

Implementing and Monitoring a Geomechanical Model for Wellbore Stability in an Area of High Geological Complexity

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Abstract

The drilling of an oil well in an area of geological complexity presents many challenges in the planning and drilling phases. In the case presented here from Colombia, the complexities included a highly-deviated well profile, dipping formations, and naturally fractured formations. Moreover, the wellbore challenges were compounded by the high stresses in a tectonically-active area. Hence, to help ensure success of the operation, it was necessary to incorporate new technologies to define the risk that the drilling case presented and to prepare for the potential problems predicted in the pre-well planning.

For this project, the best trajectory to drill the well from a geomechanical and operational point of view could not be used because of the formation dips. A different azimuth was used, which required a new wellbore trajectory. With the new wellbore profile, the safe drilling window for wellbore stability was redefined. During the successful drilling of the difficult interval, the wellbore stability issues were monitored closely with frequent updates in the modeling.

From the various issues described in this paper, the reader can better understand the necessary planning and wellbore monitoring that is required for drilling difficult formations in tectonically-active areas.

Introduction

In order to increase well production, the operator company selected an alternative trajectory to drill the wells in the area, positioning the well at the highest point of the structure and drilling in the down-dip direction, thus allowing this well to cross a thicker drainage area.

This highly deviated wellpath would drill through an inter-bedded formation of shale and naturally fractured limestone lithologies. The axis would be almost parallel to the dip formation and main faulting plane. These aspects reflect the complex drilling environment of the project. Hence, it was crucial to apply geomechanical concepts to decrease the risk associated with drilling the well.

Geomechanical modeling for wellbore stability can address the different conditions that constitute this type of well. However, in order to quantify the effect of the variables mentioned above (drilling parallel to bedding planes in a shale formation and drilling through a naturally fractured

formation), it is necessary to have fracture porosity and permeability data, fluid viscosity inside the fractures, poroelastic parameters like undrained Poisson, Biot coefficient to model the natural fracture effects, and parameters like cohesion and the friction angle of the bedding planes and the bedding plane orientation that account for the angle of attack analysis (angle between the well and the bedding plane).

Most of this information was not available, so the wellbore stability model did not include the effect of the natural fractures and angle of attack in a quantitative way but in a qualitative way. Therefore, the collapse and fracture pressures estimated during the analysis were not influenced by these aspects, but the interpretation of the results and the recommendations about mud weight window, drilling fluid aspects related to wellbore stability and some operational aspects took into account the effect of the issues mentioned.

The results of the geomechanical and wellbore stability modeling and how the various aspects were used are discussed below, including the following up during drilling.

Project Development

The geomechanical contributions to the project are divided into three principal phases:

1. "Pre-drilling" where the geomechanical model (pore pressure, mechanical properties and stresses) and wellbore stability model (collapse and fracture pressures) were initially defined based on the off-set wells.
2. "While-drilling" where a real time following up was done at the rig site.
3. "Post-drilling" where with electrical logs and the events documented during "while-drilling" stage the final wellbore stability model was defined.

This paper addresses the "Pre-drilling" and "While Drilling" phases.

It is important to mention that during most of the planning and execution phases, interdisciplinary work was performed by reservoir and operation personnel from the operator company, as well as directional drilling and geomechanics personnel from the services company. This synergy allowed the project to benefit from dynamic planning even during the execution.

Pre-drilling Phase

The field is located in the upper Magdalena valley (Colombia) where only one offset wells (PPX-1) had the complete information needed to make the geomechanical model. Information from the other eight wells was used to calibrate the models and to define the principal risks associated with drilling operations in the field.

Information like electrical logs, image logs, rock mechanic tests, final drilling reports, leak off and formation integrity tests, mini frac tests, petrophysical model defined by the operator company, injection data and production data were used to perform the analysis.

In Figure 1 a seismic section of the area shows the locations of the prospect well (PPX-2) and PPX-1 well. The differences are clear as to how the wells cross the structure with the subsequent uncertainty for the data extrapolation from well to well. Figure 1 also shows the relationship between the well trajectory and the bedding plane dips as well as the faulting zone interpreted by the operator using seismic data.

A geomechanical model is defined by pore pressure, mechanical properties and the in situ stress state (including stress orientation). With the geomechanical model as input data, a wellbore stability model can be estimated by calculating the formation's collapse and fracture pressures.

This methodology was applied to the PPX-1 well and the wellbore stability model was compared with drilling data to validate that the model could reproduce by itself what was observed during drilling. The model obtained for PPX-1 well confirmed most of the events reported. Once this validation was done, the geomechanical model was extrapolated to the PPX-2 well and evaluated with the prognosis formation tops, and trajectory.

To perform a geomechanical evaluation, the basic log suite includes sonic, density and a lithology log such as gamma ray. The logs available for the project are shown in Figure 2; all these logs are from PPX-1 well, which had more logs of better quantity and quality. However, as can be seen in Figure 2, there is an interval without density information.

To complete the density log, the Gardner et al [1] (1974) relation was used and the result is shown in Figure 3 where the synthetic density log is shown in green color. Once the electric logs were complete, the geomechanical modeling began with mechanical properties calculations, followed by pore pressure estimations and ending with stresses magnitude and orientation.

There are different methods for obtaining the mechanical rock properties to be used in a geomechanical modeling; in this study two different sources were used. One of them was calculating the mechanical properties from different mathematical correlations from electric logs. The profiles obtained with the methodology mentioned before were calibrated by using results from rock mechanics laboratory tests performed on a core from the reservoir in PPX-1. Table 1 presents the lab results. Figure 4 presents the mechanical

properties results estimated with PPX-1 well logs and the comparison with the laboratory results.

To estimate the pore pressure values, a relation between compressive sonic log and depth was defined by using normal compaction trend lines [2]. The pore pressure profile was defined by correlating the trend line and the sonic log measures. The pore pressure profile was compared and calibrated with mud weight used and events during drilling operations. Figure 5 shows the final pore pressure profile used during the pre-drilling phase.

Knowledge of stress magnitudes and orientations at great depth is of appreciable interest in both the geologic sciences and engineering. One of the most important uses of in-situ stress data in the petroleum industry is associated with problems of wellbore Stability [3].

The stress magnitudes were estimated using some correlations as a function of some mechanical properties and pore pressure. The magnitude of this theoretical horizontal stress needs to be calibrated with field data to include the effects of lateral tectonic strains and thermal rock deformations [4]. The predominant stress regime observed according with the results is strike slip (according to Anderson's classification [5]) as can be seen in Figure 6.

The orientation of breakouts corresponds to the direction of the minimum horizontal stress whereas the orientation of induced fractures corresponds to the direction of the maximum horizontal stress in vertical wells [4]. The orientation of the principal horizontal stresses was calculated using image logs, where some open natural fractures and hydraulic fractures were identified. The average orientation of the maximum horizontal stress is E-W. Figure 7 shows diagrams where the orientation of the fractures can be seen.

Generally, a wellbore fails either by exceeding the tensile strength or the shear strength of the formation. In addition, due to the laminated texture of shale, wellbore stability may be governed by failure of bedding planes [6]. Once the geomechanical model for the PPX-1 well was defined, the wellbore stability model was calculated using an elastic analysis with Mohr-Coulomb failure criteria. As a result, collapse and fracture pressures were defined and used to determine the possible mechanical status and the mud weight window.

The trajectory sensibility of the model was determined with polar charts where the required mud weight for a specific depth is a function of wellbore azimuth and inclination. As an example, Figures 8 - 9 demonstrate the effect of the stress magnitudes and mechanical properties on the most stable trajectory at different depths, even with the same horizontal stress orientation. According to multiple polar charts created during analysis, the optimum well orientation should be NE-SW. However, it is important to remember that variables like attack angle could not be introduced in the quantitative analysis, so the polar charts did not reveal the effect of bedding dip.

Figure 10 shows the wellbore stability model for the PPX-1 well. The model was calibrated using the final borehole shape according to the PPX-1 caliper log. Some examples of

the comparison between the model results and caliper log can be observed in Figures 11 - 12. Since, a good correlation between wellbore stability model and the caliper log was observed, the geomechanical model was extrapolated to prognosis formation tops and well trajectory for the PPX-2 well. The wellbore stability model for the PPX-2 well is shown in Figure 13 with the safe mud weight window proposed.

With the observations made from geomechanical and wellbore stability modeling, some risks and mitigation plans were proposed including maintaining concentrations of a sealing, bridging agent and shale stabilizers in the drilling fluid. This would help control stability related to natural fracture because friction angle reduction of fractures due to mud infiltration significantly affects wellbore stability during drilling [7]. Once this is accomplished, the mud weight can be increased to control shear failure in the borehole. A particle size distribution (PSD) analysis was recommended to determine the correct concentrations of the drilling fluid additives.

While-drilling Phase

Due to some operational issues, a sidetrack was performed in PPX-2 well. Due to this side track, it was necessary to calibrate and monitor wellbore stability model in real time. The main activities during “while-drilling phase” included caving monitoring (volume, shape and sizes), review of pressure-while-drilling (PWD) measurements and while-drilling events related to stability and hole cleaning. On the other hand, the actualization of the model with observations made at well site and according to the new well trajectory was done. The results during follow up showed that the previous wellbore stability modeling was very close to the mechanical behavior of the well.

Figure 14 shows the previous modeling (collapse and fracture pressures) and the mud weight used in the original well before the first sidetrack (ST1). This figure shows how the model predicted zones where caving rates increase (cyan line) and it became necessary to increase the mud weight. It is clear that as the collapse pressure increases, the caving volume increases too. The arrows in Figure 14 indicate the behavior of the caving rate and the correspondence between it and the collapse pressure predicted in the planning phase.

Taking into account that the predicted potentiality wellbore stability tendencies of the formations were observed by means of different factors like caving rates, increases in annular pressures and difficult trips, and that modeling does not include critical factors like the angle of attack and natural fractures influences, it is considered that the modeling represents the geomechanical response of the formations drilled.

The fracture pressure calibration can be done by means of several sources: step rate test (SRT), extended leak-off test (XLOT) or hydraulic fracturing. The formation integrity test (FIT) indicates only the minimum value that the fracture gradient may be. Due to the fact that there was no more information, the FIT values were used in the way mentioned.

Once the adjustment of the modeling in the original hole was completed, the data extrapolation was done according to the tops and trajectory of the ST1. Figure 15 shows the wellbore stability model after the extrapolation to the ST1.

The monitoring mentioned previously was the base line for the changes made to the mud weight window to drill the ST1. The main change was to increase the mud weight according to the collapse pressure estimated for ST1. As a result of the mentioned changes, a lower caving production rate was seen as shown in Figure 16. Figure 17 shows the predominant morphology registered.

Figure 18 shows an image log acquired in the 11133 ft to 11772 ft (MD) interval. In this image a difference of less than 1.5” between bit size and borehole diameter can be observed. This is evidence of the stability of the interval as predicted by the wellbore stability model. The follow up of the model at the rig site explains this widening as a combined effect of tabular caving production and drill string eccentricity due to the high inclination of the hole. Several more similar examples were done during project development.

After about 43 days of drilling the ST1, the well reached total depth achieving the principal objectives and indicating that these types of well geometries can be drilled with a daily planning work during execution, and the use of tools during the project development that can help drilling engineers reduce risk by identifying it.

Conclusions

1. The estimated mechanical properties from logs match with the test results from the laboratory.
2. The predominant stress regime in the area corresponds to a strike slip regime.
3. The most stable trajectory to drill wells in the area corresponds with E-W orientation.
4. The wellbore stability model developed during planning was accurate based on events observed during drilling, especially in the interval prior to the first sidetrack.
5. To handle instability from natural fractured zones and shear failure at the same time it is recommended to increase the concentration of sealing materials such as graphite and asphalts prior to increase mud weight.
6. The detailed caving monitoring during drilling is a very helpful tool for making decisions about increasing mud weight to manage wellbore instability.

Acknowledgments

The authors would like to thank both Halliburton and Ecopetrol for their cooperation and support in developing this project.

Nomenclature

- PWD* = Pressure While Drilling
ST1 = Side Track 1
UCS = Unconfined Compressive Strength

T_o = Tensile Strength

P Velocity = Compressive wave velocity

S Velocity = Shear wave velocity

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Tables

Table 1. Result for mechanical properties measured using a core samples from reservoir formation in PPX-1 well.

SAMPLE DEPTH (ft)		12113.63	12115.17	12119
UCS (psi)		10134.24	11947.4	12488.39
T_o (psi)		572.28	N/D	1396.6
P Velocity (m/seg)	Min.	2624.61	2667.7	2728.12
	Max.	3969.92	4185.16	3394.22
S Velocity (m/seg)	Min.	1361.35	1647.63	1696.071
	Max.	2069.01	2099.74	2075.91
Average Poisson Relation	Dinamic	0.352	0.279	0.174
	Pseudo-static	0.313	0.252	0.155
Average Young Modulus (1E06 psi)	Dinamic	2.826	3.598	3.213
	Pseudo-static	2.669	2.301	2.08

Figures

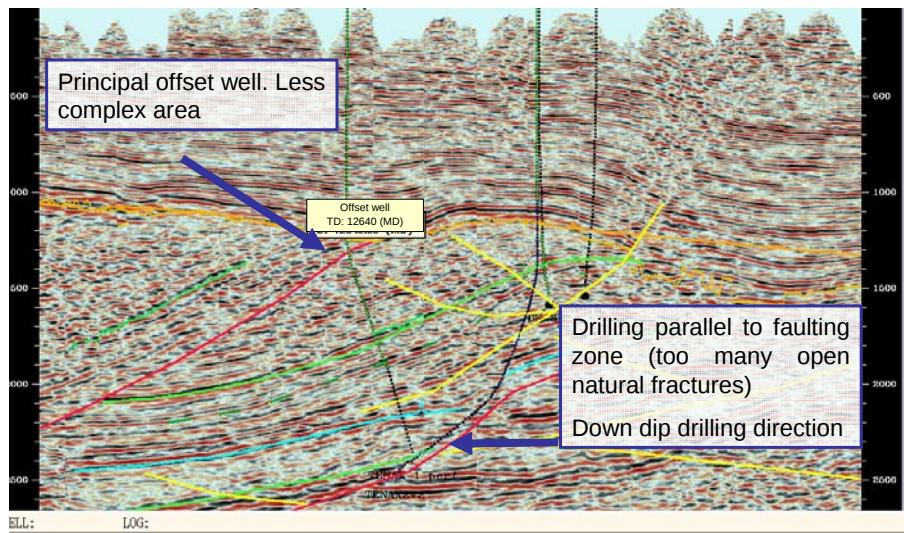


Figure 1. Seismic section of the area under analysis.

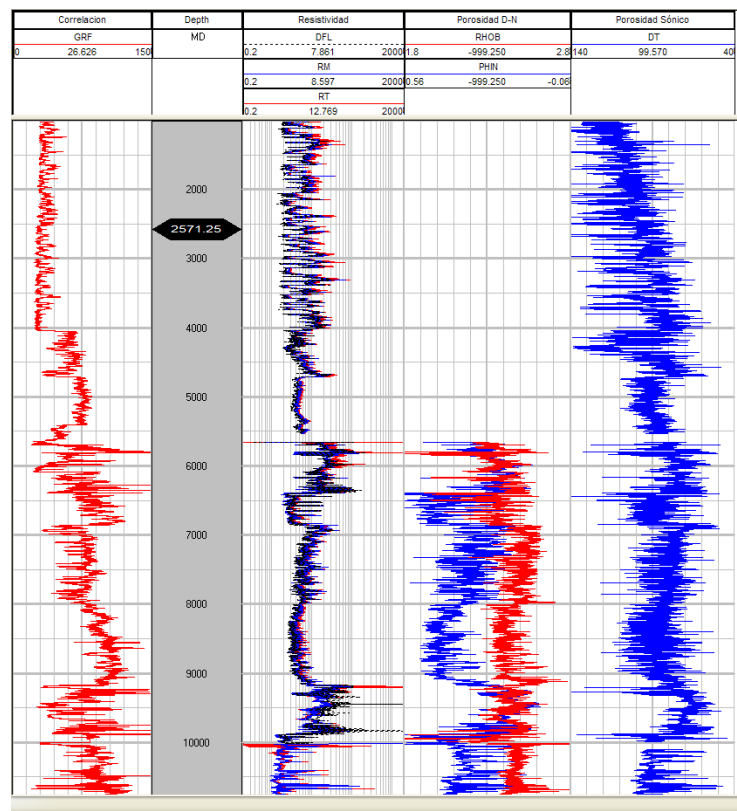


Figure 2. Logs inventory in PPX-1 well. An interval without density log is observed.

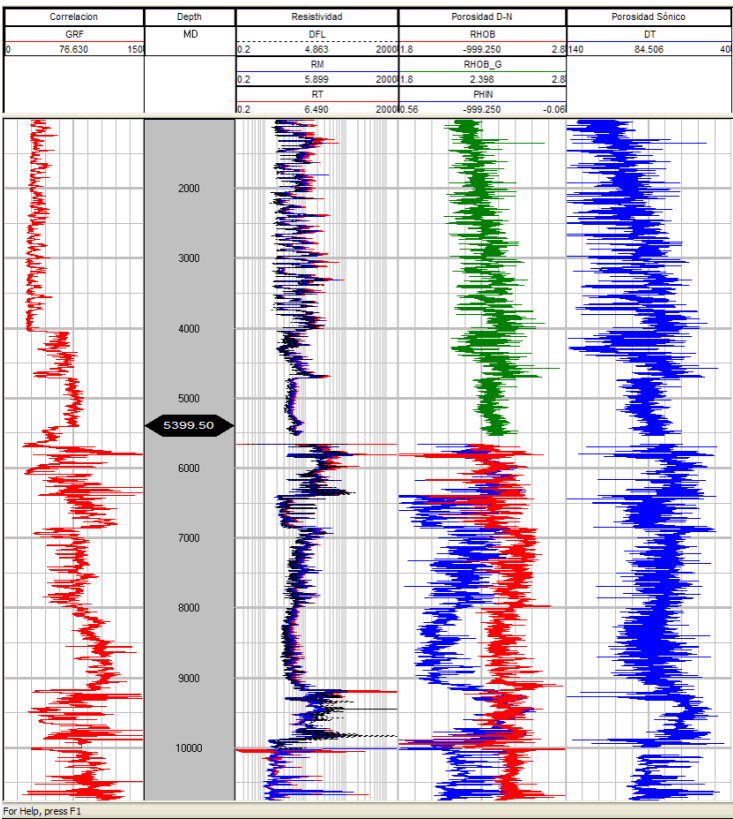


Figure 3. Synthetic density log (green curve), modeled to complete the input data to develop the geomechanical analysis.

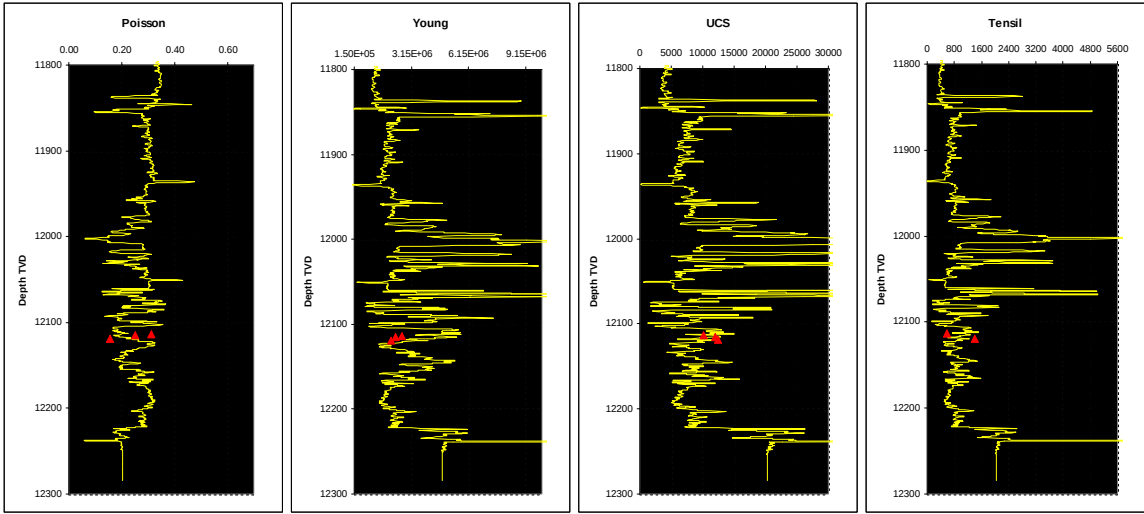


Figure 4. Comparison of the mechanical properties estimated during the analysis (yellow profiles) with lab test (red points).

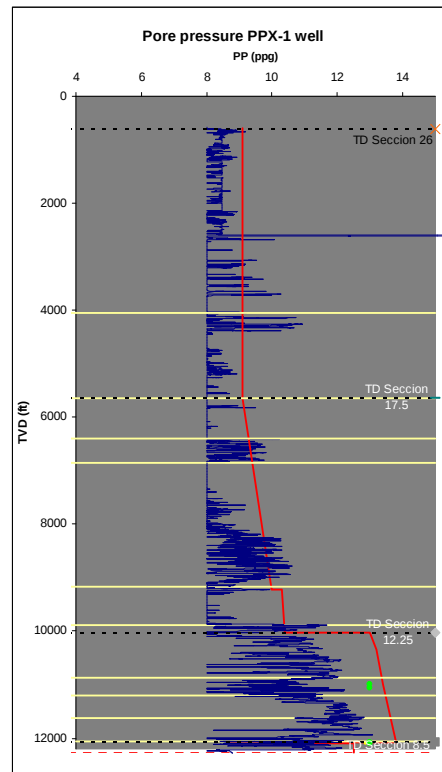


Figure 5. Pore pressure profile (blue line) estimated from sonic log in PPX-1 well. Red line corresponds to MW used during drilling. Horizontal dashed lines correspond to end of hole sections and horizontal continuous lines correspond to formation tops.

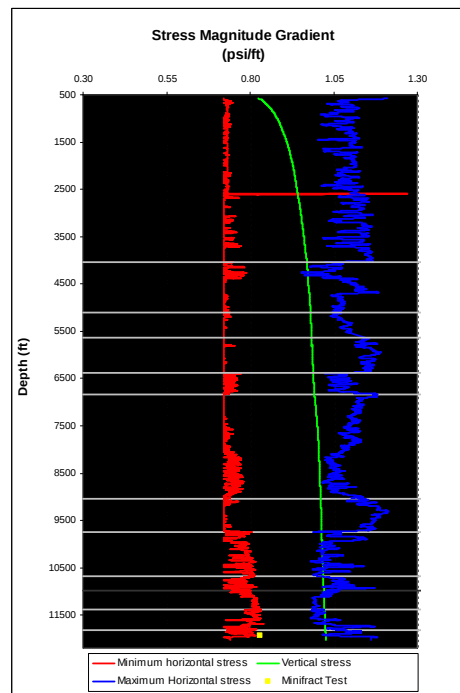


Figure 6. Stresses magnitudes estimated for the project. A predominant strike slip regime is observed.

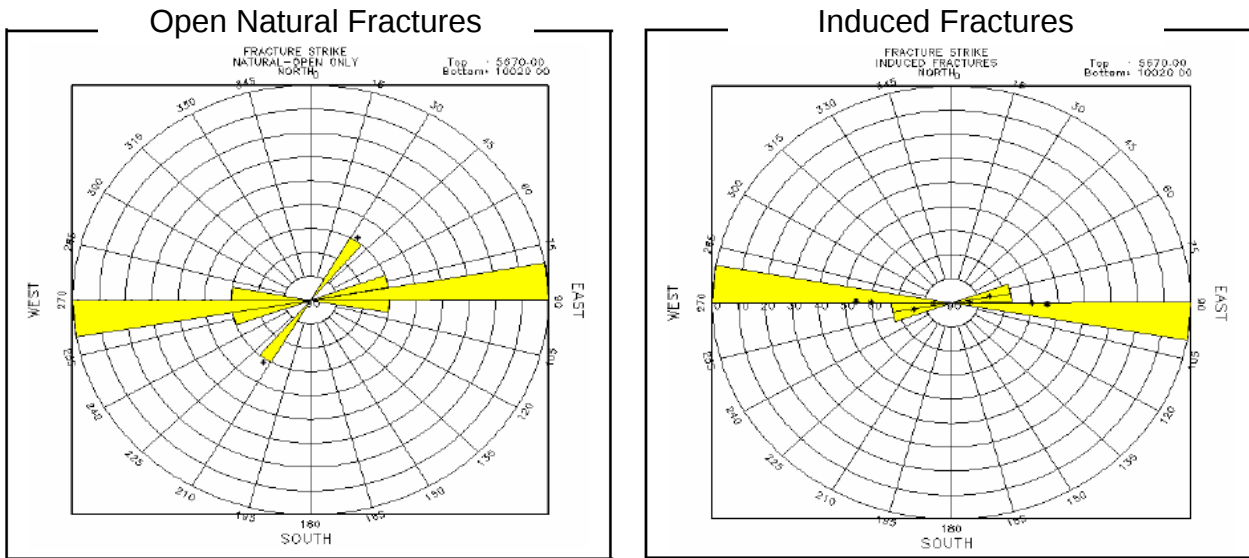


Figure 7. Open natural fractures and induced fractures orientation determined from image log from PPX-1 well.

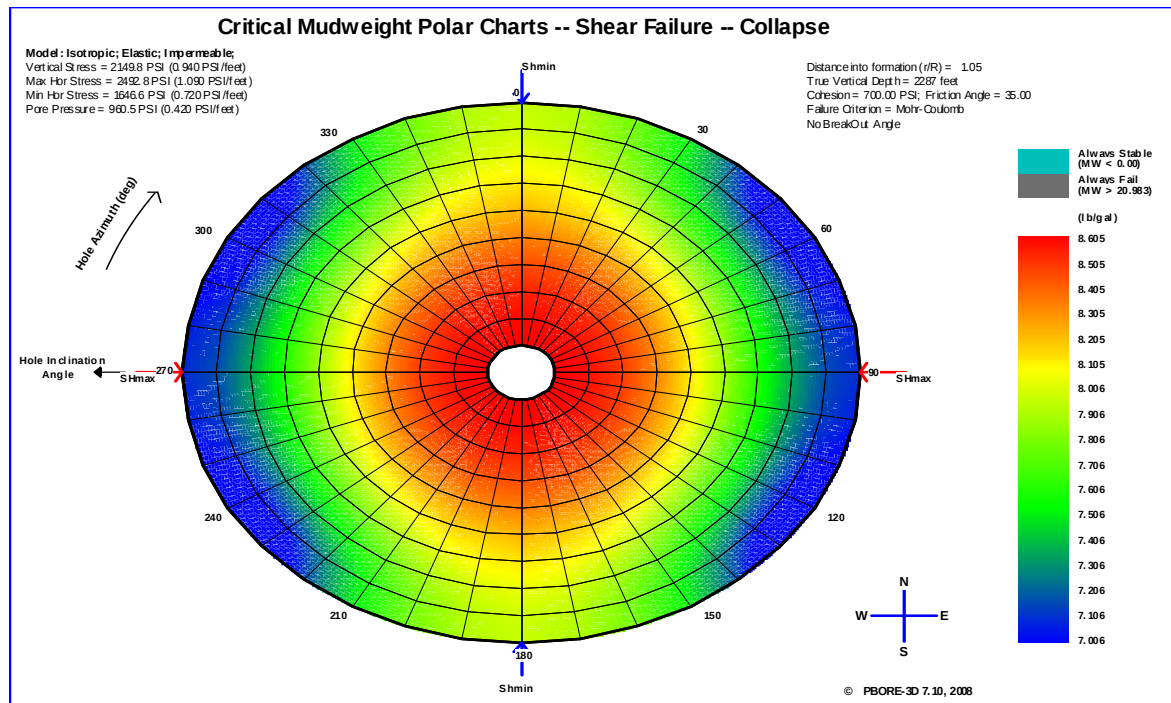


Figure 8. Polar chart at 2287ft TVD.

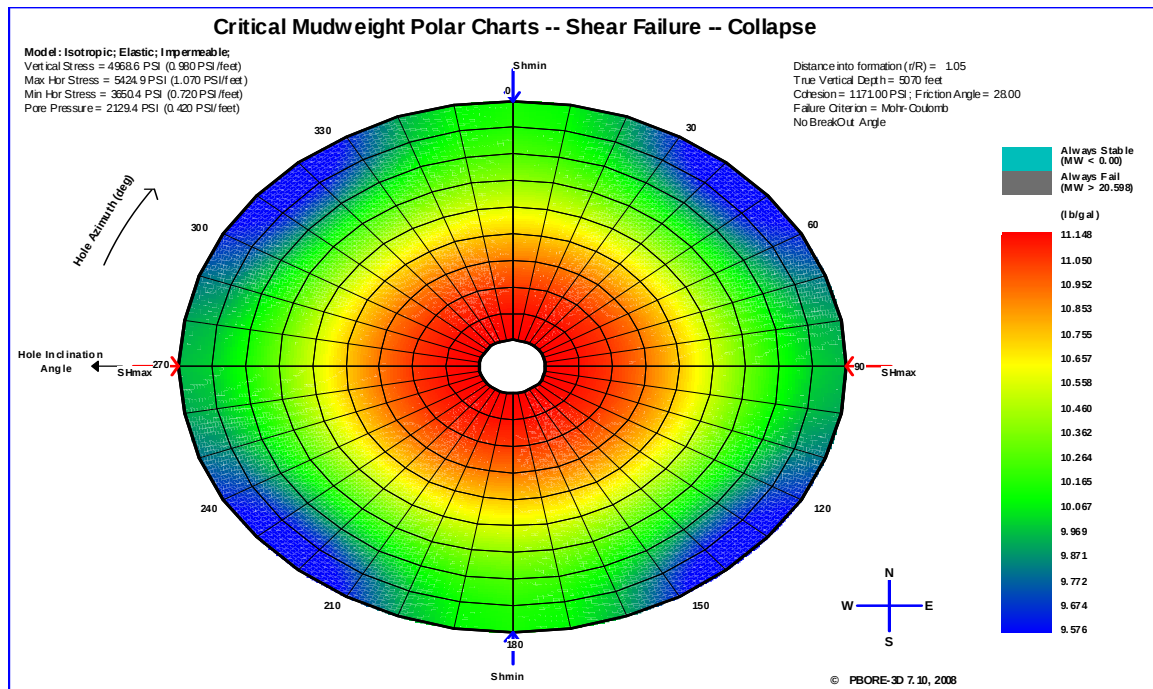


Figure 9. Polar chart at 5070ft TVD.

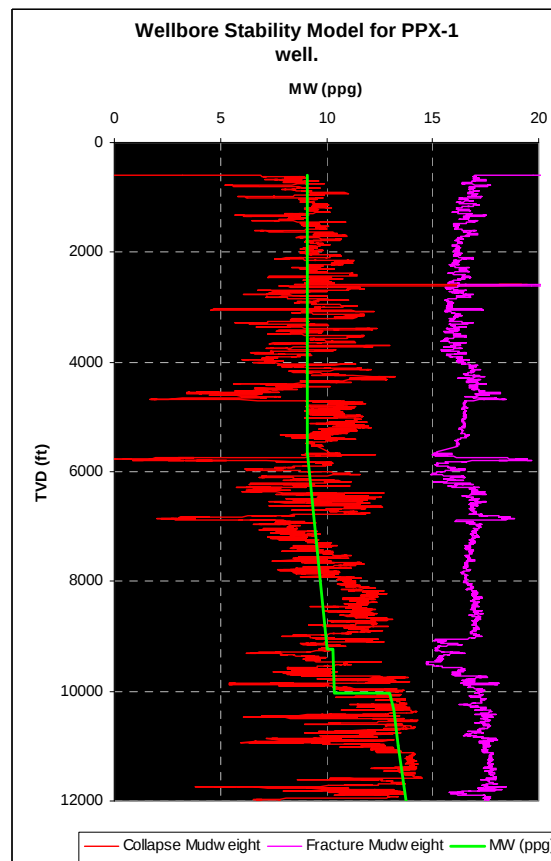


Figure 10. Wellbore Stability Model estimated for PPX-1 well.

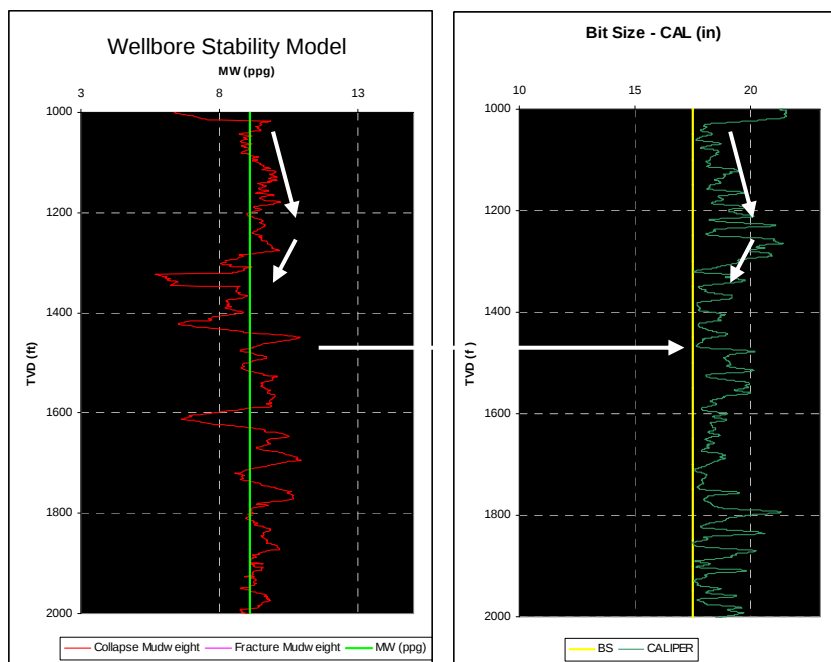


Figure 11. Comparison between wellbore stability model and caliper log in PPX-1 well. Example from 1000 to 2000 ft TVD

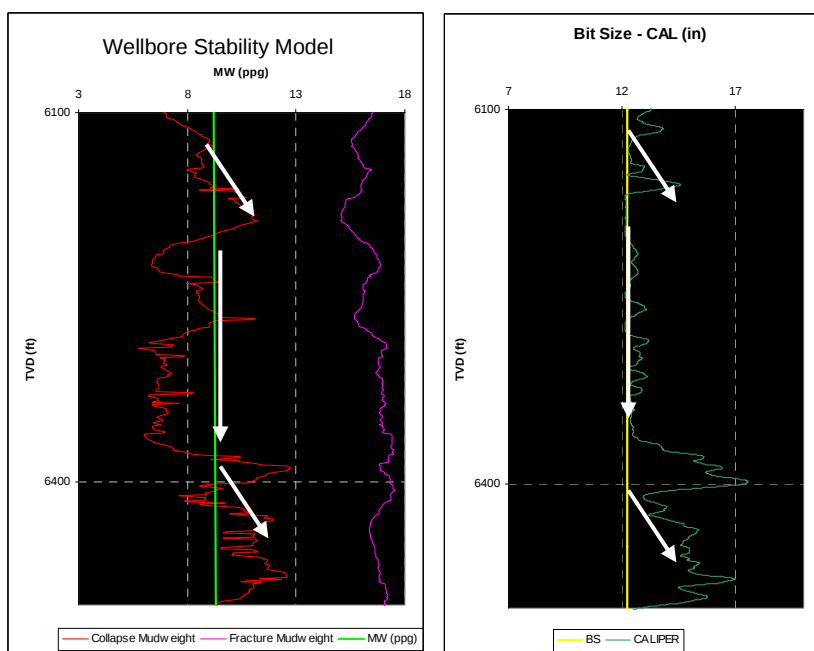


Figure 12. Comparison between wellbore stability model and caliper log in PPX-1 well. Example from 6100 to 6550 ft TVD

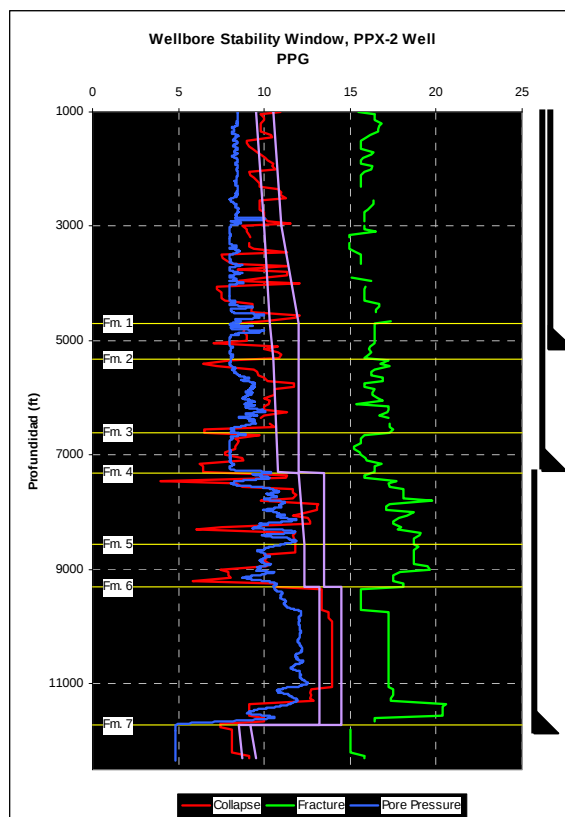


Figure 13. Wellbore stability model for the prospect well (PPX-2), and mud weight window proposed (Purple lines).

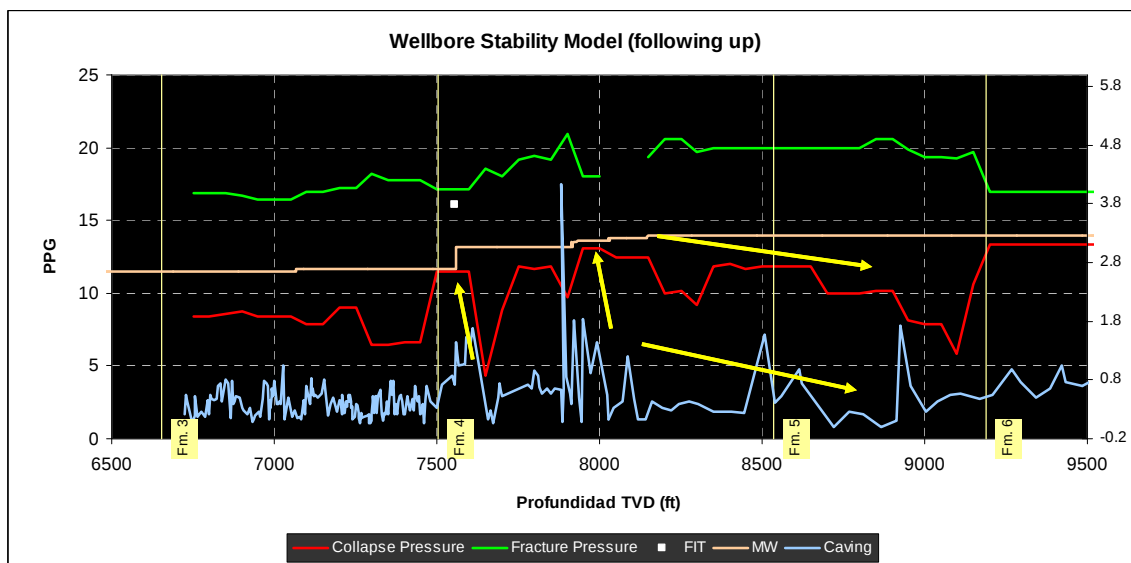


Figure 14. Comparison between wellbore stability model and caving rate during PPX2 well drilling. Observe how where MW is too close to collapse pressure the caving rate increase.

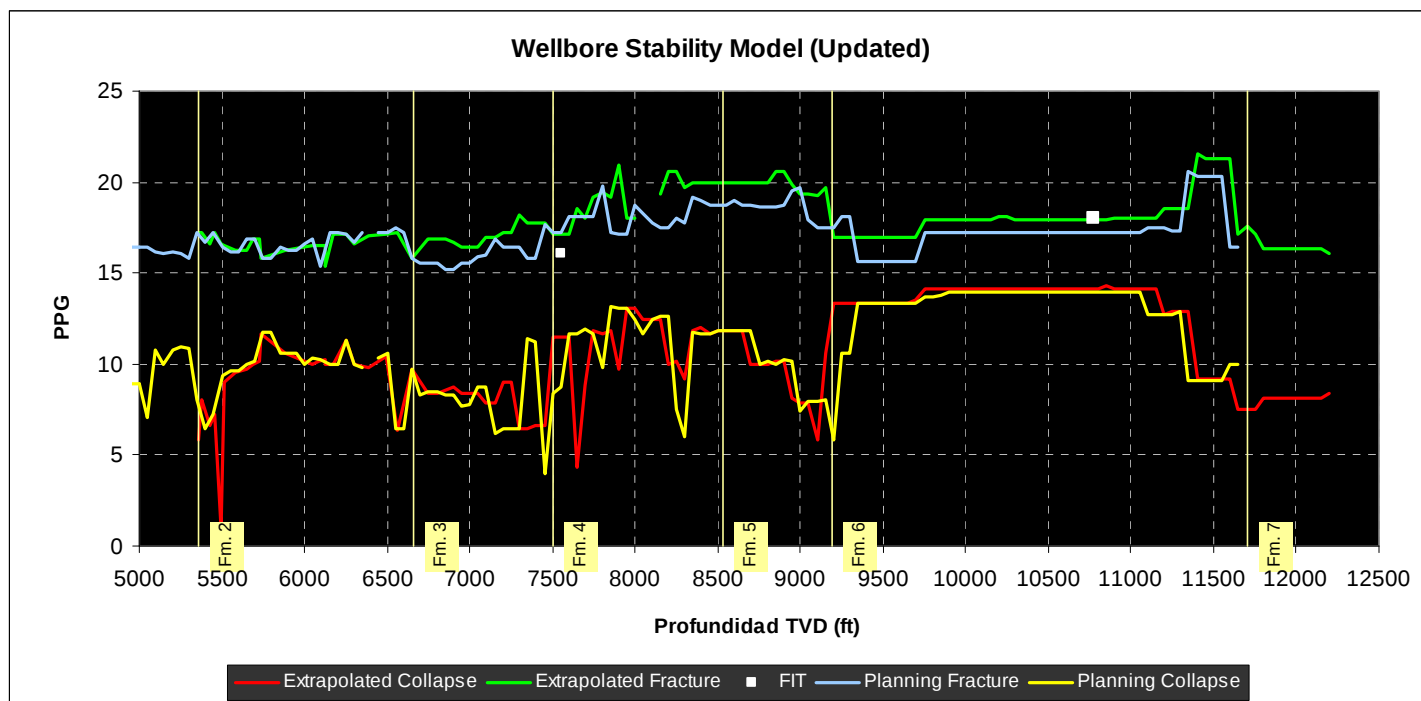


Figure 15. Comparison between wellbore stability model before updating (planning) and model after following up (extrapolated).

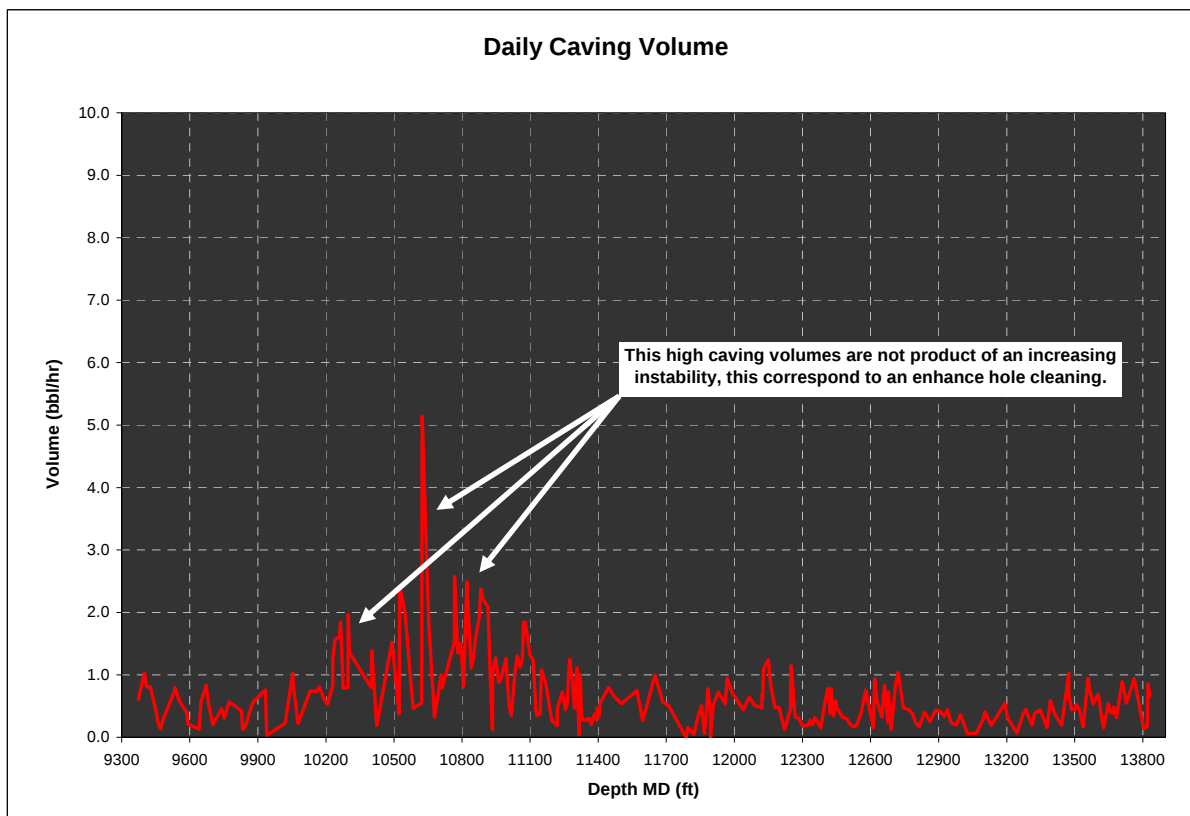


Figure 16. Caving volume during drilling ST1.



Figure 17. Example of the predominant caving morphology produced during drilling ST1. It can be observed the tabular shape.

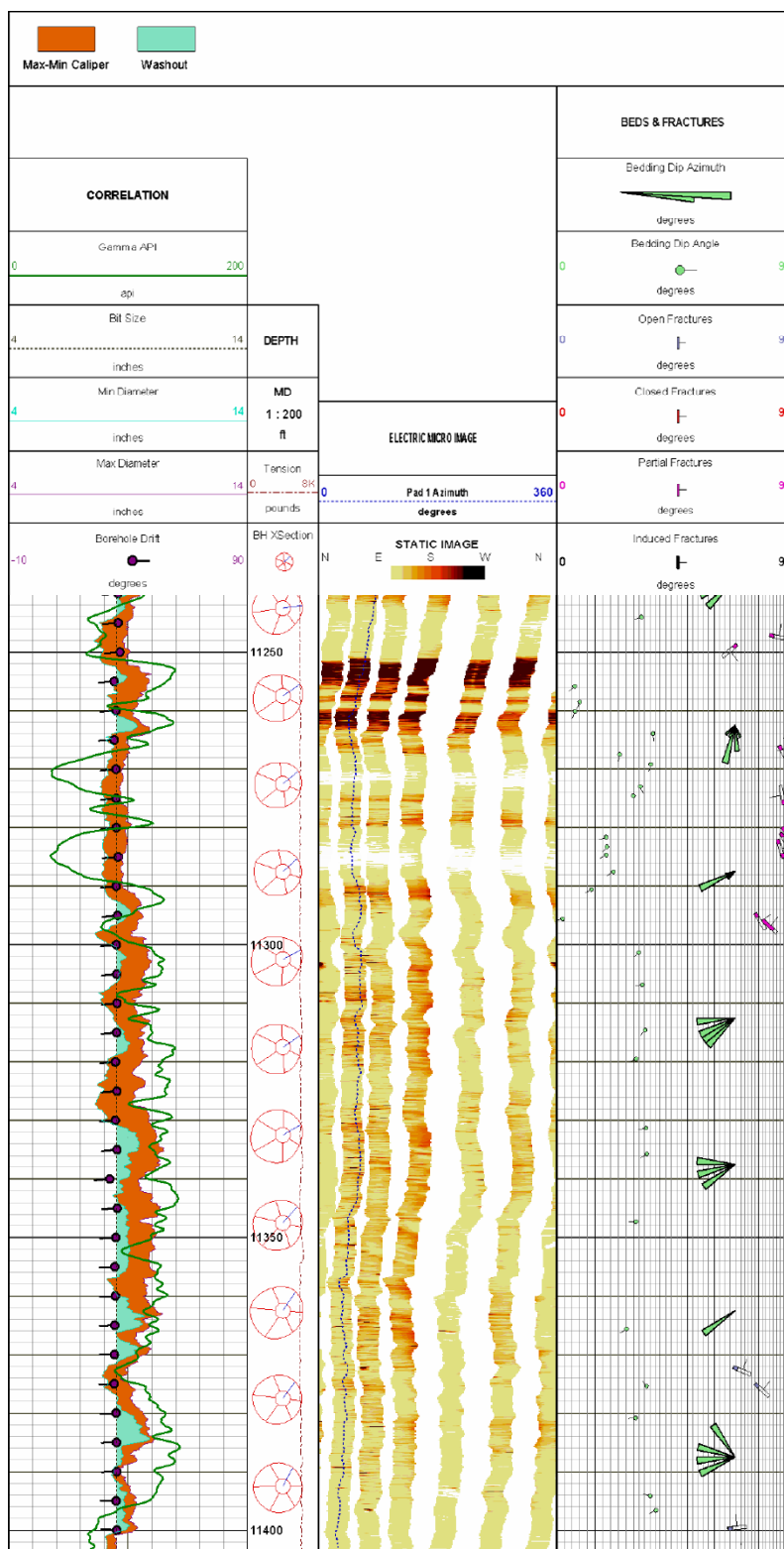


Figure 18. Example of the image log taken in PPX-2 well. No more than 10" diameter is observed in an interval drilled with 8.5" bit, in a formation drilled with high deviation angle and producing tabular cavings.