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In situ principal stress measurement using minifrac testing and borehole breakout analysis in the south range rocks of the Sudbury Basin, Canada

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Abstract

KGHM's Victoria project is in the south range of the Sudbury Basin in Ontario, Canada. The deposit includes mineralisation zones of nickel, copper and precious metals (platinum, palladium and gold).

As a part of geomechanical data collection for mine design, a series of minifrac tests were conducted in a vertical borehole (shaft's pilot hole) at the Victoria project. The minifrac tests were conducted in the exploration's shaft pilot hole at depths of between 350 to 750 m. The minifrac test results and the observed borehole breakouts at depth were used to estimate the magnitude and orientation of the in situ principal stresses and correlate them to depth. The magnitude and orientation of the minimum, intermediate and maximum principal stresses were estimated using the test data. It is shown in this paper how each of these principal stresses is spatially orientated and how their magnitudes vary with depth.

The minimum principal stress is expected to be sub-vertical. The intermediate and the maximum principal stresses are expected to be sub-horizontal. The k_H ratio is estimated to approach 2.8 at a depth of 350 m and to substantially vary with depth, approaching 1.5 at 700 m. Below 700 m, change in the k_H ratio becomes minimal and remains constant at 1.45. The intermediate principal stress shows a similar trend with depth. The k_h ratio starts at 1.94 at 350 m, approaches 1.02 at 700 m and reaches a plateau of 1 at a depth below that. The estimated magnitudes of the in situ principal stresses will also be compared with the previous measurements conducted by other mine operators in the Sudbury Basin.

Keywords: *in situ stress measurement, minifrac testing, borehole breakout, Sudbury Basin*

1 Introduction

Over the past few decades numerous studies have been undertaken to collect data on the in situ stresses within the Sudbury Basin. In the past, stress measurement methods have included overcoring (Herget 1987, Malek et al. 2008; Oliver 1987), acoustic emission techniques (Villaescusa et al. 2009), and correlating numerical models to seismicity and seismicity-induced damage (Suorineni & Malek 2014; Taghipoor et al. 2018; Trifu & Suorineni 2009). Yong & Maloney (2015) assembled a comprehensive database of 304 stress measurements to propose representative ground stress equations that covered a depth of between 12 and 2,552 m, mostly from operating mines in Ontario.

Due to the high in situ horizontal stress gradient, strong and stiff rock mass, and significant mining depths, mining-induced micro-seismicity is a major hazard expected during the life of the mine at the Victoria project. This hazard typically manifests as strainbursting or pillarbursting and stress-induced damage. Managing the risk associated with micro-seismicity is generally achieved through a combination of approaches. Geomechanical knowledge, including developing a good understanding of the magnitudes and orientation of the in situ stresses, is the first step in studying and implementing any of these approaches.

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As part of the geomechanical investigations for KGHM's Victoria project in the south range of the Sudbury Basin in Ontario, Canada, a series of minifrac tests were conducted at depths ranging from 350 to 750 m. The tests were conducted in the exploration shaft pilot hole. This borehole was along the proposed exploration shaft alignment to obtain geotechnical and hydrogeological information and provide a basis for the shaft ground support design. The borehole was 96 mm in diameter drilled to a depth of 1,852 m. The borehole was cased through the overburden. Golder Associates was retained by KGHM International to conduct a series of in situ minifrac tests in this borehole. The analysis and interpretation conducted by the author based on the minifrac tests are presented here.

In the minifrac testing method, a borehole televiewer chooses the interval of a borehole where there are no natural fractures present. A total of 24 minifrac tests were conducted at depths of between 350 and 750 m. Each test comprised initial breakdown pressurisation cycles during which water was injected at a constant flow rate. Following the first cycle were two to three re-opening cycles at constant flow rate and one to three hydrojacking (step-rate test) cycle(s) where water pressure was incrementally increased to confirm the re-opening pressure. A final re-opening cycle might follow these cycles. Figure 1 illustrates a typical minifrac test conducted at test interval of 537 to 538 m.

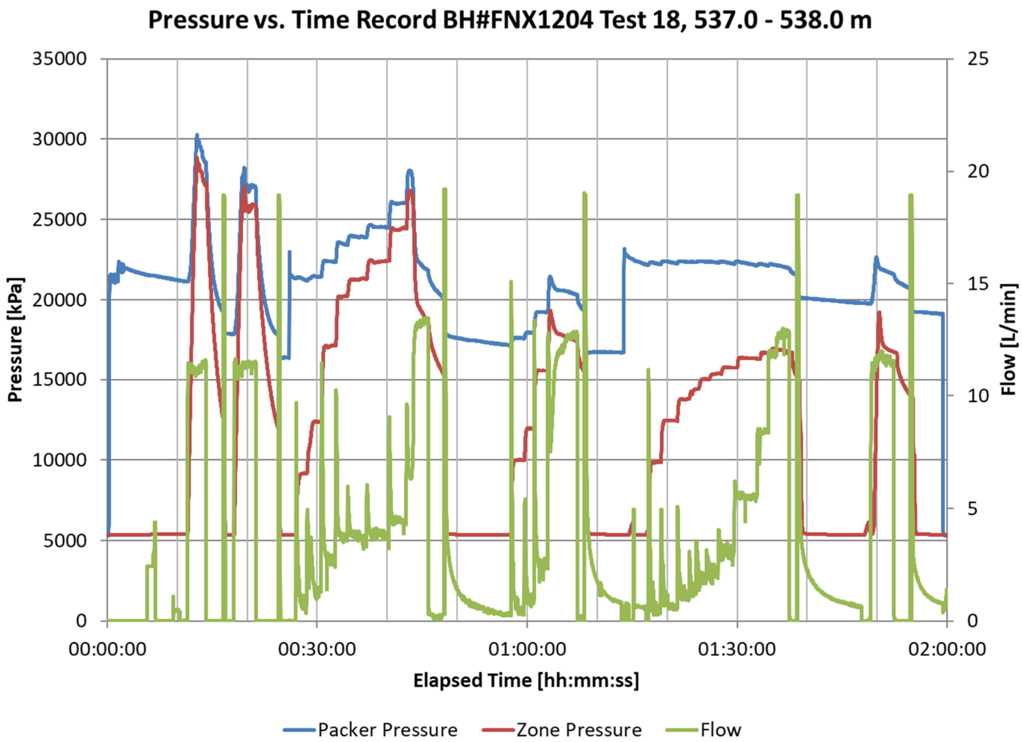


Figure 1 A typical recorded pressure-time graph

As shown in Figure 2, the test interval is isolated using two borehole packers. Fluid is injected into the test interval to induce a tensile fracture in the rock. Fracturing is expected when the stress in the borehole wall surpasses the hoop stress at the borehole wall plus the tensile strength of the rock. The onset of fracturing in the first cycle is called the breakdown pressure (P_b). If the pressure is released and the test is repeated, the maximum pressure attained indicates the hoop stress at the borehole wall, irrespective of the tensile strength of the material.

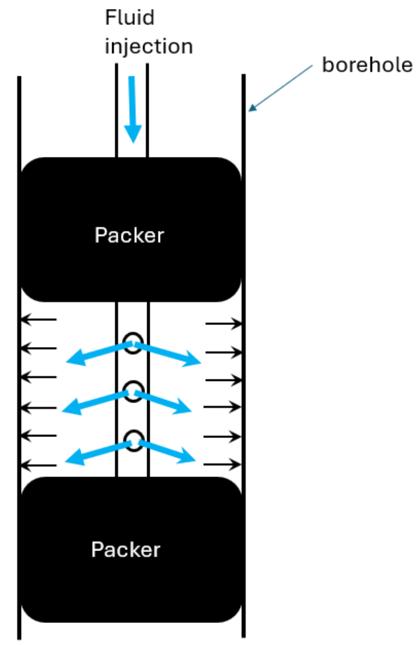


Figure 2 Schematic of the minifrac method

In a simple case where the minimum principal stress is sub-vertical (similar to conditions in the Sudbury Basin) and a borehole is drilled vertically, the stress concentration around the borehole can be calculated from the Kirsch (1898) equation. The minimum hoop stress around the borehole (point A in Figure 3) is described in Equation 1.

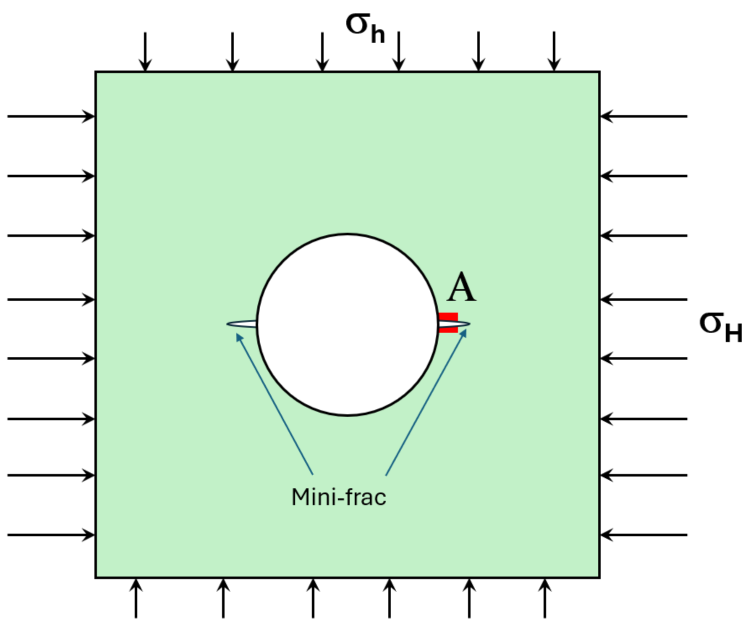


Figure 3 The minifrac induced a circular opening

$$\sigma_A = 3\sigma_h - \sigma_H - P + T \tag{1}$$

where:

σ_A = the tangential stress at point A.

σ_h = the minimum horizontal stress (the intermediate principal stress).

σ_H = the maximum horizontal stress (the maximum principal stress).

P = pore pressure.

T = the tensile strength of the rock.

The UCS (uniaxial compressive strength) of some Sudbury rocks, including Sudbury breccia, norite and metagabbro, ranges from 100 to 300 MPa. Some of these rocks are heavily fractured by nature. However, these fissures and fractures are well healed with high-strength cement (calcite to quartzite as shown in Figure 4) which affects the UCS of these rocks. The lower end of the UCS range typically results from failure occurring along these pre-existing geological structures. Given the challenges of locating fracture-free sections for minifrac testing, due to the nature of these rock types, complications may arise in the interpretation of minifrac testing in some of the hard rocks in the Sudbury Basin.

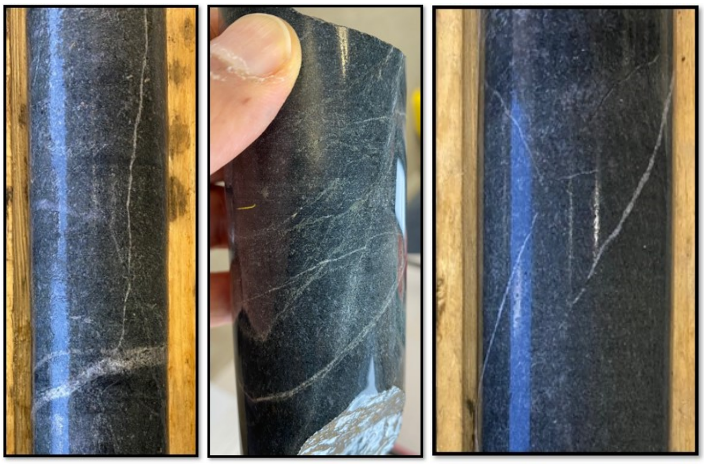
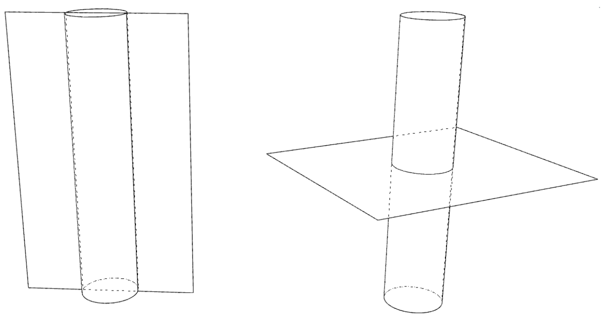


Figure 4 Natural fractures in metagabbro that are well healed with quartz infill

The expected pressure required to induce a vertical fracture in a vertical borehole aligned parallel to the minimum principal stress (Figure 5a) is the largest compared to boreholes oriented in any other direction within the same stress field (Fjær et al. 2008). As a result the fluid pressure may open other fractures, depending on their orientation and tensile strength. Fractures oriented horizontally (Figure 5b) are particularly prone to opening following the fluid pressurisation in the test interval, especially if their tensile strength is low. This phenomenon has been frequently observed during cycles of minifrac testing at the project site.



(a) (b)

Figure 5 Minifrac testing in vertical boreholes: (a) Vertical fracture; (b) Horizontal fracture

For this reason, minifrac tests carried out at the Victoria project encompass the assessment of fracture closure in various orientations.

Further, the magnitude of both horizontal stresses acting perpendicular to the borehole axis is unknown. As a result, a unique approach is necessary for interpreting the minifrac test results obtained at the Victoria site. The process of interpretation of the minifrac test results obtained is described in the following section.

2 The interpretation method

In this interpretation, the lower bound of all the test data is assumed to correspond to the formation of horizontal fractures oriented perpendicular to the minimum principal stress, i.e. the vertical stress. Conversely, the upper bound of the results is expected to be the fracturing pressure required to induce an axial (vertical) fracture in the borehole parallel to the maximum principal stress (σ_H), which can be found using Equation 1. These two lines measurements are plotted in Figure 6. Since both horizontal stresses are unknown, this equation presents two unknown variables. A relation between the two horizontal stresses must be assumed to solve these variables. However, this assumed ratio does not offer a unique solution as it potentially yields many combinations for the fracturing pressure.

However, this σ_H/σ_h relationship can be narrowed if borehole breakouts observed at depth are studied. Any σ_H/σ_h relationship that provides the σ_H required to crush the intact rock around the vertical pilot borehole would be a reasonable representation of the maximum to minimum horizontal stress ratio. With this assumption, the in situ stress magnitudes can now be calculated. The resulting in situ principal stress magnitudes are described in the following sections. More details can be found in Taghipoor (2024).

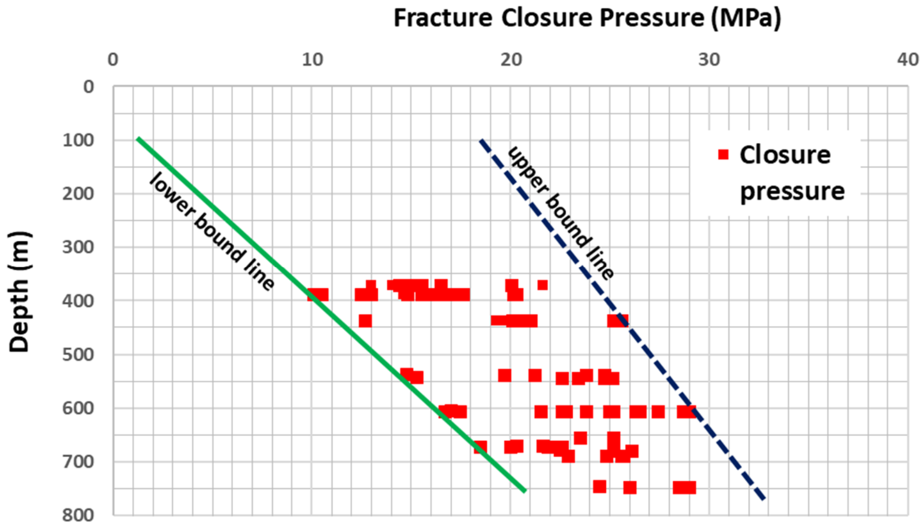


Figure 6 The upper bound and lower bound lines fitted to the minifrac test data

3 The in situ principal stresses

3.1 The minimum principal stress

The minimum principal stress magnitudes resulting from the lower bound envelope of the minifrac test data are plotted in Figure 7. In addition, the vertical stress magnitude obtained from the average density of the overburden rocks (ρ = 2,850 kg/m^3) is also plotted. As can be seen, these two lines are very close, indicating that the minimum principal stress must be vertical or sub-vertical. The minimum principal stress obtained from the lower bound line is expressed with the following equation:

$$\sigma_3 = 0.030D - 1.4 \text{ (MPa) for 350 m–700 m depth range} \quad (2)$$

where:

σ_3 = the minimum principal stress in MPa and D is depth in metres.

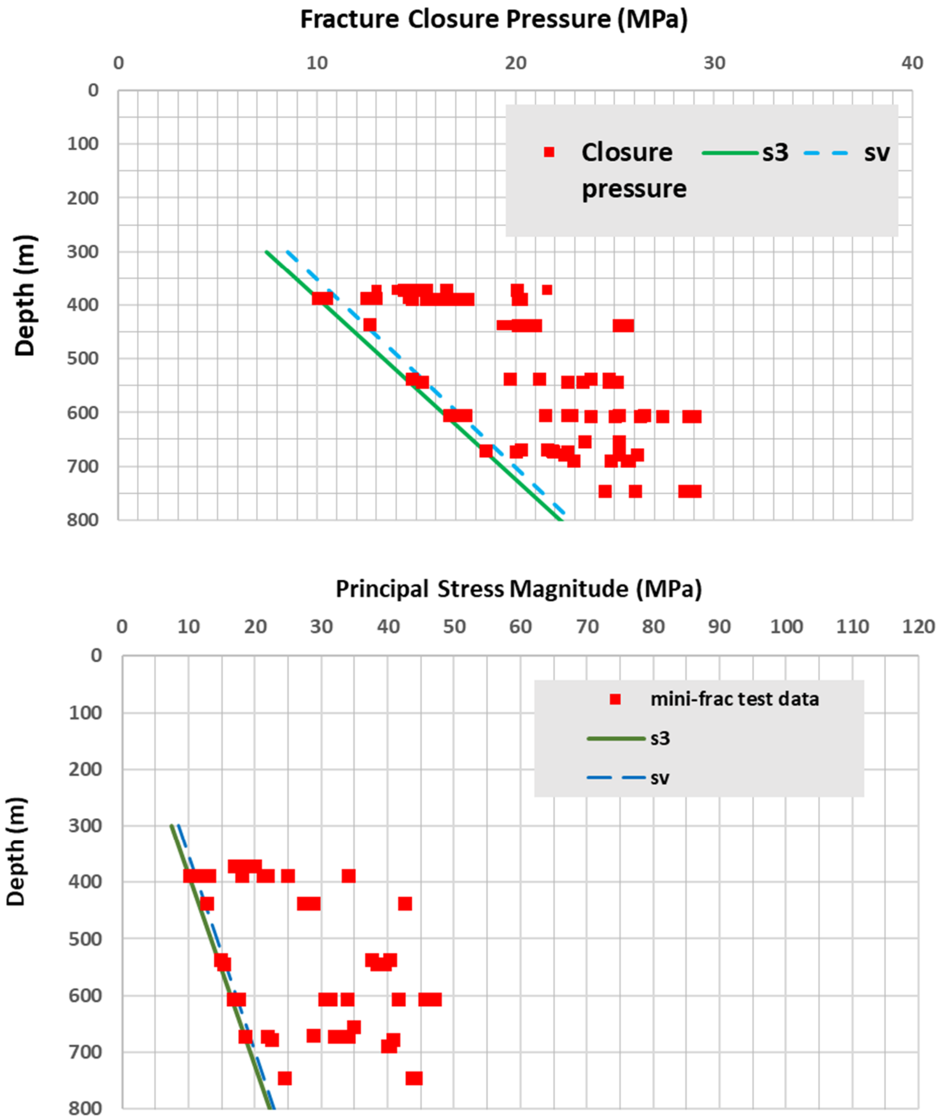


Figure 7 The plotted estimated minimum principal stress and the vertical stress magnitude versus depth

3.2 The maximum principal stress

The maximum principal stress magnitude trend was calculated using the borehole breakouts and the minifrac test data. The stress required to match the fracturing pressure, equivalent to the upper bound of the minifrac test data between the depths of 350 m and 750 m, was calculated assuming multiple σ_H/σ_h ratios. These ratios were selected based on Sudbury Basin's typical range. In addition, the σ_1 magnitudes required for the unconfined failure of the lithological rocks with the lowest UCS, the average UCS and the highest UCS in their UCS range, encountered over the depth of interest at the perimeter of the borehole, were calculated. These were five different points below 1,200 m depth where the breakouts were observed. Figure 8 demonstrates the magnitude of the maximum principal stress for two σ_H/σ_h ratios of 1.35 and 1.45. The following equations can be used to define the maximum principal stress as a function of depth using the ratio of σ_H/σ_h = 1.45 (as the best case that fits the data):

$$\sigma_H = \begin{cases} 0.019D + 15.43 & \text{(MPa) for depth range of 350 m– 700 m} \\ 0.042D - 1.09 & \text{(MPa) for depth greater than 700 m} \end{cases} \tag{3}$$

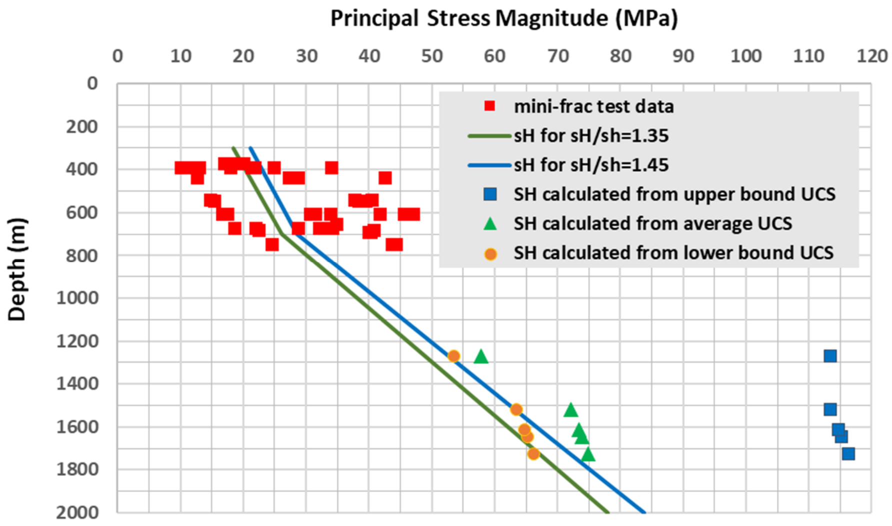


Figure 8 The estimated maximum principal stress magnitude based on the minifrac test and the borehole breakouts

A constant ratio between the magnitudes of the maximum and the intermediate principal stress (k_H/k_h) was assumed. The resulting magnitude of the intermediate principal stress approaches that of the minimum principal stress at a depth of about 700 m. Since the intermediate principal stress cannot be smaller than the minimum principal stress, it was assumed that they become equal below this depth. The breakout data were used to estimate the stress magnitudes for depths below 700 m while the assumed k_H/k_h ratio remained in effect. This created the inflexion point in the equation of the stress magnitude.

3.3 The intermediate principal stress

The intermediate principal stress was estimated by analysing the minifrac test data (as mentioned before, by assuming a ratio between the intermediate principal stress [σ_h] and the maximum principal stress [σ_H]) and matching the maximum principal stress with the borehole breakouts. Figure 9 demonstrates the magnitude of the intermediate principal stress for σ_H/σ_h ratios of 1.35 and 1.45. As can be seen, the two lines approach each other at 700 m depth and coincide below that depth. Considering $\sigma_H/\sigma_h = 1.45$ as the best match, the following equations best describe the magnitude of the intermediate principal stress.

$$\sigma_h = \begin{cases} 0.013D + 10.65 \quad (\text{MPa}) \quad \text{for depth shallower than 700 m} \\ 0.029D - 0.75 \quad (\text{MPa}) \quad \text{for depth greater than 700 m} \end{cases} \tag{4}$$

The reason for the inflection point at 700 m goes back to the assumption of a constant ratio between the maximum and the intermediate principal stress (k_H/k_h) for the analysis of the minifrac data. This assumption is needed to find a line that matches the upper bound line for minifrac pressure data. The reader is encouraged to refer to Taghipoor (2024) for details of the interpretation method.

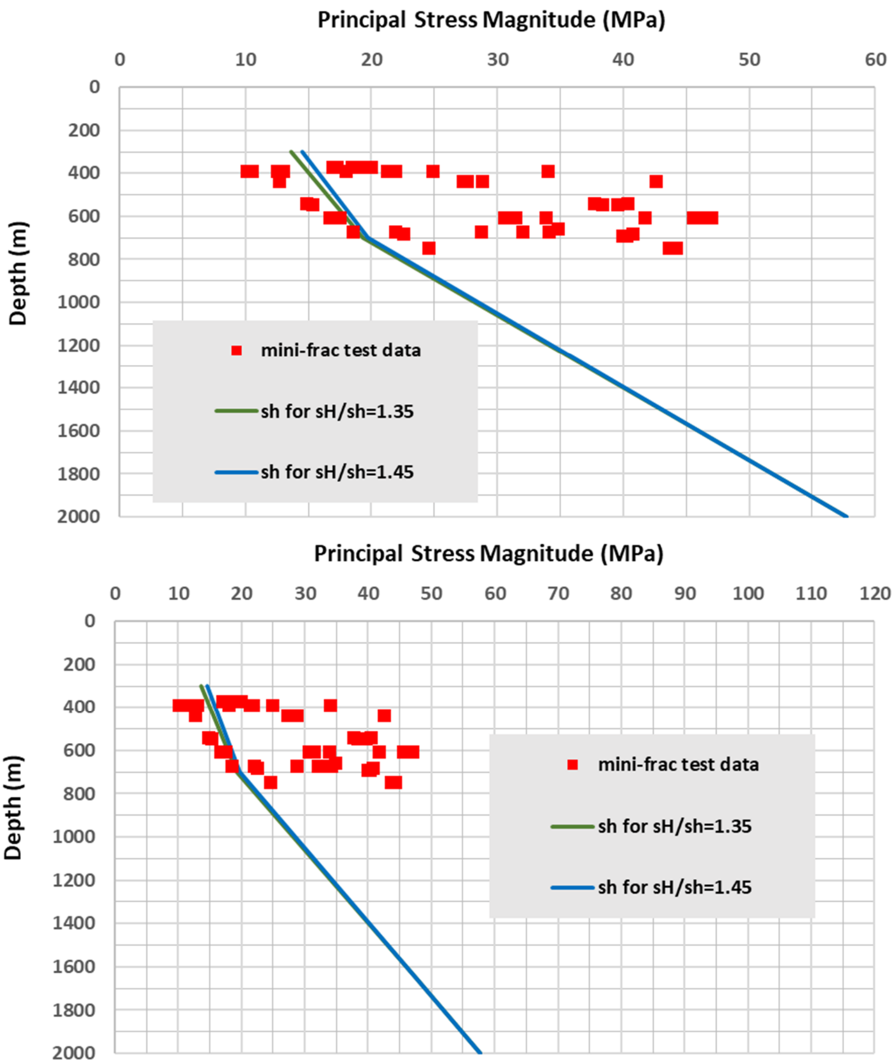


Figure 9 The intermediate principal stress magnitude

3.4 Results

The estimated magnitudes of the three principal stresses for the Victoria project are depicted in Figure 10. As previously mentioned, the magnitude of the minimum principal stress is closely aligned with the gravity-induced overburden stress. Below 700 m, the intermediate and the minimum principal stresses converge and become equal. The maximum principal stress magnitude graph also changes slope at 700 m depth below the surface and was initially assumed to have a constant ratio with the intermediate principal stress. However, the possibility of having a straight line connecting the minifrac test measurements at shallow depth to the borehole breakout data at depth should not be eliminated.

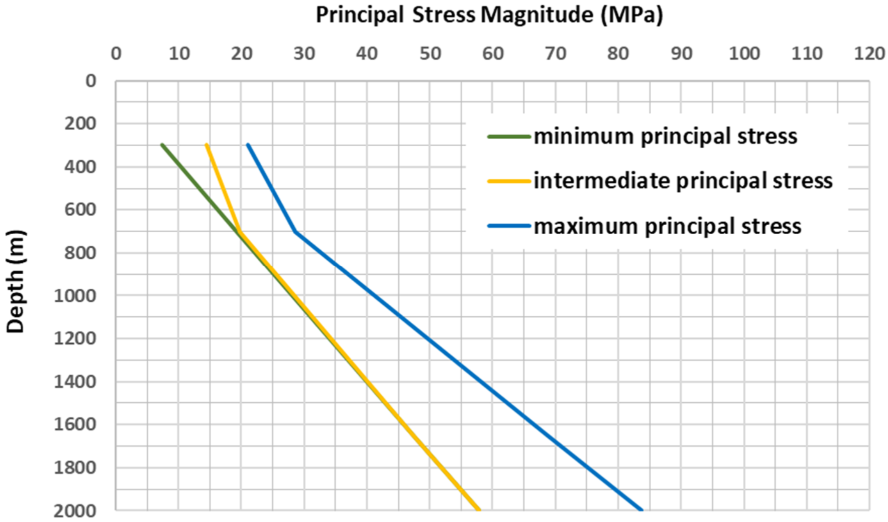


Figure 10 The principal stress magnitudes versus depth for the Victoria project

Figure 11 illustrates a comparison of the stress measurement results conducted at the Victoria project with stress measurement conducted at Craig-Onaping Mines (Villaescusa et al. 2009) in the north range rocks of the Sudbury Basin (approximately 50 km north of the Victoria project), as well as in the rest of the world (Hoek & Brown 1982). As can be seen in Figure 11, the k_h ratio is closer to 1.94 at shallow depth and approaches 1 at depths below 700 m. The k_H ratio shows a similar trend. It approaches 2.8 closer to the surface. It changes slope significantly at 700 m, approaches 1.5 below that and plateaus at 1.45 at depth.

Figure 11 shows that the stress ratios at the Victoria project, as in many other areas of the world, becomes larger closer to the ground surface. These ratios get smaller at depth below 700 m. Similar results were reported for the maximum principal stress ratio at Craig-Onaping Mines. The calculated maximum principal stress ratio at depths below 1,000 m is closer to the upper bound of the world stress measurement data but slightly smaller than what was proposed for Craig-Onaping Mines.

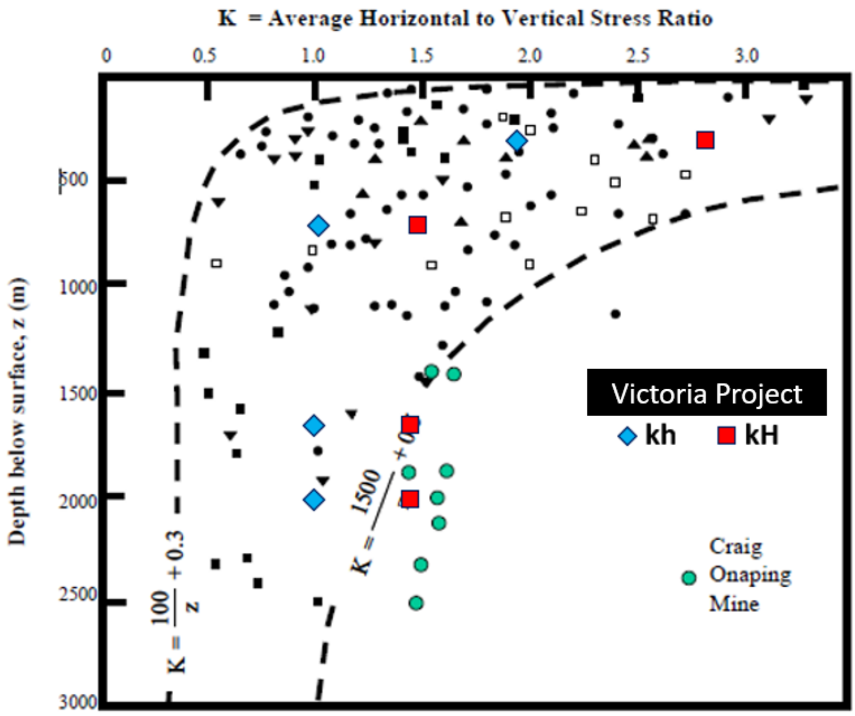


Figure 11 Comparison of the k_h and k_H ratios of the Victoria project with the previous measurement (modified after Villaescusa et al. (2009) and Hoek & Brown (1982)

3.5 The orientation of the principal stresses

It was previously shown that the minimum principal stress is vertical or sub-vertical. For most of the tests where the injection pressure is believed to have reached a breakdown pressure, no induced fracture could be confirmed in the televiewer photos as these induced fractures are hair-thin. Only in tests numbered 8 (at 690 m depth), 14 (approximately 670.5 m) and 20 (approximately 608.2 m) could a zone of induced fracture be detected throughout the whole injection interval. The pre- and post-minifrac optical televiewer images for these three tests are illustrated in Figure 12. The test intervals are marked by green colour. As can be seen, a vertical trend potentially indicating induced vertical fractures is obvious in these images. Tests 8 and 20 show a fracture azimuth of approximately east-west, while test 14 indicates a north-south trend. It should be noted that the north direction in the tests is the magnetic north, with –9° 55’ declination from the true north.

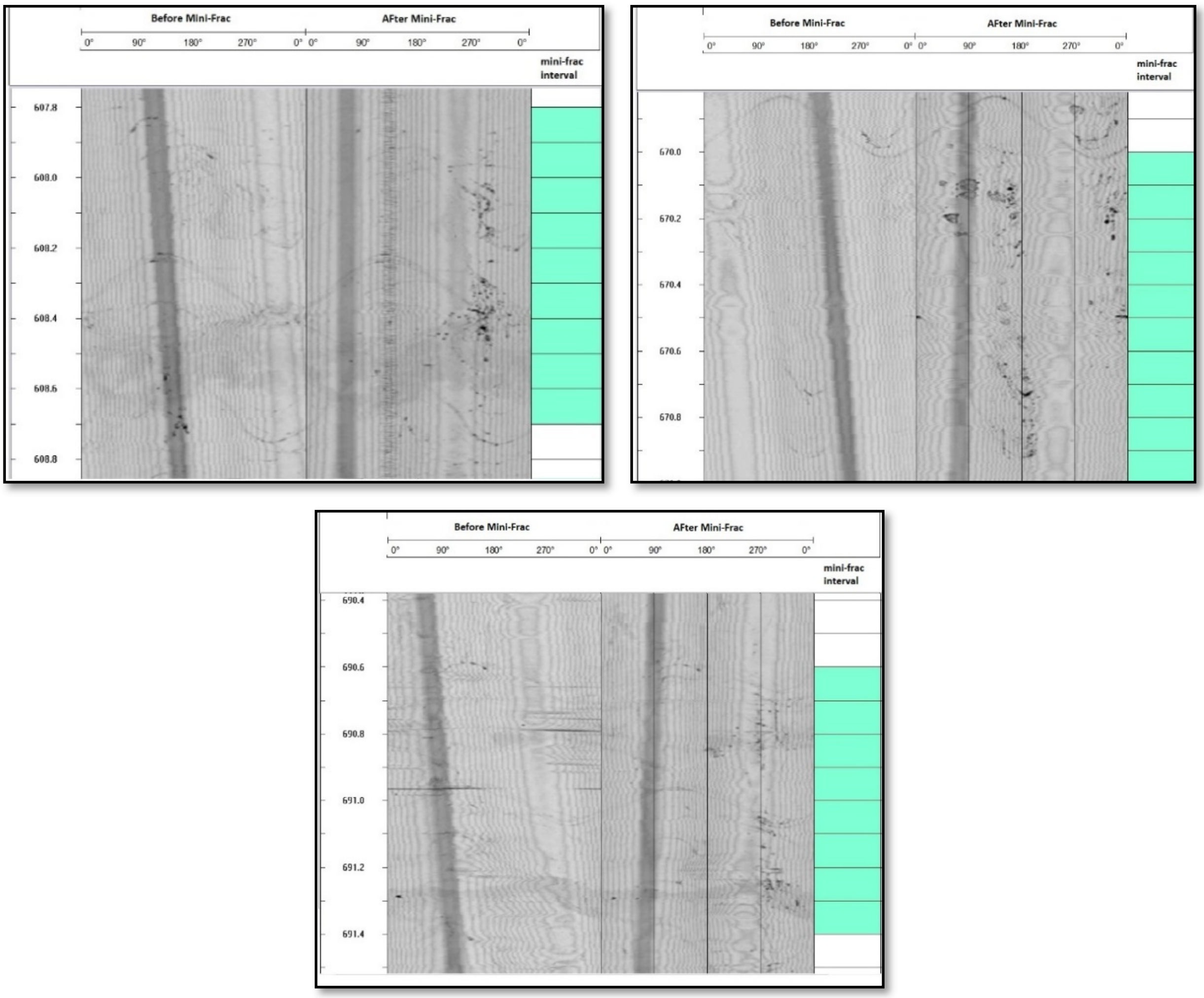


Figure 12 Pre-fracture and post-fracture optical televiewer photos of tests 8, 14 and 20

In addition to the induced hydraulic fractures, borehole breakouts from the optical televiewer survey were analysed in order to better understand the direction of principal stresses. These breakouts (shown in Figure 13) were observed in the shaft pilot hole at depths below 1,200 m. All these breakouts were located around the north-south perimeter of the borehole or close to this direction, indicating the maximum principal stress direction is approximately east-west (direction based on magnetic north) with minor deviation. As the magnetic north of the site has a –9° 55’ declination from true north, the general trend of the maximum principal stress is N80E. This is in good agreement with the images of minifrac tests numbered 8 and 20.

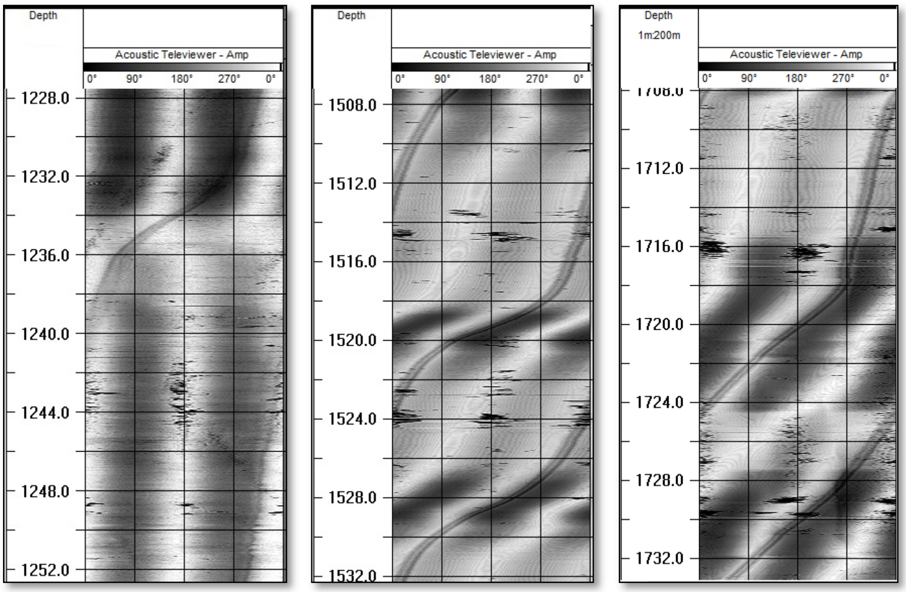


Figure 13 The borehole breakouts observed at depths below 1,200 m in the optical televiewer photos

4 Conclusion

Minifrac stress measurement is a reliable stress measurement method that is frequently used in the construction, mining, and oil and gas industries. Issues can arise when implementing this method for stress measurement in fractured or jointed rock mass. Finding fracture-free sections of rocks for minifrac testing in jointed rock mass is challenging due to the nature of these rock types. This may cause complications in the interpretation of minifrac testing if standard approaches are used for stress calculation.

The minifrac test results at KGHM's Victoria project were analysed assuming the induced fractures include all ranges of fracture orientations. This is a reasonable assumption as a wide range of stress magnitudes were obtained within the same test intervals at the same depths. This assumption was reasonable as small-scale natural fractures in the rock matrix at the test site were well healed with high-strength infill. Obtaining magnitudes of the three principal stresses and their orientations from the minifrac data and the borehole breakouts was attempted. The stress measurements from the minifrac testing were combined with the borehole breakout analysis to extend the stress equations to depths below 750 m.

The minimum, intermediate and maximum principal stress magnitudes have been calculated using the minifrac test results and observed borehole breakouts. The minimum principal stress magnitude is equal to $0.030D - 1.4$ (where D is in m) and is sub-vertical. The intermediate principal stress is described by $0.013D + 10.65$ at a depth above 700 m and by $0.029D - 0.75$ for a depth below. Similarly, the maximum principal stress follows $0.019D + 15.43$ and $0.042D - 1.09$ for depths above and below 700 m, respectively. The intermediate and maximum principal stresses are expected to be sub-horizontal. The maximum principal stress trend is N80E measured from the true north.

These proposed stress magnitudes are in reasonable agreement with other stress measurements in the Sudbury Basin and other parts of the world.

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