APPLICATION OF THE KAISER EFFECT TO THE MEASUREMENT OF IN-SITU STRESSES IN ARABIAN DEVONIAN SANDSTONE

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ABSTRACT

Well fracturing is a common completion and stimulation strategy in the deep Devonian gas fields of Saudi Arabia. Some of the reservoir rock has very low unconfined compressive strength and the potential exists to produce sand in the wells. Hydraulic fractures must be designed to maximize production and reduce the sanding potential. Proper design of the completion utilizes a multi-disciplinary approach, involving geo-mechanical testing, well testing and well log analysis. The design of the fractures requires knowledge of the mechanical properties of the rock and the minimum horizontal stress in the reservoir, and preferably knowledge of the magnitude and direction of all three principal stresses.

A rock mechanics study involving tri-axial testing and principal stress determination, utilizing the Kaiser Effect, was initiated in the candidate reservoir. Rocks and metals retain a “memory” of the highest stress to which they have been subjected. When the material is subjected to a stress exceeding the historical maximum stress, it emits acoustic energy. Monitoring the acoustic emissions (AE) while loading the rock allows one to determine the maximum stress the rock has experienced. Kaiser discovered the effect in 1950.

The tests allowed us to determine the magnitude and direction of all three principal stresses in the vicinity of the cored interval of the candidate well. In other words, the complete stress tensor was measured in the laboratory from subplugs of core. Formation image logs and drilling data were used to verify the results of the principal stress measurement based on the Kaiser Effect.

The study indicated high stress anisotropy in an area. The maximum horizontal stress was found to be the largest principal stress and the vertical stress was intermediate. The stress regime determined from our measurements is supported by evidence for similar regimes in the Permian formations in the same area.

The stress regime has important implications for completion and production of the reservoir. The ability to inexpensively determine the principal stresses in the laboratory has an important economic impact on the production of the field.

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INTRODUCTION

The Hawiyah field is a sector of the giant Ghawar field that produces hydrocarbons from several reservoirs. In recent years gas and condensate wells have been drilled in deep Devonian and Permian reservoirs of the Jauf sandstone and the Unayzah sandstone and Khuff limestone. The lithology of the Jauf sandstone varies considerably. In some zones it has high permeability and porosity and is very unconsolidated. In other zones it is extremely tight.

The variation in lithology presents challenges in well completion and stimulation. The preferred stimulation technique is propped fracturing in carefully selected perforated intervals. The strategy is to perforate and fracture the tighter zones and attempt to grow the fracture into the more permeable zones to reduce sanding problems.

The strategy requires a careful determination of the mechanical properties of the rock and of the stress profile in the well. The stress profile is often determined from dipole shear sonic logs calibrated with tri-axial tests on core. In addition a number of “mini-frac” tests have been performed to obtain information on the minimum horizontal stress.

We have attempted to characterize reservoir stress by adapting a phenomenon known as the Kaiser Effect; acoustic emission (AE) events will be detected only when a rock is loaded to its previous maximum stress. The test is extremely economical when compared to a “mini-frac” and provides a direct measurement of the principal stress tensor in the reservoir

THE KAISER EFFECT

Kaiser[1] first noted high frequency bursts of energy, or acoustic emission, during tensile tests in metals. Goodman[2] latter discovered the same effect in rocks. Studies have been carried out by a number of workers to capitalize on the effect for in- situ stress determination.[3-7]

We assume that by uniaxially loading a rock sample until acoustic emission is detected, we can determine the maximum stress that the rock has experienced in-situ in that direction. There has been at least one study that indicates that assumption may not be valid.[8] However, the Kaiser Effect is easy to demonstrate and in this study we have attempted to provide corroborative evidence that the stresses we have measured are indeed the principal stresses in the reservoir.

Figure 1 provides a demonstration of the laboratory Kaiser Effect. In this case a rock sample was instrumented with eight acoustic detectors and loaded uni-axially in a tri-axial cell. At a load of 29 KN we began to detect acoustic events. We continued to load the rock to 66 KN and then stopped the experiment and unloaded the rock. After one day, the experiment was repeated. The rock was loaded uniaxially and this time we passed through the 29 KN point without recording any acoustic events. Acoustic emission (AE) onset was at 66 KN where we had stopped loading the day before.

In the previous demonstration and in the remainder of this work we have utilized acoustic emission onset directly as the indicator of maximum stress. Some researchers[9] apply more sophisticated statistical techniques to the determination of the point that the cumulative event curve indicates the maximum stress.

The Kaiser Effect is a direct measurement of the stress tensor under the given assumptions. No other technique that we are aware of provides a direct measurement of all three principal stresses and their directions. The authors referenced above have addressed all the assumptions and caveats concerning rock age, lithology, moisture content and others, and they will not be discussed in this paper.

SAMPLE TESTING

Oriented core was available from a vertical well that was a hydraulic fracture candidate; consequently, we chose that well to conduct our tests. Orientation of the core was important to verify the direction of the stresses. Sampling was in a depth interval a few feet below the planned perforation and fracture initiation zone.

In our study we assumed that the vertical stress was the overburden due to gravity loading, and that it was a principal stress. The vertical stress was determined from integration of the density log. The assumption that the vertical stress was known and a principal stress reduced the problem to a plane stress problem. The plane stress tensor has three independent components as opposed to six for the full three-dimensional stress tensor. Consequently, only three measurements were required to determine those components. Though nothing in principle prevents us from measuring all six components the saving in time is substantial. The assumption of the "vertical" stress being a principal stress has to be examined in each case. In some cases the principal stresses may not be aligned with a Cartesian system oriented along the borehole.

Three horizontal subplugs were taken from the four-inch whole core. The subplugs were nominally 1.5 inches in diameter and 3 inches long. The plugs were oriented relative to the lead orientation scribe mark on the whole core and sampled at 0 radians, $\pi/4$ and $\pi/2$ radians relative to the scribe mark (Figure 2). The orientation survey for the core indicated that the lead scribe mark at the sampling depth had an orientation of 127 degrees south of north or 2.22 radians clockwise.

The dry subplugs were jacketed in copper. The copper jackets were set in a pressure vessel at 8 MPa, assumed to be well below the effective reservoir stress. The jacketed rocks were mounted with axial and radial strain gauges and eight acoustic emission detectors.

Additional samples were taken for standard multistage tri-axial tests and velocity measurements. The results of these tests determined the unconfined compressive strength and elastic moduli of the rock and were used to assess mechanical property logs derived from dipole shear sonic logs and formation image logs. Estimates of Biot's constant were also based on the tri-axial test results.

The samples were confined at 5 MPa. and loaded uni-axially at a constant strain rate of 5.7 microstrain per second. Figure 3 is a plot of the cumulative event count curve for each of the three samples that were tested. Acoustic emission onset occurs at 25.7 MPa. for the sample oriented at 0 radians (lead scribe knife), 32.8 MPa. for the sample at lead plus $\pi/4$ radians and 56.6 MPa. for the sample at lead plus $\pi/2$ radians.

RESULTS

The three stresses determined by acoustic emission onset are assumed to be the maximum stress experienced by the rock in a plane normal to the sampling direction and applied stress. Those stresses are not the principal stresses in the horizontal plane, but the magnitude and direction of the principal stresses relative to the sampling direction can be calculated. A graphical calculation is illustrated in Figure 4. The measured stresses are normal stresses and plot on the normal stress axis. These must project onto a Mohr's circle in the normal stress, shear stress plane. The intersection of the circle with the normal stress axis determines the two principal horizontal stresses. The angle ϕ is the angle through which the coordinates must be rotated to align the sample axis axes with the principal stress directions.

The effective principal stresses determined from the test were σ_{min}=28.58 MPa. and σ_{max}=63.9 MPa. The stress anisotropy is about 35.1 MPa. The angle ϕ, between the coordinate system relative to the lead scribe knife and the minimum stress is 0.24radians. The field stress is determined by adding the reservoir pore pressure to the effective stress. The reservoir in the study is over pressured with a pore pressure gradient of .014 MPa./m. At the sample depth the pore pressure is 59.7 MPa.

Principal Stress	**From Kaiser**	**From Well Logs**	**Stress Orientation**
σ_v	104.5 MPa	104.5 MPa	
σ_{hmin}	88.23 MPa	82.8 MPa	141 deg
σ_{Hmax}	123.6 MPa	86.8 MPa	51 deg
$\Delta\sigma_{hor}$	35.1 MPa	3.9 MPa	

Table 1 Principal stresses estimated from the Kaiser Effect and from well logs.

The effective vertical stress at the test depth, as determined by integrating the density log, is 44.83 MPa. Thus the Cartesian stresses are σ_{hmin}=88.23 MPa, σ_v =104.5 MPa, and σ_{Hmax}=123.6 MPa.
The vertical stress is intermediate.

DISCUSSION

The study predicts high horizontal stress anisotropy and an intermediate overburden stress. Additional evidence was sought to confirm our findings.

The formation image log provided the best evidence of high stress anisotropy. Figure 5 is a segment of the formation image log at the same depth in the well as that of the samples tested. Breakouts are clearly evident as blurry zones in a direction trending northwest southeast. Since the well is a vertical well, anisotropy between the minimum and maximum horizontal stress, or an unusually low mud weight, is required to produce a breakout. Given the mud weight, rock strength and Biot's constant, the stress anisotropy required producing the breakout could be determined from the standard equations of borehole stability.

We had taken auxiliary samples for tri-axial testing and were able to measure the required parameters. Figure 6 is an example of the stress-strain curve of a multi-stage tri-axial test of a rock sample from the zone of interest. The rock had an unconfined compressive strength of 62.28 MPa. and a friction angle of 39.5 degrees. Biot's parameter was estimated to be 0.75. The parameter was estimated from the bulk modulus determined from the tri-axial test, approximately 30 Gpa, and the Hill average of the grain bulk modulus, approximately 39 Gpa.

A Mohr-Coulomb failure surface was constructed for the rock. Figure 7 plots the failure surface as a function of angle around the borehole for a Biot's constant of 0.75. The tangential stress is plotted and was computed from the maximum and minimum horizontal stress that we measured utilizing the Kaiser Effect. The tangential stress is the maximum stress in this case. The radial stress is the hydrostatic stress provided by the known mud weight and is the minimum stress in the borehole. The axial stress is intermediate. The graph indicates that failure would only occur for high horizontal stress anisotropy as observed in our measurements in the laboratory. Given the parameters determined in the laboratory and the mud weight from the drilling report, the breakouts should subtend a sixty-degree arc centered on the minimum principal stress direction. This is observed in the formation image log.

Since the core was oriented, the direction of the minimum and maximum stress could be determined. The lead scribe mark was oriented at 2.22 radians southeast of true north in the depth interval at which the subplugs were sampled. The Mohr's circle analysis indicates that the direction of the minimum stress is 0.24 radians (14 degrees) clockwise from the sample taken in the direction of the lead scribe mark. In other words, we add 0.24 radians to the 2.22 radians of the lead scribe knife to obtain 2.46 radians (141 degrees) for the direction of the minimum principal stress. Thus the minimum principal stress is oriented on a north south line about 39 degrees west of north to 39 degrees east of south. The maximum principal stress is oriented orthogonal to the minimum stress and roughly east west. The orientation of stresses is in complete agreement with directions determined from regional breakout analysis.[10]

Knowledge of the stress regime is important in the design of well fracture stimulation but also impacts horizontal drilling in the area. Without additional information, one might expect the ordering of stresses to be $\sigma_V>\sigma_H>\sigma_h$. In that case, maximum horizontal borehole stability would be obtained by drilling in the direction of σh, possibly determined from a study of hole ovalization in vertical wells (caliper log). However, the stress regime in the Devonian reservoirs of Saudi Arabia is $\sigma_H>\sigma_V>\sigma_h$ and the magnitudes are such that drilling in the direction of σ_H should provide maximum stability. That is actually found to be the case.

CONCLUSIONS

The in-situ stress tensor was measured in the laboratory using the Kaiser Effect to estimate the maximum stress experienced by the rock in the earth. Analysis of breakouts observed on formation image logs coupled with known mudweight form the drilling log and rock strength derived from triaxial testing was used to corroborate the results of the Kaiser Effect analysis.

The stress tensor was consistent in direction with regional stress directions determined from breakout analysis of other boreholes in the area. The stress magnitude and stress order, that is $\sigma_{hmin}<\sigma_v<\sigma_{Hmax}$, is consistent with observations from dipole shear sonic logs in the area. The minimum horizontal stress is also consistent with stresses determined form “mini-frac” tests.[11]

The use of oriented core allowed us to determine the stress directions in an absolute sense. In the absence of oriented core one could rely on regional breakout analysis to provide the stress direction, or local breakout analysis of the sampled well using ultrasonic borehole imaging , resistivity imaging or caliper logs.

The advantage of using the Kaiser Effect on oriented core is that the complete stress tensor is derived. The magnitude of the stress is important in determining the stress order, which may impact directional drilling. Furthermore, knowledge of the stress magnitude is useful in the design of well fracturing jobs and in determining sanding potential of a well.

Although application of the Kaiser Effect to the determination of in-situ stress remains controversial there are a number of studies where it has been successful and this case study can be added to that list. To date it is the only technique that provides a direct measure of the magnitude and direction of the stress and is considerably cheaper than competing methods of stress measurement.

ACKNOWLEDGEMENTS

We would like to thank the management of Saudi Aramco and the Laboratory R&D Center for providing support and permission to publish this work.

REFERENCES

1. Kaiser, J., ”An Investigation into the Occurrence of Noises in Tensile Tests or a Study of Acoustic Phenomena in Tensile Tests,” Ph.D. Thesis, Tech. Hosch. Munchen, Munich, Germany, 1950.
2. Goodman, R. E., “Subaudible Noise During Compression of Rocks,” *Geol. Soc. Amer. Bull.* (1963) **74,** pp.487-490.
3. Yoshikawa, S., and Mogi, K., “A new method for estimation of the crustal stress from cored rock samples: laboratory study in the case of uniaxial compression,” *Tectonophysics*, (1981) **74,** pp. 323-339.
4. Holcomb, D. J. and Martin, R. J., ”Determining peak stress history using acoustic emissions,” *26th US Symposium on Rock Mechanics*, 26-28 June, 1985, Rapid City, SD, pp. 715-722.
5. Michihiro, K., Fujiwara, T. and Yoshioka, H., ”Study on estimating geostresses by the Kaiser Effect of AE,” *26th US Symposium on Rock Mechanics*, 26-28 June, 1985, Rapid City, SD, pp. 557-564.
6. Momayez, M. and Hassani, F. P., “Application of Kaiser Effect to measure in-situ stresses in underground mines,” *Rock Mechanics,* Balkema, Rotterdam 1992, 979-988.
7. Jingen, D, Kangping, W. and Rongzun, H., “In-situ stress determination at great depth by using acoustic emission technique,” *Rock Mechanics,* Balkema, Rotterdam 1995, pp. 245-250.
8. Holcomb, D. J., “General Theory of the Kaiser Effect,” *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, (1993) **30**, 7, pp 929-935.
9. Momayez, M., Hassani, F. P. and Hardy, H. R., “Maximum Curvature Method: A Technique to Estimate Kaiser-Effect Load from Acoustic Emission Data,” *Journal of Acoustic Emission,* (1992) **10**,3/4, pp 61-66.
10. Temeng, K. O., Al-Amoudi, M. O. and Chardac, O., “Magnitude and Orientation of In-Situ Stresses in the Ghawar Khuff Reservoirs,” *SPE Annual Technical Conference, Houston, Texas*, October, 1999, **SPE 56511**.
11. Frignet, B., “Evidence of Dominant Horizontal Stress in Haradh’s Khuff Formation from Shear Anisotropy and Breakout,” *Internal Report for Saudi Aramco*, 1997.

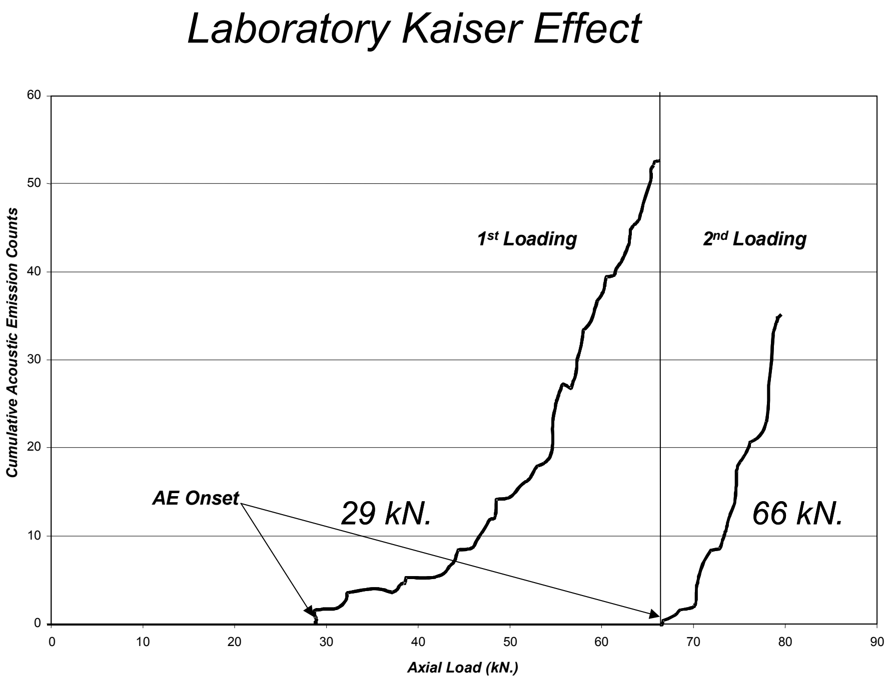

Figure 2 Subplug sampling was with respect to the lead scribe mark which was initially assumed to be oriented north.

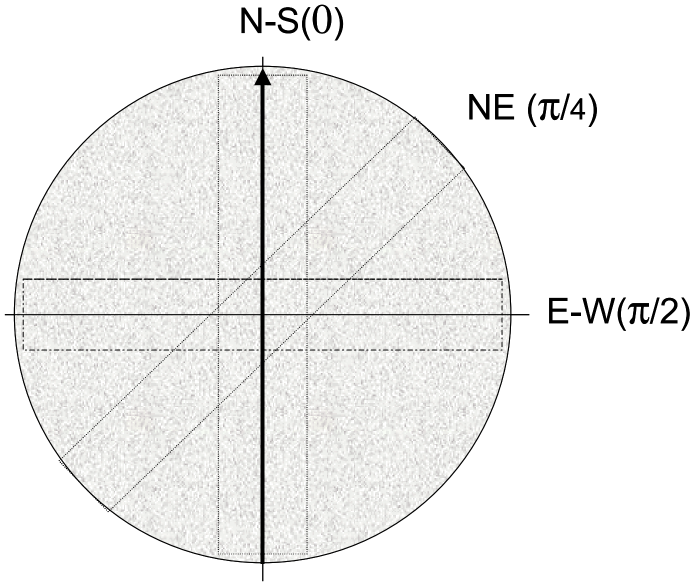

Figure 1. Demonstration of the laboratory Kaiser effect. AE onset begins in the second loading at the maximum stress applied to the rock sample in the first loading

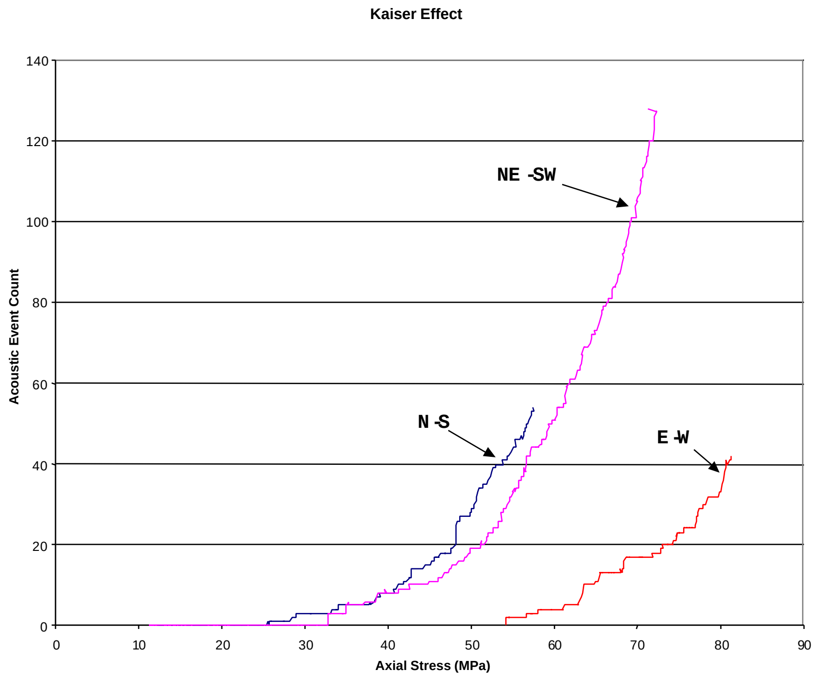

Figure 3 Cumulative AE curves from three subplugs. Note AE onset at 26 MPa (N-E), 33 MPa (NE-SW) and 54 MPa (E-W).

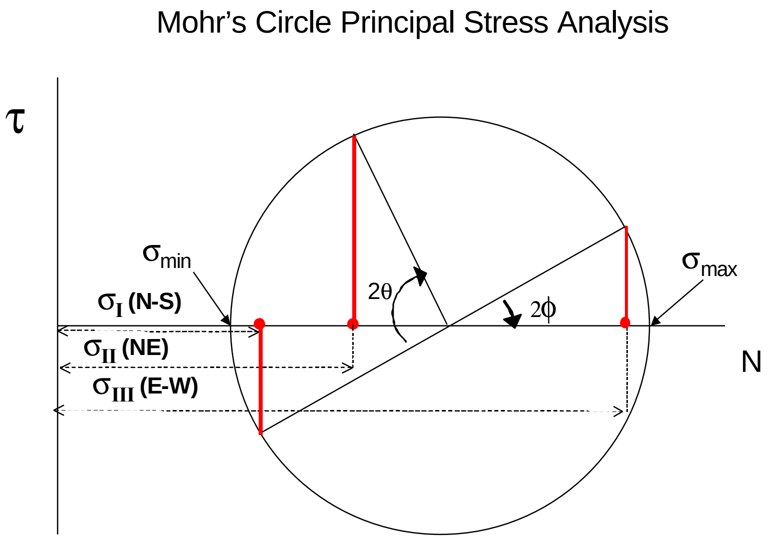

Figure 4 Graphical analysis of the data in Figure 3. s_{I}, s_{II} and s_{III} refer to the minimum, intermediate and maximum stress at AE onset in Figure 3. $s_{\min}$ and $s_{\max}$ are the computed minimum and maximum horizontal stress.

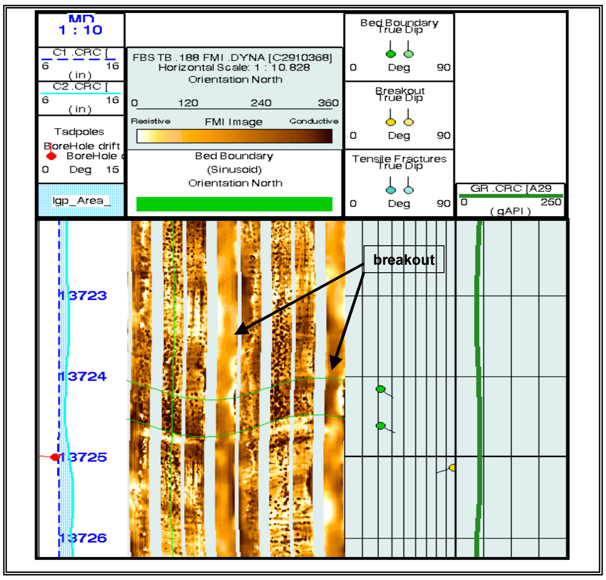

Figure 5 An image log of the borehole wall at the depth where our test specimens were sampled. Note the breakouts trending northwest to southeast and subtending angles of about 60 degrees.

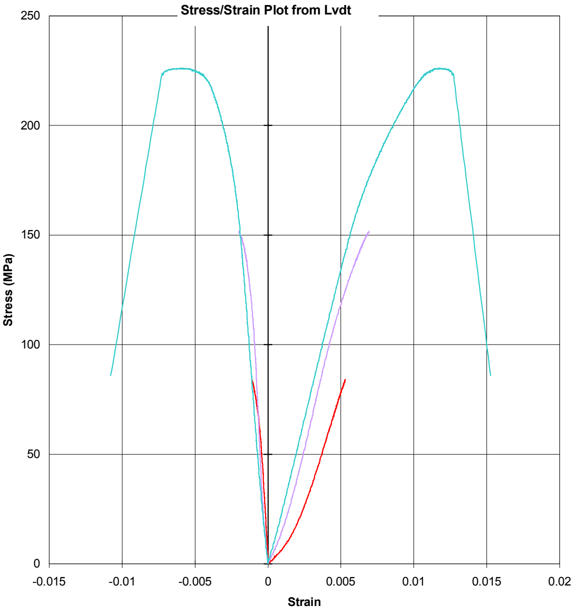

Figure 6 A typical multistage triaxial test on a sample from the study.

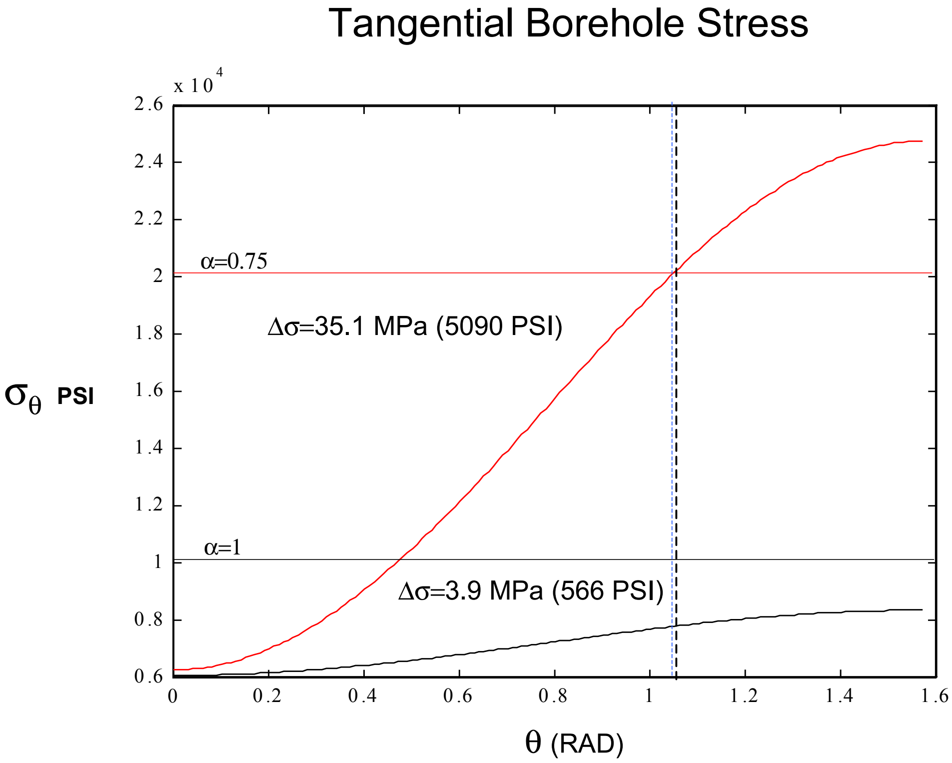

Figure 7 A graph of tangential stress at the borehole wall for stress anisotropy estimated from the Kaiser Effect and from well logs (see Table 1). The constant alpha lines represent failure envelopes for Biot's constant equal to 1 and 0.75. The graph indicates that for stress anisotropy of 35.1 MPa (Kaiser Effect estimate) borehole breakouts would begin at about 1.05 radians (60 deg.) consistent with breakouts observed in the image log (Figure 5).

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