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# *In-situ Stress Measurements at Deep Underground Reserves of Zawar Group of Mines for Stopes Design*

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**ABSTRACT**

In-situ stresses are important parameters required for stability analysis of any underground structure. This is an input parameter to various closed-form solutions, empirical correlations and numerical codes used for analyzing the stability of the structure. It is therefore measurement of in-situ stresses becomes indispensable. This paper discusses about the in-situ stress measurements carried out at five different locations of Zawar group of mines. The tests were conducted using hydrofracturing technique in five deep boreholes (depth range 500 to 900m) drilled in mined out stopes. Shut-in pressure ($P_{si}$) method was used for pre-existing fractures.

Ratio of horizontal to vertical in-situ stresses (k-value) plays a vital role in designing the underground openings. The k-value ranged from 0.45 to 1.44 at Balaria, 1.09 to 1.14 at Mochia, 0.78 to 0.87 at Central Baroi and 0.75 to 0.76 at Zawarmala mines. The prevailing Maximum principal horizontal stress directions ranged from N105° to 120° at Balaria, N110° at Central Baroi, N116° at Mochia and Zawarmala mines. The major principal stress direction is in line with major geologic structures present in the area.

A lower magnitude of in-situ stresses (ranging between 1.36MPa and 9.42MPa) was observed at 553.43m to 715.17m depth in Balaria mines. This may be due to the fact that the study area is characterized by low compressive stresses. A moderate to high stress magnitude of 22.07MPa to 25.60MPa was observed at 702.8m to 852.8m depth in Mochia mine, 12.78 to 14.68 MPa at 530.43m to 680.43m depth in Central Baroi mine and 15.82MPa to 18.81MPa at Zawarmala mine at 751m to 901m depth.

***Keywords:*** Hydrofracturing; in-situ stress; shut-in pressure; deep mining; tectonics

## 1. INTRODUCTION

True values of in-situ stresses help in designing of mine-stopes. Further, stability analysis using numerical codes determines size of safe and stable mine-stopes and hence number of stopes can be planned to work simultaneously. As the hydrofracturing and over-coring methods of in-situ stress measurement have least assumptions, these are reliable to use in mines.

The Zawar group of mines run by Hindustan zinc limited under Vedanta resources Ltd. consists of four mines namely Mochia, Balaria, Zawar Mala and Baroi mines with an average zinc-lead reserve grade of 4.6%. Zawar mine has 34.492MT of reserves as on 01.04.2021. Zawar group of mines are located about 40km south of Udaipur, Rajasthan, India (Fig. 1). Ore body is being mined at depth varying from 400m to 600m.

All the four Mochia, Balaria, Zawar Mala and Baroi mines are located within the radius of 4km. Some undesired events like roof fall, pillar crushing, spalling is noticed in underground caused due to area is subjected to high or low stress conditions. Due to deeper mining activities, there are some incidents that occurred like major subsidence at 250m north side of Central Mochia mine shaft (Fig. 2). The reason may be due to some anomalies at the vicinity of the test locations.

Sindesar Khurd mine (Hindustan zinc Ltd.) is located at about 110 km North-East of Zawar group of mines. It is characterized by low horizontal stress gradients of 0.025 to 0.01MPa/m, which is less than that of the values (0.051-0.027MPa/m) measured by NGRI (National Geophysical Research Institute, Hyderabad) at Malajkhand (Rajasthan). This may be due to the reason of the area being characterized by low horizontal compressive stresses. Further, this might have led to vertical stress higher than the horizontal in-situ stresses below 850m depth (Gowd, 2005).

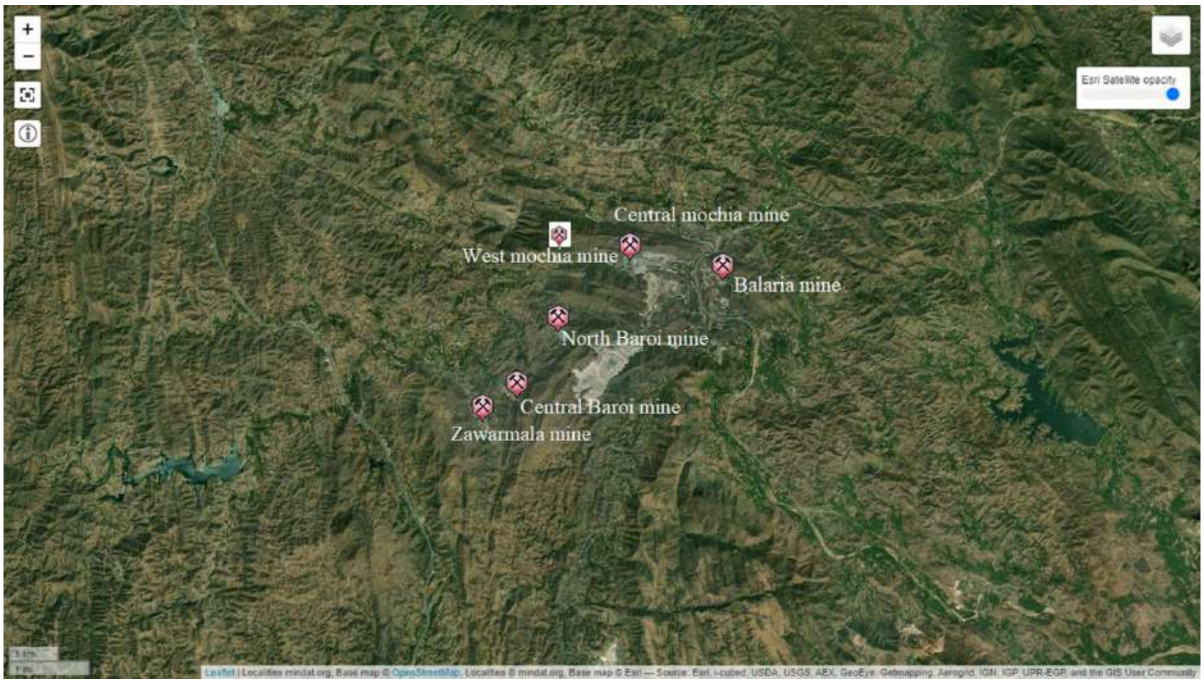


Figure 1 - Location of the project area

Investigations conducted by CSIR-Central Institute of Mining and Fuel Research (CIMFR) Dhanbad in the year 1988 revealed that the direction of major horizontal stresses observed at Balaria and Zawarmala mines were influenced by the geological structures in the area. The direction of major horizontal stress in Balaria varied from N 110º to N 120º, which was in the direction nearly parallel to the plunge of the cross-fold present in the area. The major horizontal stress in Zawarmala mine varies from N 156º to N 167º and its direction is almost parallel to the plunge direction of Zawarmala anticline (NNW) (Sinha, 2005).


Figure 2 - Areal view of Central Mochia mine shaft indicating major subsidence

Even though there may be similarities in local tectonics and geological conditions. In the view of the aforementioned cases, it is always recommended to conduct field tests to measure in-situ stresses for input values to conduct stability analysis o the underground structures. Hydro-fracture technique of in-situ stress measurement follow least assumptions therefore, the method is suitable for the cases of weathered and closely jointed rock mass. It consists of moderately weathered and jointed rock mass. In over-coring method, it will be difficult to observe the strains in presence of close spaced joints and weathered formations.

## 2. GEOLOGY OF STUDY AREA

### 2.1 Balaria Mine

Balaria mine consists of a series of lenses 2800m long along the strike, trending N45º W to S45º E in the West and almost North - South in the east. The formations are striking overall N 40-60º W to S40-60º E; dip steeply at 65-90º towards north-eastern direction. Balaria constitutes a part of North limb of Mochia-Balaria-Baroi iso-anticline plunging westerly. Common rock types are dolomite and phyllite with their variants like Arkosic dolomite, siliceous dolomite, Phyllitic dolomite, carbonaceous phyllite and rarely quartzite and quartz veins. The mineralization at Balaria mine can be divided into two zones namely, (i) Central Balaria, and (ii) Western Balaria. All the lenses follow en-echelon pattern with sinisterly shift and laterally follow a general strike of N10º W to N65º W and becoming E-W in the area beyond Railway / River pillar on the west. The average valley level is 350m RL and the highest peak is at 550m RL. Steep ridges are of dolomite and quartzite with adjacent valleys of Greywackes. Mineralization is confined to the main dolomite horizon. Ore zone comprises of stringers and veins of variable width. The central dolomite & western part of Northern dolomite carry most of the economic mineralization. Average mineralization is around 8m and varies from 2m - 40m. Test location in Balaria (Fig. 3) is at 45m RL/S7-2 (ISM 01) and 105m RL/2E-8 (ISM 02).

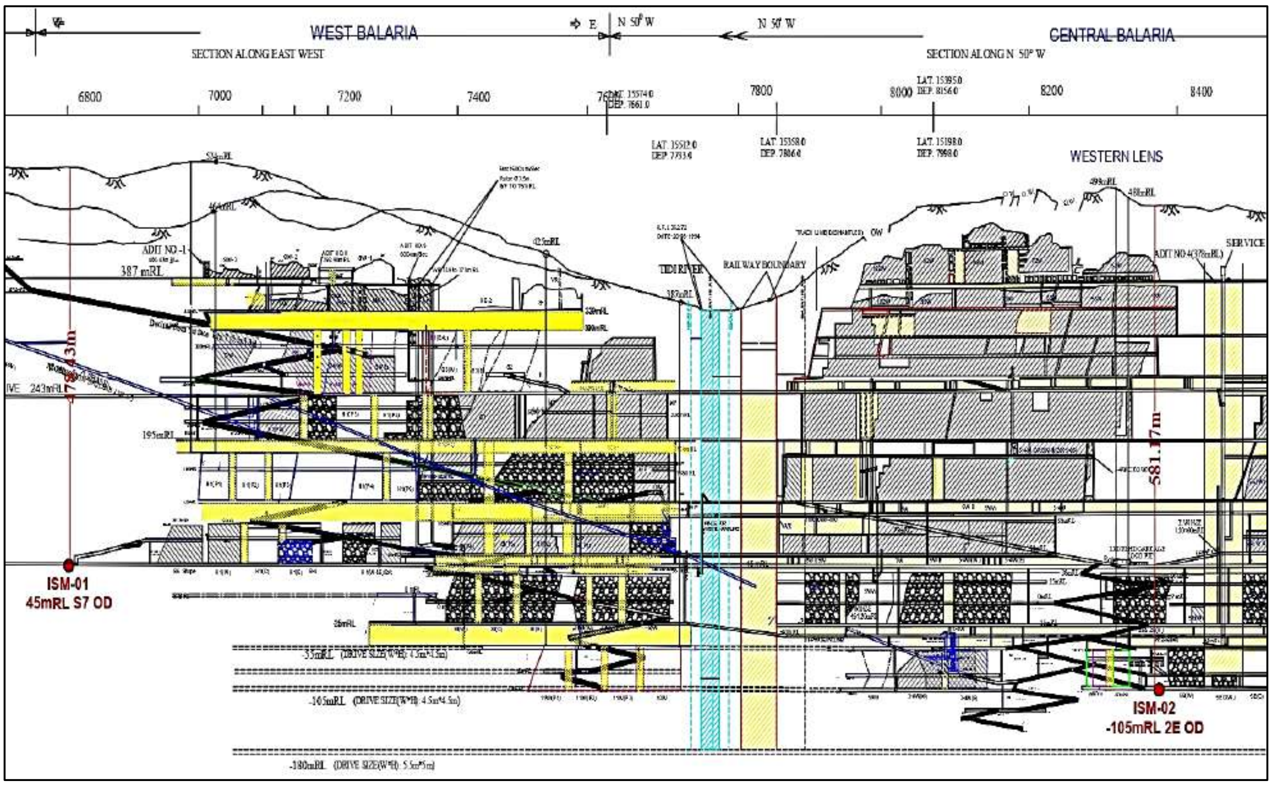


Figure 3 - LVS of Balaria mine locating boreholes ISM01 and ISM 02

### 2.2 Mochia Mine

Mochia mine consists of a steeply strike ridge, 2750m in strike length, trending E-W to ESE-WNW. The formations are striking overall towards east-west, dipping steeply at 75-90º towards North direction. The mine constitutes a part of North limb of Mochia-Mochia-Bawa iso-anticline plunging westerly. Rock formations probably constitute a part of Pre-Cambrian Aravalli system (about 2.2 billion years old). Common rock types are dolomite and phyllite with their variants like Arkosic dolomite, siliceous dolomite, pure dolomite, phyllitic dolomite, carbonaceous phyllite, rarely quartzite and quartz veins with intrusion of dolerite dyke. The lensoid lead–zinc mineralization at Mochia mine can be divided into two zones namely (i) Central Mochia, and (ii) Western Mochia. All the lenses follow pinch and swell, en-echelon pattern. The average valley level is 393m RL and the highest peak is 452m RL. Steep ridges are of dolomite and quartzite with adjacent valleys of greywackes. Mineralization is confined to the main dolomite horizon. Ore zone comprises of stringers & veins of variable width. The central dolomite & part of Northern dolomite carries most of the economic mineralization. Average mineralization width is around 6.0m and varies from 2m to 40m. Test location in Mochia (Fig. 4) is at 23m RL/CW0/P1W-Rib Pillar (ISM 03).

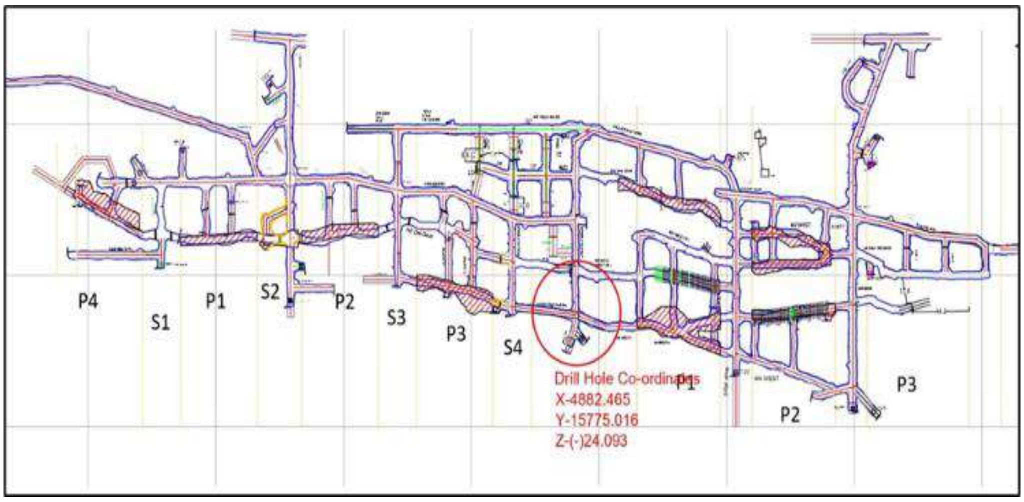


Figure 4 - Plan of -25m RL west Mochia mine locating borehole ISM 03

## 2.3 Baroi Mine

The rocks of Baroi area form a part of Aravalli Super group of Palaeo Proterozoic age. Meta sedimentary rocks belonging to Aravalli Super group overlie a basement exposed south of Zawar. It is a polyphase deformed complexly folded geological structure formed out of two distinct epochs of post Aravalli and post Delhi orogenies. Baroi hill represents the N-S trending and northerly plunging first generation fold system. The deposit lies between latitudes 24º 19'00" and 24º 20' 53" and longitudes 73º 41' 27" and 73º 42' 43". The rock units consist of dolomite, greywacke, Sub greywacke, phyllite / Quartzite interbeds. Baroi deposit has a lateral extent of 3.5km out of which the northern portion of 2.5km strike length, where major concentration of ancient mine workings lies, form the most prominent part of the deposit. This 2.5km strike length has been divided into three blocks viz., Baroi North – 600m, Baroi Central – 1200m and Baroi South 700m strike length respectively. The mineralization is confined along the brittle fractures that were developed during various orogenies that the deposit has undergone in past. The fractures trend almost 30º form the E-W. Test location in Baroi (Fig. 5) is in Central Baroi 110 m RL South Haulage (ISM 04).

## 2.4 Zawarmala Mine

Zawarmala mine is located 6km west of Zawar mines township and 3km east of Tidi village. The Zawarmala hill is an NS trending structure. There are numerous spectacular ancient mining pits on surface rich veins. The deposit is hosted in meta-sedimentary sequence for base metal mineralization. Host dolomite is flanked by Greywacke, Phyllite in the south and Phyllite-Quartzite in the north. Mineralization concentrated at the core of the anticline and follows the axial plane of the fold plunging 40º due North with a strike length of approximately 550m. The host rock mass consists of primarily Siliceous Dolomite with some foliated dolomite. The ore body strikes N15º degrees and dips 30-50º NW for C & W Zone. The average valley level is 393m RL and the highest peak is 452m RL. The plunge of the ore body is around 45º towards N15º. Test location in Zawarmala (Fig. 6) is at -130m RL/P-0/ Approach Drive (ISM 05).

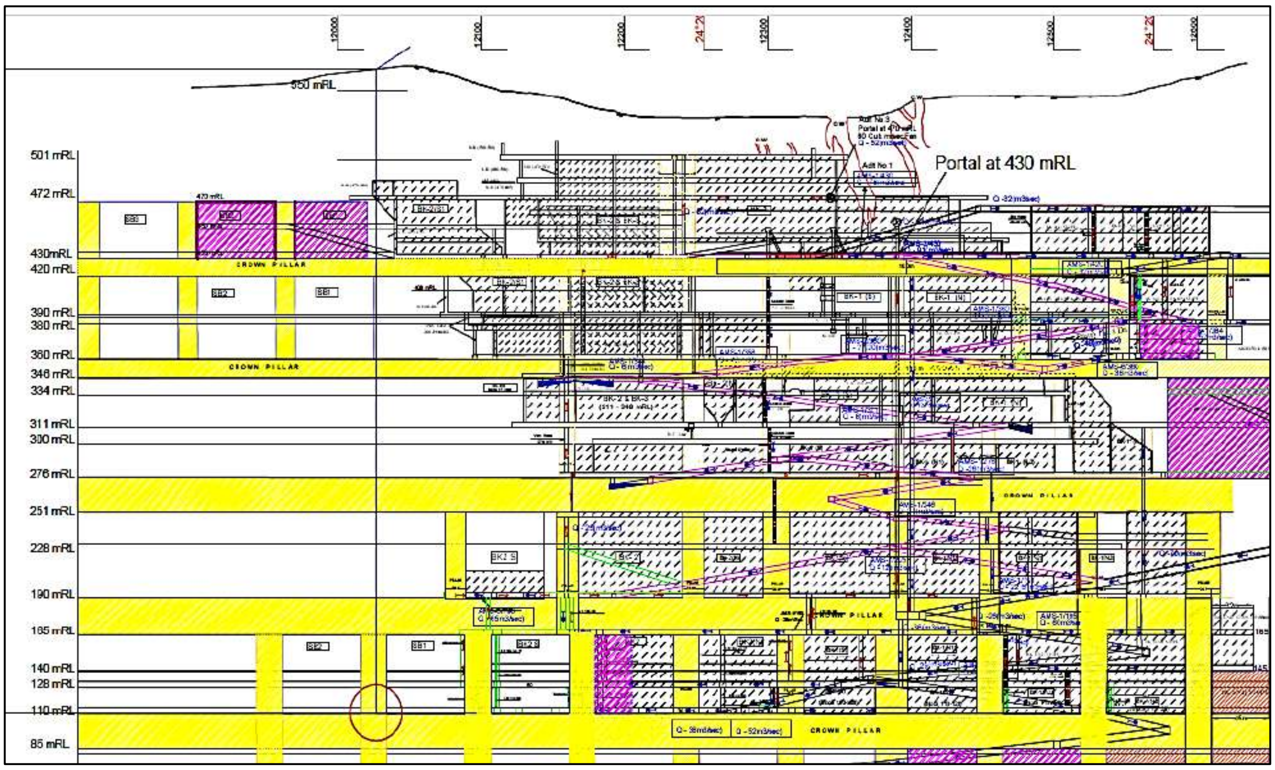


Figure 5 - LVS of Baroi mine-BK Series locating borehole ISM 04

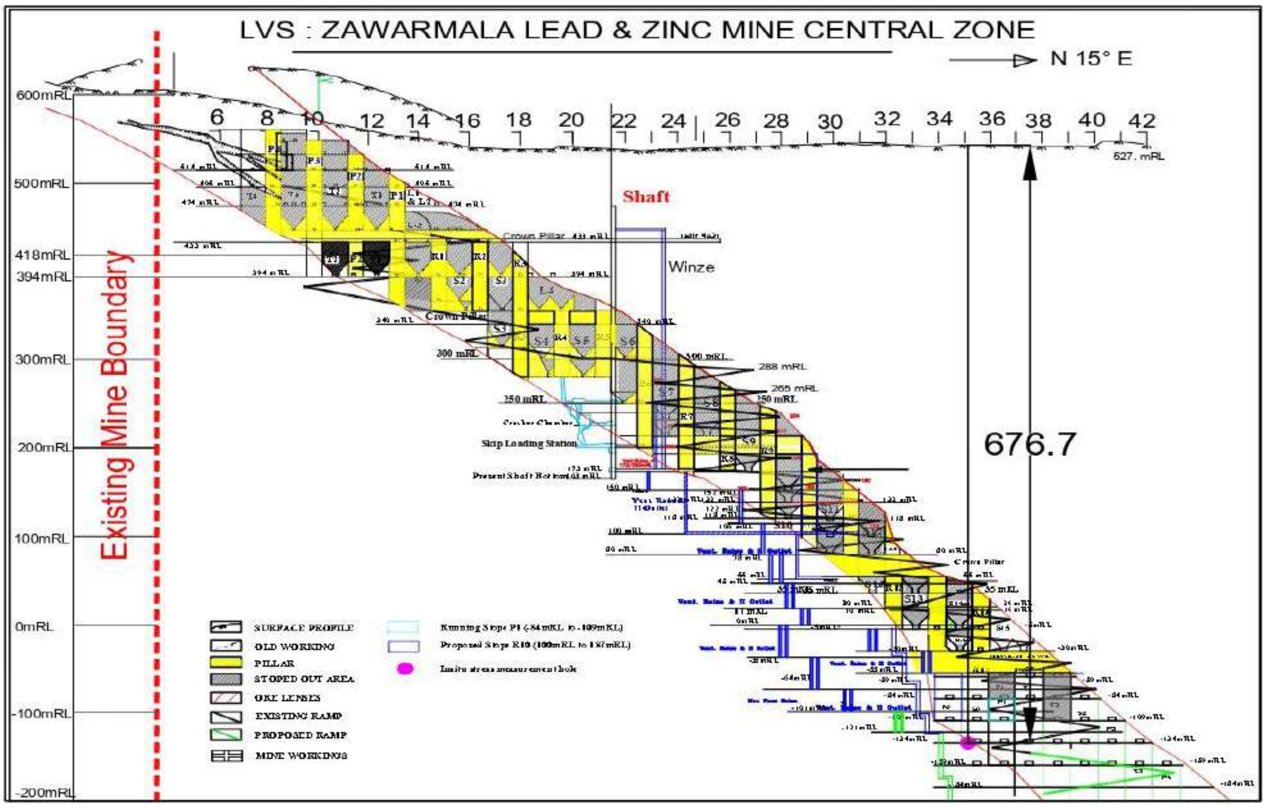


Figure 6 - LVS Zawarmala mine locating borehole ISM 05

The hydraulic testing of pre-existing fractures method is intended for the determination of in-situ stress parameters viz. magnitude and direction of maximum principal stress at the vicinity of the testing area. It is generally conducted in a borehole at desired locations, normally consisting of three or more zones at different depths. For determination of stress at greater depths, the zones can be decided accordingly to the site-specific requirements.

## 3. METHODOLOGY

Two numbers of high-pressure hoses (diameters 3/8 and ¼ inch, working pressure 78MPa / burst pressure 280MPa) is used for water injection and packer inflation. The maximum injection rate of the electric pump was about 14-16 l/min. Packer and interval pressures were monitored by pressure gauges and pressure was controlled by control panel unit (Fig. 7). Data was stored digitally in laptop through data acquisition system. Acoustic borehole televiewer is used to obtain information on the orientation of the induced or opened fracture traces at the borehole wall. The schematic illustration of the hydraulic fracturing test and acoustic borehole televiewer setup is shown in Figs. 8 & 9.

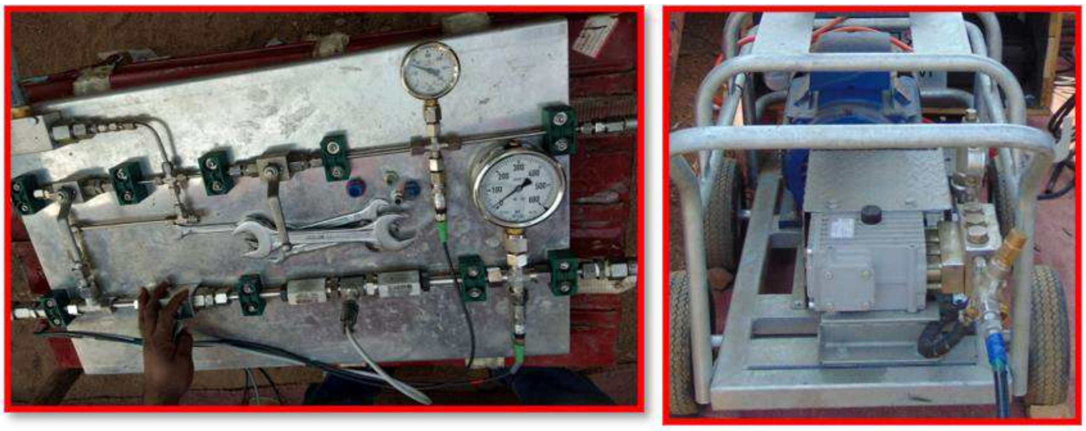

Figure 7 - Flow control panel and high-pressure water pump

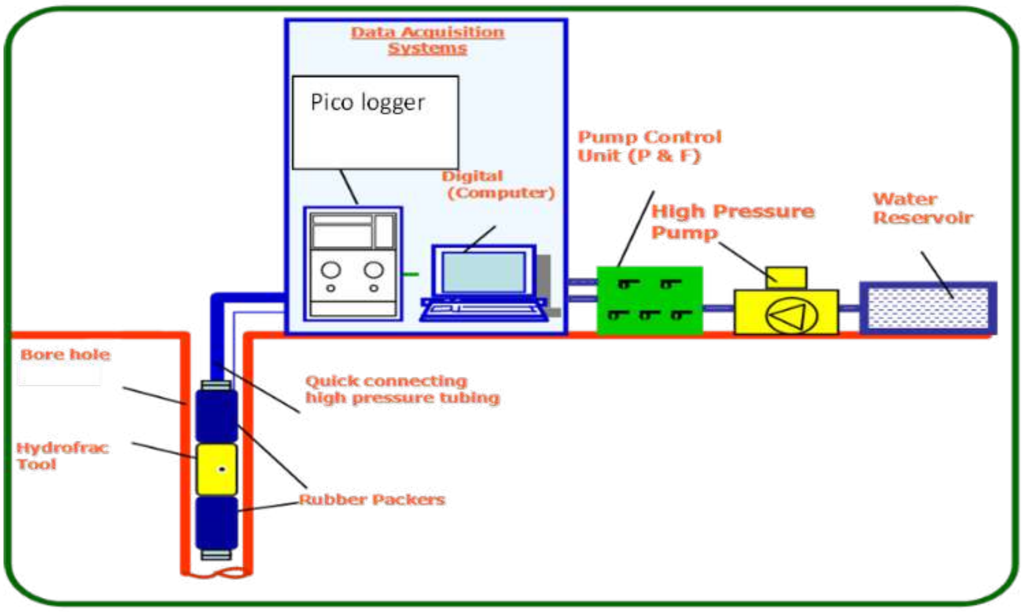


Figure 8 - Schematic diagram of hydraulic fracture experimental set-up

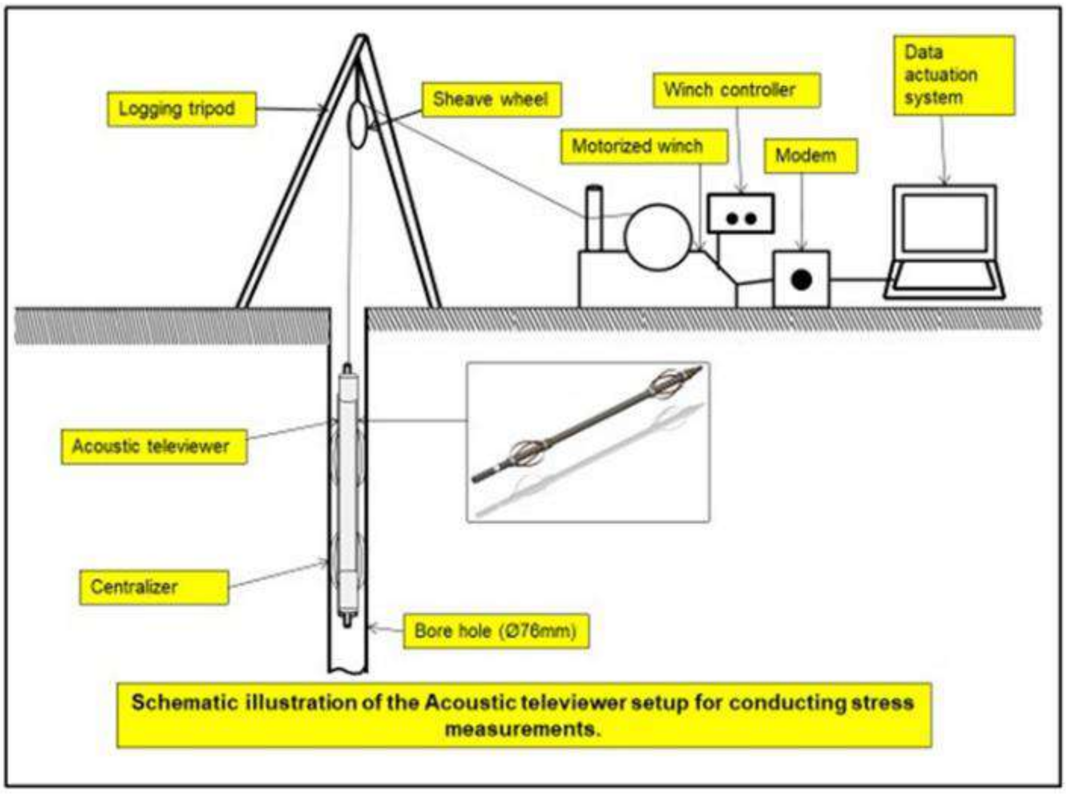


Figure 9 - Schematic diagram of acoustic borehole televiewer set-up

## 3.1 Equipment

The hydraulic fracturing assembly having steel reinforced packer elements with outer diameter 70mm was used for fracture initiation and extension (Fig. 10). The length of each packer element was about 635mm, whereas the test interval length was about 350mm. The equipment is manufactured by IPI (Inflatable Packers International), Australia.

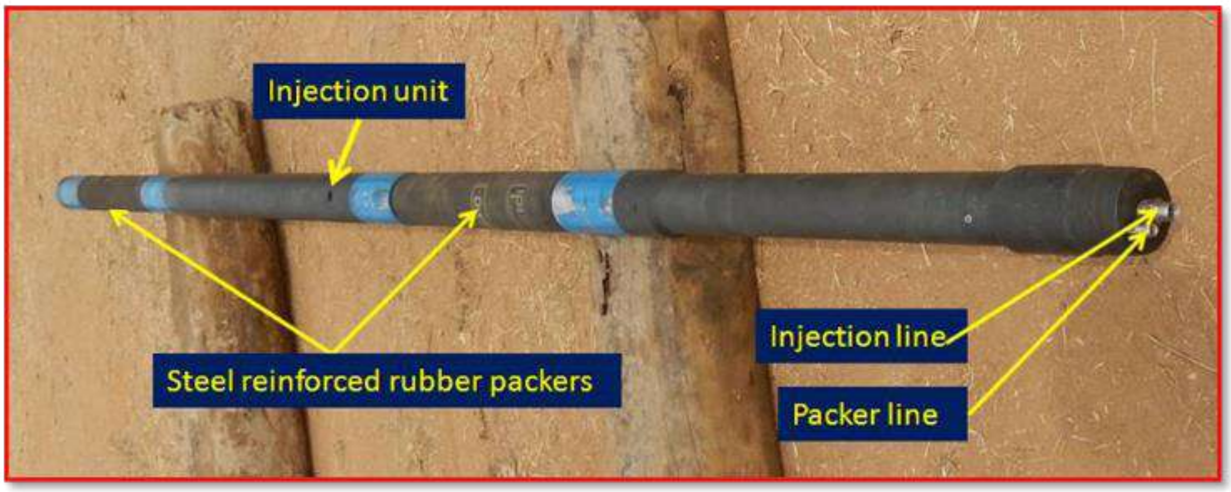


Figure 10 - Hydraulic fracturing tool

## 3.2 Test Procedure

After the Hydraulic fracture assembly was positioned at a pre-determined test section (selection is based on core inspection and pre-scan data from acoustic borehole televiewer), the injection pressure was increased until a hydraulic fracture was initiated, or a pre-existing fracture was opened. Subsequently, two to three refrac-cycles were conducted. Between the injection cycles, the system was vented. The back flow from the fracture into the interval section was observed by short valve closures during the venting phase. Finally, the packers were deflated, and the tool was moved to the next test section.

After all the hydraulic fracturing tests were conducted in the borehole, the acoustic borehole televiewer tool was run to obtain the information on the orientation of the induced or opened fracture traces on the borehole wall. The geometry of major subsurface structural discontinuities and the geological formations surrounding the borehole was recorded and processed in sophisticated WellCAD software.

## 4. DATA ANALYSIS

The in-situ stress measurements were conducted in a pronounced topography of anisotropic rock mass. Medium to large scatter in fracture orientation data was noticed, which negated the use of classical simple hydro fracture hypothesis suggested by Hubert and Wills (1957). Therefore, data analysis required a more sophisticated method, namely the interpretation of measured normal stress acting across arbitrary oriented fracture planes.

In this method the shut-in pressure $P_{si}$ is used to measure the normal stress component under the assumption that the vertical is a principal stress axis and the vertical stress $\sigma_V$ is equal to the weight of the overburden. The analysis program GENSIM was used to calculate the magnitude and the direction of principal stresses based on the Equation 1.

$$\sigma_h = (P_{si} - n^2. \sigma_V) / (m^2 + l^2. (\sigma_H/\sigma_h)) \quad (1)$$

where

l, m, n = direction cosines of the induced fracture plane w.r.t. the principal stress axis,
$\sigma_H$ = maximum horizontal principal in-situ stress, and
$\sigma_h$ = minimum horizontal principal in-situ stress.

## 5. TEST RESULTS

The fracture traces are obtained by processing sonic log data in WellCAD numerical code. The boreholes are logged both in pre and post testing period to differentiate between the induced and pre-existing fracture traces. In all the test locations, the traces were of pre-existing fractures only. There were no induced fractures due to the presence of closely spaced joints. Also, there were some test zones where shut-in pressure could not be able to be achieved due to presence of joints scattered close enough. Due to this, results of measurements could not be obtained at these depths. Some of the test zones in ISM 01 and 02 where horizontal fractures are logged and at these depths, measurement of vertical in-situ stress was measured directly as normal stress across the fracture.

To evaluate the stress regime at the Zawar group of mines, stress measurements were carried out by hydraulic testing of pre-existing fractures method inside the five boreholes. A sophisticated data interpretation method, $P_{si}$ (Shut-in–pressure) method was used under the analysis program GENSIM. The determination of shut-in pressure was straight forward when a sharp break after the fast pressure decline following pump shut off. The shut-in pressure was computed from the last cycle of the pressure vs. time graph (Figs. 11 & 12). The orientation of the fracture traces along with corresponding shut-in pressure and the results are given in Table 1 and Table 2 respectively.

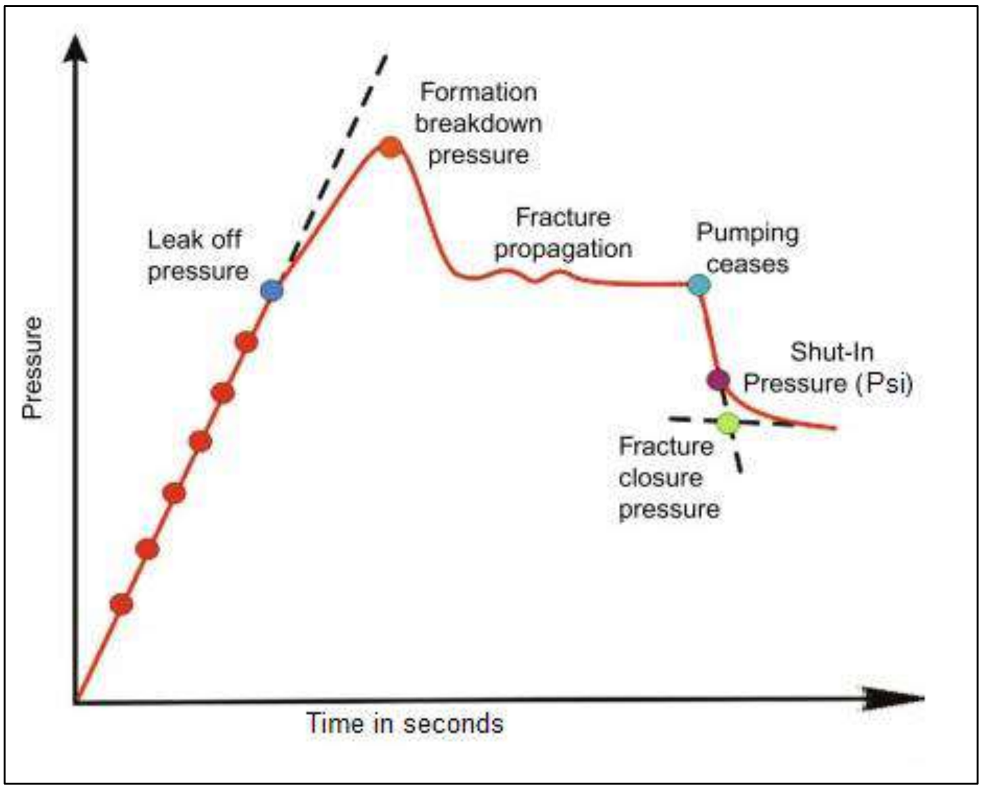


Figure11 - Determining the shut-in pressure

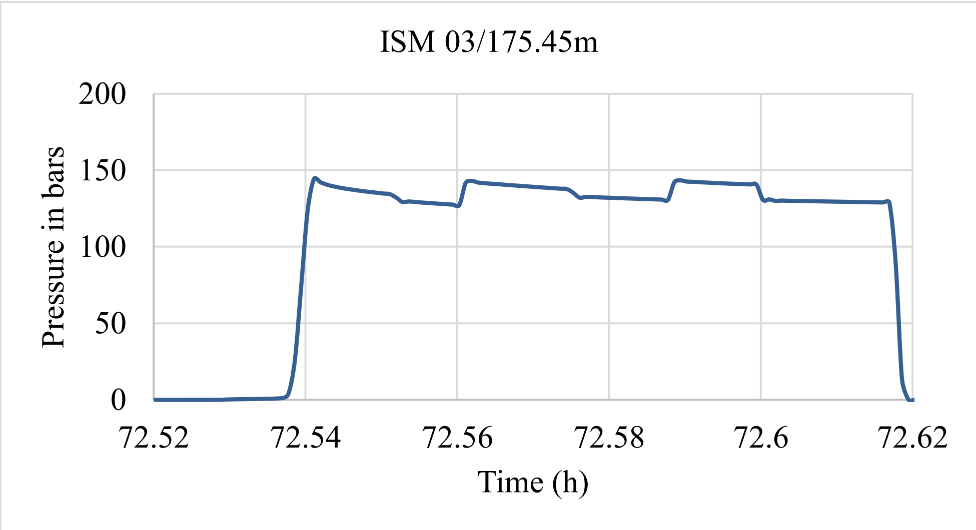


Figure 12 - Variation in pressure with time

Table 1 - Orientation of the fracture traces

(i) Location: ISM 01 (45m RL) Balaria mine

| Sl. No. | Depth (m) | Fracture strike N-E (º) | Fracture inclination (0-90º) | Shut-in pressure (MPa) |
|---|---|---|---|---|
| 1 | 67.5 | 175 | 20 | 1.21 |
| 2 | 71.7 | 215 | 35 | 0.87 |
| 3 | 74.2 | 111 | 0 | 1.018 |
| 4 | 76.0 | 269 | 26 | 0.91 |
| 5 | 87.5 | 183 | 47 | 1.43 |
| 6 | 142.2 | 196 | 0 | 1.432 |
| 7 | 145.2 | 279 | 35 | 0.972 |
| 8 | 148.0 | 261 | 41 | 0.941 |
| 9 | 156.5 | 266 | 30 | 0.954 |
| 10 | 184.0 | 90 | 30 | 0.961 |
| 11 | 189.5 | 220 | 38 | 0.906 |
| 12 | 191.5 | 260 | 35 | 0.803 |
| 13 | 201.2 | 118 | 0 | 1.071 |
| 14 | 206.0 | 132 | 42 | 0.986 |
| 15 | 216.0 | 241 | 25 | 1.004 |
| 16 | 230.7 | 142 | 30 | 0.936 |
| 17 | 236.5 | 229 | 10 | 0.966 |
| 18 | 252.3 | 97 | 8 | 1.074 |
| 19 | 255.7 | 187 | 30 | 2.137 |
| 20 | 257.4 | 196 | 40 | 2.148 |
| 21 | 281.1 | 110 | 24 | 1.108 |
| 22 | 284.7 | 107 | 52 | 1.505 |
| 23 | 289.5 | 143 | 0 | 1.664 |
| 24 | 294.3 | 195 | 56 | 1.151 |

(ii) Location: ISM 02 (-105mL) Balaria mine

| Sl. No. | Borehole/Test zone depth (m) | Fracture strike N-E (º) | Fracture Inclination (0-90º) | Shut-in-pressure (MPa) |
|---|---|---|---|---|
| 1 | 76 | 26.61 | 33.20 | 4.5 |
| 2 | 100.5 | 45.47 | 33.20 | 4.07 |
| 3 | 113 | 87.47 | 75.53 | 4.53 |
| 4 | 125.3 | 69.13 | 60.26 | 5.05 |
| 5 | 144 | 114.78 | 75.07 | 5.46 |
| 6 | 174.5 | 136.66 | 28.44 | 4.79 |
| 7 | 176.5 | 144 | 45.98 | 1.7 |
| 8 | 189.5 | 133.71 | 36.17 | 2.2 |
| 9 | 194.5 | 162.29 | 49.75 | 3.0 |
| 10 | 200 | 135.84 | 39.15 | 4.5 |
| 11 | 204.5 | 142.35 | 55.21 | 5.4 |
| 12 | 223.5 | 20 | 30 | 7.25 |
| 13 | 228 | 140 | 70 | 5.8 |
| 14 | 231 | 185 | 80 | 7.85 |
| 15 | 252 | 160 | 80 | 6.25 |
| 16 | 259 | 140 | 55 | 5.82 |

| | | | | |
|---|---|---|---|---|
| 17 | 282.3 | 179 | 39 | 9 |
| 18 | 284.5 | 82 | 57 | 5.34 |
| 19 | 286 | 145 | 84 | 6.25 |
| 20 | 288 | 185 | 0 | 7.5 |
| 21 | 294.5 | 217 | 90 | 8.8 |

(iii) Location: ISM 03 (-23m RL) West Mochia mine

| Sl. No. | Borehole/Test zone depth (m) | Fracture strike N-E (°) | Fracture Inclination (0-90°) | Shut-in-pressure (MPa) |
|---|---|---|---|---|
| 1 | 55.97 | 277.5 | 85.1 | * |
| 2 | 77.5 | 223.4 | 78 | * |
| 3 | 93.4 | 290.8 | 85.1 | * |
| 4 | 134.43 | 306.2 | 86.2 | 11.06 |
| 5 | 159.0 | 271.3 | 84.8 | 13.4 |
| 6 | 175.45 | 145 | 60.6 | 13.07 |
| 7 | 207.45 | 315.3 | 88.8 | 11.0 |
| 8 | 228.69 | 269.2 | 61.2 | 8.7 |
| 9 | 237.298 | 197.8 | 89 | 24.0 |
| 10 | 249.8 | 283.3 | 71.1 | 9.0 |
| 11 | 283.19 | 275.1 | 89.4 | 18.0 |
| 12 | 292.44 | 116.5 | 84.9 | 17.8 |
| 13 | 293.86 | 337.3 | 87.3 | 20.0 |

Notations: *Shut-in pressure could not be achieved

(iv) Location: ISM 04 (110m RL) Central Baroi mine

| Sl. No. | Borehole/Test zone depth (m) | Fracture strike N-E (°) | Fracture Inclination (0-90°) | Shut-in-pressure (MPa) |
|---|---|---|---|---|
| 1 | 57.1 | 340.6 | 89.6 | 7.8 |
| 2 | 76.2 | 214.1 | 89.4 | 13.0 |
| 3 | 91.8 | 221.3 | 72.6 | 12.9 |
| 4 | 126.4 | 177.8 | 55.1 | 12.09 |
| 5 | 132.8 | 145.9 | 89.2 | 11.45 |
| 6 | 150.6 | 351.7 | 88.5 | 12.36 |
| 7 | 168.4 | 202.2 | 88.5 | 13.94 |
| 8 | 207.5 | 263.5 | 89.4 | 8.0 |
| 9 | 220.6 | 147.6 | 77.2 | 11.5 |
| 10 | 235.0 | 342.4 | 85.4 | 13.29 |
| 11 | 243.5 | 291.5 | 87.2 | 7.3 |

Notation: Borehole was jammed after 250m

(v) Location: ISM 05 (-130m RL) Zawarmala mine

| Sl. No. | Borehole/Test zone depth (m) | Fracture strike N-E (°) | Fracture Inclination (0-90°) | Shut-in-pressure (MPa) |
|---|---|---|---|---|
| 1 | 59.64 | 119.28 | 77.8 | 13.6 |
| 2 | 64.02 | 25.21 | 83.42 | 14.0 |
| 3 | 89.49 | 76.61 | 83.57 | 13.0 |
| 4 | 142.71 | 265.3 | 89.4 | 13.8 |

| | | | | |
|---|---|---|---|---|
| 5 | 150.41 | 153.4 | 72.8 | 13.5 |
| 6 | 163.64 | 181.9 | 75.1 | 14.6 |
| 7 | 210.9 | 259.5 | 80.7 | 14.1 |
| 8 | 215.66 | 207.4 | 82.1 | 14.2 |
| 9 | 240.32 | 246.9 | 84.4 | 12.8 |
| 10 | 252.82 | 306.3 | 75 | 16.5 |
| 11 | 281.45 | 275.1 | 89.4 | * |
| 12 | 286.72 | 116.5 | 84.9 | * |
| 13 | 293.39 | 337.3 | 87.3 | * |
| 14 | 299.21 | 283.7 | 84.2 | * |

<u>Notations</u> *Shut-in-pressure could not be achieved.

Table 2 - Results

(i) Location: ISM 01 (45m RL) Balaria mine

| Rock cover (m) | Test depth (m) | $\sigma_h$ (MPa) | $\sigma_H$ (MPa) | $\phi$ (°) | $\sigma_{Vc}$ (MPa) | $\sigma_{Vm}$ (MPa) | 'k' ($\sigma_{Vc}$) | 'k' ($\sigma_{Vm}$) |
|---|---|---|---|---|---|---|---|---|
| 553.43 | 75 | 0.91 ± 0.03 | 1.36± 0.05 | 90 | 15.2 | 1.01 (552.63m) | 0.09 | 1.34 |
| 628.43 | 150 | 0.94± 0.05 | 1.41± 0.08 | 90 | 17.26 | 1.43 (620.63m) | 0.08 | 0.98 |
| 703.43 | 225 | 1.03 ± 0.03 | 1.55± 0.05 | 130 | 19.32 | 1.07 (679.63m) | 0.08 | 1.44 |
| 778.43 | 300 | 1.27 ± 0.24 | 1.9 ± 0.37 | 100 | 21.38 | 1.66 (767.93m) | 0.09 | 1.19 |

(ii) Location: ism 02 (-105 mRL) Balaria mine

| Rock cover (m) | Test depth (m) | $\sigma_h$ (MPa) | $\sigma_H$ (MPa) | $\phi$ (°) | $\sigma_{Vc}$ (MPa) | $\sigma_{Vm}$ (MPa) | 'k' ($\sigma_{Vc}$) | 'k' ($\sigma_{Vm}$) |
|---|---|---|---|---|---|---|---|---|
| 515.17 | 100 | 4.7 ± 0.32 | 7.05 ± 0.49 | 120 | 14.14 | - | 0.49 | - |
| 565.17 | 150 | 4.76 ± 0.24 | 7.14 ± 0.36 | 130 | 15.51 | - | 0.46 | - |
| 615.17 | 200 | 5.43 ± 0.14 | 8.14 ± 0.21 | 130 | 16.38 | - | 0.48 | - |
| 665.17 | 250 | 5.49 ± 0.22 | 8.23 ± 0.33 | 120 | 18.25 | - | 0.45 | - |
| 715.17 | 300 | 4.71 ± 0.31 | 9.42 ± 0.63 | 100 | 19.62 | 7.5 (703.17m) | 0.48 | 1.25 |

(iii) Location: ISM 03 (-23m RL) West Mochia mine

| Rock cover (m) | Test depth (m) | $\sigma_h$ (MPa) | $\sigma_H$ (MPa) | $\phi$ (°) | $\sigma_{Vc}$ (MPa) | $\sigma_{Vm}$ (MPa) | 'k' ($\sigma_{Vc}$) | 'k' ($\sigma_{Vm}$) |
|---|---|---|---|---|---|---|---|---|
| 702.8 | 150 | 11.03 ± 0.17 | 22.07 ± 0.35 | 120 | 19.28 | - | 1.14 | - |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 777.8 | 225 | 7.97 ± 0.59 | 23.93 ± 1.77 | 110 | 21.34 | - | 1.12 | - |
| 852.8 | 300 | 17.06 ± 0.51 | 25.6 ± 0.77 | 120 | 23.4 | - | 1.09 | - |

(iv) Location: ISM 04 (110m RL) Central Baroi mine

| Rock cover (m) | Test depth (m) | $\sigma_h$ (MPa) | $\sigma_H$ (MPa) | $\phi$ (°) | $\sigma_{Vc}$ (MPa) | $\sigma_{Vm}$ (MPa) | 'k' ($\sigma_{Vc}$) | 'k' ($\sigma_{Vm}$) |
|---|---|---|---|---|---|---|---|---|
| 530.434 | 75 | 6.39 ± 0.14 | 12.78 ± 0.29 | 120 | 14.55 | - | 0.87 | - |
| 605.434 | 150 | 9.21 ± 0.35 | 13.82 ± 0.535 | 110 | 16.61 | - | 0.83 | - |
| 680.434 | 225 | 7.34 ± 0.18 | 14.68 ± 0.37 | 100 | 18.67 | - | 0.78 | - |

(v) Location: ISM 05 (-130m RL) Zawarmala mine

| Rock cover (m) | Test depth (m) | $\sigma_h$ (MPa) | $\sigma_H$ (MPa) | $\phi$ (°) | $\sigma_{Vc}$ (MPa) | $\sigma_{Vm}$ (MPa) | 'k' ($\sigma_{Vc}$) | 'k' ($\sigma_{Vm}$) |
|---|---|---|---|---|---|---|---|---|
| 751 | 75 | 10.55 ± 1.21 | 15.82 ± 1.81 | 130 | 20.6 | - | 0.76 | - |
| 826 | 150 | 11.43 ± 0.6 | 17.15 ± 0.9 | 120 | 22.66 | - | 0.75 | - |
| 901 | 225 | 12.54 ± 0.6 | 18.81 ± 0.9 | 100 | 24.72 | - | 0.76 | - |

**5.1 Balaria Mine**

i) A low stress magnitude of 1.36MPa to 9.42MPa has been observed at 553.43m to 715.17m depth. This may be due to the study area is characterized by low compressive stresses. This may be due to the the fact that region is subjected to extension tectonics (Rummel, 2005).

ii) Vertical in-situ stress was measured to be in the range from 1.01MPa to 7.5 MPa. This is measured at certain depths where the fracture traces were horizontal. Normal stress measured across the fracture is along the axis of the borehole, which is along overburden / rock cover. It is assumed in HTPF method that the borehole axis is kept vertical where it acts along one of the principal stress directions i.e., vertical stress.

iii) The k-value i.e., ratio of major horizontal stress over vertical stress is ranging from 0.45 to 1.44. This is normal at these depths. Usually, it varies between 0.5 to 3.5 at 500m to 1000m depth (Fig. 13). The stress condition is found to be moderate in this case.

iv) The average major horizontal stress direction is ranging from N105° to N120°. This is in line with the major geological structures in the area. The direction is nearly parallel to the direction of the plunge of the cross-fold present in this area. It is also sub-parallel to the trend of the lineaments in the area. Horizontal in-situ stress varies from 1.36MPa to 1.89MPa (Fig. 14).

v) A low horizontal stress gradient has been observed ranging from 0.002 to 0.01 MPa/m. This is less than the stress gradients 0.025 to 0.01 MPa/m observed at Sindesar Khurd mine, Rajasthan. This may be due to the area subjected to extension tectonics. The area may be characterized by low horizontal compressive stresses. Due to this, vertical stress may be found higher than horizontal stresses at 850m depth implying that region is subjected to extension tectonics (Gowd,, 2005).

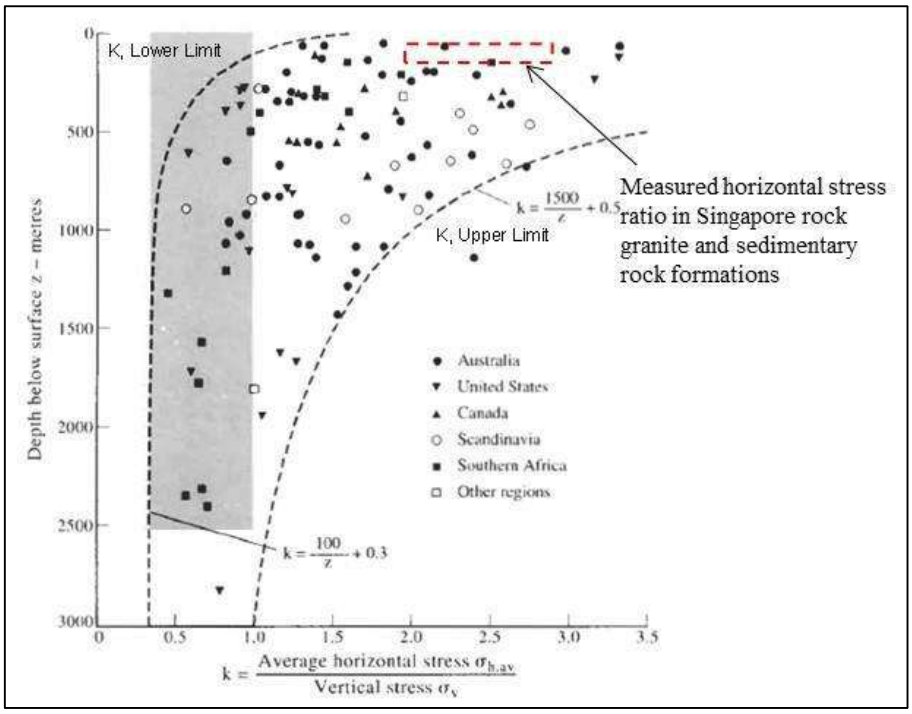


Figure 13 - Comparison of horizontal stress ratios

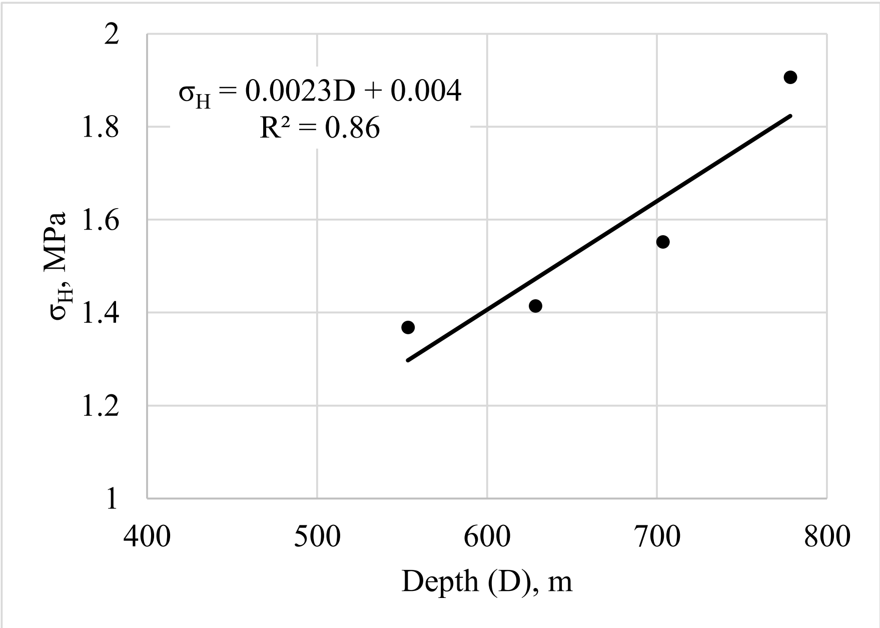


Figure 14 - Stress gradient ISM 01 (45m RL) Balaria mine

**5.2 Mochia mine**

i) A moderate to high stress magnitude of 22.07 to 25.60 MPa has been observed at 702.8m to 852.8m depth. Values of "k" ranged from 1.09 to 1.14. The stress condition is found to be moderate. This may be due to deeper depths and rock mass is found to be highly massive and competent.

ii) Vertical stress is calculated with respect to rock cover above the test location. It ranges between 19.28MPa and 23.4MPa.

iii) The average major horizontal stress direction is N 116°. This is in line with the major geological structures in the vicinity of the test location.

iv) A moderate stress gradient of about 0.023MPa/m was observed at three test zones in the borehole ISM 03 between 577.8m to 677.8m depth. Shut-in pressure was not achieved due to not achieving required fracture closing pressure. There was a sudden drop in pressure and critical pressure could not reach (Fig. 15).

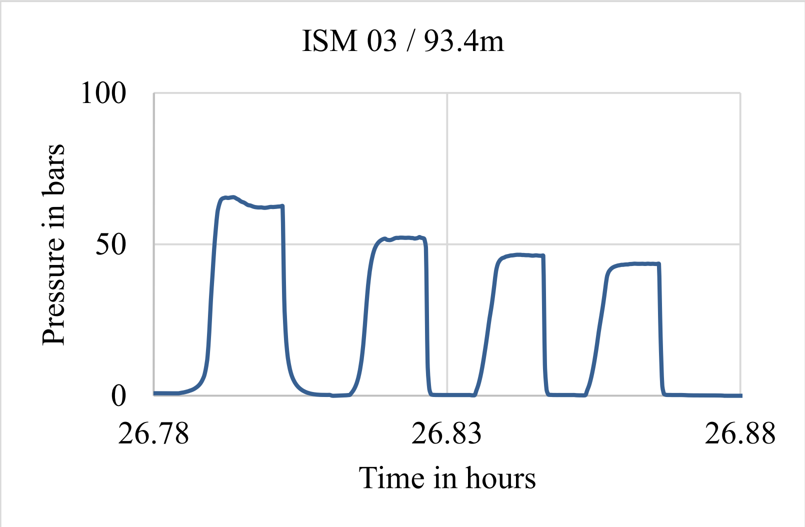


Figure 15 - Pressure vs time graph where sudden drop in fracture closing pressure.

**5.3 Baroi Mine**

i) A moderate stress magnitude was observed ranging from 12.78MPa to 14.68MPa between 530.43m and 680.43m depth. Vertical stress was computed using rock cover above the test location. It ranged from 14.55MPa to 18.67MPa. The “k” value varied from 0.78 to 0.87.

ii) The average major horizontal stress direction is N 110°. This is in line with the major geological structures in the vicinity of the test location.

iii) A moderate stress gradient of 0.012 MPa/m was observed. The number of observations were limited to three only because the borehole jammed at 705m depth. Thus, beyond this depth the stress gradient could not be measured.

**5.4 Zawarmala Mine**

i) A moderate stress magnitude ranging from 15.82 to 18.81 MPa has been encountered at 751m to 901m depth. Vertical stress is calculated with respect to rock cover over the test location. It ranges from 20.6MPa to 24.72 MPa. The k-value varies from 0.75 to 0.76. This is normal at these depths. Stress condition is found to be moderate in this case.

ii) The average major horizontal stress direction is N $116^0$. The direction is almost parallel to the plunge direction of Zawarmala anticline (NNW).

iii) A moderate stress gradient of 0.019MPa/m is observed. This is normal at these depths. The number of observations has been limited to three. This was due to the test zones in the borehole ism 05 having been intersected by closely spaced joints in between 926 to 976m depth. Shut-in pressure was not achieved due to required pressures could not be built up for attaining fracture closing pressure. There was a sudden drop in pressure and critical pressure could not be able to be reached (Fig. 16).

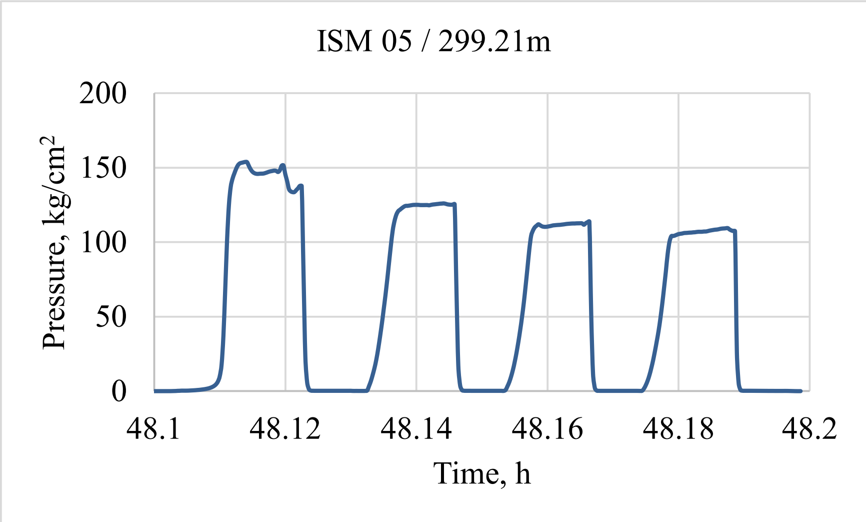


Figure 16 - Pressure vs time graph where fracture closing pressure drops suddenly

## 6. CONCLUDING REMARKS

Quality of rock mass is one of the parameters which influences value of horizontal in-situ stresses at same depth even in very close proximity. The direction of major horizontal stress in Balaria is nearly parallel to the direction of the plunge of the cross-fold present in this area. It is also sub-parallel to the trend of the lineaments in the area. The major horizontal stress in Zawarmala mine is almost parallel to the plunge direction of Zawarmala anticline (Sinha, 2005).

The stress gradient observed in Balaria was very low (0.002 to 0.01MPa/m). According to the test conducted by NGRI in the year 1999, stress gradient reported at Sindesar Khurd mine was also low i.e., 0.025 to 0.01MPa/m. On the other hand, stress gradient was found to be moderate at Mochia, Central Baroi and Zawarmala mines.

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