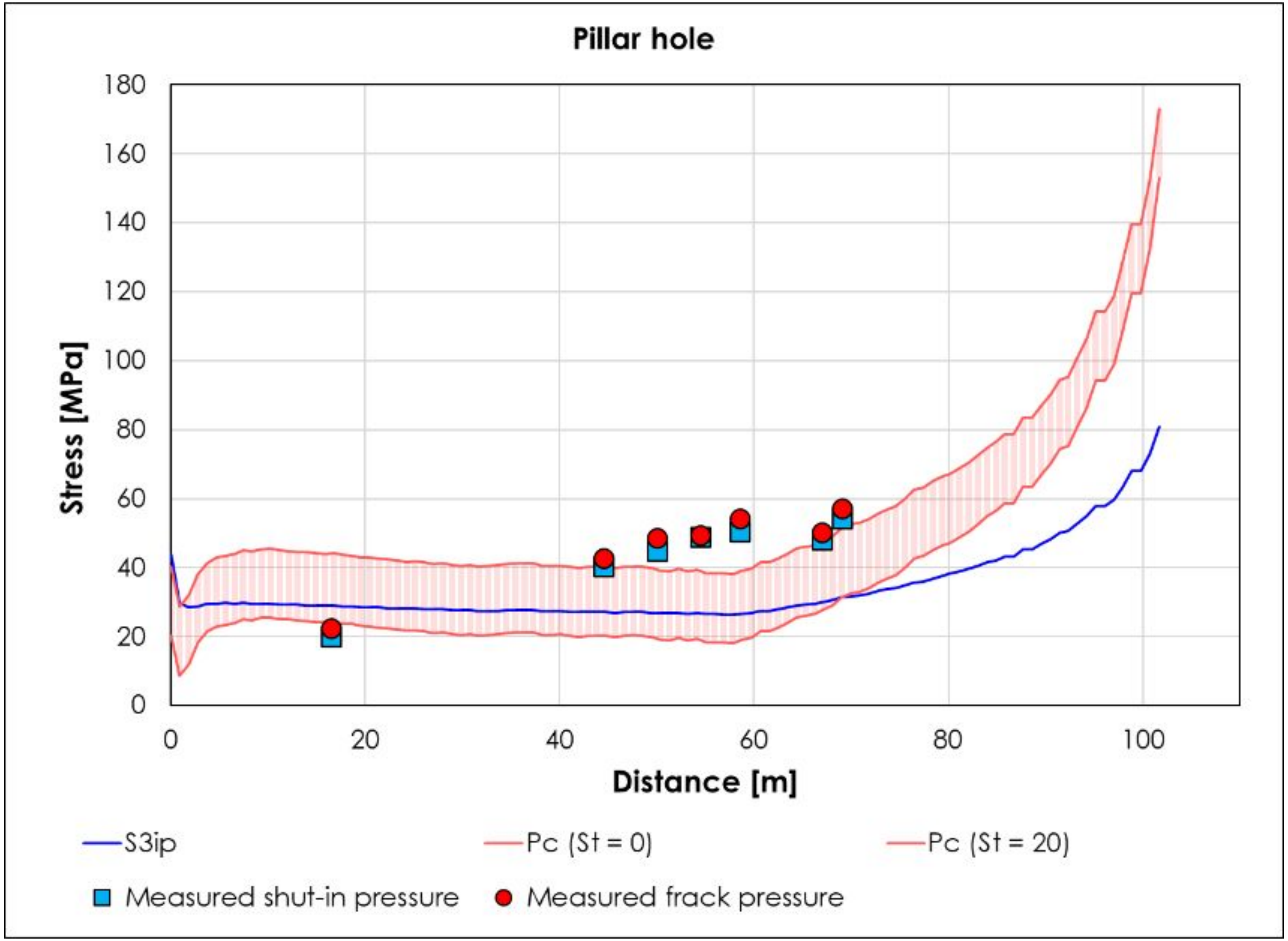
Comparison with modelling

Comparison with frack hole 2 (overstoped) result



Comparison with modelling

Comparison with frack hole 3 (in-pillar) result



Conclusions

- Drilling trials
  - It is possible to drill holes over 110 m with reasonable accuracy
  - These holes can be controlled if they are parallel to S1

- Mini-frack tests
  - 20 successful tests were conducted
  - Pressure distributions along the holes showed consistent trends
  - Inconsistencies were attributed to stimulation of existing fractures
  - A maximum pressure of 60 MPa was encountered
  - Extrapolating pressures in the in-pillar hole suggests that the maximum permissible pressure of 80 MPa will not be exceeded

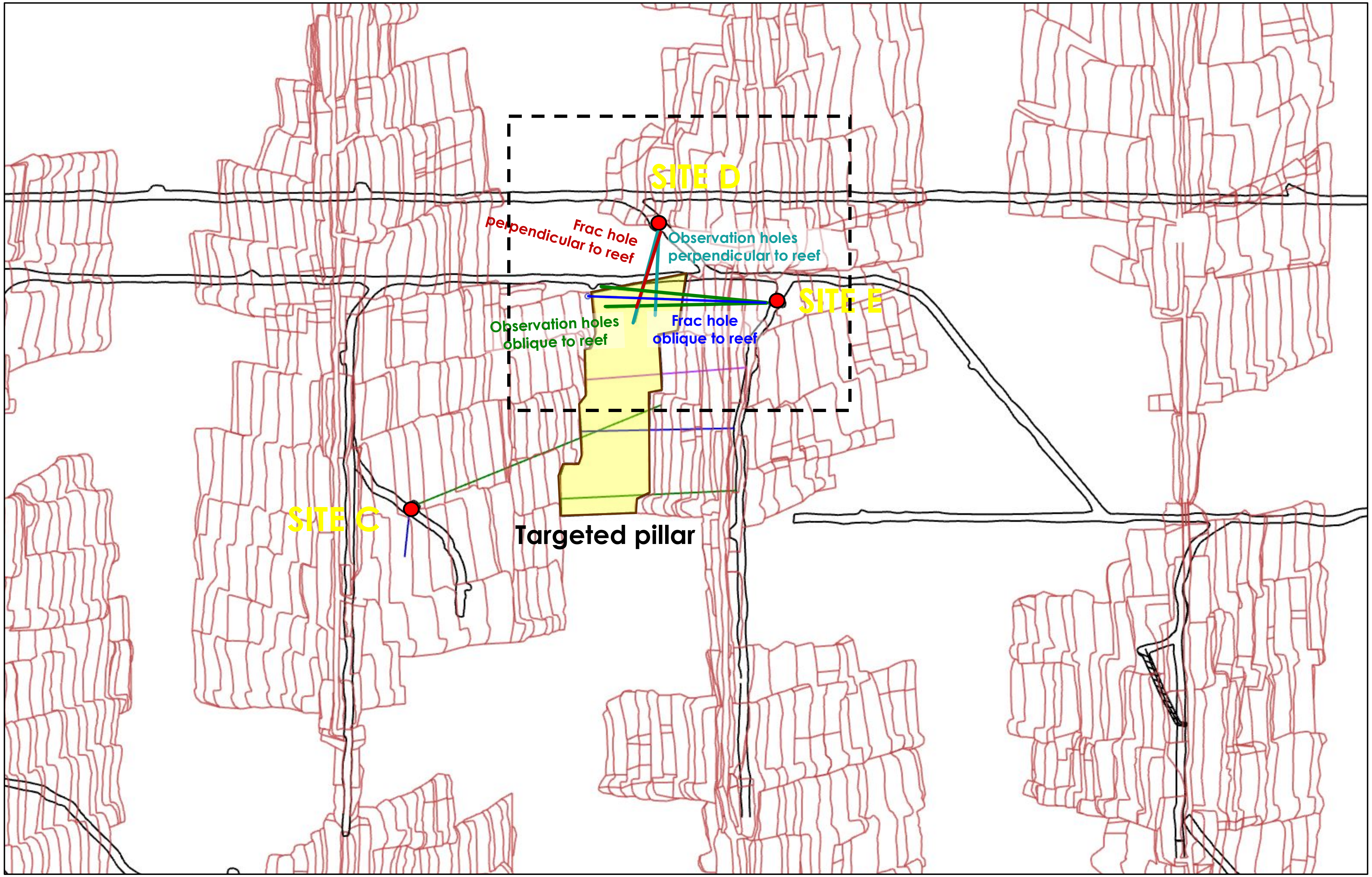
Conclusions

- Modelling
  - Similar trends were observed in the measured and modelled results
  - Magnitudes were not well matched at the measurement positions, but the range of magnitudes overlapped
  - The effect of overstoping on the modelling results is under-represented
  - The virgin S3 may need to be increased
  - Obtaining correlation between the modelled and measured stresses will inform further efforts to characterise the stress field, and how it is influenced by the presence of mining

Phase 3: fracture growth

- We have now established that it is possible to fracture the rock, but we don’t yet know how far we can drive these fractures
- Growing fractures requires high pressures (up to 65 MPa, as we have seen) to be maintained while pumping water into an ever-increasing crack volume
- This requires a pump capable of maintaining high flowrates and pressures, while allowing for fine control

Site details: full frack and observation holes



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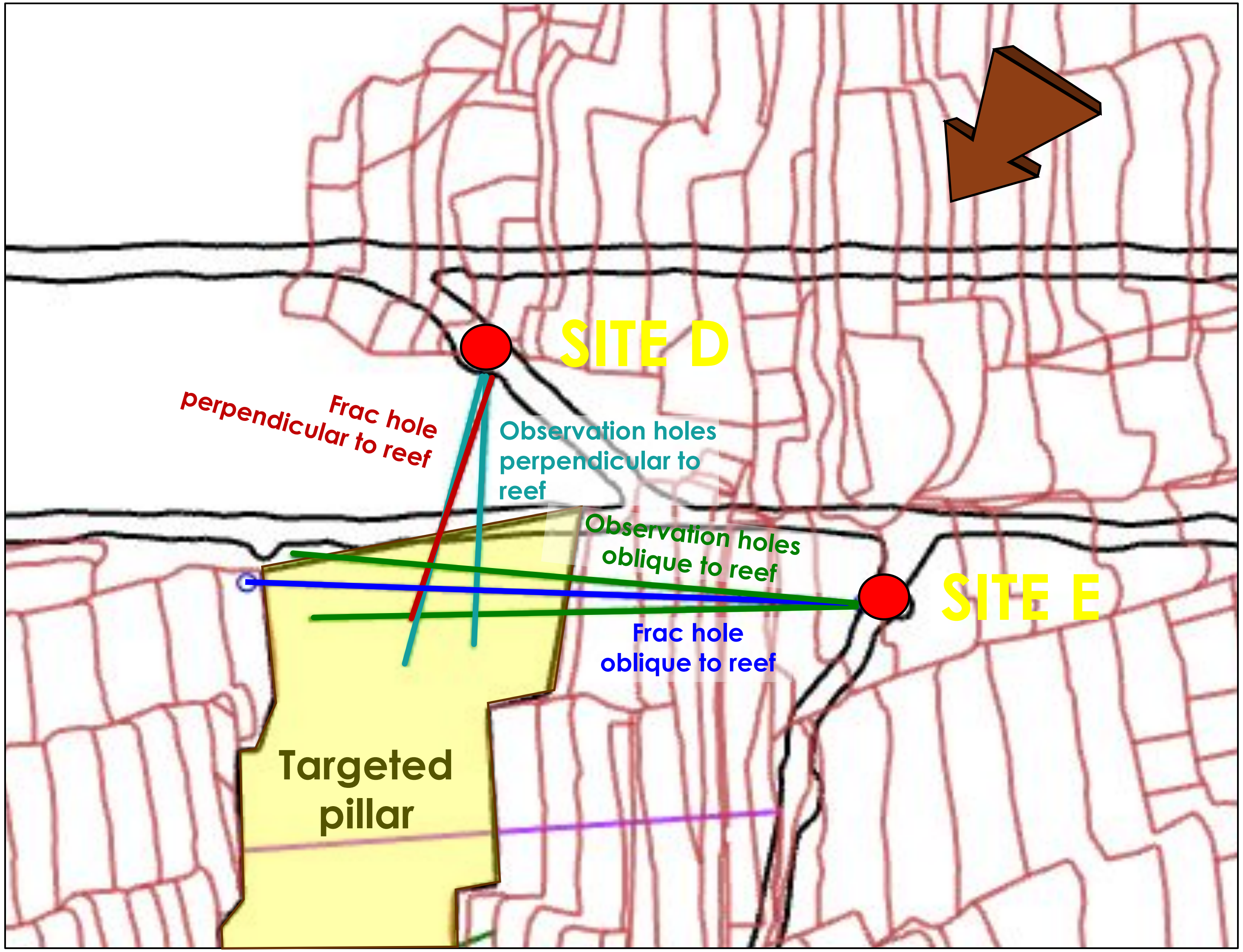
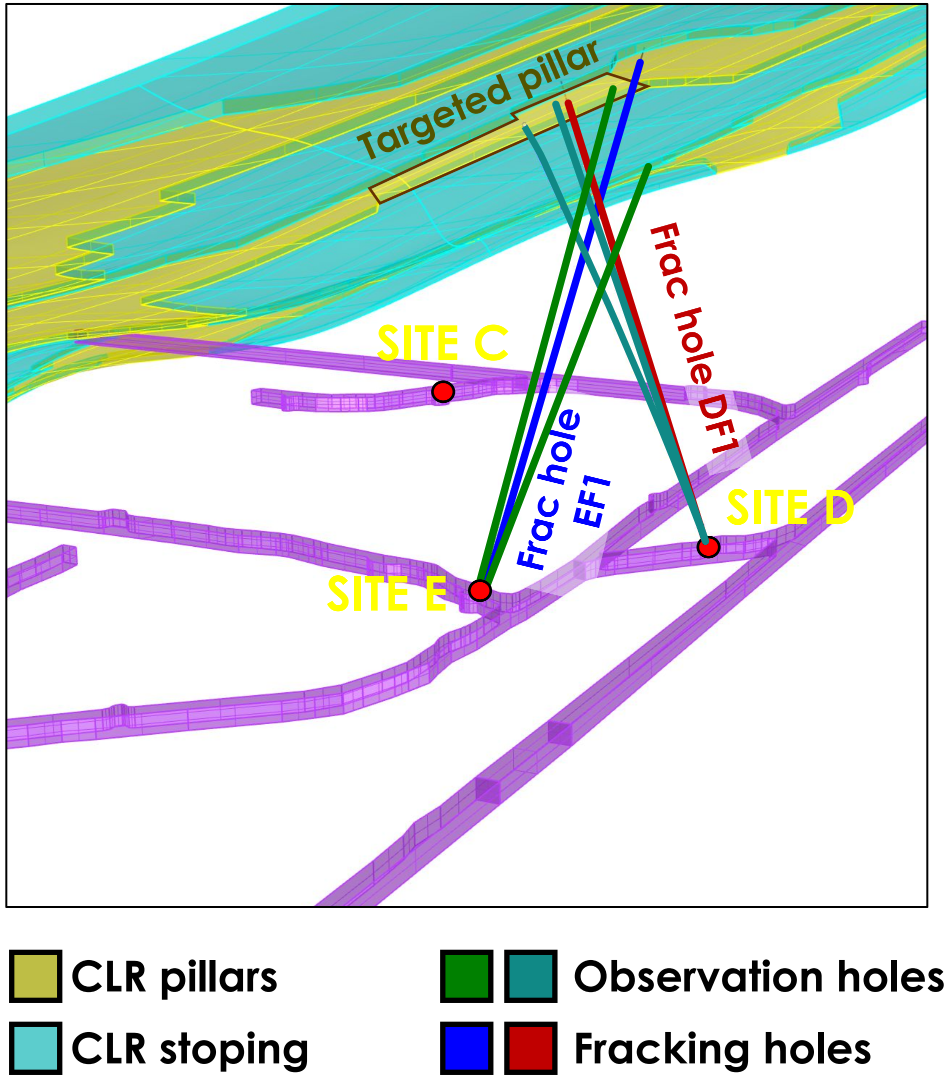
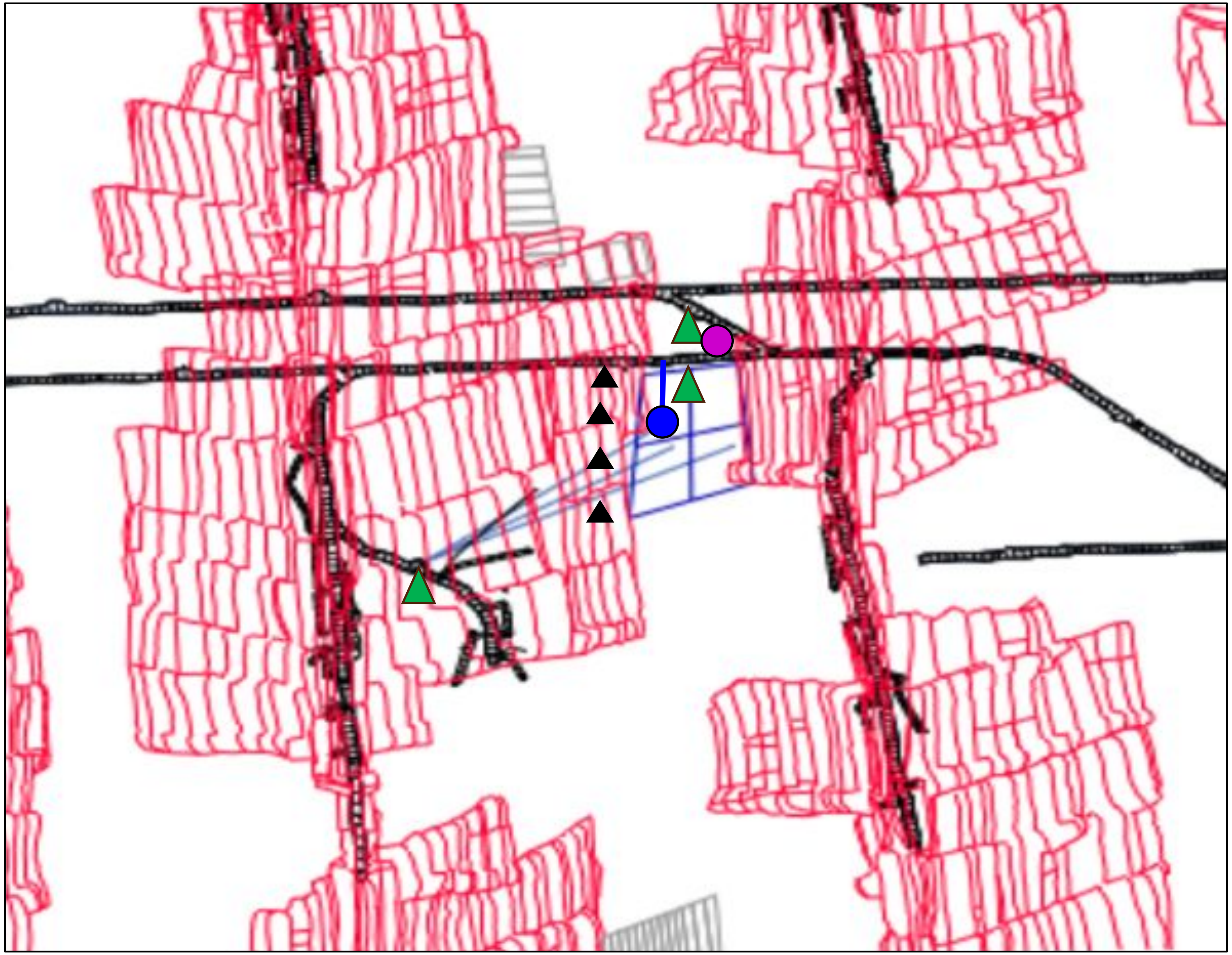




Experiment rationale

- **Fracking will take place in both NQ holes (one from site D and one from site E)**
  - In each hole, multiple fracking treatments will be done from the end of the hole towards the collar
  - One of these holes will be cemented and reamed the hole before fracking
- **Observation holes**
  - Two BQ observation holes are drilled at each site
  - We expect water to emerge from these holes as the growing fracture intersects them

Phase 3- Instrumentation



- ▲ 8G Accelerometers
- ▲ Closure meters
- ● Ishii strain meter
- ● CCBO strain meter

- 8G Accelerometers at the connecting XC (40 level) and at the end of the 65° up hole
- Ishii strainmeter installed under the pillar on 40 level
- CCBO (without overcore) to be installed on 40 level
- Continuous closure meters to be installed in the old 40-16 E stope

Phase 3- Instrumentation

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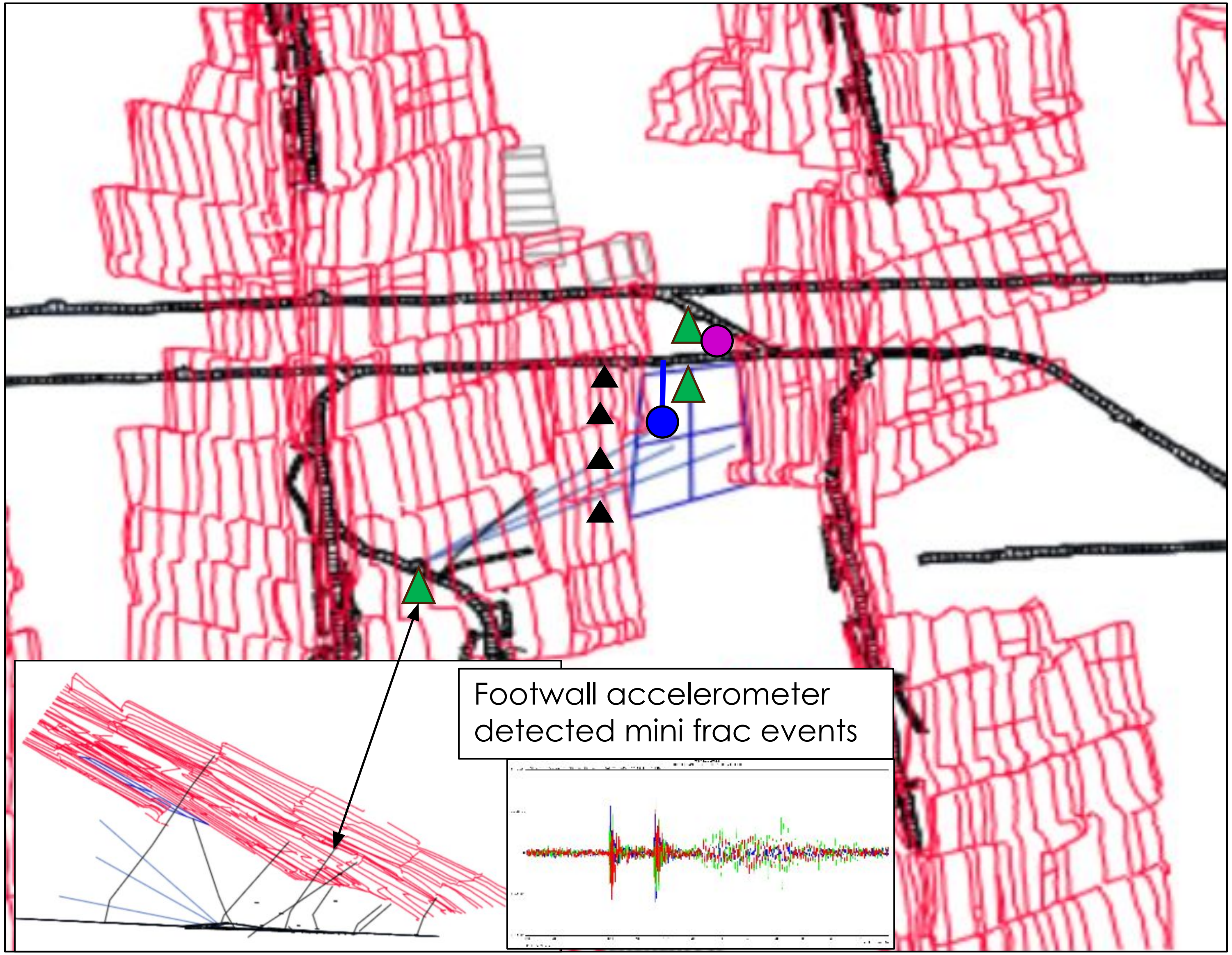

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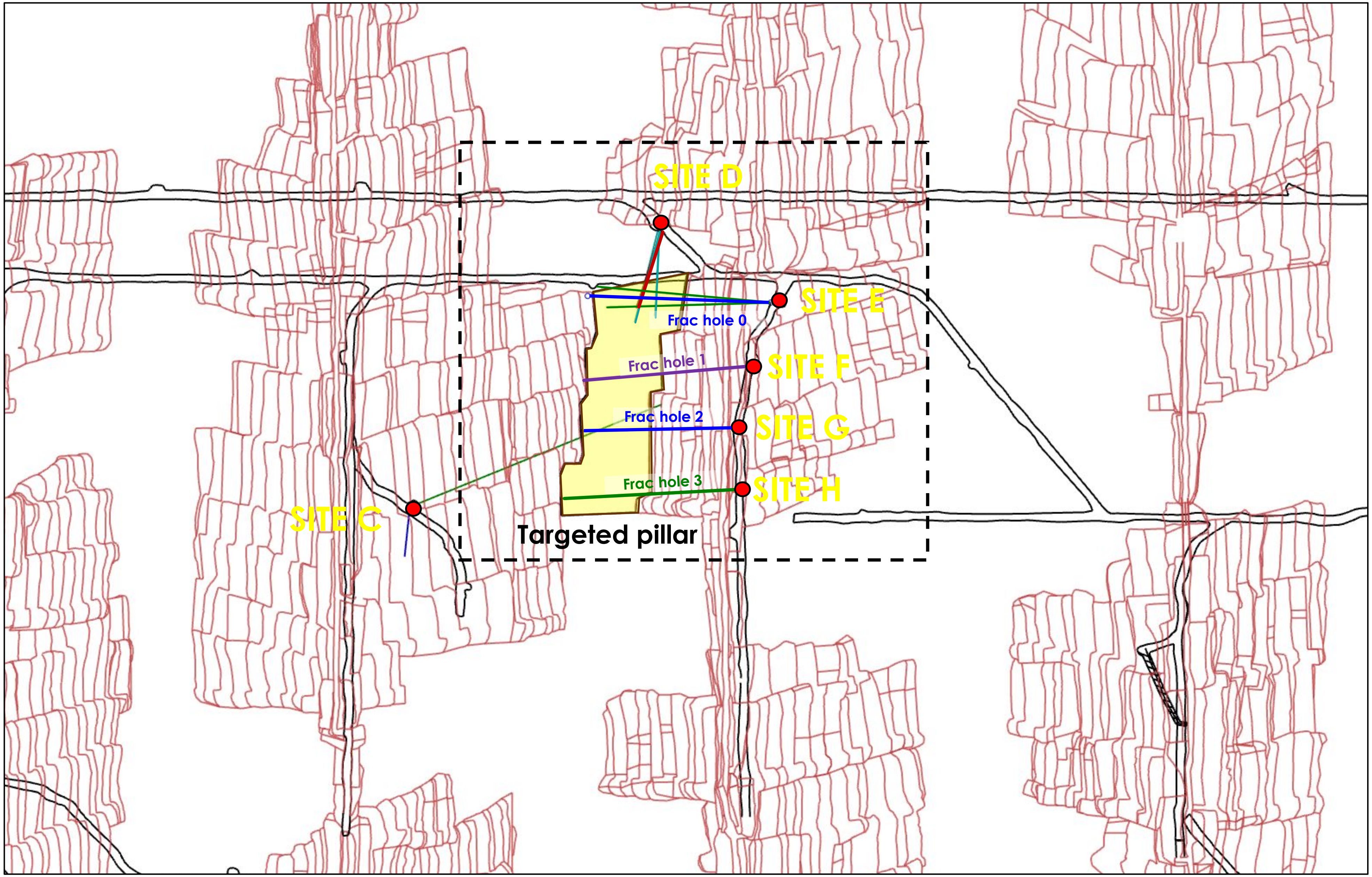
Way forward: 2025/6 plan

- The next phase is to implement fracking in multiple holes to precondition the targeted pillar for extraction

Site details: full pillar fracking layout



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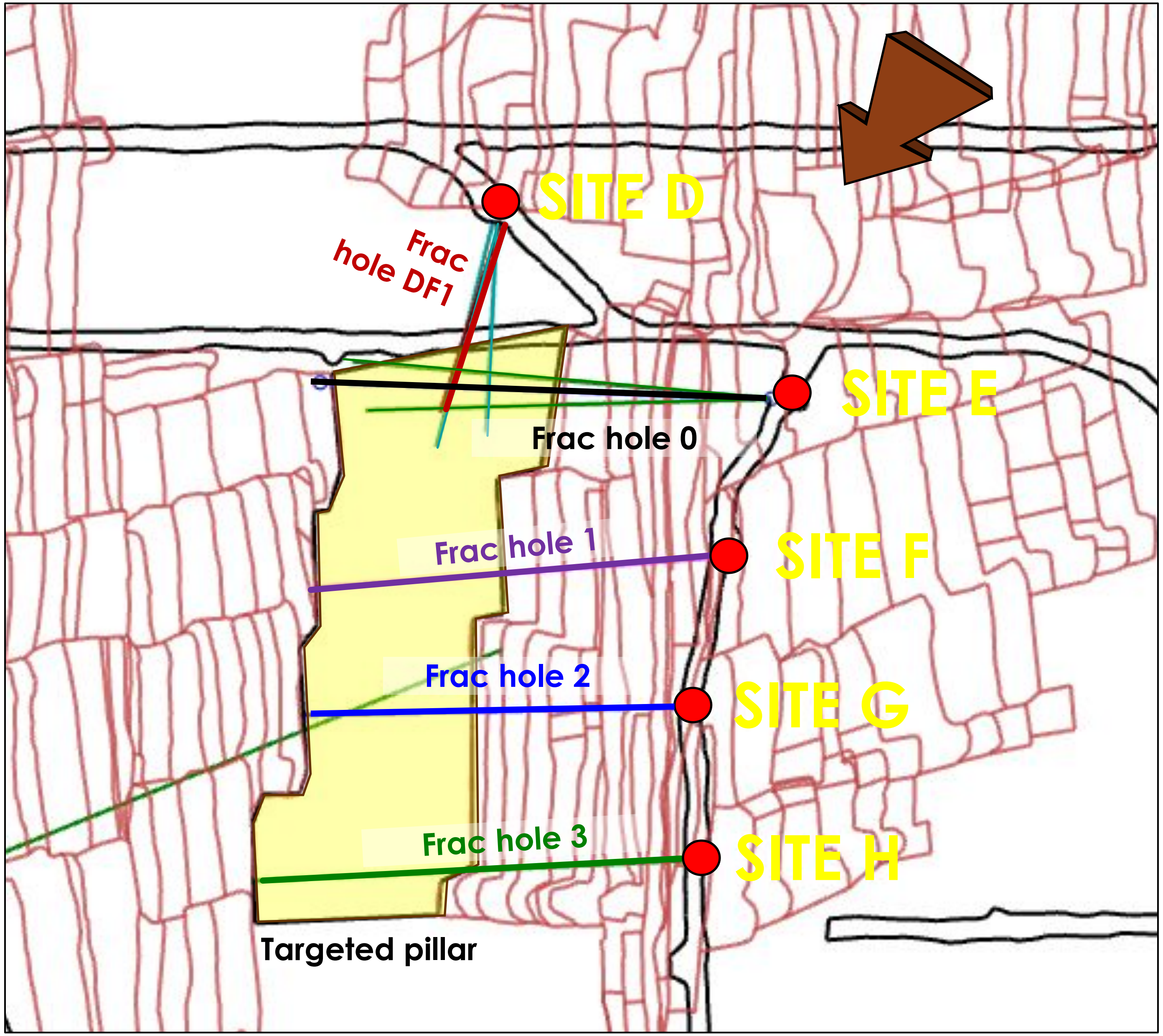

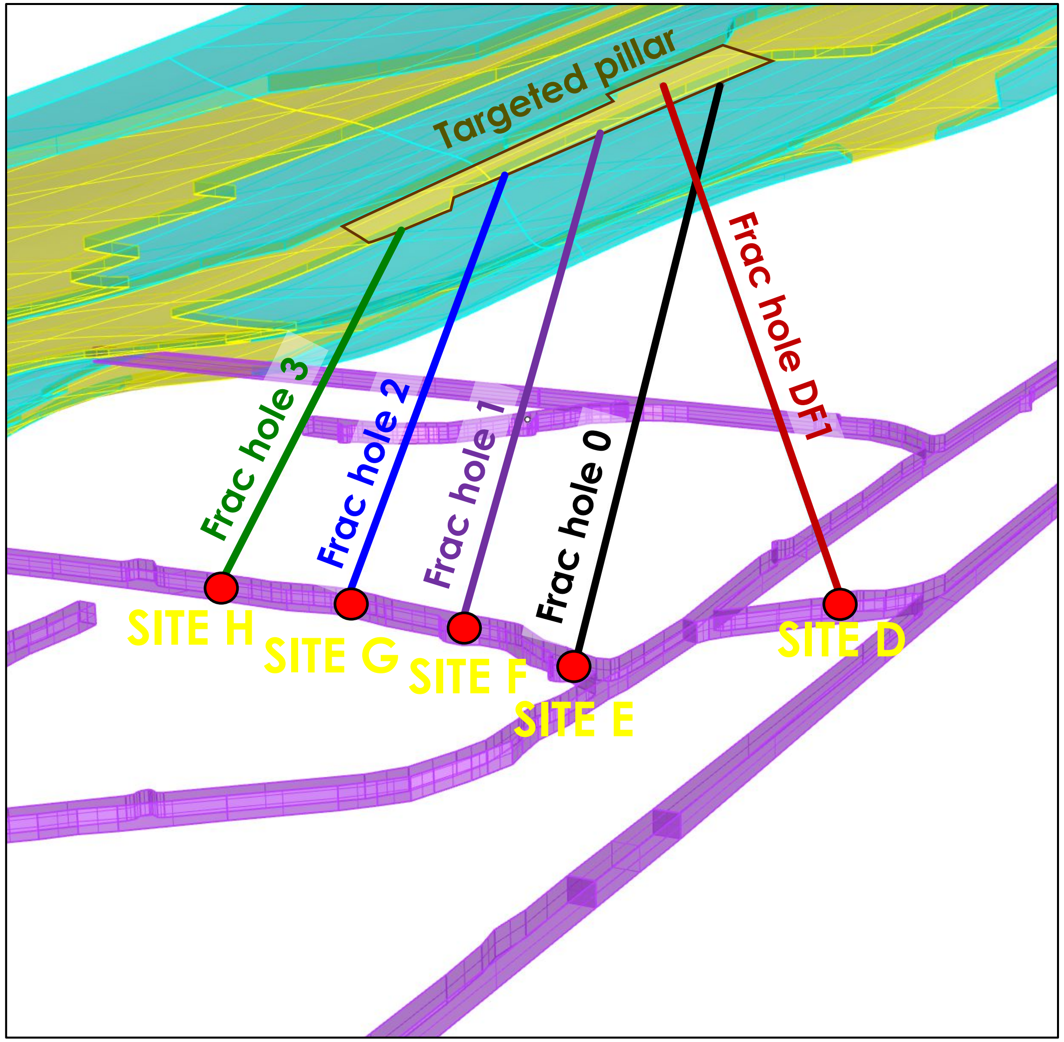

- CLR pillars
- CLR stoping

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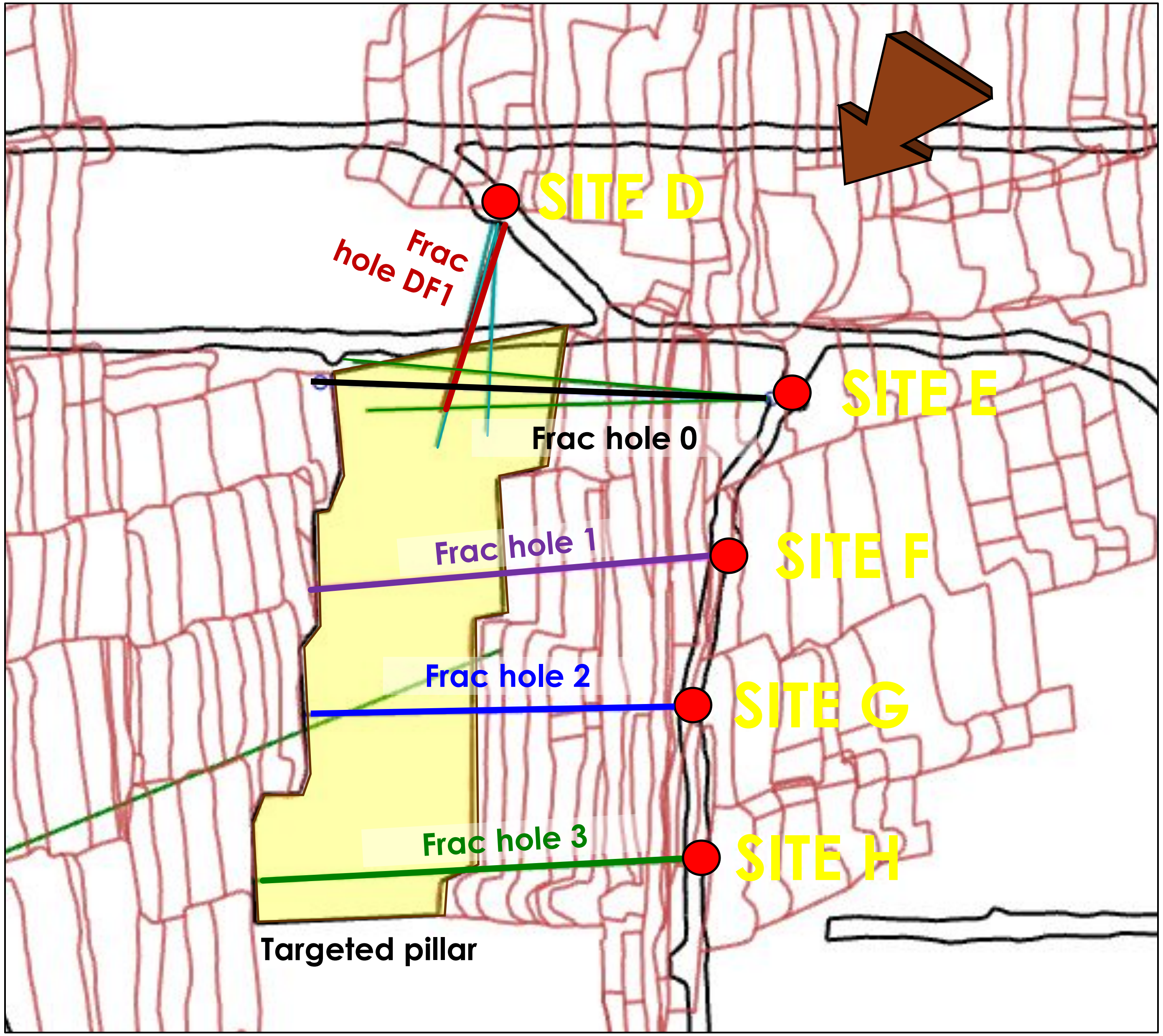
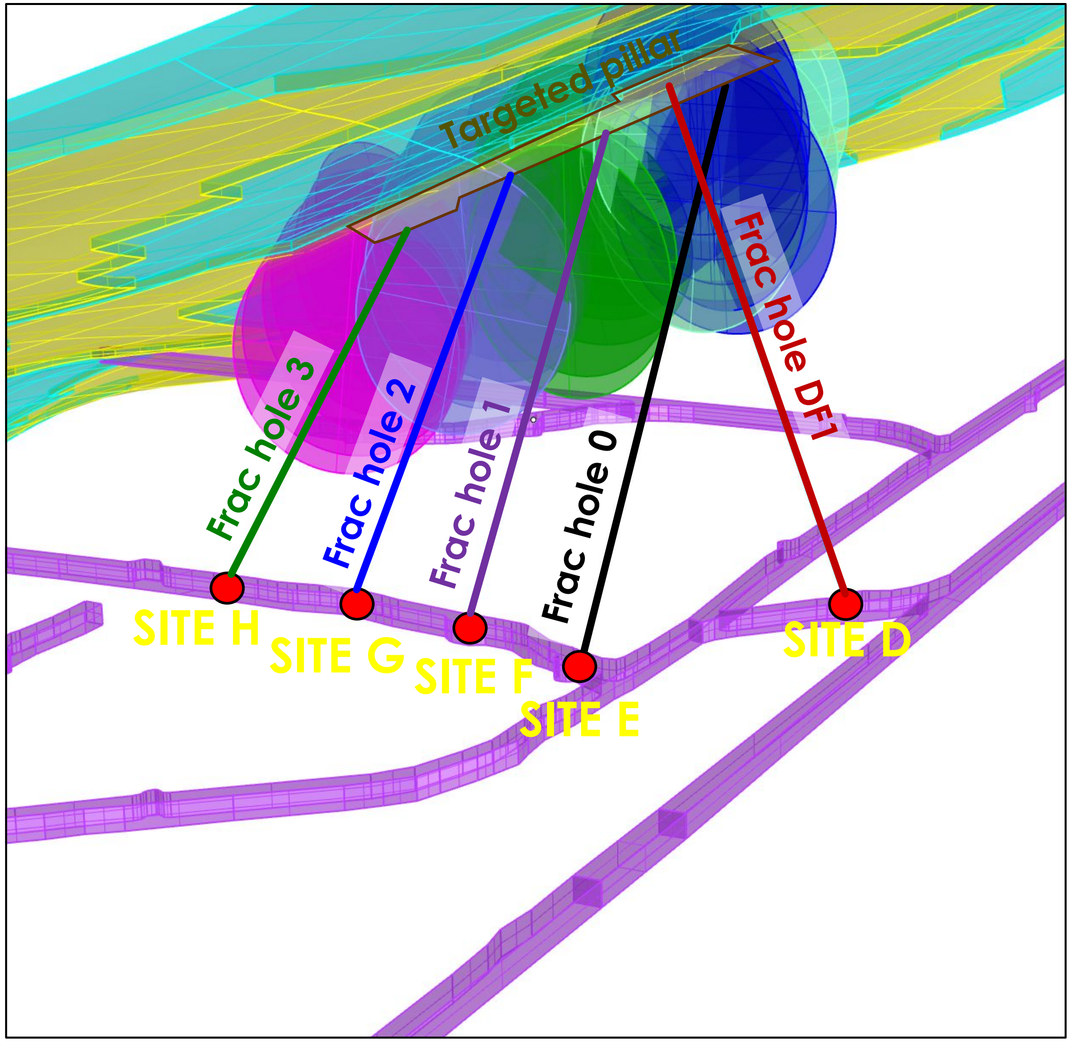


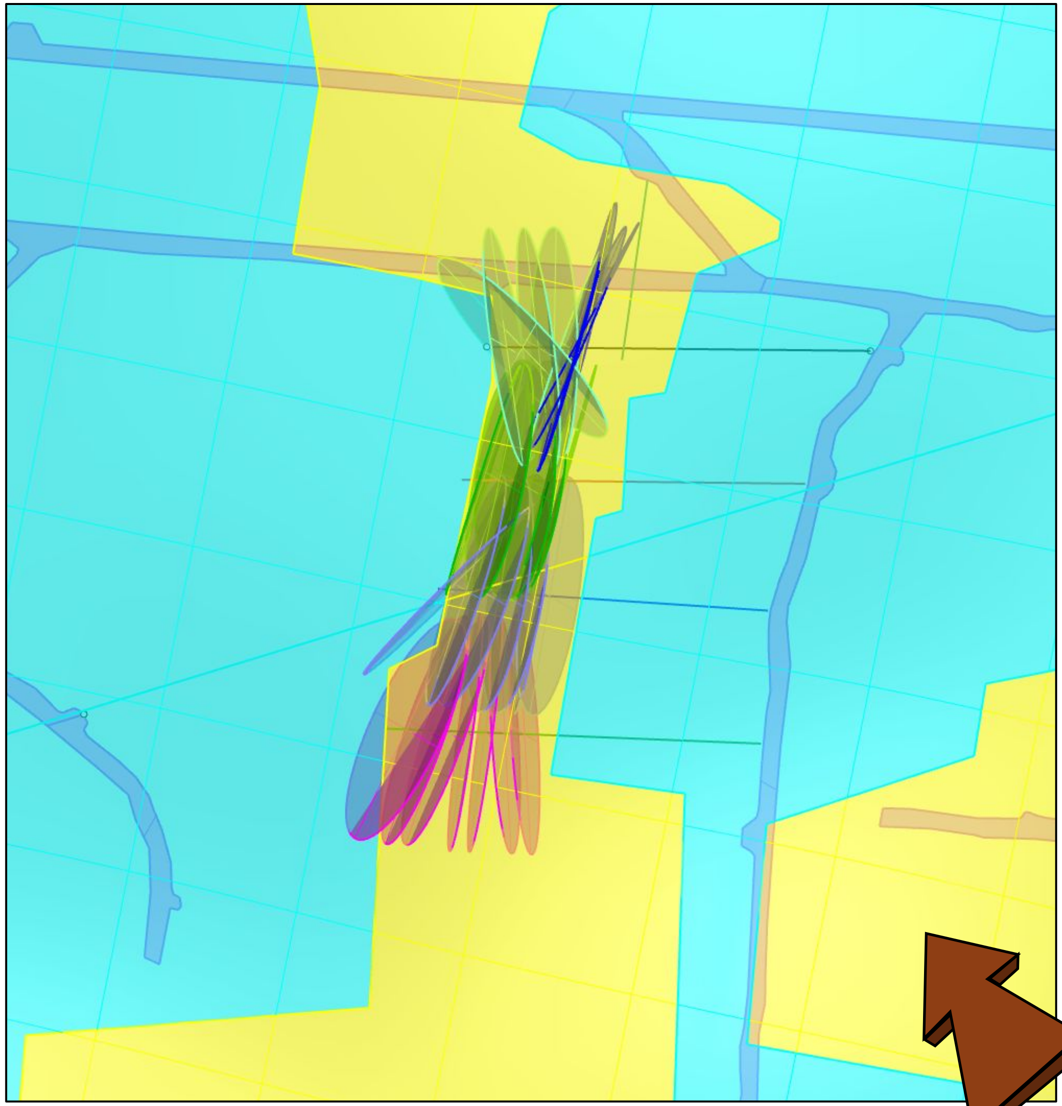


CLR pillars

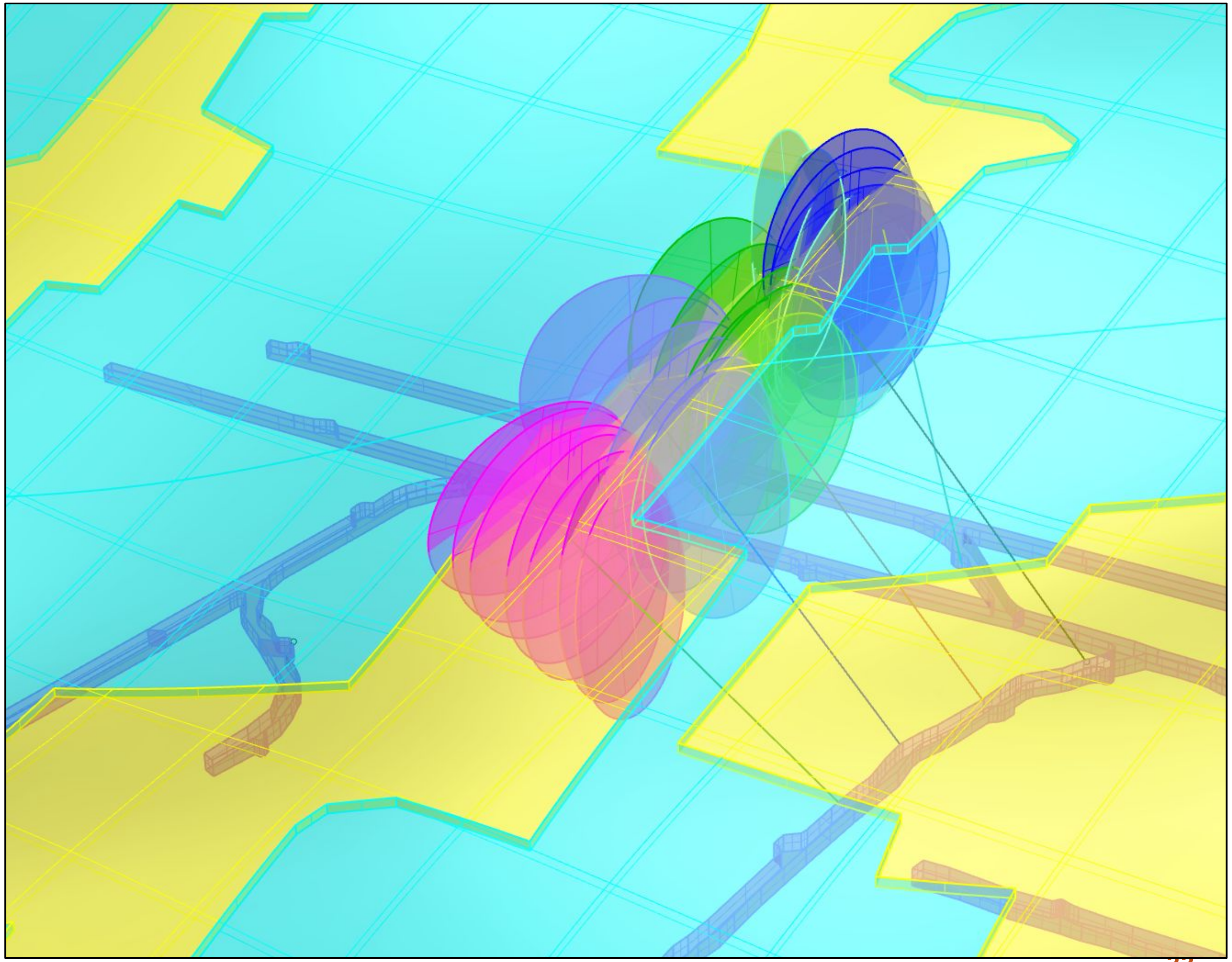
CLR stoping

Site details: expected fracturing

Plan view



Oblique view



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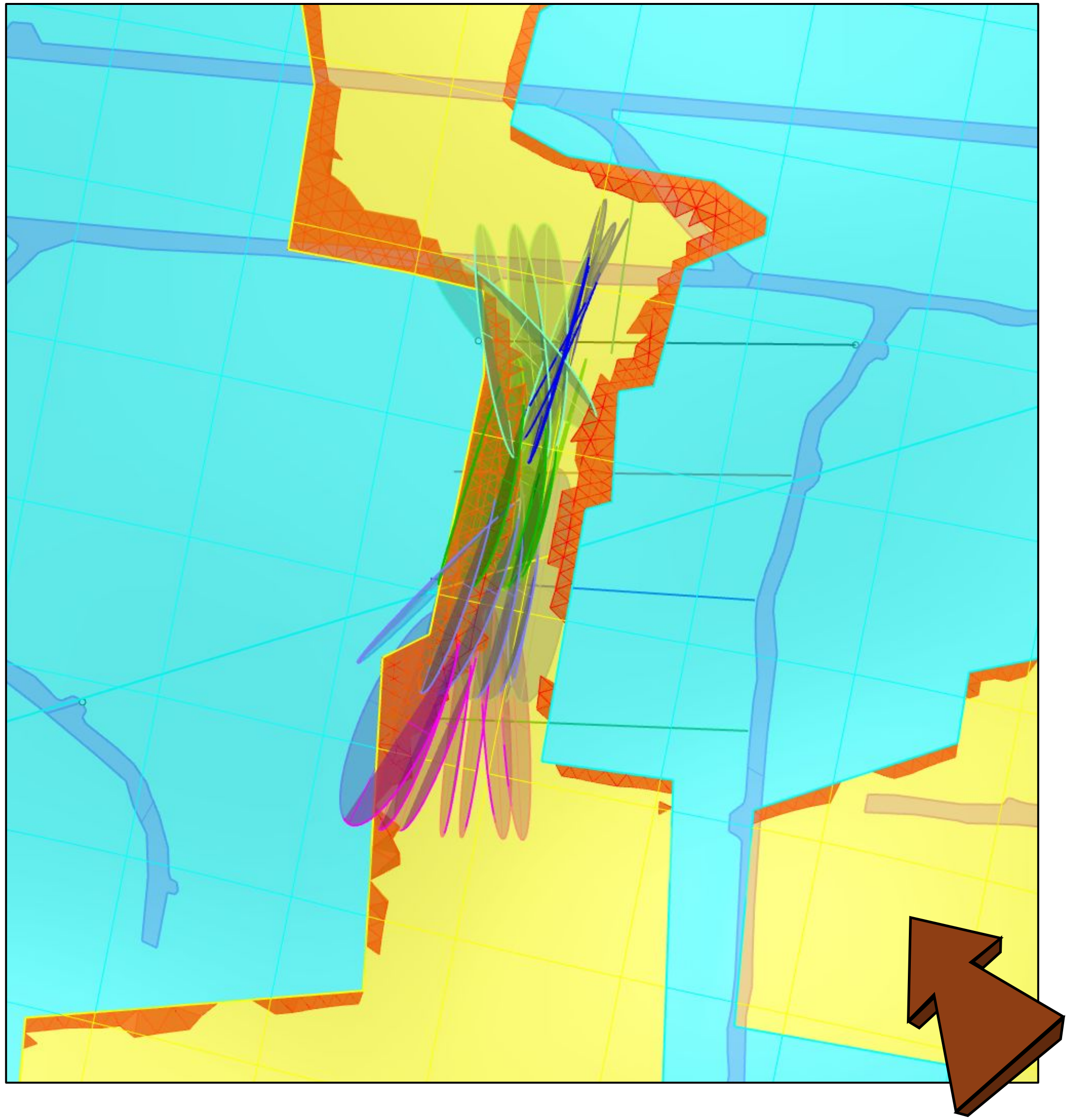

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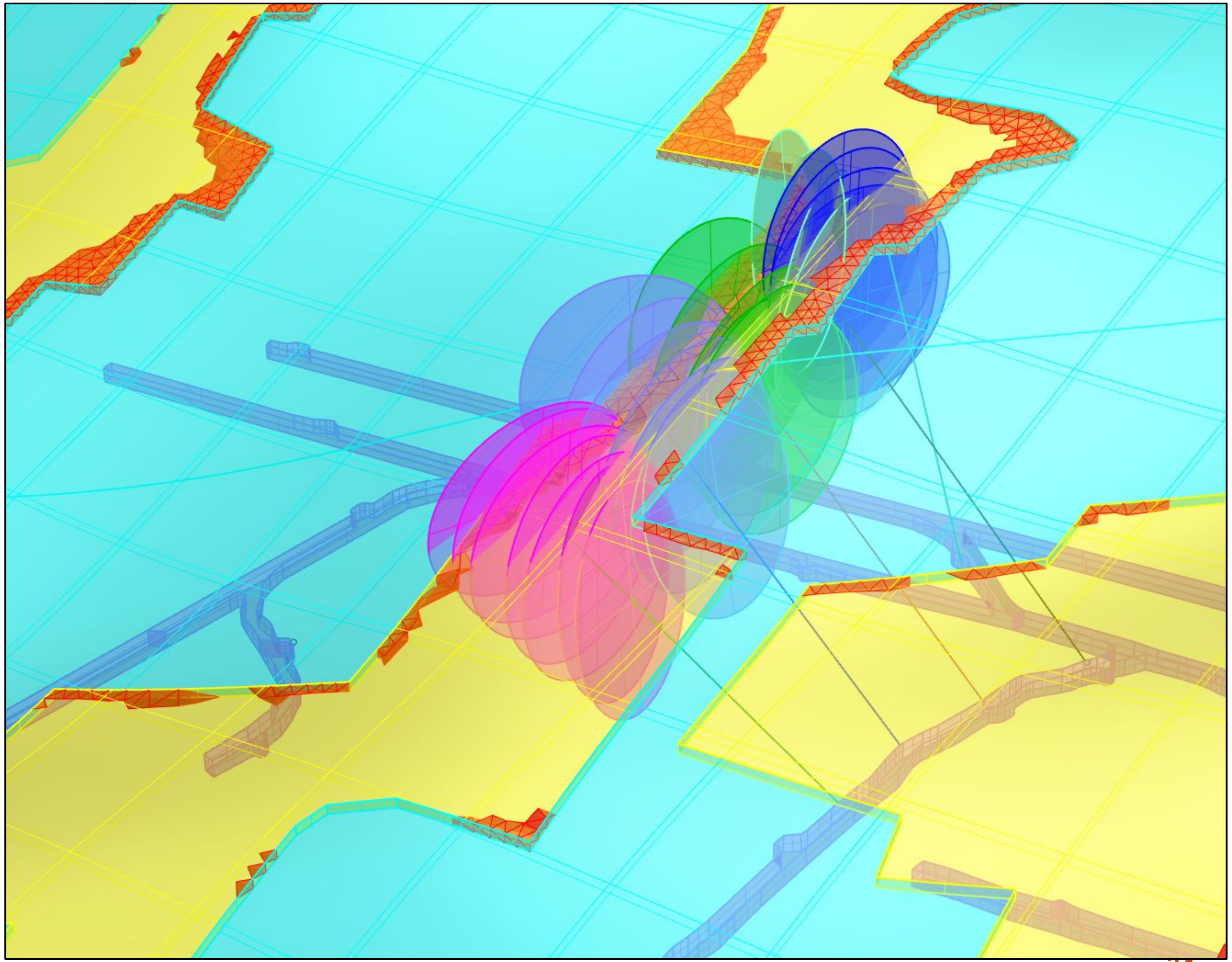
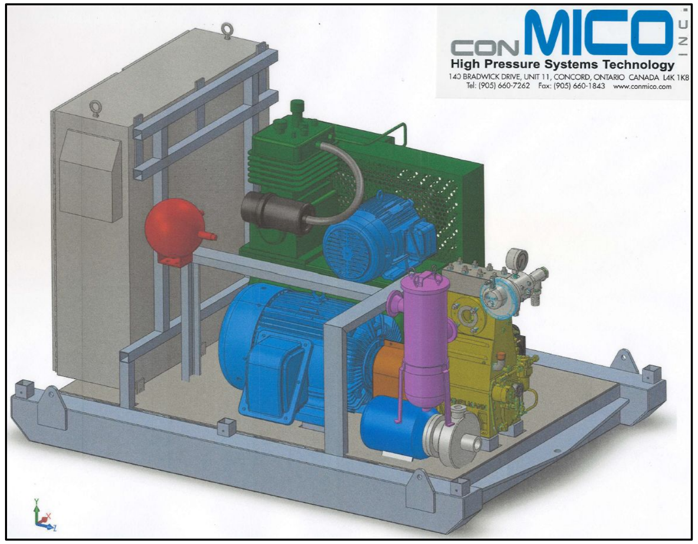


Current Status

- The pump
  - Will be completed at the end of August
  - Training and testing will be completed on surface
  - The pump will be transferred to site and commissioned



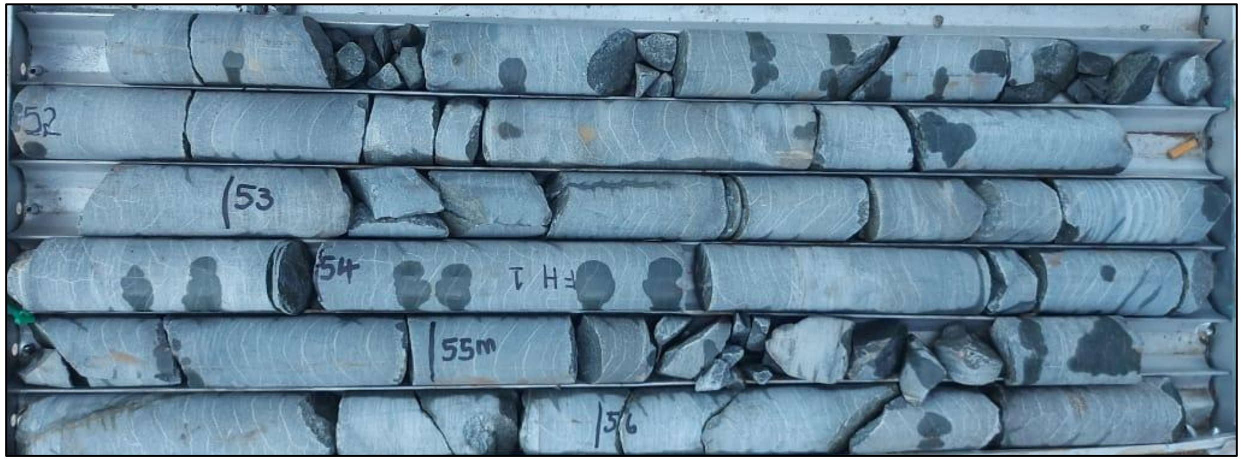
- Drilling
  - Two NQ fracking holes have been completed
  - Two (of four) BQ observations holes have been completed
- Fracking
  - Fracking to be done in the two NQ holes described above
  - We expect to complete the fracking by the end of September

Conclusions

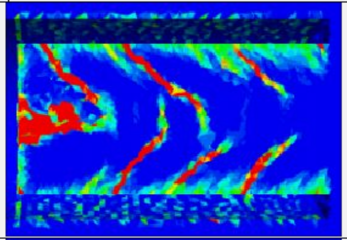
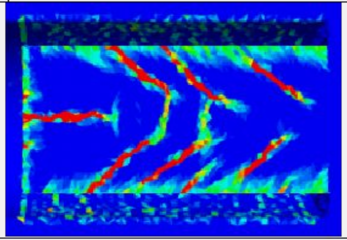
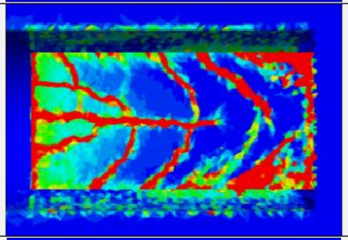
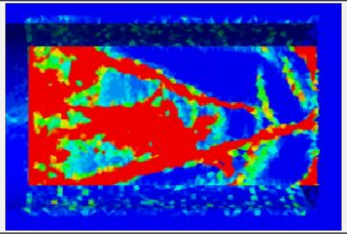
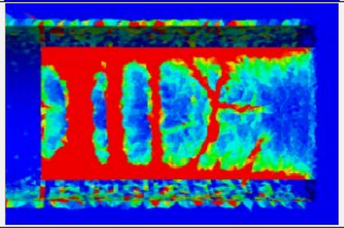
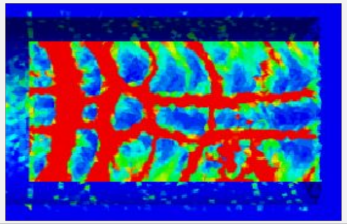
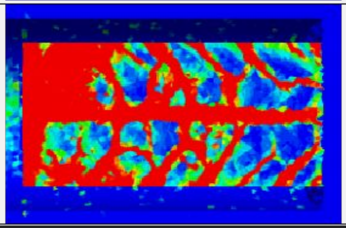
- Drilling trials showed it was possible to drill holes reasonably accurately over distances of up to 120 m in highly stressed quartzites
- Mini frack tests showed that it is possible to initiate hydraulic fracturing in strong quartzites at depth, and under high stress conditions
- In the next phase we will determine if it is possible to grow hydraulic fractures
- We hope to quantify the extent of these fractures and the effect that they have on the rockmass
- If we can demonstrate changes in strain or a seismic response while fracking, we can infer the amount of stress relief in the pillars

Interesting fractures

- Holes were drilled where S1 is parallel to the hole and greater than 100 MPa and the minor perpendicular stress could be as low as 25 MPa
- This resulted in some unusual fracturing in the core
- This lines up nicely with prior research where modelling predicted composite fractures when drilling into high stress conditions



Interesting fractures

Major lateral stress/UTS	Minor lateral stress/UTS	Axial stress/UTS	Tensile plastic strain in XZ plane	Tensile plastic strain in YZ plane
5.3	4.8	11.1		
3.5	0.3	12.2		
15.1	5.3	12.6		
16.3	5.5	18.1	All failed	

Acknowledgements

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- Eugene Peters, Lesego Mekgwe, Hester Williams and John Lewington for their tireless assistance in finance and contracting
- The Sibanye-Stillwater Projects Management Office
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