



Advanced acoustic measurements aided rock mechanics calculation for successful hydro-fracturing design and wellbore stability analysis in unconventional reservoirs of western onshore, India

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Keywords

Perforation, closure pressure, Tight Oil, Frac, Temperature

Summary

There are number of small oil fields located in western onshore undergoing a fast-track development campaign, wherein wells have witnessed NPT due to various drilling challenges such as tight hole, stuck pipe etc. Bad borehole condition has affected the data quality being recorded for formation evaluation and poor cement quality. Most of these drilling problems are reported in shallow shale formations like Tarapur, Post-Kand and Babaguru. Target reservoirs like Kalol and Cambay shale are relatively silty with porosity in range of 6%-10% which requires hydro-fracturing jobs to enhance production. Simulations for Hydro-fracturing operations to estimate the fracture height and width are primarily dependent on rock mechanical properties such as anisotropic Young's Modulus, Poisson's Ratio and closure pressure which are estimated using Geomechanical analysis.

Far field and near wellbore advanced acoustic measurements have been recorded in recent wells to estimate direct horizontal stress profile in stress induced anisotropic layers and to map regional variation of tectonics across two fields. 1D Mechanical Earth Models (MEMs) have been constructed for different wells in the area to develop a geomechanical understanding of the reservoir as well as in the overburden and underlying layers. Anisotropic stress profile provides better understanding on rock fabric based tectonics effects to check feasibility of optimized hydro-fracturing operations. History match of predicted failures using 1D MEM with caliper and drilling events suggest that shales and coals are relatively weaker than sands in both fields with 10%-15% variation of stress gradient magnitude laterally. Triaxial test results provided UCS calibration for better wellbore stability analysis (WBS) and stable mud weight window prediction in new wells. Both fields have shown significant improvement in reduction of NPT over last one year

with better borehole condition and cement quality. An integrated approach of completion quality and reservoir quality has provided optimized perforation depths selection process and better hydro-fracturing job design. New wells are being monetized which provides significant improvement in production rate over previous wells.

Introduction

Fields under study has high oil accumulations and is in the western onshore. Targets reservoir of these wells are tight and require unconventional techniques to expediate the huge hydrocarbons. Different challenges have been faced while drilling and hydraulic fracturing operations. This paper summarizes these challenges and provides current learnings based on acquired advance acoustic data.

A comprehensive geomechanical model makes it feasible to assess the drilling risks and facilitates by minimizing the impact of geomechanical problems, which will help to reduce the cost and time of the drilling operation. The key requirement for any geomechanical analysis is the construction of a MEM (Plumb et al. 2000). The MEM is a numerical representation of the state of in-situ stress and rock mechanical properties for a specific stratigraphic section in a field or basin. It includes rock elastic and strength properties, pore pressure and in-situ earth stresses. Once the MEM is rigorously validated, it can be used to identify geomechanical problems during drilling and to devise contingency plans for the planned wells. It is done by conducting a wellbore stability analysis taking MEM as input. Wellbore stability analysis serves multiple purposes as not only it helps to validate the MEM but also assist in estimation of stable mud weight window. Estimated stable mud weight window can be used to estimate optimum mud weight program and casing setting depths along the well trajectory.

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During drilling operations targeting Kalol and Cambay formations in vertical and deviated wells, wellbore stability remained one of the major concerns. Major drilling problems included breakouts/cavings, stuck pipe, bad data quality etc., which increased nonproductive time (NPT), inflated the costs of drilling, and impacted the quality of critical formation evaluation data. Shale layers present are anisotropic with horizontal Young's modulus higher than vertical Young's Modulus ($C66 > C55 = C44$).

The presence of high stressed sandstone layers together with low strength anisotropic shale formations adds complexity for well design planning, drilling, logging and completion. Estimated pore pressure values range approximately 1.05gm/cc to 1.13gm/cc with increasing trend from top of Cambay formation. Presence of weak coal layers near target Kalol layers make perforation and hydro-fracturing design more challenging. Stress barriers are located around 30m-40m away from target zones with height expected in range of 50m-80m depending on cement quality and geological variations laterally.

Sonic shear radial profiles with stiffness matrix are used to constrain horizontal strains in the field, providing more reliable calibration method as per Sinha et.al (2006, 2009) as seen in **Figures 1-3**. In the current study, post-drill MEMs for different offset wells are constructed with history matching of drilling events, caliper logs, images against MEM based predicted failures (**Figure 4**).

MEM outputs are utilized to plan and execute the hydraulic fracturing (HF) operations. Closure pressure and breakdown pressure from HF results in wells came close to predicted ones. There has been change in perforation strategy utilizing effective porosity, permeability, closure pressure and breakdown pressure.

Wellbore Stability Analysis

Prior to drilling a well, the initial state of existing compressive stress in the rock formation can be resolved in three components: vertical stress (σ_V), minimum horizontal stress (SHMIN), and maximum horizontal stress (SHMAX). As the well is drilled, stress redistribution takes place near the rock with

replacement of the initial support of drilled out rock by mud pressure. The redistributed stresses can be resolved in form of hoop stress acting circumferentially along wellbore and the radial stress and the axial stress acting parallel to the wellbore axis. With well deviation, the additional component of shear stress comes into play. If the rock strength is enough to sustain redistributed stresses, either in compression or tension, the wellbore will remain stable with the present mud weight. Hence, the computation of strength becomes a pivotal part of wellbore stability analysis. All geomechanical calculations have been done with assumption of linear elastic behavior. Following equations are valid for VTI anisotropic medium where Thomsen Gamma is positive as seen in shale layers of Kalol Formation, containing pore pressure p_p , overburden stress σ_v , Biot constants α_v and α_h , static Poisson's ratios ν_v and ν_h , and static Young's moduli E_v and E_h , for σ_i and σ_H :

$$\sigma_h = \frac{E_h}{E_v} \cdot \frac{\nu_v}{1 - \nu_h} \cdot (\sigma_v - \alpha_v \cdot p_p) + \frac{E_h}{1 - \nu_h^2} \cdot (\epsilon_h + \nu_h \cdot \epsilon_H) + \alpha_h \cdot p_p$$

$$\sigma_H = \frac{E_h}{E_v} \cdot \frac{\nu_v}{1 - \nu_h} \cdot (\sigma_v - \alpha_v \cdot p_p) + \frac{E_h}{1 - \nu_h^2} \cdot (\epsilon_H + \nu_h \cdot \epsilon_h) + \alpha_h \cdot p_p$$

Using estimated rock mechanics parameters during MEM-WBS analysis, breakdown pressure has been estimated considering tensile strength $\sim 1/10$ of UCS value. Estimated UCS varies 700psi to 5100psi.

$$Pbd = 3 \cdot \sigma_h - \sigma_H - p_p + \text{Tensile Strength}$$

Findings

- Most of the drilling incidents are reported near breakout layers as predicted using MEM and seen in caliper data. Mud weight and corresponding ECD seems to be lower than shear failure limits at most of the depth intervals in offset wells.
- Based on different wells analysis in the field, 8.5" section should commence with 1.19sg-1.20sg inside Post-Kand formation and further raised to 1.25sg-1.28sg prior encountering target Kalol sandstone layers.
- Ratio of maximum horizontal stress to minimum horizontal stress is 1.02-1.14 depending on stiffness of layer. Anisotropic stress profile provides more realistic variation as compared to isotropic profile in higher Gamma values where

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TIV is present. There is stress contrast of 200psi-500psi between target Kalol layer with potential shale barrier layers using anisotropic rock properties and stress profile. Closure pressure ranges 3700psi-4200psi in target zones with good petrophysical properties (**Figure 5**).

- Estimated breakdown pressure ranges 5200psi-5400psi in Kalol formation with barrier layers having 6000psi-6500psi values. If weak planes are present, breakdown pressure will be lower considering minimum tensile strength.
- There are three coal layers with very low rock strength and pose risk of fracture growth through them. Perforations should be carried out away from coal layers towards bottom of reservoir with thickness of 6m-11m.
- Frac height is observed to be higher in few wells due to poor cementation and lower stress contrast. To confine frac height, focused deep perforations are required so that frac width and length would be more.

Results

- Implementation of stable mud weight window concept helped to improve borehole condition significantly in new wells and increase in effective ROP by 15%-20% with no major drilling events (**Figure 6**).
- As per recommendations from lessons learnt in the field, Propellant Stimulation (PST) with explosives was performed prior to hydro-fracturing in well B. The PST was designed to create around 6000 psi pressure to cross the estimated breakdown pressure. Advanced acoustic based BARS show near wellbore reflectors around the perforated interval when compared to BARS from well A (**Figure 7-8**). This is due to micro-fracture network created by the PST. The micro-fracture network created by the PST has helped in improving the Injectivity across the perforated interval and enabled 45 MT of proppant placement against earlier 25 MT.

Proof of concept in another field

Applying same workflow in well Z of different field, perforation depth intervals were optimized using Geomechanical outputs and petrophysical parameters. Mild overpressure is present in Cambay Shale Formation which is due to normal compaction phenomenon. Estimated pore pressure gradient varies

from 1.03SG to maximum of 1.08SG. Estimated stress profile shows strike slip to normal faulting stress regime. Ratio of maximum horizontal stress to minimum horizontal stress is 1.03-1.26. The maximum horizontal stress azimuth is found to be in the range of N55degE to N75degE based on FSA at layer with stress induced anisotropy and Breakouts seen in FMI as seen in **Figure 9**.

Available core data has been utilized to build dynamic to static logs conversion. Triaxial test provides more reliability on UCS value estimation through cohesion and friction considering VTI layers. ELAN volume together with estimated anisotropic closure pressure and Breakdown pressure was utilized to perforate interval to have more effective results within the pay sand of Cambay shale section. Major stress barriers in anisotropic model are at 883m-923m (**Figure 10**).

Interval 903.0m – 908.0 m was found to have better reservoir facies with negative Gamma value and likely to support lateral extension of fracture due to HF (**Figure 11**). The well was perforated conventionally followed by HF through mono-bore casing. Frac half-length obtained after net pressure match is around 50 m which is good seeing the plasticity of the formation. Analysis of temperature log suggests the mini-frac was effective in the interval 887m – 917 m and Main-stage HF was effective in the interval 882 – 924 m (**Figure 12**) which is exactly matching with stress barrier analysis. Present production status exhibiting more than average production rate as compared to other wells.

Conclusions

- Drilling high angled wells parallel to maximum horizontal stress azimuth (N-S) will require higher mud weight as compared to well-planned parallel to minimum horizontal stress azimuth.
- HF geometry is contained by the layers with high YME layers and anisotropic minimum horizontal stress as estimated using TIV model.
- Production rate has improved significantly in two fields with new integrated strategy of reservoir quality and completion quality in vertical as well as deviated wells.

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Pneumonic

- Sig V/SVERTICAL: Vertical stress
- SHMAX: Maximum horizontal stress
- SHMIN: Minimum horizontal stress
- VTI/TIV: Transverse Anisotropic with vertical axis of symmetry
- PST: Propellant Stimulation

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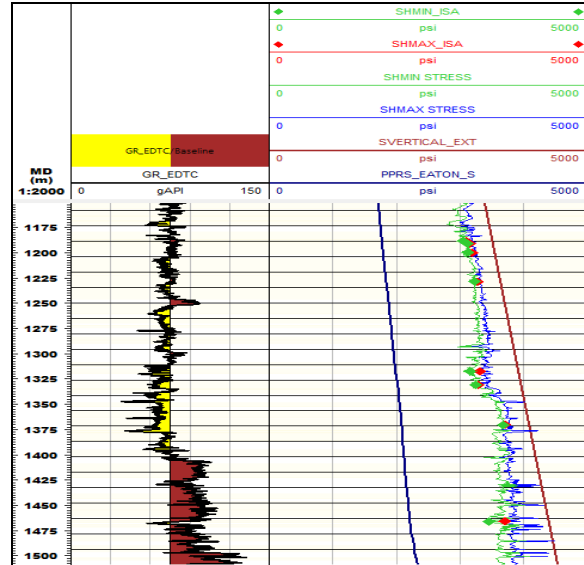


Figure 1: Horizontal stress calibration using shear radial profiles at stress induced layers

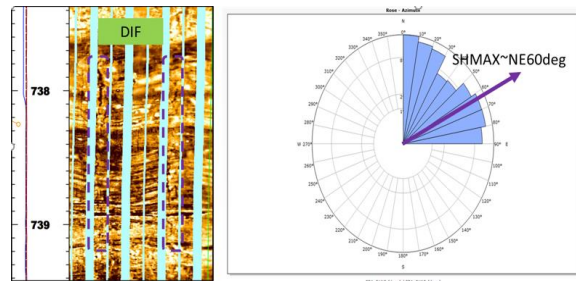


Figure 2: Horizontal stress azimuth using borehole image and fast shear azimuth

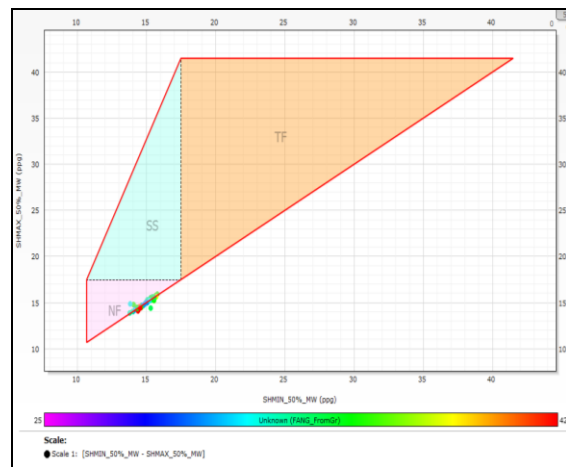


Figure 3: Stress polygon using acoustic far field data

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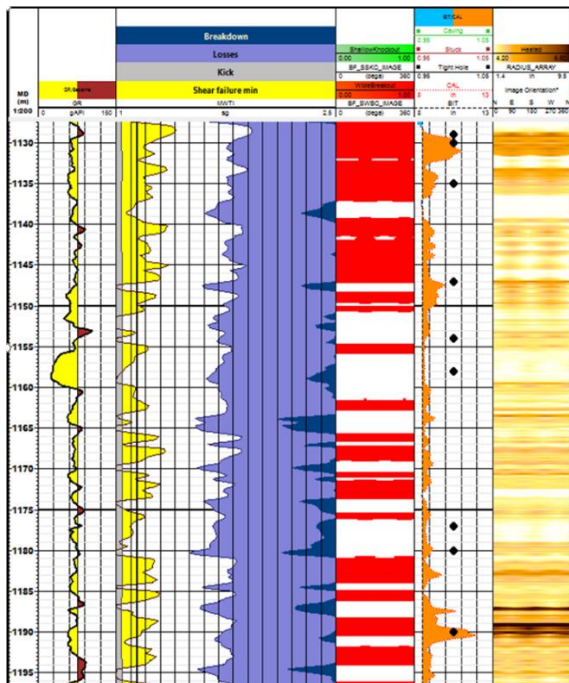


Figure 4: Post-drill MEM-WBS for well X with drilling events and caliper data prior geomechanical analysis

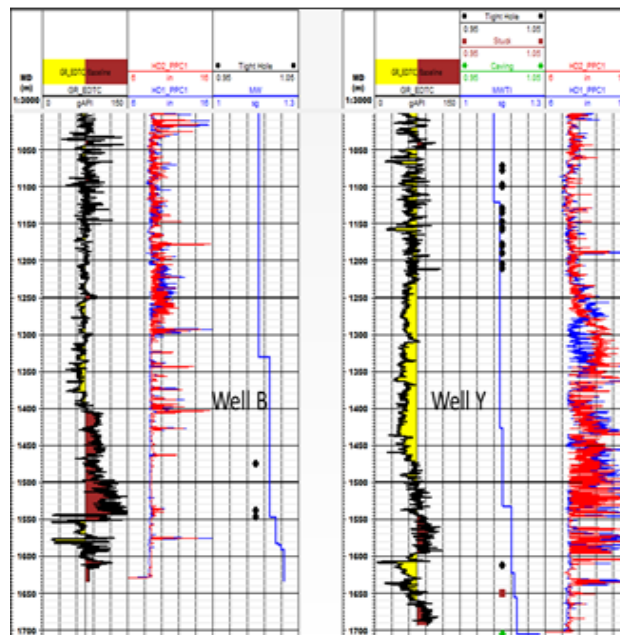


Figure 6: Comparison of hole condition in two wells

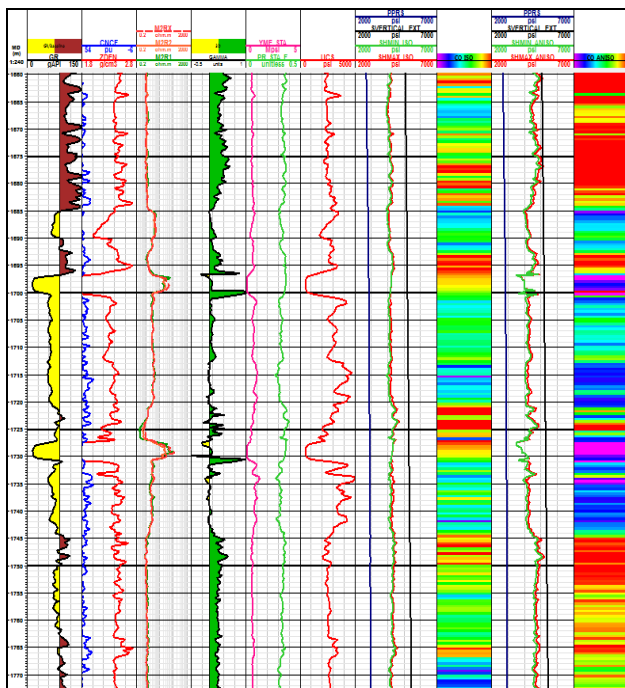


Figure 5: Isotropic vs Anisotropic Completion Quality (CQ) at target zone (1685m-1745m) in well A

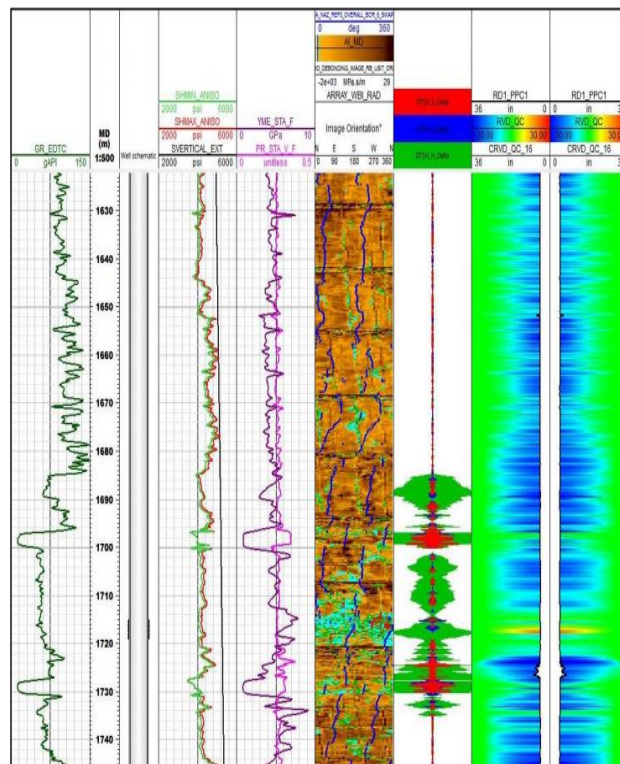


Figure 7: 3D shear radial profile at well B after hydro-fracturing job

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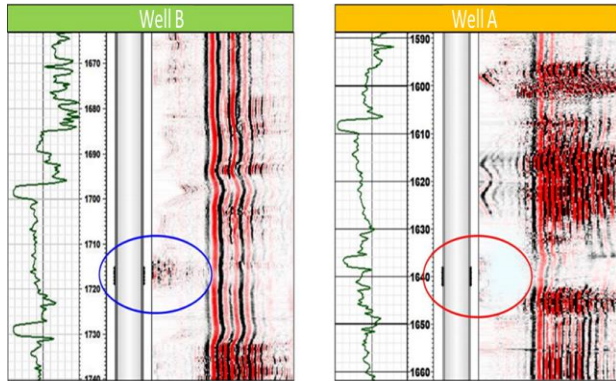


Figure 8: BARS image reveals micro-fracture network around the perforated interval in Well B vs Well A

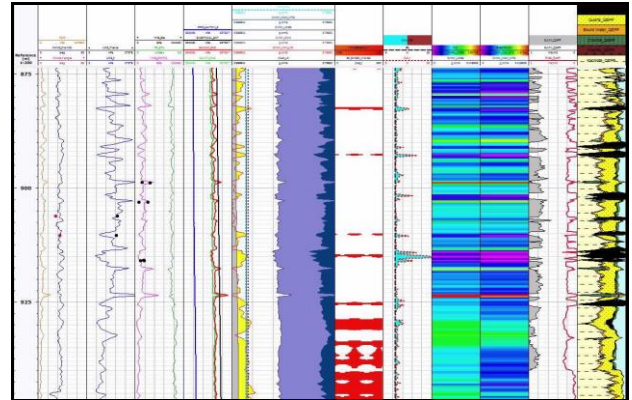


Figure 11: 1D MEM results with ELAN volume at well Z

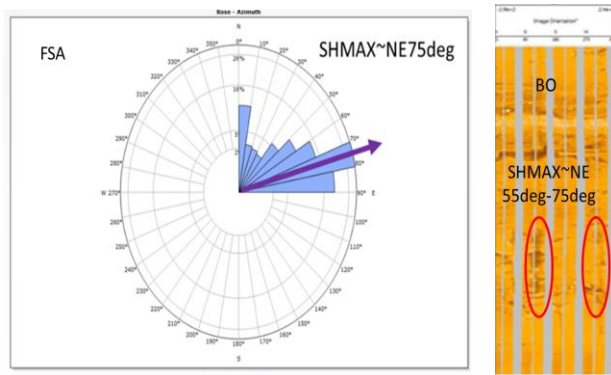


Figure 9: Horizontal stress direction using breakout and fast shear azimuth in well Z

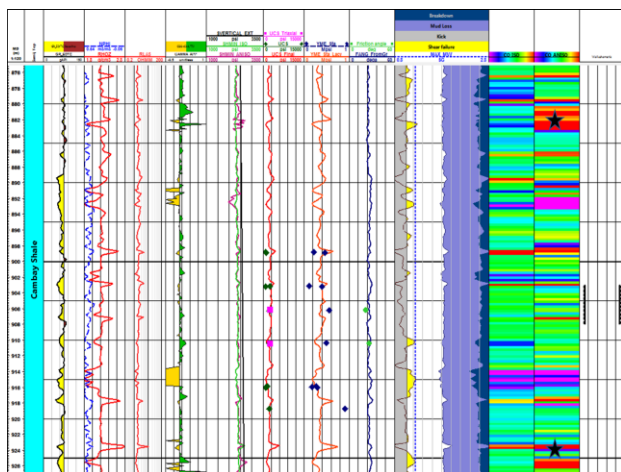


Figure 10: Anisotropic MEM with stress barriers at well Z

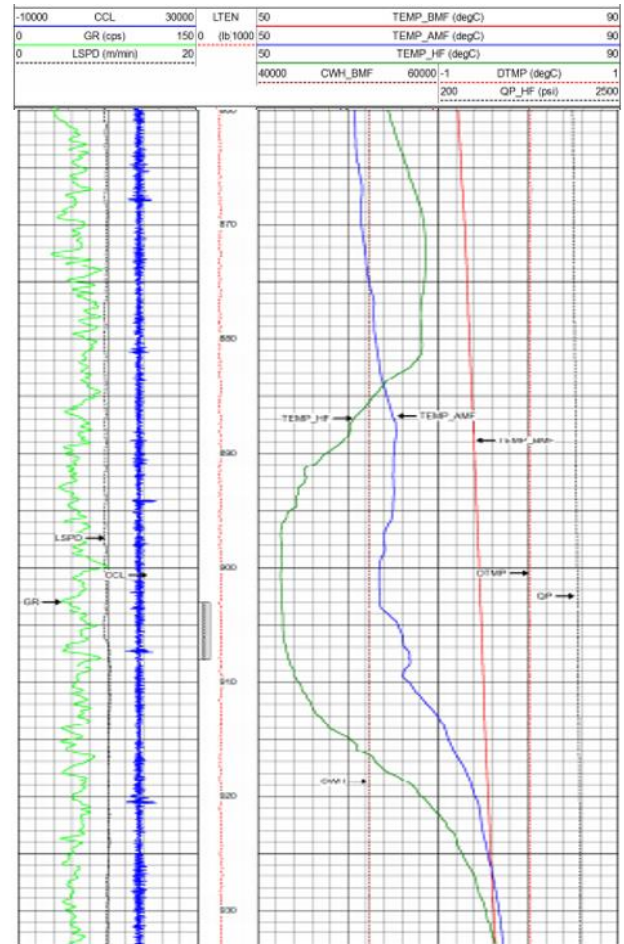


Figure 12: Temperature log at well Z