The Shale Activity Test (SAT)*

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Search and Discovery Article #41855 (2016)**
Posted August 15, 2016

*Adapted from extended abstract based on oral presentation given at AAPG GEO 2016, The 12th Middle East Geosciences Conference and Exhibition March 7-10, 2016, Manama, Bahrain

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Abstract

Shale (compacted clay and/or mudstone) has potential properties of swelling, softening and micro-fracturing when exposed to the fresh water. A conventional swell test on shale is very slow, takes months to achieve full swelling potential and provides a very limited amount of quantitative petrophysical parameters which could be used to predict shale behavior during interaction with drilling and completion fluid. This article introduces the Shale Activity Test (SAT) on shale samples interacted with water, which is based on a continuous measurement of density fluctuation in time due to swelling (volume increase in the same mass of sample in water) and subsequent micro-fracturing.

Measurements obtained from SAT could be used to design a new approach to calculate mechanical properties of shale formations in the well bore affected by drilling or completion. The test is run in real time with the Rate of Swelling (ROS) being the output parameter as measurement of variations of density. This parameter could be calibrated with any other parameters of a conventional swell test for four distinctive behaviors of the shale: non-swelling, nonlinear swelling, linear swelling and periodical swelling. Each behavior corresponds to a particular shale type.

During the test, first the swelling process develops and is reflected on the chart as a decrease in density. Then, subsequent fractures parallel to the sedimentary layered surfaces take place, and are reflected on the chart as an increase in density. The ratio of density change over the time is called Rate of Swelling (ROS). In some shales the ROS is represented by a saw tooth ripple on the main trend of shale activity. ROS secondary variations represent the mechanical models of micro laminations filled with thin films of seasonal clay/silt deposition. The frequency and quantity of the ripples are subsequently used to predict the well stability and fractureability properties of the shale. Since the ROS can be measured within a substantial range of mud salinities and in oil base mud, the ROS applicability covers most type wells.

The SAT has been successfully applied to well stability evaluations in both conventional and unconventional oil fields. The final results of the test played the critical role in the determination of the best perforation zones, sweet spots within a horizontal well, and formation fractureability

for the completion stage. This article presents the fundamentals of the test, associated technology, and a comprehensive geo-algorithm for the application of SAT measurements in well log analysis.

Scope

The Shale Activity Test is an alternative independent shale activity quantitative analysis performed on drilling cuttings. The SAT provides information on a multitude of processes. These processes transpire in shale formations due to drilling, completion, and production damages in the near wellbore region. These interventions disturb the original state of the shale.

The initial distortion occurs by the mechanical drilling process inflicting the formation damage. SAT measures the shale stability parameters, shale condition, stage, and properties of mechanical stability. The second distortion is inflicted by the drilling fluids interaction with fluids of the reservoir formation shale. This is the complex system where some of the disturbances will be associated with micro-fractures, incident fracture, micro and structural layering, micro-folding and cross lamination layering. The drilling mud fluids are invading the formation and this is called a filtrate parameter or liquid loss. The third distortion is the complex of the three-dimensional stress system on the path of the well. There will be regional stresses, local faults and the direction of formation dipping in relation to the direction of the well.

Another part of the scope is the measurement and definition of fractureability parameters where the intervention is in reverse direction (from force outside in to formation). Usually fractureability is associated with Brittleness estimation; where the brittleness is calculated from logs using dipole sonic and calibrated to core plugs. The measurements of Young's Modulus and Poisson's Ratio are done on cores, logs and other measurements parameters by different API methodologies. We will expend this understanding by demonstrating the use of SAT measured parameters to compute brittleness.

Lastly we extend the completion recommendations to use the natural properties of the shale to conduct hydrocarbons for completion and production optimization. Some of the measured parameters are Rate of Swelling (ROS), Frequency of Fracturing (FF), Density of Shale, Matrix Density of Shale, and the Liquid Absorption process of swelling shales and micro fractures.

The visual monitoring of the drill cuttings in the field (using kGeo-Algorithm, advanced digital wellsite geology and mudlogging) can also provide the early warnings upon well stability. Mud interaction with the formation influences the well stability. Recommendations can be made on mud parameters, its composition, and influence on the stability of the formation and the well bore. The Nahr Umr Shale (see Figure 1) has a splintery form of shale cuttings which reflect the well damage inflicted on the well bore during drilling. The shale is fissile and caving. The mud properties are not adequate for stability and safe drilling. There is also visible structural deformation - micro folding, which requires additional attention during the drilling activity.

Introduction

The Shale Activity Test is a new process and algorithm which is based upon the shale's ability to absorb water and dilate. The increase in volume of the sample with a fixed mass will follow with a decrease in density. This process is also associated with swelling.

The method is based upon measuring the density variations of a sample in time when exposed to target fluids. A continuous time record of the sample weight in water (or calibrated target fluid) is recorded using a modified Archimedes apparatus (Figure 2).

The sample is submersed in the target fluid and the weight is recorded as a function of time. Figure 3 illustrates the graphical presentation of SAT. A downward deflection on the graph (the weight in liquid decreases) demonstrates swelling and the decrease of the density. An upward deflection on the graph represents an increase in sample density. Some of the density fluctuations are due to incident fractures and micro-laminations in shale. The liquid is injected in the shale structure, micro-laminations, incident and micro-fractures by capillary forces, at atmospheric pressure, and is opening the incident fractures aperture and converting them to micro fractures. These micro fractures are open to liquids which fill the volume created.

The example SAT (Figure 4) illustrates a variety of swelling - ROS in time. There are different methods to present quantitatively the swelling rate. This technique is practical for well stability and fractureability characterization and has the advantage that it is performed on drilling cuttings. This could be done in real time at the rig site.

In some cases the natural fissile shale is composed of hard argil-shale separated by seasonal micro-layered dust surfaces. The dust surfaces are generally siltier than the shale matrix and have higher capillary properties than the argil-shale. During formation intervention (both drilling and completion) the capillary suction of water is started and creates a wedge force, splitting the shale in micro laminations. This water later is adsorbed by clay minerals and swelling commences. Once the adsorption process starts, it acts as a wedge to split the solid part of fissile shale structure. This process is much quicker in time as the fissile aperture is much greater than regular inter-crystalline clay swelling which occurs due to diffusion of water molecules. The process of wedging the shale micro laminations is quantified by SAT with the FF (Frequency of Fracturing) parameter which is presenting the quantity of fracture ripples on the curve per unit time (Figure 5).

The frequency of the events is calculated and is used to adjust the acoustic and elastic properties of the shale formation. Using the Matrix Density and component analysis the parameters DT_C and the DT_S are calculated. This methodology contrasts to the more conventional techniques

- The conventional stress and strain test usually is run on core plugs and the extrapolated to the whole area (Worthington et al., 2011; Lyu et al., 2015).
- The logs method uses parameters that are averaged by 3 ft or 1 m. Thus the shale micro-structure is not reflected on the logs.

The SAT parameters could fill up missing information in conventional petrophysical and geo-mechanical analysis.

SAT Process

The SAT test requires special sample preparation.

Stage 1: The cuttings are sieved and washed with surfactants to eliminate the possible surface oil contaminations from drilling mud and pipe dope. Next the cuttings are air dried in special dryer.

Stage 2: The sample is split into 4 parts. One sample is processed by SAT and 3 samples are processed by kLab. Associated kLab analysis provids additional information for the kGeo-Algorithm and are not presented in this article. Examples of the kLab parameters used are Bulk Density, Matrix Density, Lithology component, Hydrocarbon type and content.

Stage 3: Continuous density fluctuation charts are recorded and analyzed using SAT. Figure 6.

Stage 4: During the SAT microscopic photography is performed and the visual analysis is performed. The swelling and fracturing process is observed within the shale sample submerged in the target fluid. The incident fractures expand to micro-fractures which grow subsequently into open fractures (Figure 7).

Stage 5: Next the sample is dried and a Digital Lithological Analysis (DLA) is performed to analyze the shale distortion after the test.

Stage 6: In parallel the 2 dry sample splits are analyzed using kLab Digital Lithological Analysis (DLA) and kLab Digital Density Analysis (DDA) methodologies. In these tests the mineralogical component and granulometry parameters are obtained.

Stage 7: All SAT measured data is tabulated and then processed using the kLab kGeo-Algorithm filtering, and a subsequent normalization process is employed to convert to conventional type measurements, dimension and values.

Stage 8: The results are then imported into conventional petrophysical software for display. The kGeo-Algorithm inversion process is used to produce the continuous log curves from discrete sample data. The inversion algorithm is designed on individual petrographic and petrophysical characteristics of the reservoir formation obtained. The kGeo-Algorithm uses direct mechanical and lithological properties of the formation, and compliments conventionally used statistic and stochastic methods. Next, the kGeo-Algorithm processing and correlation of the kLab data to conventional log data sets is performed.

Stage 9: Then the brittleness, fractureability, and well stability are defined and interpreted.

Algorithms

The three densities of shale are measured and calculated: kLab DDA Bulk Density, kLab DDA component Density, and kLab DDA Clastic Density. The Matrix density is calculated as a sum of component densities. In addition, two kLab analyses are performed. The micro granulometry (MGA) derives the grain distribution and frame work which defines the quantity of each fraction by size. The kLab Hydrocarbon Analysis (HCA) derives the extractable oil saturation, kSo_res, and total organic content (TOC).

1. Bulk Density of Shale calculated from DDA measurements of weight in air and weight in water.

2. Density of Clastic component Shale calculated from DDA measurements of weight in air and weight in water.

3. Matrix Density of Shale is calculated as a sum of components density (mass balance)
kDDA_NRhoM = 0.01*∑ (kDDA_NRhoM_ls*kDDA_Q_ls + kDDA_NRhoM_dol*kDDA_Q_dol
+ kDDA_NRhoM_clast*kDDA_Q_clast)

Where:

kDDA_NRhoM	= matrix density from DDA
kDDA_NRhoM_ls	= matrix density of limestone
kDDA_Q _ls	= quantity of limestone as a $CaCO_3$
kDDA_NRhoM_dol	= matrix density of dolomite as a $CaMg\ (CO_3)^2$
kDDA_Q_dol	= quantity of dolomite
kDDA_NRhoM_clast	= density of clastic
kDDA_Q_clast	= quantity of clastic total

The clastic density can be further subdivided by separating out the clay particles. The density of the resulting components would be:

kDDA_NRhoM_NoClay_clast	=density of clastics without clay components
kDDA_Q_NoClay_clast	=quantity of clastic without clay components (usually quartz, pyrite and other heavy minerals)

kDDA_NRhob_clast_NoClay *100 = kDDA_NRhoM_Qtz *(100-X) + kDDA_NRhoM_Pyr *X

Where the X; is the quantity of pyrite in the clastic portion of the sample.

4. Using the inversion process the bulk density, RhoB, obtained from log measurements can be corrected by DDA_RhoM and a corrected porosity can be calculated as kDDA_PhiB.

5. The compressional sonic travel time of the matrix, kDTC_ma, can be calculated as the volumetric sum of computational components travel time. The resulting equation is:
kDTC_ma = $\sum_{i=1}^{n} Vol_i * \Delta tc_i$ (after Crain)

6. The compressional sonic travel time can be calculated using the following equation:
kDTc = {kDTC_ma/(1-PhiB)} + PhiB*DT_{water}

7. Similarly the kDTs can be computed using the component volumes and shear transit times as:
kDTs = $\sum_{i=1}^{n}(Vol_i * \Delta ts_i\ )$ (after Crain)

8. The poro-elastic parameters can be computed as follows:

8.1 Shear Modulus, **N** (x10^6 psi) = 13400*$^{\rho_b}/_{\Delta t_s^2}$

8.2 Poison's Ratio, **PR** = (.5* $({}^{\Delta t_s}/_{\Delta t_c})^2$ -1)/($({}^{\Delta t_s}/_{\Delta t_c})^2 - 1)$

8.3 Bulk Modulus, $\boldsymbol{k_b}$ (x10^6 psi) = 13400*ρ_b/$({}^1/_{\Delta t_{c\_}^2})$ - $\frac{4}{3}$*$({}^1/_{\Delta t_s^2})$

8.4 Bulk Modulus of the matrix, $\boldsymbol{k_m}$ (x10^6 psi) = 13400*ρ_{ma}/$({}^1/_{\Delta t_{c\_}^2})$ - $\frac{4}{3}$*$({}^1/_{\Delta t_s^2})$

8.5 Bulk Compressibility, $\boldsymbol{C_b}$ = $1/k_b$

8.6 Matrix Compressibility, $\boldsymbol{C_m}$ = $1/k_m$

8.7 Biot's Constant, **α** = 1 - k_b/k_m or 1 - $C_m/\ C_b$

8.8 Young's Modulus, **Y** (x10^6 psi) = 2* N * (1 – PR)

8.9 Lame's Constant (Brittleness index), **L** (x10^6 psi) =$^{(Y * PR)}/_{(1 - 2 * PR)}$

8.10 Glorioso brittleness index:

$$\boldsymbol{BI_{lith}} = \frac{\text{(kDDA\_Q\_qtz + kDDA\_Q\_ls+ kDDA\_Q\_dol+ kDDA\_Q\_anhy)}}{\text{(kDDA\_Q\_qtz + kDDA\_Q\_ls+ kDDA\_Q\_dol+ kDDA\_Q\_anhy+ kDDA\_Q\_sh+ kDDA\_Q\_ker)}}$$

8.11 Sample Volume, $\boldsymbol{V_{smp}}$ (cm^3) = $^{(Wt_{air} - Wt_{liq})}/_{\rho_{liq}}$

1) If V_{smp} increases with time then shale swelling is indicated

2) If V_{smp} decreases with time then shale fracturing is indicated

8.12 The ROS by weight, **ROSwt** = Const*$\frac{dWt_{liq}}{dt}$

8.13 The ROS by volume, **ROSvol** = Const*$\frac{dV_{smp}}{dt}$

One can estimate the formation pressure increase due to swelling in time using ROSvol.

8.14 The frequency of fracturing, **FF**, is measured as fractures per second during the SAT. The quantity of fractures, **Qfr**, is the cumulative count of events between time=start and time=end.

FF =$^{Qfr}/_{(t2 - t1)}$ or $\frac{dQfr}{dt}$

Discussion

The SAT captures the dynamics of the cuttings samples as they interact with test fluids. Three events are possible: (1) no reaction with time, (2) a decrease in density indicative with swelling, or (3) an increase in density when micro-fracturing occurs. It is not unusual to see first swelling followed by micro-fracturing. In Figure 8, the densities, D_0, D_1, and D_2, represent specific density measurements during the test.

- D_0 is the density of the shale at the initiation of the SAT.
- D_1 is the minimum density of the shale after swelling and at maximum stress, σ_{max}.
- D_0 is the maximum density of the shale following micro-fracturing. The fissures expand and fill with the test liquid. The stress is at a maximum, σ_{max}
- And subsequently a hydrostatic balance is established, σ_{end}.
- The difference between D_0 and D_1 is the density differential caused by swelling of the shale. The pressure applied on the surrounding formation is a function of the Bulk Modulus, B, of the shale and can be calculated thusly:

$$P = \sigma_v = B * \varepsilon_{vc}$$

- The pressures associated with the minimum and maximum strains can be derived using the previous equation. By employing the SAT measurements one can extract the pressures, Pmin and Pmax to perform Mohr Circle analysis (Figure 9).

Analyzing the FF (Frequency of Fractures) the shear stress with which one can further characterize the interaction of micro-fractures and micro-laminations with the conventional Mohr Circle Analysis. The Time to Critical Limits of shear stress accumulation can be read directly from the plot to predict exposure time for the onset of rock failure while swelling.

Results

1) The Petrographic DLA Analysis of shale before and after the SAT documents the onset of swelling, new fractures, and interaction of existing micro-fractures within the sample.
2) The visual effect of shale swelling matches the SAT curves that show a decrease in density with ROS > 0.
3) The micro laminated shale is developing micro-fractures along the fissile surface. The SAT chart captures this effect with saw tooth ripples when FF > 0.
4) The non-swelling shale is illustrated when the ROS = 0 and the SAT curve has a horizontal response.
5) The combined effect of a saw toothed rippled SAT curve with a positive (upwards) trend is indicative of observable shale splintering with increasing density due to the adsorbed liquids.
6) The micro-folded shale samples are fracking associated with increasing density as the micro-fractures fill with liquid.

7) The incident fractures are followed by swelling with a subsequent increase in density as the fractures open. This is presented on SAT as FF effect.
8) Brittleness can be redefined as a function of ROS and FF as: L = f(Y, PR, ROS, FF)
9) The brittleness model in shale can consider the inter-lamination wedging mechanism to define the fractureability.
10) The brittleness of shale with defined FF will be adjusted for frequency and amplitude of force application.
11) The shale with swelling and incident fractures are usually hard to frack. To frack this type of shale the wave force can be considerate. A process of decompression below the hydrostatic pressure is needed to initiate the incident fracturing conversion to micro-fractures and thereafter followed by compressional force.
12) The natural oil migration in shale during maturity will follow the path of micro-lamination surfaces and micro-fracture networks.
13) Well stability in shale needs to consider the ROS and FF as quantitatively measured properties of shale structure, and component mineralogical characterization.
14) The high mud weight in micro-laminated and micro-fractured shale with FF > 0 may not be the appropriate answer for well stability. A higher viscosity may be required to decrease the rate of swelling. The ECD has to be carefully considered to avoid connecting well bore erosion and pressure jump due to mud flow friction.
15) The SAT can define inherited deformation, paleo-tectonic stress or stress that is not coherent from today major axis orientation. Therefore, the closed micro-fractures will be defined by the SAT and not by the sonic. Closed micro fractures are not sensed on acoustic devices because they are a non-reflecting surface.
16) SAT defines the incident fractures as a reaction on stress, bit, or mud weight damage issues.
17) SAT and micro-cleat counts from DLA can be easily correlated with open fractures and filled fractures with calcite or silica filled fractures counts.
18) The DLA count of pyritization as an indication of open hydrothermal flow existence and DDA. Pyrite content is a quantitative quantity which can be correlated with SAT and Brittleness.
19) Using kLab Lithological composition and component density parameters, Vs and Vp, can be calculated at measurement frequency than conventional logs or LWD. Variances between the kLab results and log/LWD responses can identify anisotropy which needs to be investigated in greater detail
20) Using SAT we can run the statistics on the parameters and select the ones with correlation to major conventional parameters in the static model. Convolute these parameters to Vs and Vp using the petrophysical logs to obtain a multi-dimensional image of rock brittleness and stability and extrapolate with geophysical data.

Interpretation Example

The Cretaceous Nahr Umr Shale section illustrated in this example from the UAE offshore is a compartmentalized 300 foot section of notorious “3 day shale” (Figure 10). The formation is typically drilled with a brine saturated drilling fluid and it is not uncommon that by the time wireline logs are run the hole is significantly washed out. The issue was to determine the source of well bore instability and derive a means to mitigate it.

To define the shale properties compartments, the method combined variation difference of Formation Mechanical properties based on Density and Formation Continuity (fractures, micro-layering, micro-structures, and mineralogical variations) properties. The kGeo-Algorithm is designed. This example is one of kLab kGeo-Algorithm applications. Other combinations of kLab parameters and SAT parameters may be used. The kLab DDA Density parameters combined with SAT Density variation parameters are included in calculation of inversion curves. The inversion curves are selected to convolute the petrophysical properties of the shale and the tools measurement properties.

Parameters selected for the Inversion process to obtain the petrophysical curves for analysis of variations difference are:

- From the available open hole logs we selected the Resistivity, Micro-Resistivity, DT, and GR.
- From kLab kDDA_RhoB – bulk density of cuttings is measured.
- From kLab kDDA_RhoM – matrix density is calculated.
- From SAT the ROS – rate of swelling is calculated
- From SAT the FF – frequency of fracturing is calculated
- From SAT the Visual Analysis is used to define the type of dominant forces.

Using the kGeo-Algorithm and the parameters of kLab and SAT above, the Inversion Curves produced are:

- kDDA_RhoB_B — the bulk density tool properties to react on formation mineralogy and formation continuity.
- kDDA_RhoB_RT — the resistivity tool to react on fractures and shale layering.
- kDDA_RhoB_SFL — shallow spherical focused tool to react on micro-fractures.
- kDDA_RhoB_DT — acoustic tool properties to react on mineralogical variations.
- kDDA_RhoB_GR — the gamma ray tool properties as a correlation parameter.

To identify the compartments the curves are compered to kDDA_RhoB_B by placing them in the same column. The difference of the two curves is the visual values for interpretation. For this presentation the difference is shaded (Figure 11). The columns from left to right are:

Column 1. kDDA_RhoB_B and kDDA_RhoB_RT.
Column 2. kDDA_RhoB_B and kDDA_RhoB_SFL.
Column 3. kDDA_RhoB_B and kDDA_RhoB_DT.
Column 4. kDDA_RhoB_B and kDDA_RhoB_GR.

Zone A is differentiated through log patterns in column 1 and 4. This is illustrates the zone of dominant deformations inflicted by the fractures parallel to shale facility. The SAT curve analysis defines the ROS as linear positive.

The small amplitude FF can be observed. On the photomicrograph are the fractures generated during the SAT test (Figure 12).

Zone B is differentiated by log patterns in columns 1 and 2. This zone illustrates that the dominant deformation inflicted by fractures and micro-fractures is not parallel to the facility. This is the typical local stress (Figure 13).

The SAT curve analysis illustrates the ROS as linear, positive and with small amplitude of FF. The fractures are creating definitive peaks.

Zone C is differentiated by log patterns in columns 2 and 4. This zone illustrates that the dominant deformation is inflicted by fractures. No sample was available for SAT. The data are obtained using the extrapolation rules of kGeo_Algorithm.

Zone D is differentiated by log patterns in column 2. This zone illustrates that the dominant deformation inflicted by both micro-fractures and incident fractures (Figure 14).

The SAT identifies nonlinear curve type in the first part of test and stable thereafter. There is small amount of swelling due to micro-structures water inhibition and stable state afterwards.

Zone E is differentiated by log patterns in columns 1, 2, 3 and 4. This zone illustrates that the dominant deformation inflicted by fractures with micro-lamination swelling - fracturing sequence defining by FF present in the entirety of the test. This part will be most brittle and unstable. On the SAT visual picture analysis in the bottom part is visible arch type fracture inflicted by tectonic/sedimentary pre-folding of the shale formation (Figure 15). This is the historical stress deformation.

The conventional practice of elevating mud weight as a means of mitigating shale soughing while drilling the shale to mitigate breakout was in fact exacerbating the problem. The presence of water sensitive clays allows the clays to adsorb water, swell then locally exceed the fracture gradient causing micro-fractures to permit water influx deeper into the rock system. The process continues until substantial portions of the well bore fails. The answer is to lower the mud weight, increase viscosity and to add inhibitors to reduce water adsorption, or use oil-based muds to drill this section of the hole.

Conclusions

- The Shale Activity Test (SAT) is a new approach in the analysis of shale oil/gas plays.
- SAT illustrates the mechanical properties of shale formations in the well bore affected by human intervention created during drilling. The stress test defines the mechanical properties of the virgin formation, and is run under original pressure conditions.
- SAT measurements identify micro structural and continuity parameters that conventional stress test overlooks.
- The discontinuity of shale mechanical properties is recorded by SAT quantitative measurements and is used for calculating

conventional stress and strain parameters.

- The brittleness of hydrocarbon bearing shale acting as a source is defined by its properties in the Shale Activity Test.
- Using SAT the compartmentalization of the shale formation is defined when we have few conventional indictors for formation compartmentalization as determined by conventional logs.
- SAT parameters combined with kDDA component analysis can complement the conventional geo-mechanical analysis on well stability, brittleness, and fractureability.
- The brittleness of shale measured from conventional core plugs can be corrected by the SAT parameters reflecting the micro properties of formation.
- Applying the SAT measured parameters and the Mohr Circle principal the maximum shear stress is defined.
- SAT test interpretation aids in the relationship of drilling mud formulation and formation penetrated performance.
- SAT measurements help define the effect of drilling mud additives on shale stability while drilling.
- SAT parameters are applicable for the hydraulic fracture treatment design and stages placement.
- Cut core recovery in shale is low, extremely difficult and costly. Subsequent cutting of core plugs from shale formation, for stress and strain analysis, is complicated and costly process - very often it is impossible. The SAT methodology is designed to use the abundant shale cuttings availabile. Cuttings analysis from cross sectional wells in the field or basin can aid in the definition of parasequences which would otherwise be hard to identify from conventional correlation methods.
- Availability of drill cuttings, in opposition to whole core, makes the use of SAT an effective tool for geo-mechanical modeling and to decrease uncertainties.

Acknowledgments

This work was made possible due to active support of co-authors Chris Smart and Steve Zamfes. The personal and corporate contribution of Mr. Neville Henry included data availability, lab work performed, field work and personal guidance in the research part of numerous projects, data of which are used in this article. The authors also acknowledge Dr. Luis Quintero who was instrumental to the development of the technologies and TDA during his managing ODS in previous years. Eldar Hasanov contribution was essential in analyzing the petrophysical aspects of the project and guidance in the details required in practical applications. Steve Zamfes was essential in the derivation of the mathematical algorithms utilized.

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Figure 1. Nahr-Umr Shale. The shale is fissile and caving. The mud properties are not adequate for stability and safe drilling.

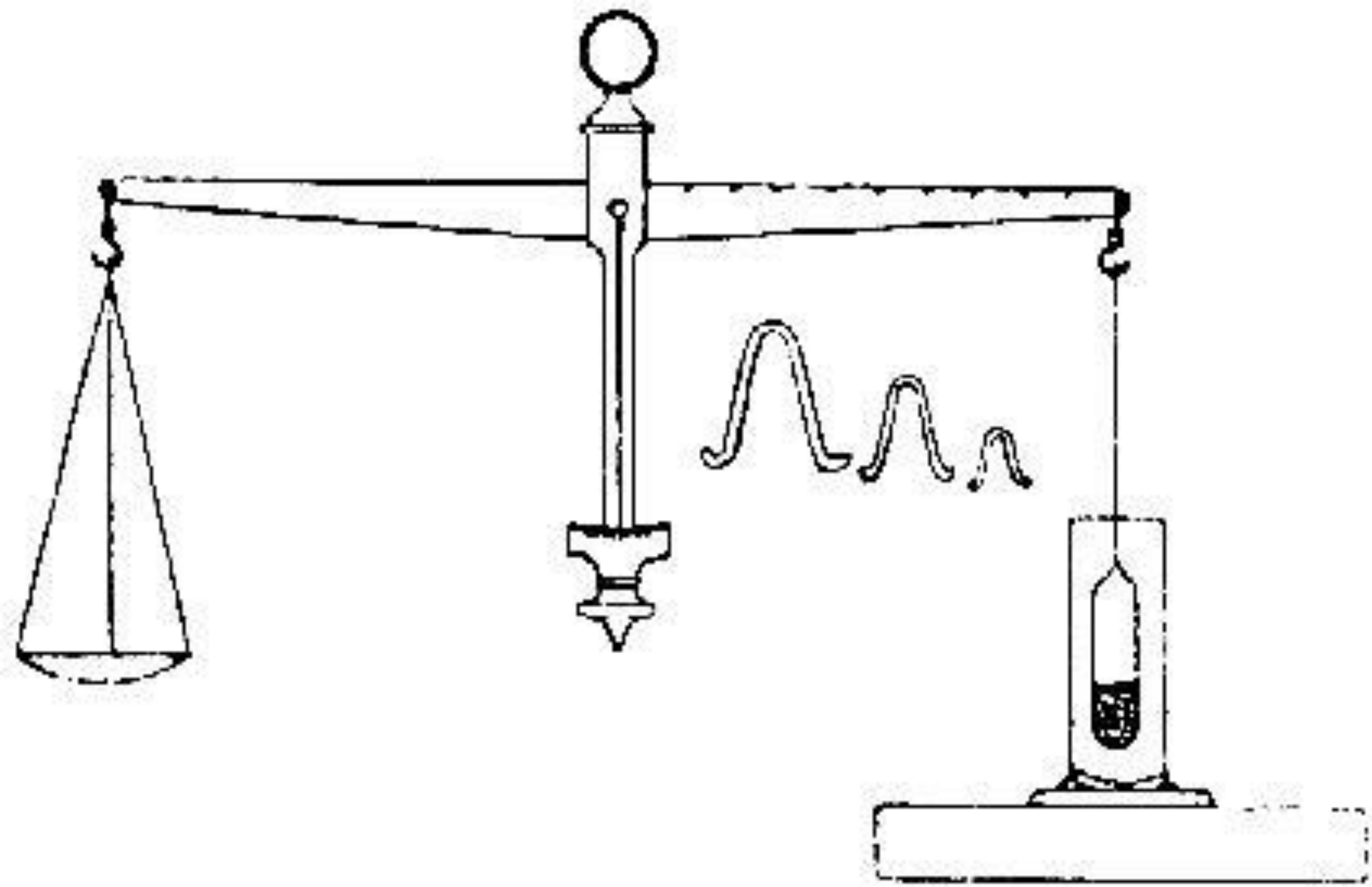


Figure 2. The continuous time record of sample weight in the target fluid is obtained using the modified Archimedes apparatus.

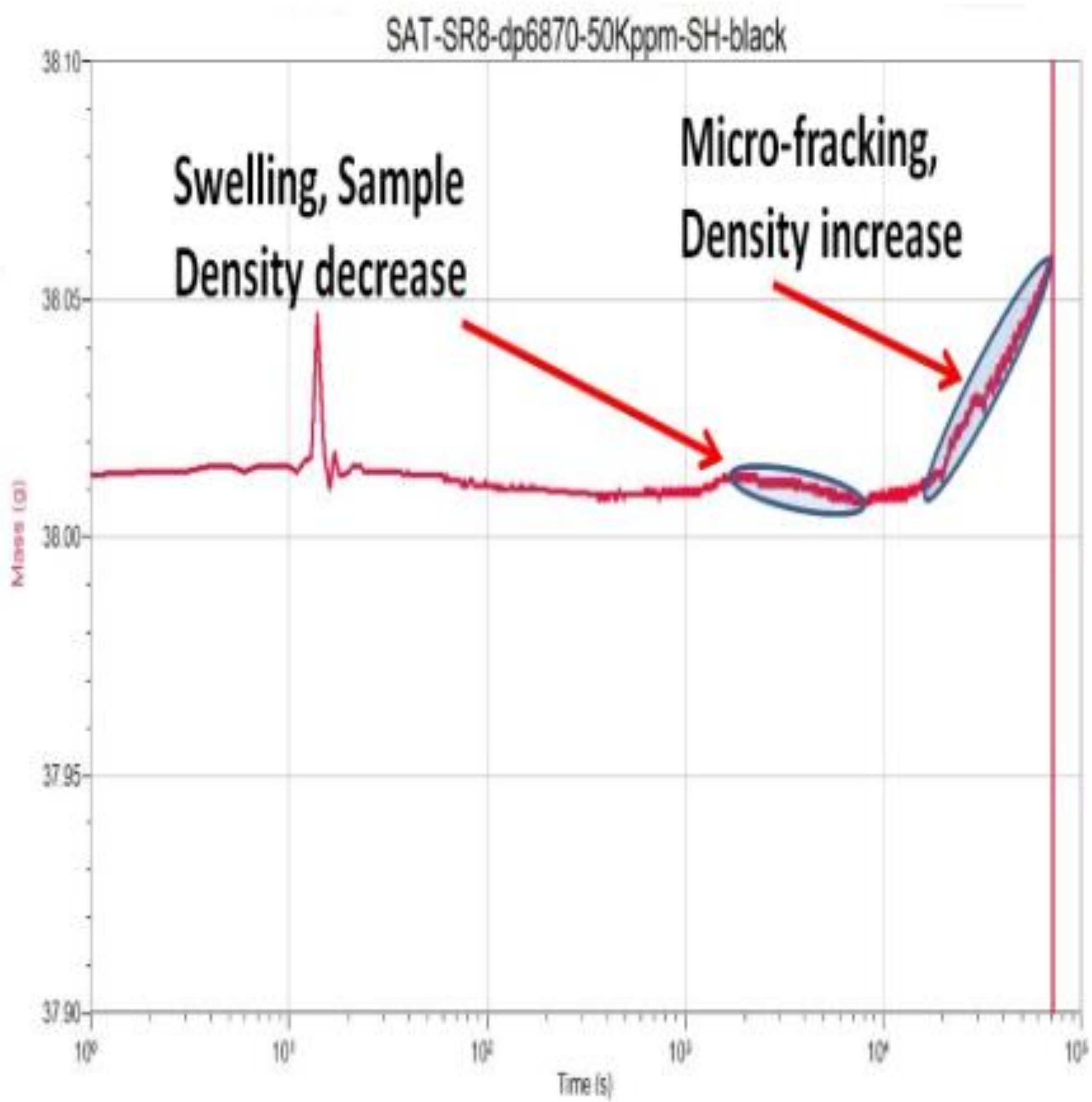


Figure 3. Example SAT time record.

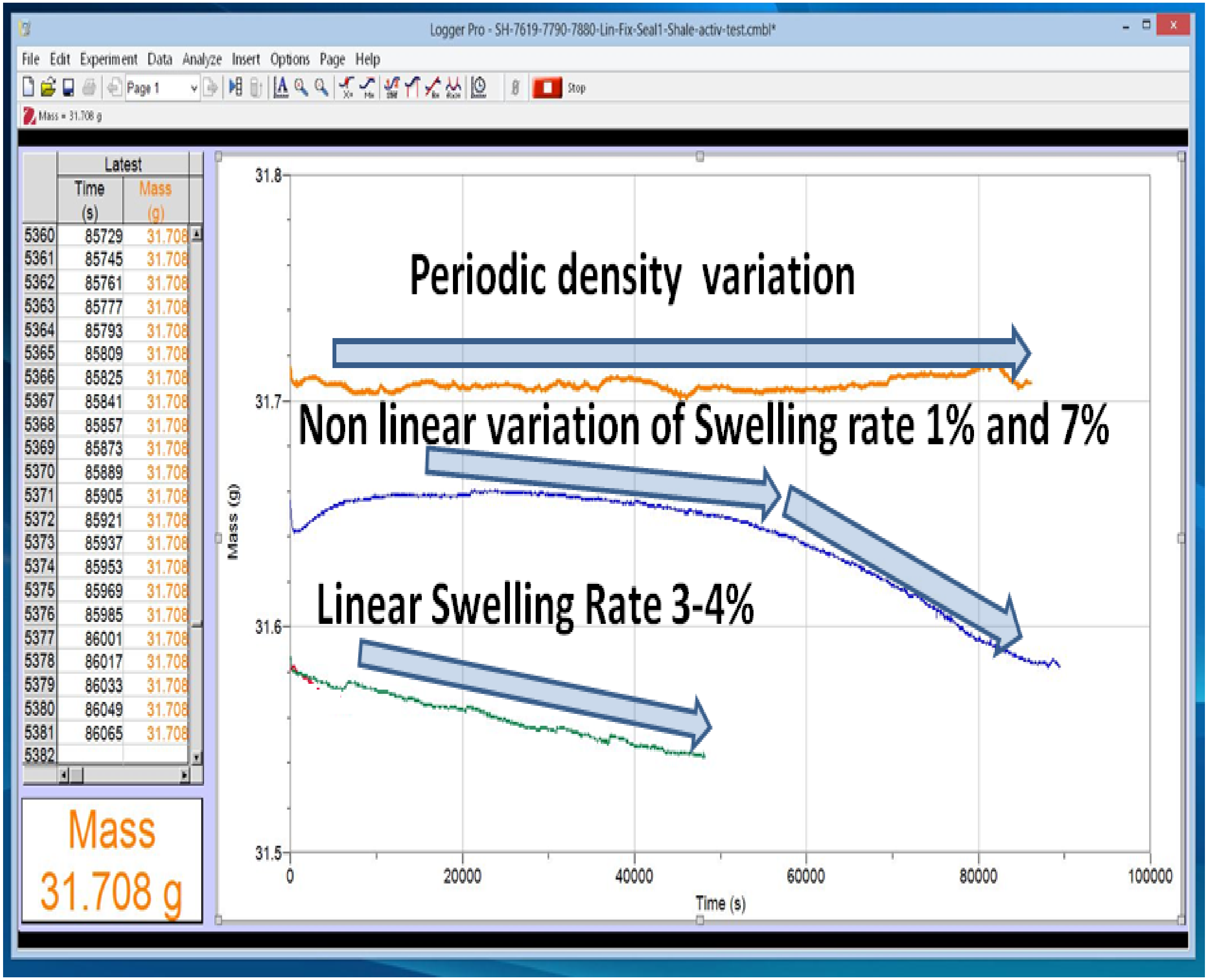


Figure 4. Examples of SAT in the Woodbine Shale from Texas.

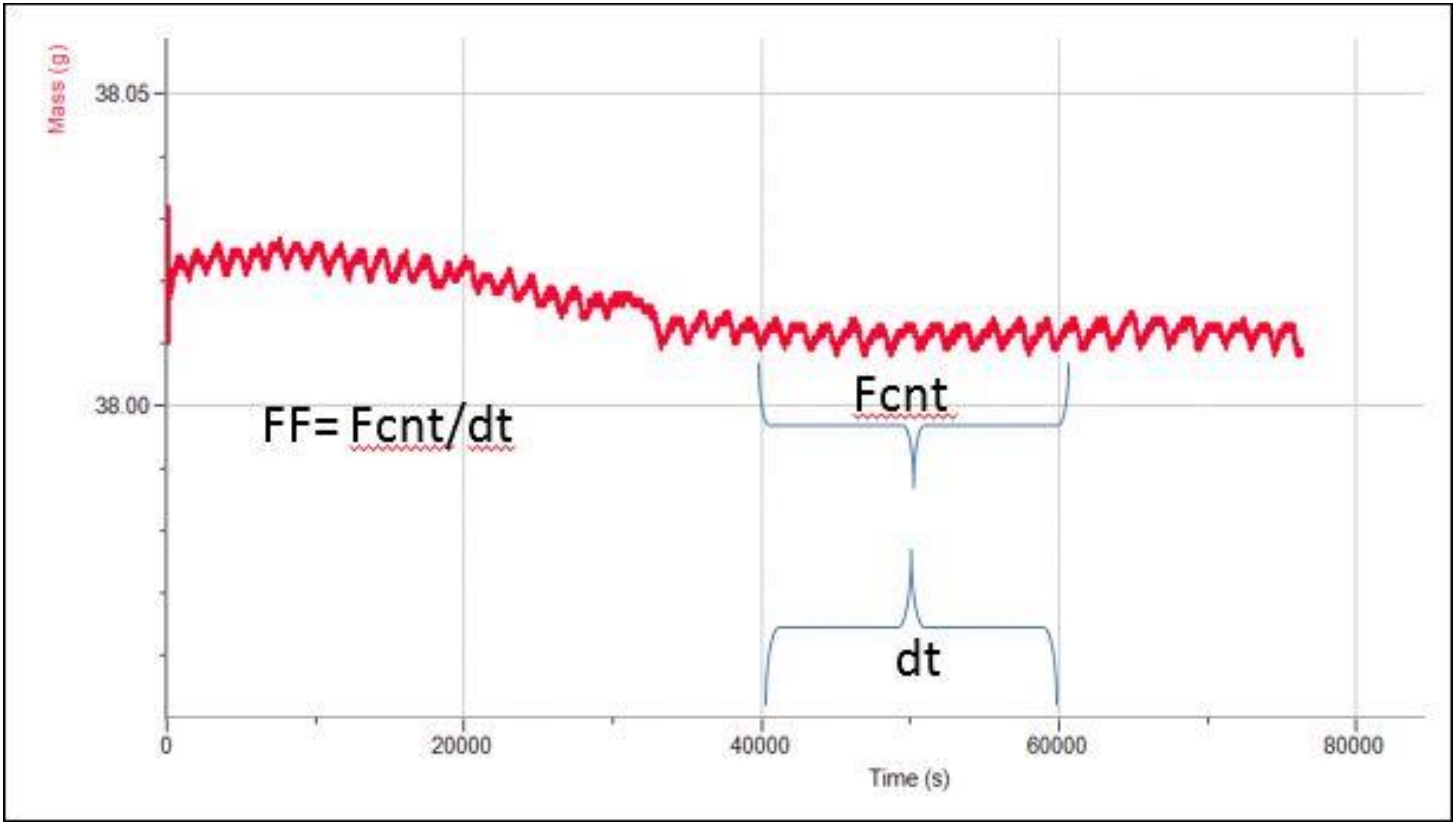


Figure 5. FF example.

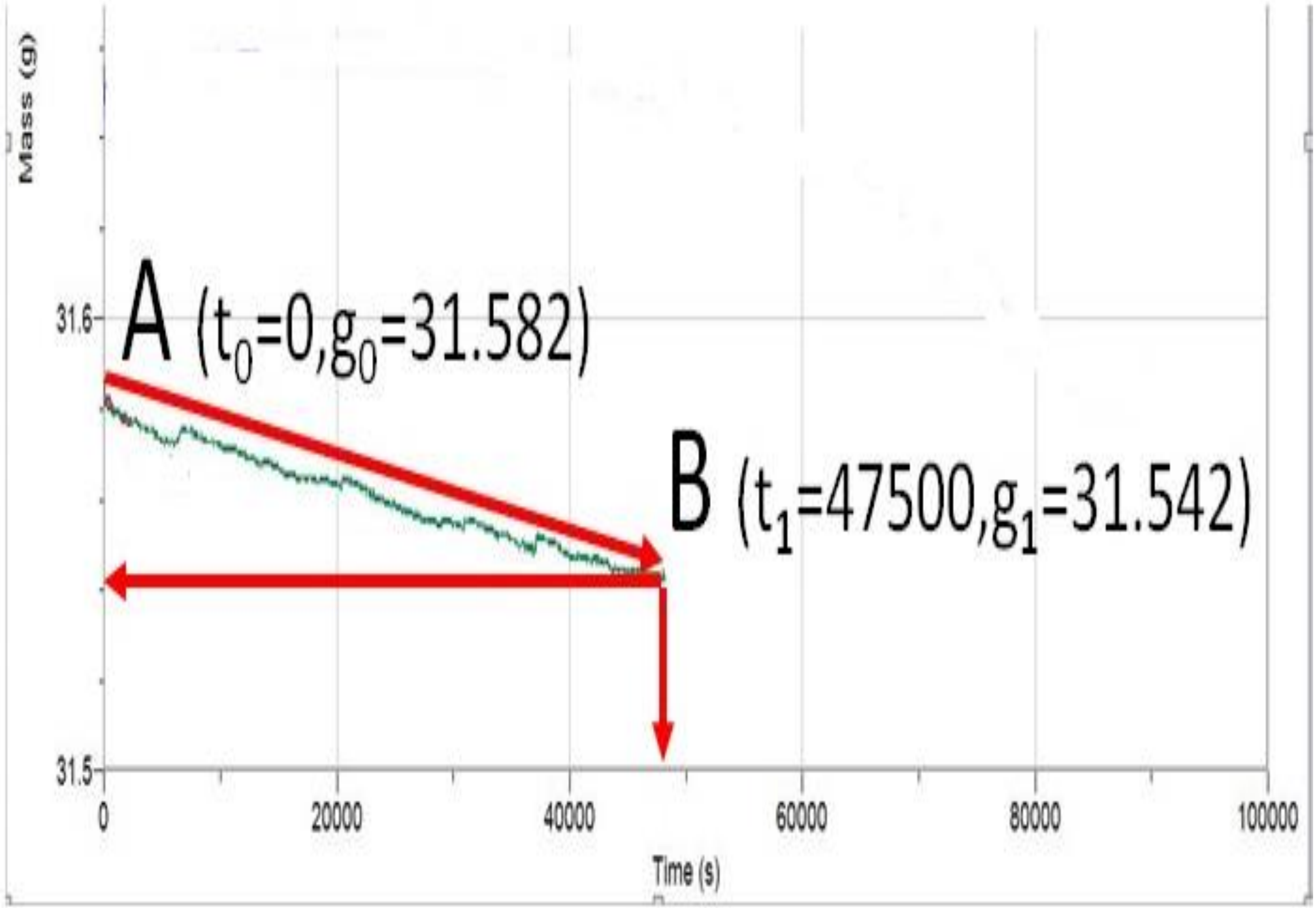


Figure 6. The parameter ROS measured as a value of the slope of the curve. ROS = (g1 – g0) / (t1 – t0)

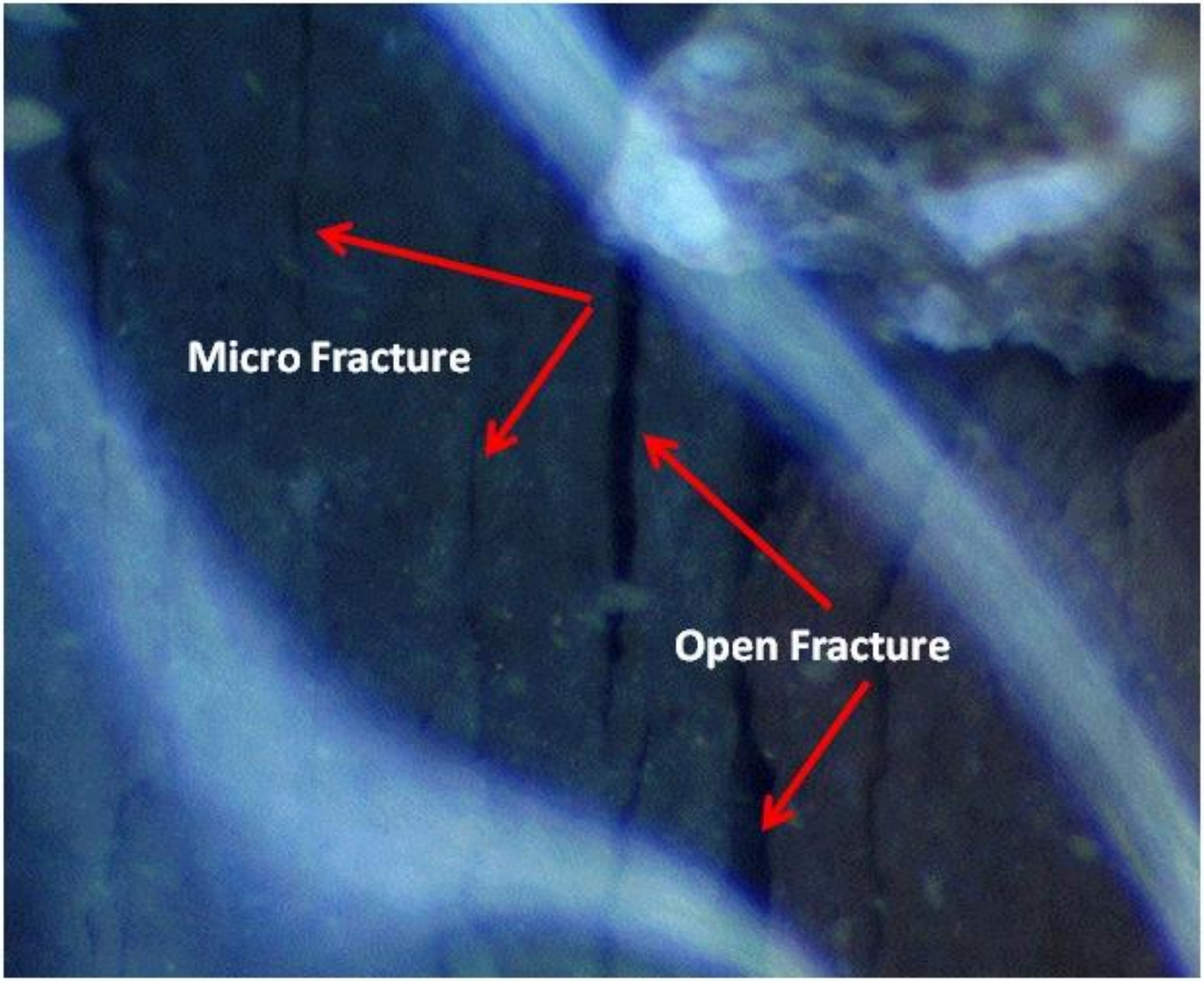


Figure 7. The distortion of shale is observed and fracture growth is documented.

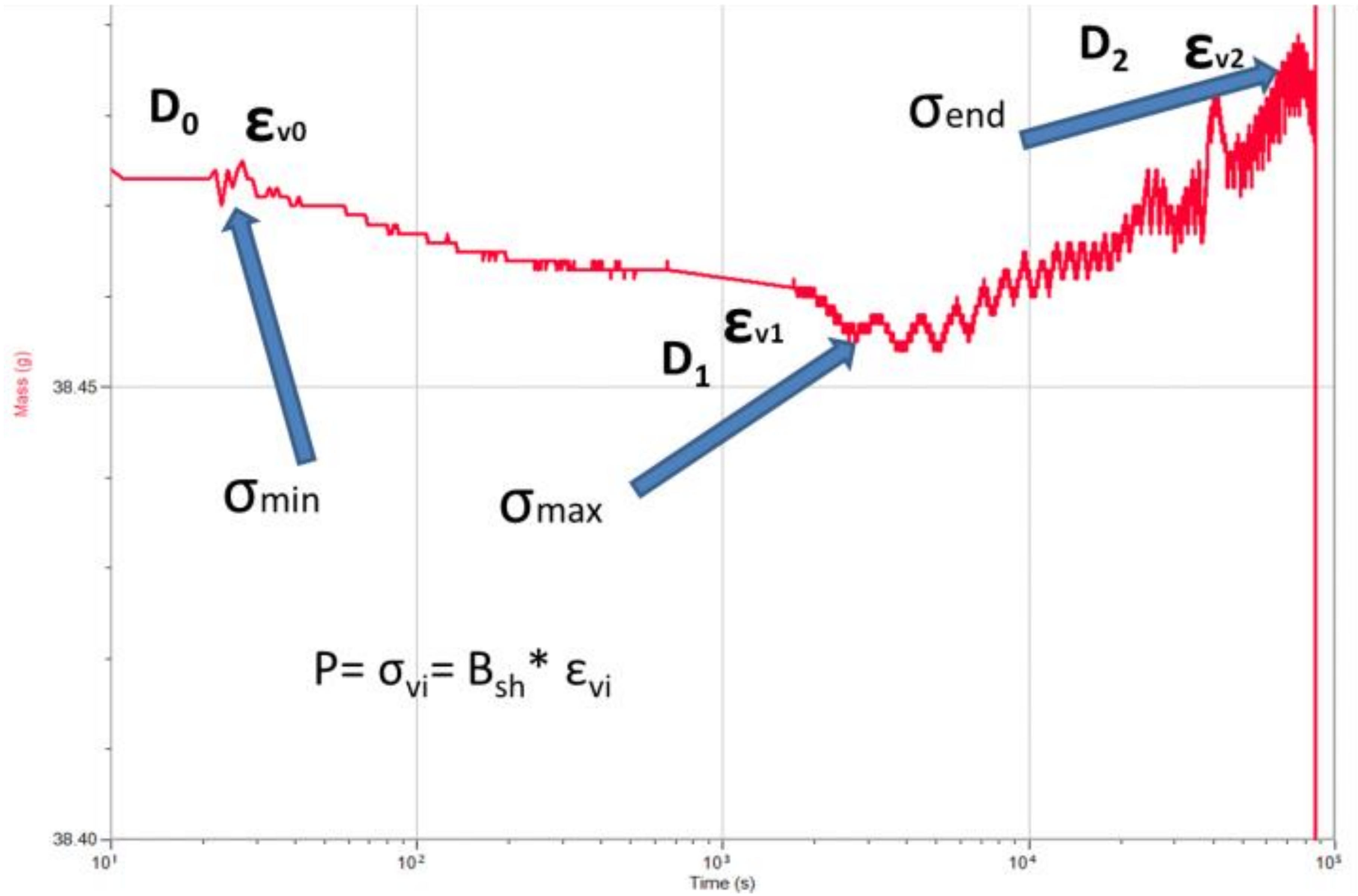


Figure 8. Stress and strain parameters manifested in the SAT.

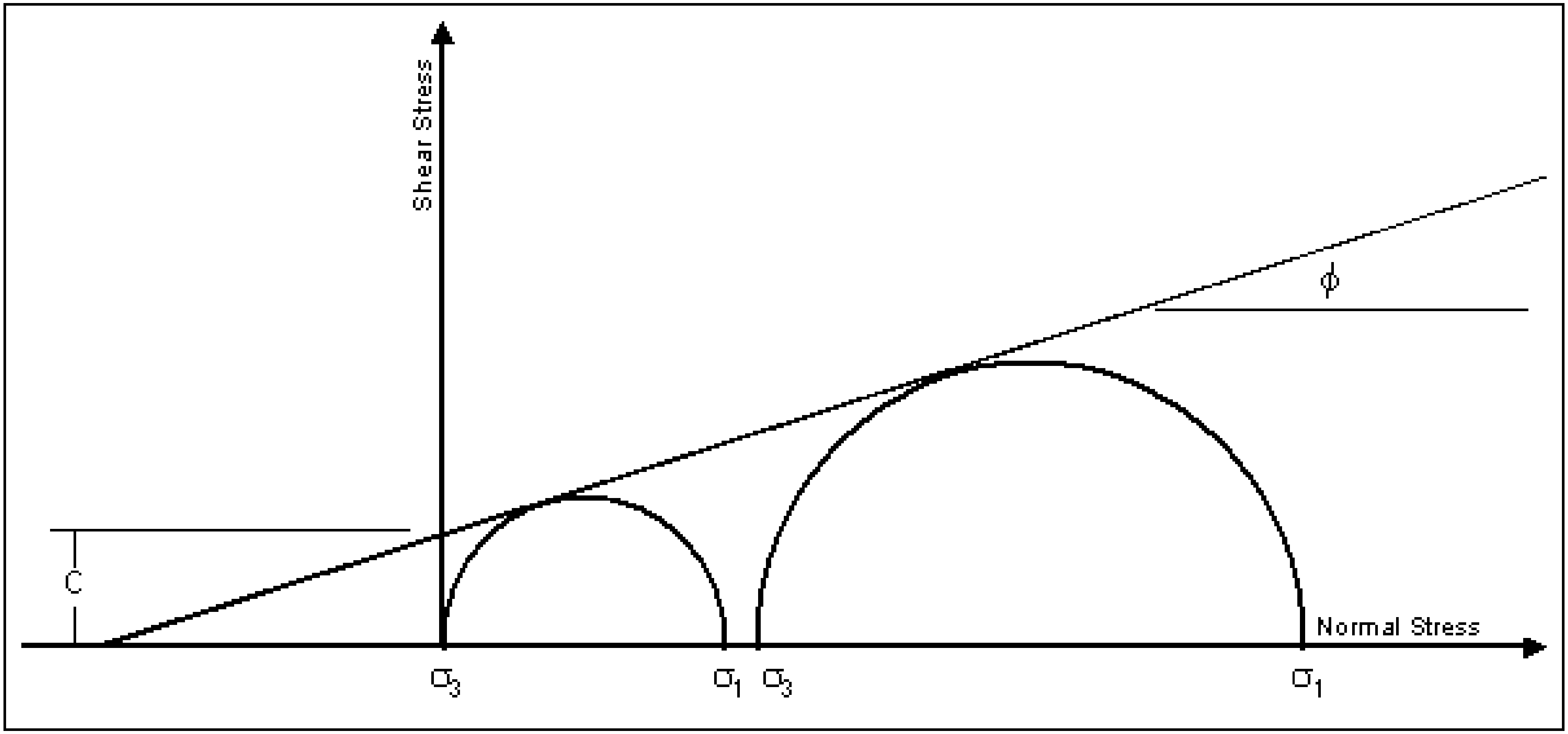


Figure 9. shear stress, $\sigma_s = (\boldsymbol{\sigma_{max}} - \boldsymbol{\sigma_{min}})/2$

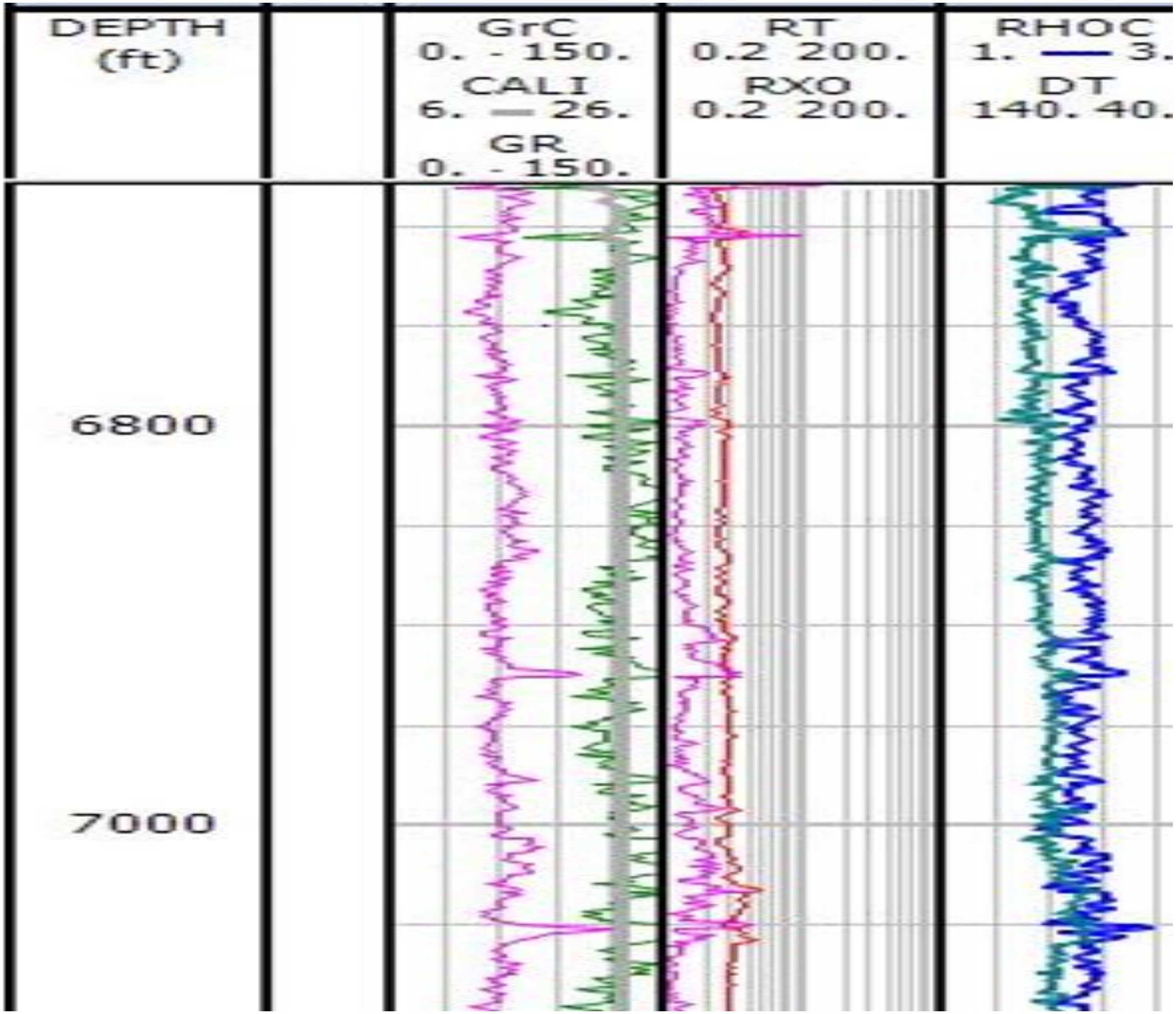


Figure 10. Open hole logs for Nahr Umr Shale.

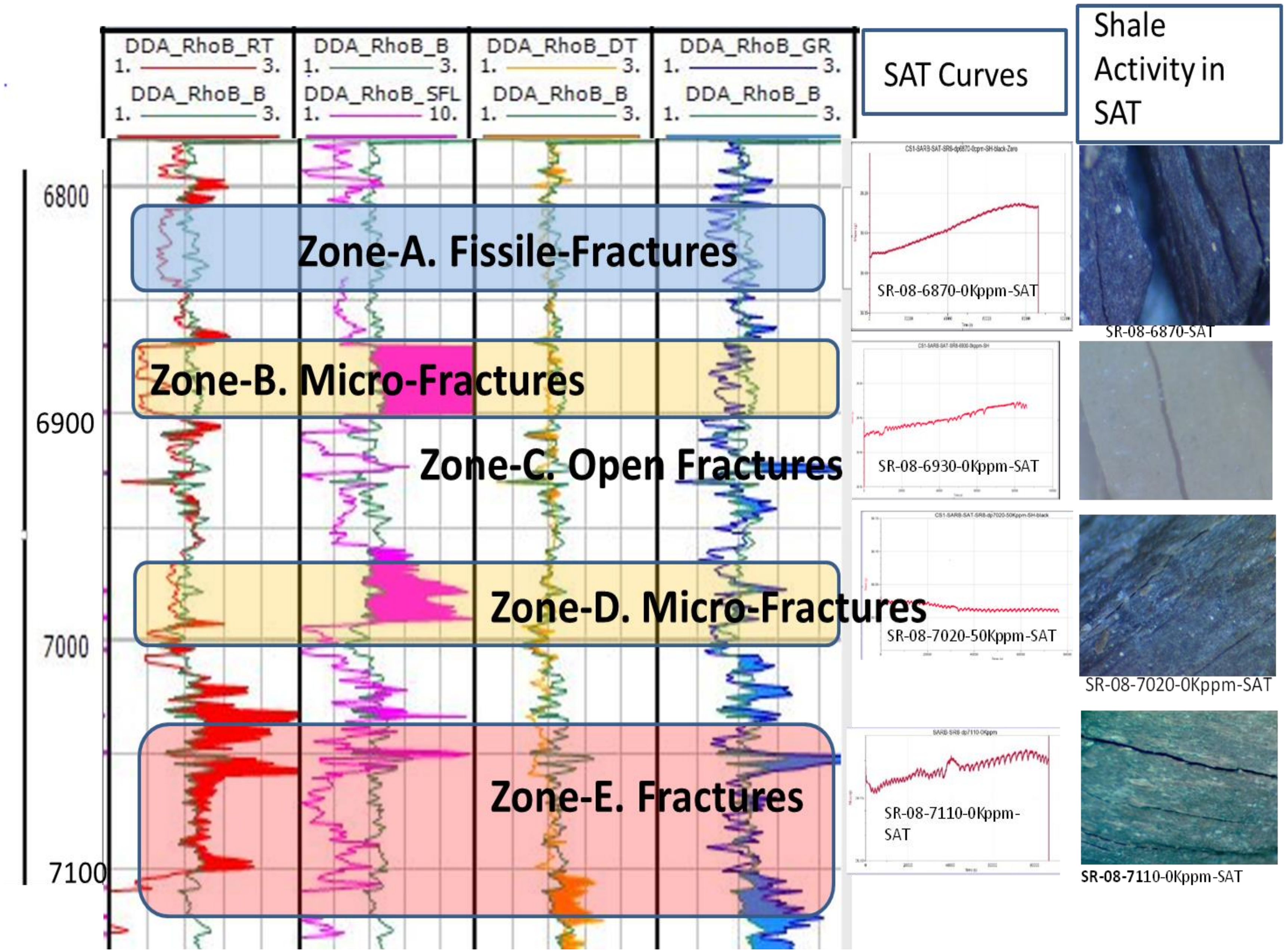
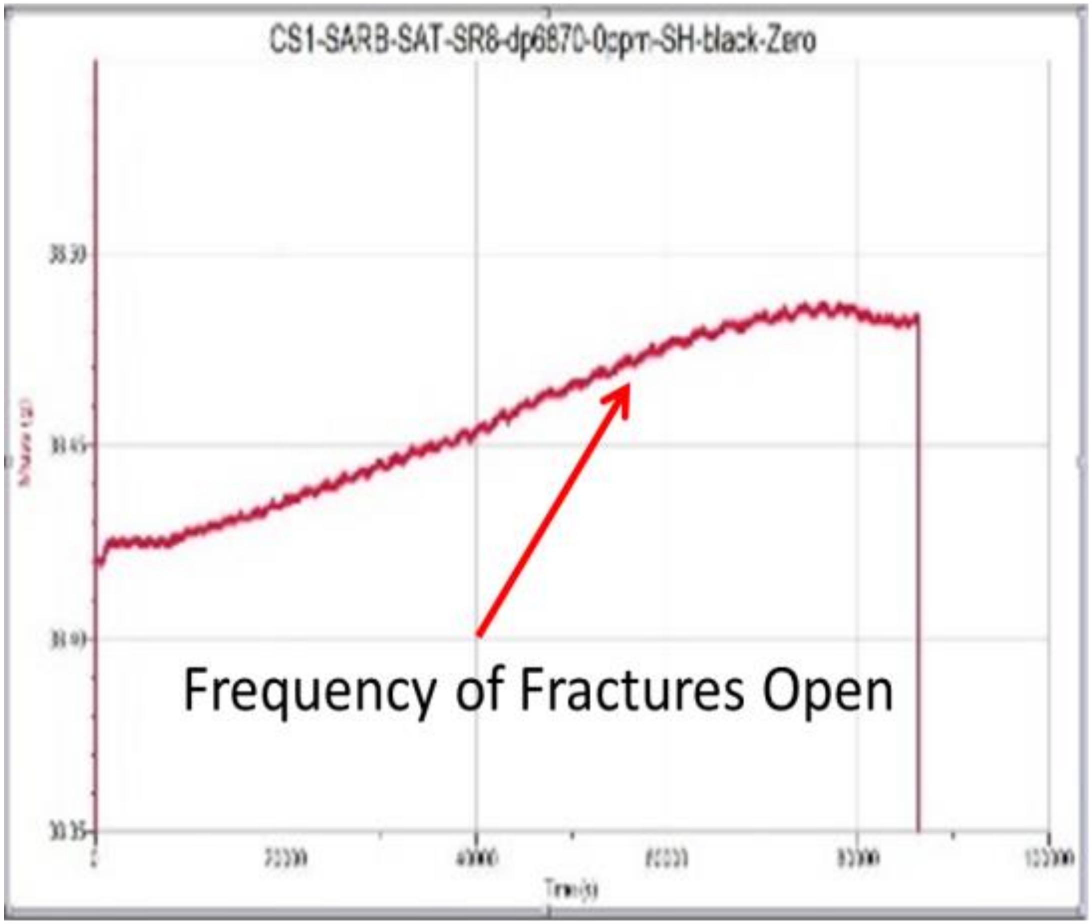
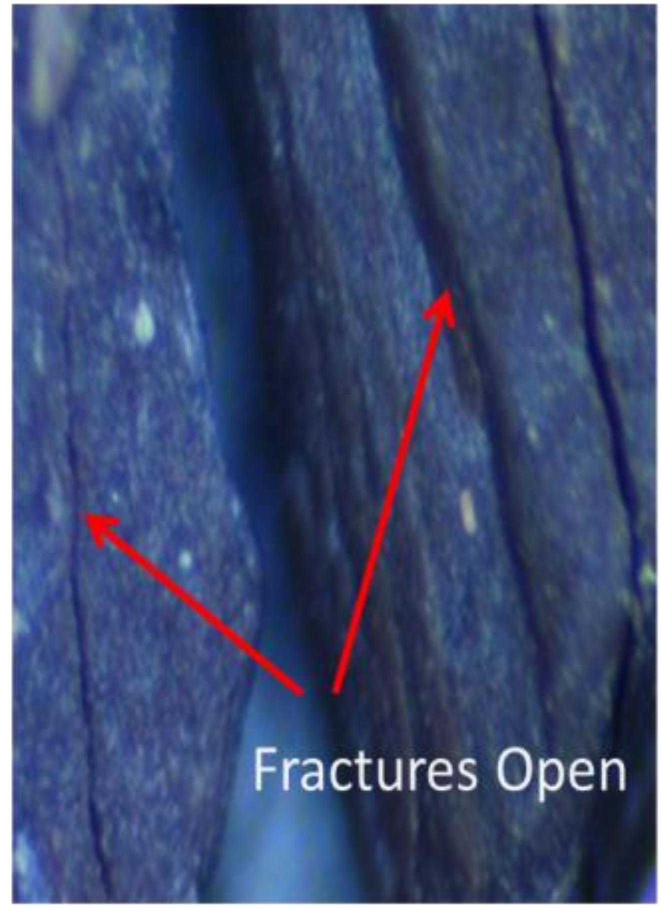


Figure 11. kLab mechanical properties and SAT results identify the compartments in the Nahr Umf.

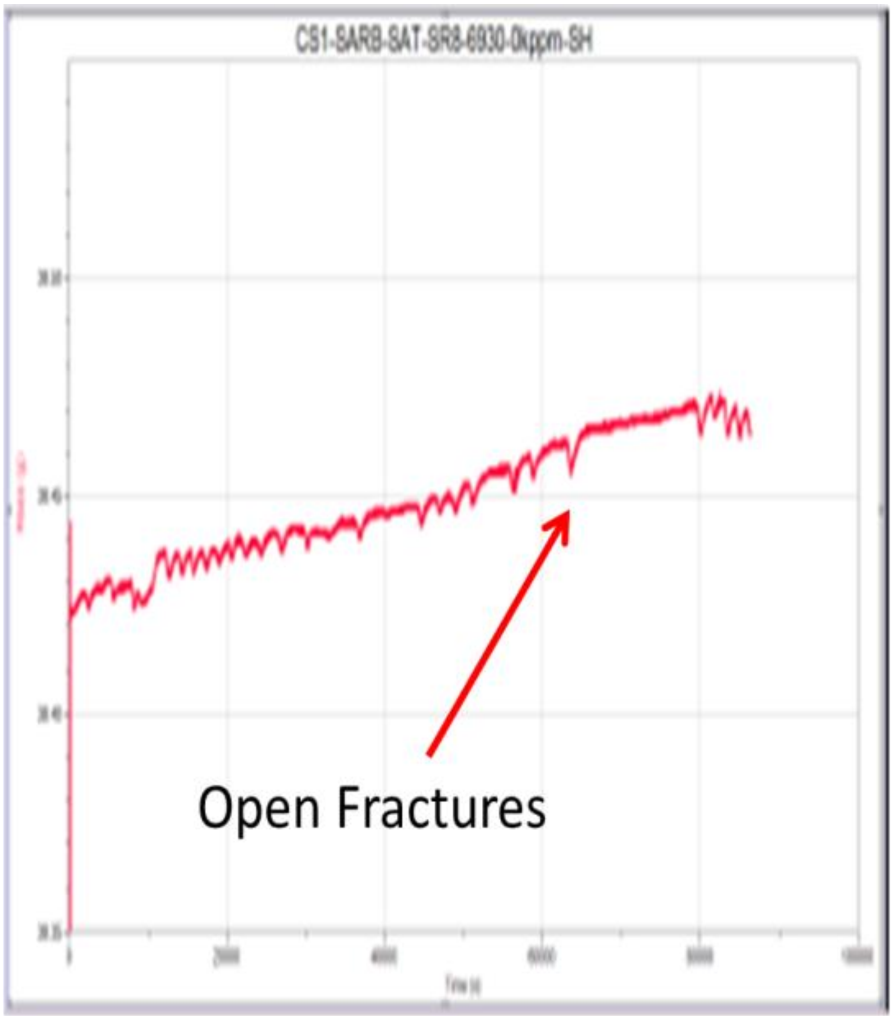




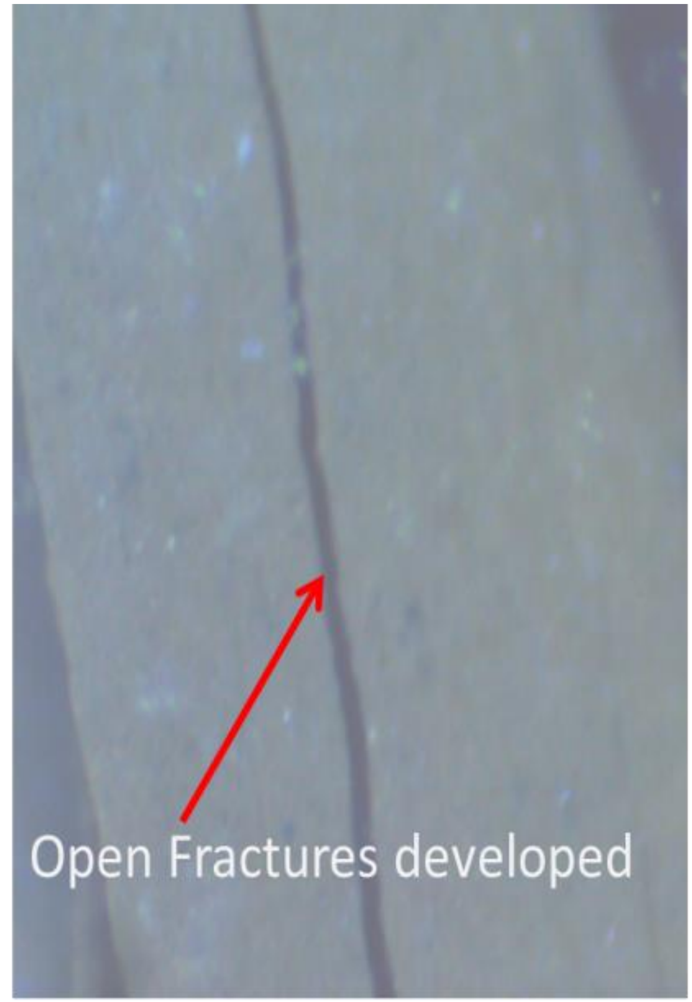
SAT digital record on sample SR-08-6870-0Kppm-SAT

SAT fractures developed during test on sample SR-08-6870-0Kppm-SAT

Figure 12. Fissile fracture interval "A".

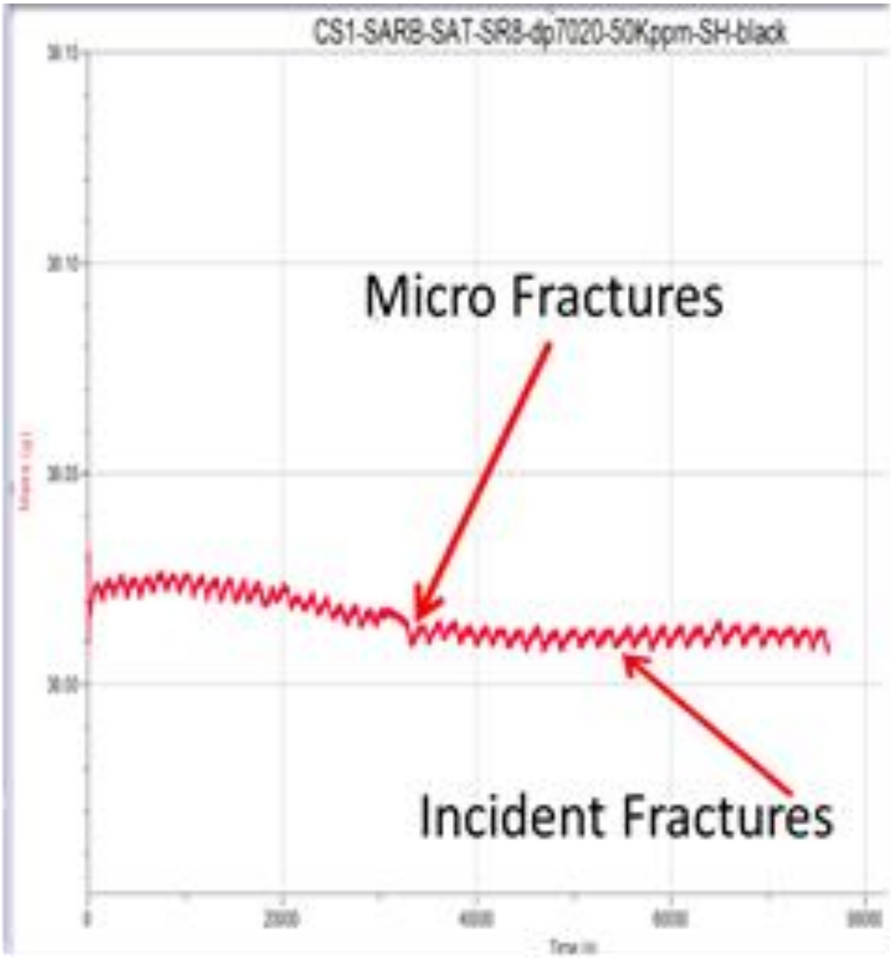


SAT digital record on sample SR-08-6930-0Kppm-SAT



SAT fractures developed during test on sample SR-08-6930-0Kppm-SAT

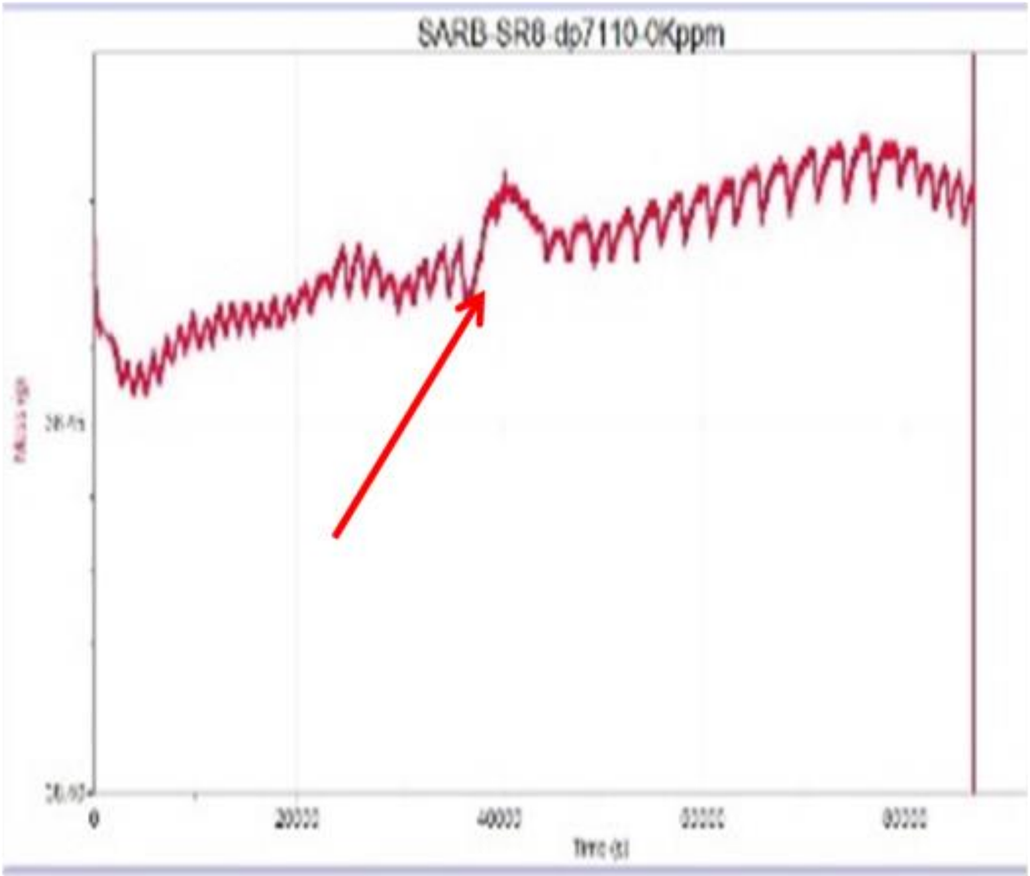
Figure 13. Micro-fracture interval "B". Typical of a local stress field. Note low amplitude of FF.



SAT digital record on sample SR-08-7020-0Kppm-SAT

SAT fractures developed during test on sample SR-08-7020-0Kppm-SAT

Figure 14. Nahr Umr Zone D; incident and micro-fractures.



SAT digital record on sample SR-08-7110-0Kppm-SAT

SAT fractures developed during test on sample SR-08-7110-0Kppm-SAT

Figure 15. Zone E is defining the dominant deformation inflicted by Fractures with micro-lamination swelling - fracturing sequence defining by FF and historical stress as pre-folding fractures.