Remote High Resolution Stress Change Monitoring of Hydraulic Fractures

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Abstract

This paper describes the use of strain gauge based borehole instruments to monitor stress changes associated with the creation and extension of hydraulic fractures in massive rock strata at Northparkes Mine in Australia and Salvador Mine in Chile. This work was conducted as part of the International Caving Study ICSII. These instruments proved very sensitive to the stress changes induced by the hydraulic fractures close to the fracture plane. Analysis of the stress changes observed allowed the fracture orientation and non-symmetric fracture growth to be constrained sufficiently that a clearer insight into fracture behaviour could be obtained at both sites, particularly when combined with other observations. Recognition of the elastic stress reorientation about an opening mode hydraulic fracture has proved to be an important element in the interpretation of stress change monitoring data. The nature of the stress reorientation is useful in discriminating between opening and shearing mode fracture growth. A technique of identifying a range of possible solutions of fracture orientation and non-symmetric fracture growth consistent with the stress changes observed on multiple instruments has been developed. Unique definition of fracture orientation from the stress change instruments is possible if the instruments are sufficiently distributed relative to the hydraulic fracture plane.

1 INTRODUCTION

This paper describes the use of strain gauge based borehole instruments to monitor stress changes associated with the creation and extension of hydraulic fractures in massive rock strata at Northparkes E26 Mine in Australia and Salvador Mine in Chile.

The stress change monitoring described in the paper was one of several monitoring systems used to measure the behaviour of hydraulic fractures at two field sites as part of the International Caving Study ICSII. The stress change monitoring described is a new method to monitor hydraulic fracture growth to obtain stress change and fracture orientation information. Further details of the other work conducted at the two sites are presented elsewhere in these proceedings (van As et al. 2004, Chacon et al. 2004).

The operation of the stress monitoring instruments, their in situ calibration and analysis procedure are common to both sites and these are described first. The installations, results and implications for the hydraulic fracture behaviour are then described for each site.

2 INSTRUMENTATION AND ANALYSIS PROCEDURE

ANZI stress cells are strain gauge based stress change monitoring instruments. Their operation is described in detail by Mills (1997). Each instrument comprises eighteen electrical resistance strain gauges of various orientations. The instrument is internally inflated using air pressure to press the strain gauges into contact with the rock until an epoxy cement coating applied to the outside of the instrument has cured. Figure 1 shows a photograph of one of the instruments during installation at Salvador Mine.

ANZI stress cells are able to be tested in situ prior to the commencement of monitoring, and subsequently if required, to check their correct operation and determine the equivalent stiffness of the rock into which they were installed. This process gives a field calibration that takes into account cable lengths, temperature effects and the data logging system.

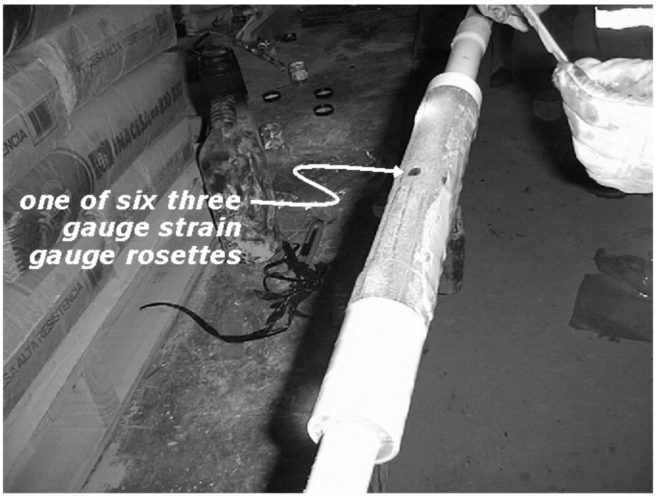


Figure 1(a): Epoxy cement being applied to one of the two ANZI cells installed in each hole.

Figure 1(b): Installation of the instrument into the monitoring hole.

The internal pressure of the instruments is incremented in stages from the initial set pressure and back again while the instruments are being continuously logged. In each case a high initial set pressure was necessary to inflate the instrument against the hydraulic head in the water filled borehole plus provide sufficient pressure to bond the strain gauges to the rock.

Figure 2 shows the pressure test results for one of the instruments installed at Northparkes as an example. The pressure test shows that the instrument is operating correctly. The six circumferential gauges go into tension and the axial gauges going slightly into compression as the pressure was incremented. Any individual gauges that are identified as being not properly bonded to the rock or bonded across joints can be ignored in the subsequent analysis.

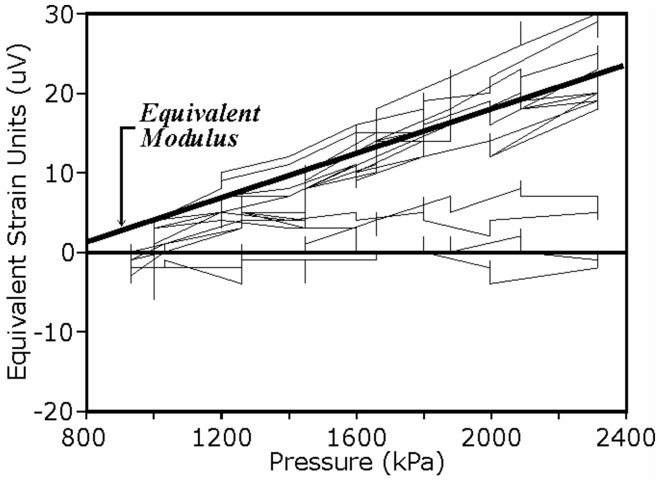


Figure 2: Pressure test results - NPK7.

The thick black line in Figure 2 indicates an equivalent stiffness or modulus for the instrument. The monitoring results have been analysed using this equivalent modulus. It should be recognised that the equivalent modulus can not be determined with a high degree of precision because of the low strain magnitudes involved. The effect of an error in the modulus reflects on the magnitude of the stress changes determined but not the orientation of the stress tensor.

The strain changes measured on the data logger during each hydraulic fracture treatment were recorded at a resolution of $1\mu V$ and a signal noise level of about $5\mu V$ with occasional electrical interference spikes of $100\mu V$.

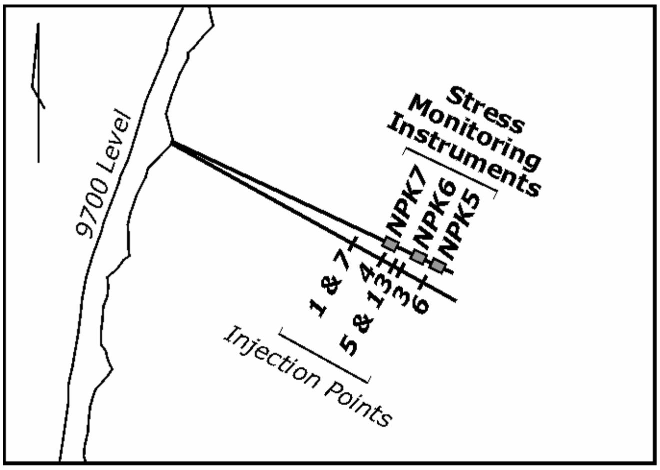
The data was prepared, before analysis, in four stages. A reference gauge located within each instrument but not subject to any strain changes was used to eliminate systematic strain changes in the cable and data logger system. Electrical spikes were then removed from the record and replaced with the strain values from the previous scan. A triangular, moving average filter of two minute duration was applied to the smooth out random variation. The stress changes were then determined every 10 minutes by averaging strains over a four minute interval.

The determination of the stress field uses a standard multiple linear regression analysis. Multiple strain readings are analysed statistically to give a best fit estimate of the stress field. This process is standard for reduction of borehole strains to determine stress changes. An important characteristic of this process is that a statistical correlation between redundant strain gauges gives an indication of the confidence that can be placed in each result.

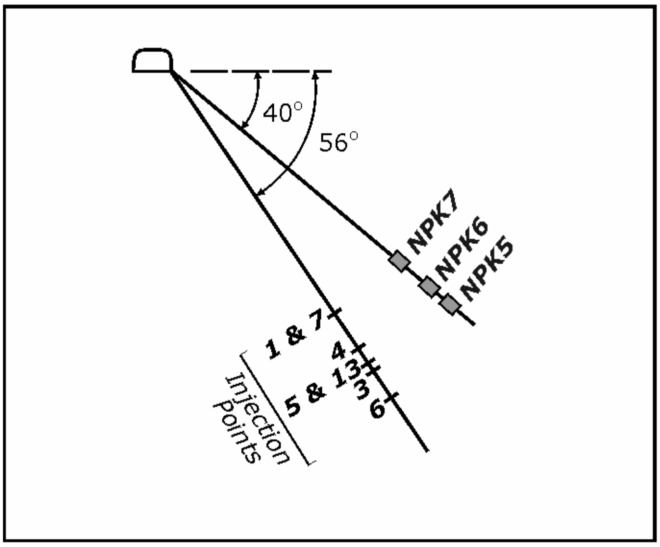
3 STRESS CHANGE MONITORING AT NORTHPARKES MINE

3.1 Site Description

Figure 3 shows the locations of the stress change monitoring hole, the instruments and the hydraulic fracture treatments conducted at Northparkes Mine.



Plan View



East - West Section looking north

Figure 3: Location of stress change monitoring instruments at Northparkes.

Three ANZI stress cells were installed in a single BQ hole drilled from Drill Cuddy 5 on 9700 Level. The instruments were installed at depths of 83m, 76.3m and 69.7m respectively in a borehole dipping at 39° from horizontal at an orientation of 112°-115°GN.

The hydraulic fracture treatments were conducted in a hole collared 0.75m from the stress monitoring hole, dipping 56° and oriented at 119°GN.

Table 1 summarises the timing of the hydraulic fractures and the injection details. Injections not listed either did not result in breakdown or were associated with reopening existing fractures to allow intersections in monitoring holes to be located. The stress cells were not monitored during these injections.

The three stress monitoring instruments are located 14-48m above and 5-20m laterally from the initiation point of the hydraulic fractures.

The full three dimensional stress field had previously been measured at the site using ANZI stress cells and the overcoring method of stress relief (Mills 2002).

The results of these measurements indicated that at this site the major horizontal stress is dipping 5° at 132°GN with the minor principal stress dipping 67° at 235°GN. The vertical stresses are slightly less than the anticipated weight of overburden consistent with the proximity of the site to the extraction in the overlying block cave.

3.2 Results

Figures 4 and 5 summarise the results from one instrument (NPK5) for two treatments, Fracture 1 and Fracture 7. Both these treatments were conducted at the same location in the injection borehole, one using water as the injection fluid and the other using cross-linked gel. Each of the figures is plotted on a consistent time base.

Figure 4a is a record of the hydraulic fracture treatment. Figure 4b is a record of the strain readings on all the strain gauges after pre-processing to remove electrical spikes and application of the moving average filter. Figure 4c shows the vertical stress change calculated for the strains averaged over a four minute interval every ten minutes. Figure 4d shows the horizontal stress change components plotted as they would appear if projected onto a horizontal plane at the same stress scale as the vertical stresses.

Table 1: Summary of the Hydraulic Fracture Treatments

Frac	Date	Injection Period	Straddle Interval (m)	Injection Fluid
1	25/09/2002	11:09-11:45	79.76-80.26	Water
3	27/09/2002	12:56-13:37	99.36-99.86	Water
4	28/09/2002	17:42-18:12	93.76-94.26	Water
5	29/09/2002	10:36-11:08	96.56-97.06	Water
6	29/09/2002	16:19-17:02	110.56-111.06	Water
7	1/10/2002	9:50-10:34	79.76-80.26	x-linked gel
13	3/10/2002	9:24-10:02	96.56-97.06	water/broken gel

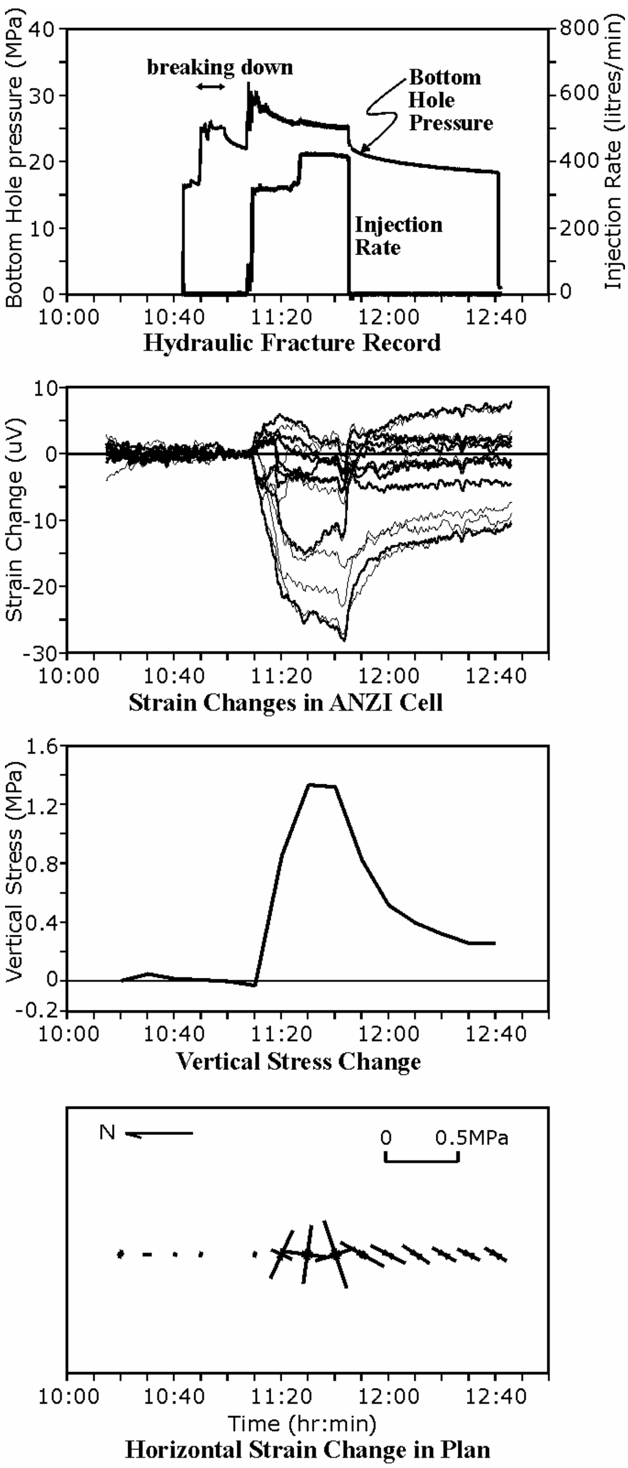


Figure 4: Stress changes measured by NPK5 during Hydraulic Fracture 1 at Northparkes.

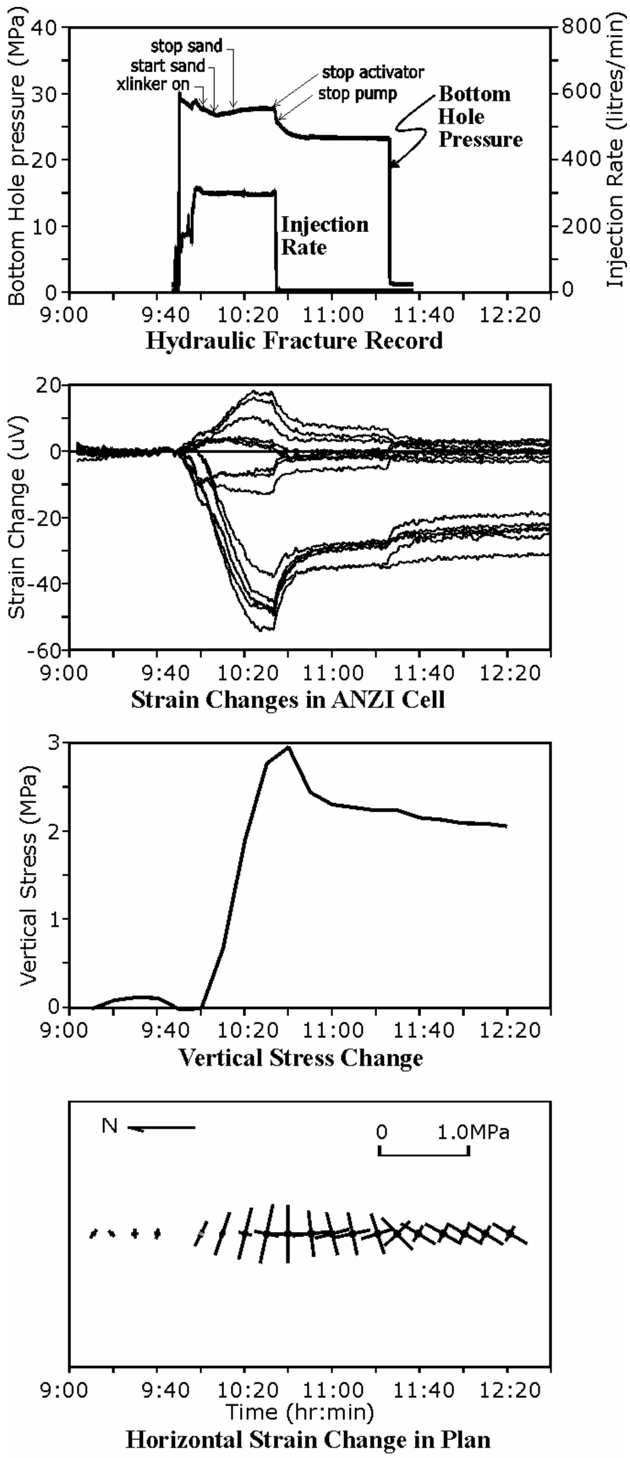


Figure 5: Stress changes measured by NPK5 during Hydraulic Fracture 7 at Northparkes.

These stress monitoring results show a high degree of internal correlation with the correlation coefficient approaching 1.00 once the stresses begin to change. Other characteristics that increase confidence in the results are:

- The timing of the stress changes correlates closely with the start and end of the hydraulic fracture treatments.
- The orientation of the stress changes is consistent across all three instruments.
- The alignment of the stress vectors appears to be broadly consistent with the expected orientation of the hydraulic fracture.

In each treatment there are four clearly defined stages.

There is a steady state of essentially zero stress change before the treatment starts.

The vertical stress increases almost immediately after each treatment commences. Changes in strain are apparent within one minute of the commencement of pumping.

A peak is reached and the stress change induced in the rock remains steady. The peak is typically in the range 0.7-1.4MPa for the water treatments at a distance approximately normal to the fracture plane of 15-30m. When this distance is greater than about 30m, the peak vertical stress is consistently lower at 0.5-0.8MPa. In the gel treatment (Fracture 7), the peak vertical stress indicated is 2.3-3.3MPa with the stress change decreasing with distance away from the fracture plane.

Once pumping stops, there is a gradual decay in pressure. The rate of the pressure decrease reduces over time in the form of a classical decay curve. Logging typically only continued for 1-2 hours after pumping stopped. By the time logging is discontinued, the residual vertical stress is in the range 0.4-0.6MPa for the water treatments and 1.1-2.1MPa for the gel treatment.

Table 2 summarises the maximum principal stress orientation for the last stress change calculated prior to the cessation of pumping for each treatment that was monitored. These measurements give an indication of the hydraulic pressure in the fracture and the orientation of the hydraulic fracture.

The observation that the major stress change is sub-vertical, while the horizontal stress changes are small by comparison, is consistent with the hydraulic fractures forming on a sub-horizontal plane. A plane of this orientation is consistent with the measured in situ stress field at the site and further corroborated by borehole intersection and tiltmeter measurements.

3.3 Fracture Orientations Based on Stress Orientations

The orientation of the major stress change vectors is expected to provide an indication of the dip and dip direction of the hydraulic fractures once the fracture becomes large relative to the distance of instruments from the fracture initiation point.

Table 2: Summary of Measured Stress Changes at Nearest Time Period Analysed Prior to Maximum Extent of Each Hydraulic Fracture Being Reached

Frac	Time	NPK5		NPK6		NPK7	
		Stress (MPa)	Dip /Brg	Stress (MPa)	Dip /Brg	Stress (MPa)	Dip /Brg
1	11:40	1.41	74/244	0.93	81/212	0.69	86/253
3	13:30	1.27	75/103	1.08	64/114	0.50	60/117
4	18:10	1.43	80/65	1.34	71/100	0.78	68/109
5	11:00	1.28	77/73	1.22	67/98	0.61	66/105
6	17:00	0.84	64/133	1.38	53/125	0.57	51/123
7	10:30	3.27	67/291	2.90	77/301	2.25	77/261
13	10:00	1.59	86/122	1.67	71/113	0.92	72/123

Figure 6 shows the compressive principal stress vectors that would be expected from modelling of a hydraulic fracture in an elastic, isotropic, homogeneous half space. Close to the centre of the hydraulic fracture, the compressive stress change component is oriented normal to the fracture plane. However, toward the fracture tip and at greater distance from the fracture plane, there is a tendency for rotation of the stress change component outward and therefore away from the fracture plane.

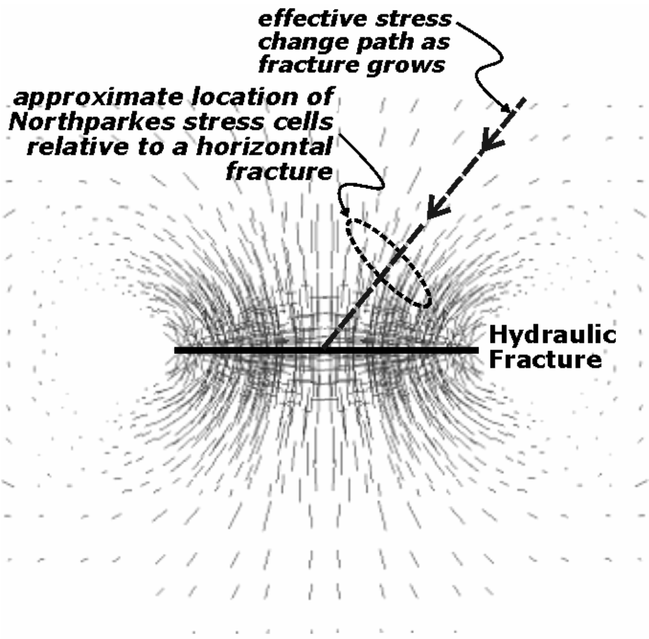


Figure 6: Compressive stress vectors about a horizontal hydraulic fracture.

The hydraulic fractures at Northparkes are estimated to have grown to a maximum radius of 30 to 50m. Assuming a 40m radius fracture, the stress cells are located on the diagonal shown in Figure 6 at the time of maximum fracture extent (assuming the hydraulic fractures are sub-horizontal).

A process of matching the stress changes measured with the stress changes modelled allows a number of admissible orientations to be determined. The number of admissible orientations based on the stress change measurements is a function of the spatial relationships of the stress change instruments to the hydraulic fracture, the size of the hydraulic fracture and the symmetrical or otherwise growth of the hydraulic fracture about the initiation point.

Table 3 summarises some of the admissible orientations indicated by the stress change measurements for each of the hydraulic fracture treatments. These orientations are based on the assumption that the fracture plane passes through the injection point (i.e. there are no bypasses through other holes or fracture cross-over).

While there are other combinations of fracture size, fracture orientation and non-concentric growth that would fit the stress orientation data from each measurement, other independent information narrows the possibilities. For instance, a fracture radius of about 40m is indicated by intersection and modelling data, so this is assumed as a first pass.

The fracture orientation that would fit the stress orientation assuming concentric fracture growth is shown in the first instance. The fracture orientation that would fit assuming some non-symmetric growth of the hydraulic fracture about the injection point is also shown for a fracture plane that is dipping slightly to the east. The orientations that would be consistent with other different sized fracture are also shown.

The results presented in Table 3 suggest that in general the stress changes measured support an east dipping fracture only if there is some possibility of non-concentric fracture growth. Only the stress changes observed during Fracture 7, the crosslinked gel treatment, are consistent with an east dipping fracture without there being a requirement for some non-concentric (or possibly non-circular) fracture growth.

In a pre-mining stress environment, the vertical stress would tend to increase with depth and therefore the preferred fracture growth direction would be to the west (up dip in an east dipping fracture), although it is recognised that the effect would be small in a shallow dipping fracture. However, at the trial site, the extraction of the Lift 1 orebody above is expected to have significantly lowered the vertical stress to the east of the trial site.

In fact, measurements of fracture shut-in pressure, after each treatment at the site show a reduction in the shut-in pressure with increasing depth down the hole. This data implies a stress gradient exists with lower stress occurring down dip and to the east (van As et al., 2004). Therefore, it is considered quite likely that a hydraulic fracture would preferentially grow toward this lower stress (i.e. in an easterly direction).

Table 3: Admissible Hydraulic Fracture Orientations on a Plane Striking 117°GN Based on Stress Change Measurements

Frac No	Assumed Radius (m)	Fracture Offset To East 1 (m)	Plausible Fracture Orientation (°)
1 2	40	0	7°W
	40	8	2°E
3	40	0	50°W
	40	26	10°E
	25	21	3°E
4	40	0	42°W
	40	26	7°E
	25	20	10°E
5	40	0	47°W
	40	26	7°E
	25	17	10°E
6	40	0	No fit possible
	40	24	30°E
	60	0	60°W
7	40	0	7°E
	40	14	29°E
	60	0	11°E
	25	No fit possible	
13	40	0	34°W
	40	20	5°E
	25	7	50°W

1 The fracture offset is a measure of the degree of non-symmetric growth of an assumed circular fracture relative to the injection point along the plane of the fracture.
2 There is significant component of dip out of the projection plane for Fracture 1 so the dips in the plane are less meaningful.

If only concentric fracture growth is assumed, then the stress change orientations from all the deeper treatments (all those except Fracture 1 and Fracture 7) are not consistent with east dipping hydraulic fractures. The data would only be consistent with west dipping fractures at dips of between 34° and 50°. There does not appear to be any other observations that support fracture growth of this orientation so the implication is that the water fractures did not grow symmetrically about the injection point. Independent measurements using tiltmeters (van As et al. 2004) indicate that fractures formed were sub-horizontal with an east dip, but the size and shape of the fractures cannot be determined independently from the tiltmeter data.

Fracture 7 is not particularly sensitive to the size of the hydraulic fracture and this fracture appears to have grown concentrically about the injection point. The stress change data supports a fracture radius of about 40m, but the fracture radius could be as low as about 30m (no match was possible at 25m) or upwards of 60m. The concentric growth is thought likely to be a consequence of the higher viscosity of the cross-linked gel fluid.

Principal stress change magnitudes shown in Table 3 indicate that the water injections generate smaller stress changes in the rock mass than did the gel injections as would be expected. It should be noted that the hydraulic pressure in the fracture may be slightly greater than indicated because of the distance the monitoring points are from the plane of the hydraulic fracture.

4 STRESS CHANGE MONITORING AT SALVADOR MINE CHILE

4.1 Site Description

Figure 7 shows the layout of the monitoring site at 2600 Level in Inca East sector at Salvador Mine. The locations of the stress change monitoring holes, the instruments and the hydraulic fracture treatments are shown.

Four ANZI stress cells were installed in two BQ boreholes. These instruments were installed at depths of 37.39m and 39.90m in borehole S1 and 41.13m and 44.31m in borehole S2. Hole S1 dips at 59° from horizontal at an orientation of 85°GN. S2 dips 58° from horizontal at an orientation of 89°GN.

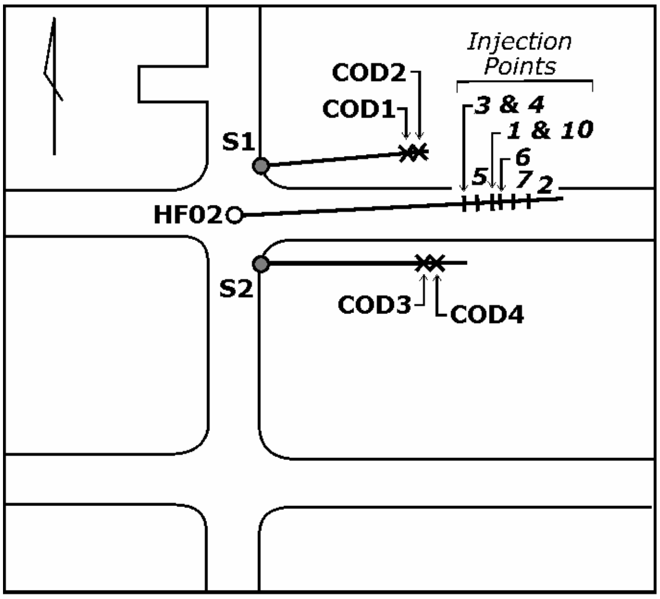
The hydraulic fracture treatments were conducted in a hole HF02 collared midway between the stress monitoring holes. This hole also dips 59° and is oriented at 87°GN. Table 4 summarises the timing of the hydraulic fractures and the injection details.

4.2 Results

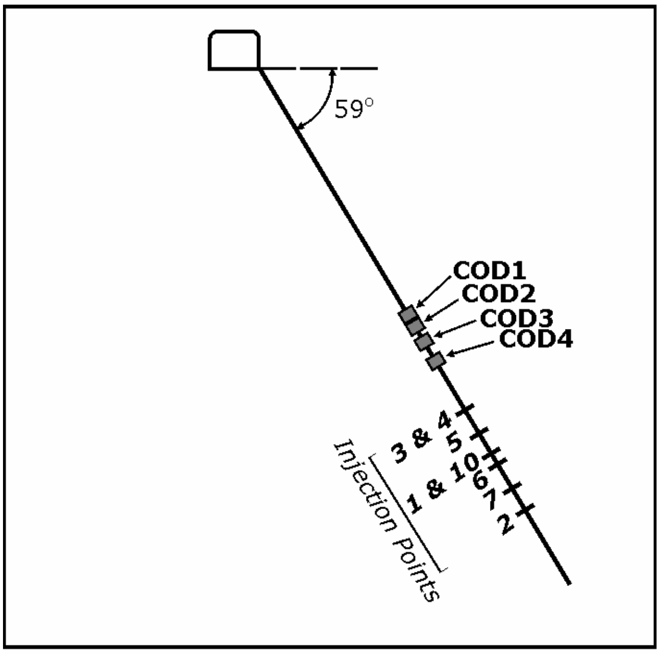
Figure 8 summarise the stress changes measured during Fracture 7 on COD1.

The stress monitoring results show a high degree of internal correlation with the correlation coefficient approaching 1.00.

The observation that the major stress change is sub-horizontal, while the vertical and other horizontal stress changes are small by comparison, is consistent with the hydraulic fractures forming in a sub-vertical plane. There is corroborating evidence from other measurements made at the site that this is indeed the case.

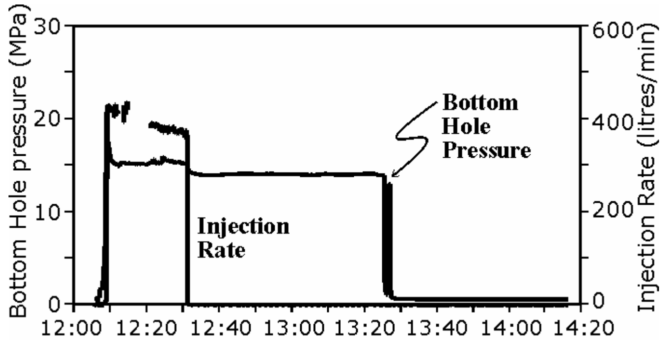


Plan View

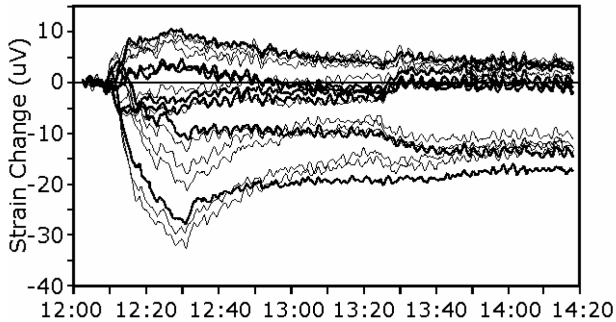


East - West Section looking north

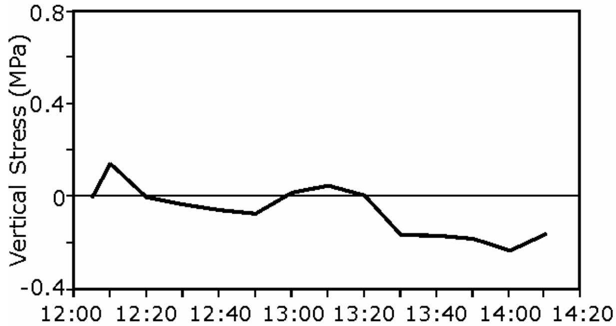
Figure 7: Location of stress change monitoring instruments at Salvador Mine (Chile).



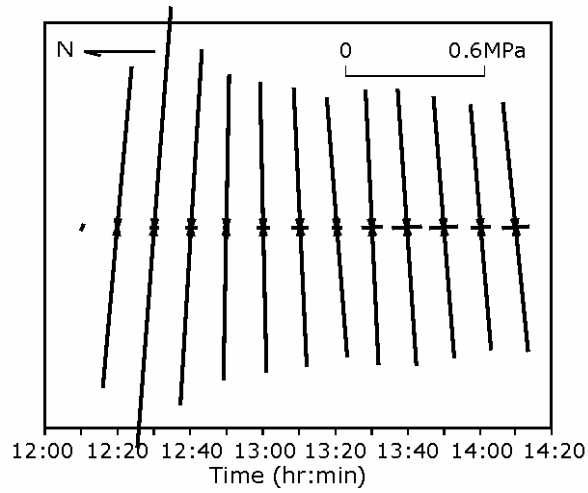
Hydraulic Fracture Record



Strain Changes in ANZI Cell



Vertical Stress Change



Horizontal Strain Change in Plan

Figure 8: Stress changes measured by COD1 during Hydraulic Fracture 10 at Salvador Mine (Chile).

Table 4: Summary of the Hydraulic Fracture Treatments

Frac	Date	Injection Period	Straddle Interval (m)	Injection Fluid
1	26/11/2002	10:50-11:20	57.55-58.05	Water
2	27/11/2002	14:44-15:15	66.55-67.05	Water
3	28/11/2002	11:28-11:52	51.55-52.05	Water
4	29/11/2002	11:13-11:30	51.55-52.05	X-linked gel
5	29/11/2002	14:22-14:45	54.55-55.05	Linear gel
6	30/11/2002	10:56-11:16	60.55-61.05	Water
7	1/12/2002	13:07-13:25	63.55-64.05	X-linked gel
8	2/12/2002	16:12-16:41	117.55-118.05	X-linked gel
9	3/12/2002	13:13-15:00	111.55-112.05	Linear gel
10	4/12/2002	12:08-12:31	57.55-58.05	X-linked gel

The hydraulic fractures at Salvador Mine are estimated to have grown to a maximum radius of approximately 40 to 50m based on the length of injection and the timing of various intersections. The principal stress changes are expected to be approximately normal to the plane of the hydraulic fracture when the fracture is at maximum extent.

Table 5 summarises the maximum principal stress orientation for the last stress change calculated prior to the cessation of pumping. These measurements give an indication of the maximum hydraulic pressure in the fracture and the orientation of the hydraulic fracture.

No stress changes were perceptible in the results for Fractures 8 and 9. These treatments were conducted at a much lower horizon for other purposes. The correlations on some of the results from COD4 were too low to give meaningful indications of the stress orientations.

Assuming that the maximum stress changes are oriented approximately normal to the plane of the hydraulic fractures, the measured stress changes indicate that all the hydraulic fractures except Fracture 7 are dipping to the west (normal to the plane oriented at 87°GN) at about 15° from vertical.

The fracture plane orientations appear to be much more consistent in the vicinity of stresscells COD1 and COD2 than in the vicinity of the other two instruments. Nevertheless, the average orientation indicated by COD3 and COD4 is still essentially the same as indicated by COD1 and COD2, and the scatter may be a result of more variable behaviour in the rock mass in the vicinity of COD3 and COD4. However, other measurements indicate only limited growth of the hydraulic fractures occurred to the south of HF02 (Chacon et al., 2004)

The different orientation observed in Fracture 7 is apparent in all four instruments. Fracture 7 was a new hydraulic fracture using cross-linked gel as the injection fluid and it would appear from the stress monitoring results that it grew predominantly in a northerly direction toward COD1 and COD2.

Fractures 1, 2, 3 and 6 are all water treatments and the maximum stress change from these treatments are all closely aligned dipping 12° at 80°GN ± 4° in the vicinity of COD1 and COD2.

Fractures 4, 5 and 10 also show similar alignment to each other. These are either linear gel treatments (Fracture 5) or cross-linked gel treatments injected into pre-existing hydraulic fractures. These tend to be aligned more easterly with the stress changes dipping 13° at 90°GN. Fracture 7 is a cross-linked gel treatment injected into a previously untreated section of the borehole. This fracture dips at 30° from vertical with the normal aligned at 87°GN.

The average results for all four instruments indicate westward dipping hydraulic fracture that dip at an average of about 15° from vertical.

5 FRACTURE GROWTH AND STRESS CHANGE

The stress change around a hydraulic fracture can be obtained from analytical solutions for certain fracture geometries. The stress change around a circular or penny-shaped fracture that is uniformly pressurised (Sneddon, 1946) has been used in this section to compare the modelled and measured stress change.

Table 5: Summary of Measured Stress Changes (σ1) at Nearest Time Period Analysed Prior To Maximum Extent of Each Hydraulic Fracture being Reached

Frac	Time	COD1		COD2		COD3		COD4	
		σ1 MPa	Dip /Brg	σ1 MPa	Dip /Brg	σ1 MPa	Dip /Brg	σ1 MPa	Dip /Brg
1	11:20	0.47	11/80	0.93	12/84	0.85	12/90	1.0	4/80
2	15:10	0.95	14/79	0.97	11/84	0.54	8/78	-	
3	11:50	0.97	15/85	1.2	16/89	0.90	22/110	1.6	6/113
4	11:30	1.8	15/90	2.1	13/94	1.6	11/103	2.1	3/107
5	14:40	1.5	15/92	1.7	12/96	0.39	23/61	0.98	29/75
6	11:10	0.92	17/81	0.90	13/84	0.67	29/73	0.46	12/56
7	13:20	0.59	49/85	0.91	43/86	0.34	37/50	0.42	42/38
8	16:40	0	-	0	-	0	-	0	-
9	15:00	0	-	0	-	0	-	0	-
10	12:30	1.8	12/89	2.0	9/92	1.7	7/87	2.0	9/71

If the fracture growth is assumed to occur symmetrically about the injection point, then the stress change at the location of any instruments is easily found as the fracture grows from an initially small radius to a radius much larger than the distance separating the instruments from the injection point. The stress change for such symmetric growth is found by tracking along a straight line running from the centre of the model fracture outward at an angle to the fracture plane that passes through the location of the instrument. This line is shown in Figure 6. When the fracture is small relative to the distance to the instrument, the stress change corresponds to points located at large r/R on this line. Conversely, as the fracture grows r/R decreases.

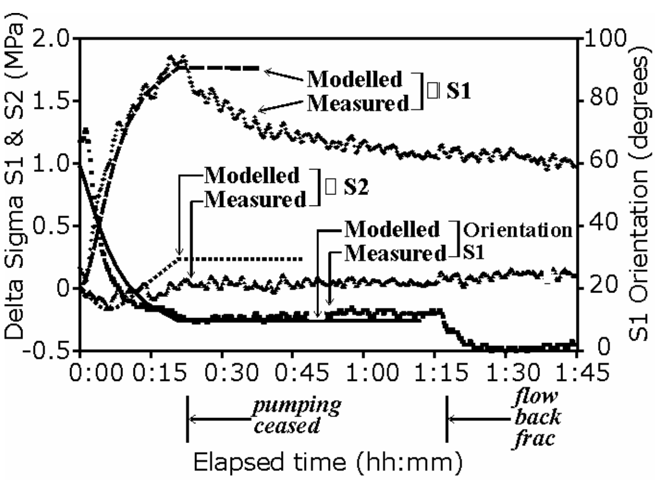


Figure 9: Stress changes measured and modelled for Fracture 10 at Salvador Mine (Chile).

The stress change can be calculated along such a line and both the stress change magnitude and orientations can be compared to the measured stress changes. Such a calculation has been carried out for Fracture 10 at Salvador and is shown in Figure 9.

The relative distance r/R has been translated into a time by using the fracture growth relationship established by direct measurement of fracture growth at this site. The growth relationship is:

$$R = 7.56t^{0.55} \quad (1)$$

Equation 1 can be rewritten as:

$$t = \left(\frac{R}{7.56}\right)^{\frac{1}{0.55}} \quad (2)$$

The model results are calculated in terms of r/R, where r is the distance between the injection point and the location at which the stress change is measured. Figure 9 compares the measured and modelled data after applying equation 2 to obtain a time from the start of fracture growth for the modelled data. The model assumes the fracture strikes north-south and dips at 80^{o} to the west. A uniform pressure of 2MPa was used inside the model fracture to obtain the fit shown. Pressure falloff after shut in is not modelled. The fit to the stress magnitudes is reasonable considering the assumptions used and the orientation fit to the orientation of the maximum stress change is quite good and also shows the sensitivity of this measured parameter to fracture growth and flow back. The magnitude of the secondary principal stress change, which corresponds to the north-south stress change, is overestimated by the model suggesting the Poisson's ratio used for this calculation may be too high.

6 CONCLUSIONS

The stress changes observed are consistent in terms of timing and magnitude with the commencement and cessation of pumping in all the hydraulic fracture treatments. The stress changes orientations are consistent across the instruments at both sites when elastic stress distributions about hydraulic fractures are taken into account.

At Northparkes, the initial stress monitoring results indicate that the hydraulic fractures have formed in a sub-horizontal plane, consistent with the in situ stress measurements made at the site using the overcoring method of stress relief. The orientations of the hydraulic fractures are not able to be uniquely defined using only the stress monitoring information because of the locations of the instruments relative to the fracture plane and the directions that the fractures have grown.

Nevertheless, the stress change monitoring constrains the possible fracture orientations to only a few possibilities. Using other information, these possibilities are further constrained to give a unique result. The measurements indicate that all the hydraulic fractures dip gently to the east at an orientation consistent with the in situ stress field at the site, but the fractures have grown non-symmetrically in a down dip direction consistent with the stress geometry expected about the overlying block cave.

The magnitude of the stress change measured is consistent with the nature of the injection fluid. For water treatments, the magnitude of the stress change observed was about 0.5-1.4MPa for distances of 15-40m from the fracture plane. For the cross-linked gel, the stress changes measured were 2.3-3.3MPa at 15-25m from the fracture plane.

The pressures locked into the fracture at the completion of the treatment were also reflective of the nature of the injection fluid. In water treatments, the residual stress change observed several hours after the treatment was complete was typically about 0.5MPa (0.2-0.6MPa). For the cross linked gel treatments, the residual stress change was about 1.5MPa (1.0-2.1).

At Salvador Mine, the initial stress monitoring results indicate that the hydraulic fractures are generally westward dipping at an average dip of about 15° from vertical.

A detailed model of the stress change associated with Fracture 10 produced a good fit to the measured data and illustrated the sensitivity of the orientation of the maximum stress change vector to fracture growth relative to the position of the stress change monitoring instruments.

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REFERENCES

Chacon, E, Barrera, V, Jeffrey, RG, and van As, A, 2004. Hydraulic fracturing used to precondition ore and reduce fragment size for block caving, *Proceedings of the MassMin 2004 symposium, Santiago, August 22-25.*

Mills, KW, 1997. In situ stress measurements using the ANZI stress cell, *Proceedings of the International Symposium on Rock Stress*, edited by Sugawara and Obara, Kumamoto 7-10 October 1997, published by A.A. Balkema. pp 149-154.

Mills, KW, 2002. *SCT Report to Northparkes Mine* In Situ Stress Measurements – 9700 Level and Lift 2 Decline.

Sneddon, IN, 1946. The distribution of stress in the neighbourhood of a crack in an elastic solid, *Proceedings Royal Soc. Of London, 229-260.*

van As, A and Jeffrey, RG, 2004. Preconditioning by hydraulic fracturing for block caving in a moderately stressed naturally fractured orebody, *Proceedings of the MassMin 2004 symposium, Santiago, August 22-25.*