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Case Study: Geomechanics Modeling with Limited Data Can Provide Critical Understanding for Drilling Optimization

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Abstract

It is not only expensive but sometimes impossible to gain access to all the data for a wellbore stability study. Engineers are constrained to using what they have on hand to provide the best design for drilling. However, with thorough understanding of the drilling activities, geo-mechanics and available data in various formats, substantial understanding still can be achieved for improved design with a robust wellbore stability analysis program. In this paper, using a wellbore stability analysis case study, it is demonstrated how fundamental understanding can be obtained even with limited data.

Introduction

Drilling is a direct human interaction with rock. Maintaining a functioning wellbore is critical after it is created by rock fragmentation from bit rotation. A functioning wellbore should be able to contain a range of wellbore pressures or provide a mud weight window so that normal drilling operations can proceed to achieve all drilling objectives. Drilling troubles may be encountered when drilling operations are executed outside this window, especially when the window is incorrectly predicted or when the window is too narrow for the drilling conditions. This mud weight window is defined by many factors including rock characteristics, stress and pressure, borehole orientation, wellbore quality and wellbore fluid properties. However, the availability of these data types is questionable most of the time. Predicting the mud weight window or analyzing drilling troubles can seem very difficult.

However, in different scenarios, the importance of different data varies and only those key data will affect the most of the analysis results. Not knowing other data is not a large barrier for a good analysis most of the time. Meaningful interpretation can be achieved by using a robust computer program for wellbore stability analysis, combined with thorough understanding of available geomechanics data and subtle investigation logic. With this approach, rigorous results still can be obtained by evaluating those unknown factors.

Using a wellbore stability analysis case study, this paper demonstrates how critical understanding of a geomechanical environment for drilling can be obtained with limited data and how the understanding can be linked to determining the root cause of drilling troubles.

The Drilling Challenge

Several wells have been drilled at basically the same Gulf of Mexico location and have encountered tight-hole problems that required reaming to pull the drillstring out of the hole. A summary of the problems in one well related to this case study is provided in **Table 1**. It is important to point out that the problems were encountered only after two days of drilling, while pulling out of hole. Therefore, it appeared to be a time-dependent issue. Also from Table 1, it can be seen that these two wellbores are highly deviated and the lithology of these problematic zones was basically shale. Consequently, a thorough understanding of the root cause of the situation is needed so that solutions can be provided for subsequent wells based on the analysis.

Data Available

Though limited, there are still some data available. These include the following from an offset wellbore and its one sidetrack hole:

- Pore pressure / fracture gradient (PP/FG)
- Wellbore trajectory
- E-log (Gamma Ray, Caliper, Resistivity)
- Mud weight and the overburden gradient
- Mud log
- End of Well Report
- Maximum horizontal stress (S_{Hmax}) direction
- Synthetic-based mud properties

There is no data on the magnitude of S_{Hmax}. The wellbore pressure varies during drilling basically from equivalent static density (ESD) to equivalent circulating density (ECD), and this was recorded by pressure-while-drilling tools (PWD). **Table 2** summarizes the pertinent data for wellbore pressure.

Some rock strength data are also available for a different offset well. The properties are listed in **Table 3**.

For the proposed well to be drilled, predicted PP/FG data, well trajectory and wellbore schematic are available.

The Software

For complicated wellbore stability analysis, computer software programs are necessary to tie all the factors together to gain a quantitative result. The software program used here has various modules which allow engineers to do analysis by considering various factors such as elasticity, permeability, chemistry, fractures, etc. This program has been evaluated by different industry users over several years.

The Approach[1]

For wellbore stability analysis, in general, a geomechanics model has to be built first. This can provide the basic input data for wellbore stability analysis modeling. The stability model then has to be calibrated with factual data so that it will reflect reality. After this, the model can be used for predicting wellbore behaviors for a new well with a defined wellbore trajectory.

However, when there are not enough data to satisfy the input needs, it does not seem to be possible to build such a model for further analysis. In the case of limited data, numbers must be guessed in order to have a working model. This can leave a degree of uncertainty concerning the result. Then a unique step is needed. In this step, guessed numbers must be evaluated for their influence on the final results or how large an error could be made if they are not accurate.

In this example case, a major unknown is S_{Hmax}. Another major one demonstrated is the chemical effect of the drilling fluid.

Results and Analysis

1. Evaluation of Maximum Horizontal Stress (S_{Hmax})

In this case, the items described above provide the basic data set for wellbore stability analysis modeling. The most needed for modeling this case is the maximum horizontal stress: S_{Hmax}. This value is very difficult to obtain. People have been using wellbore breakout data with a wellbore stability model to back-calculate this value.

As a starting point in this study, with the understanding that the stress regime in the Gulf of Mexico is normal, we assume that $S_{Hmax} = (S_v+S_{hmin})/2$. Using the minimum compressive strength from Table 3, for no fluid effects or pure linearly elastic conditions, the stability model can be easily constrained to have a critical mud weight of 11.73 ppg, which meets the wellbore lowest pressure when overpull was observed during pulling-out-of-hole operations.

Without fluid invasion or impermeable boundary conditions, for poroelastic conditions, **Figure 1** shows that this poroelastic effect has very little influence on critical mud weights over time. The critical mud weight varies only about 0.05 ppg over two days and then stabilizes. Therefore, a pure linearly elastic approach is a good approximation.

Now let's have a closer look at the S_{Hmax} issue. For this investigation, assuming linearly elastic conditions, two different runs of the simulation were done. The first one focuses on how the critical mud weight varies with the hole angle and azimuth. This variation is summarized in **Figure 2**. The simulation input data are also summarized in the figure. From Figure 2, it can be seen as usual, there is a preferred direction of drilling, in which the critical mud weight is the lowest. However, with a closer look at this result, one can also see that the range of the critical mud weight varies only by 0.06 ppg. This is really trivial difference. What does it mean then? It means that from a practical point of view, there is no preferred direction of drilling. In other words, it would be equally safe with the same mud weight when drilling at any direction in this area. The second run is the same but assumes that $S_{Hmax} = S_v$. From **Figure 3**, it can also be seen that the critical mud weight varies by only 0.02 ppg for all the directions of drilling, and a preferred direction does not seem to exist.

This further verifies that not knowing the magnitude of S_{Hmax} has little or no effect on the accuracy of the study, if the drilling conditions can basically satisfy the assumptions such as little fluid invasion and rock continuity. This also tells us that the direction of S_{Hmax} is also of little importance. Due to this insensitivity to direction, there is basically no preferred drilling direction within the assumed conditions.

Therefore, when there is no fluid invasion, with the model as defined, the critical mud weights for different zones for the new well can be predicted as in **Table 4**.

The above analysis is based on the assumption of no fluid invasion. However, it may not be the case in reality. Because a non-aqueous drilling fluid was used, the fluid invasion into shale would be limited primarily to osmosis and permeability of natural fractures. Due to the interfacial tension, invasion into water-wet tiny shale pores with non-aqueous fluids requires a substantially high differential pressure and normally it is not possible. However, where fractures are wide enough, only little differential pressure may be needed. For osmotic invasion, the main driver is the water activity differential between the shale and the non-aqueous mud.

In the Gulf of Mexico, the majority of young shales have not been through much tectonics, and therefore, rich tectonic fractures are not likely. Due to the low compaction in the Gulf of Mexico, the shale is of relatively high plasticity, and therefore, it is more difficult to maintain open natural fractures over geological time. However, it is possible that natural fractures may be opened by shrinkage of shale caused by osmotic effects.[2]

Therefore, if no adverse osmotic effects occur, it is not very likely that the natural fractures would be a substantial factor in wellbore instability in this case. It is natural, in this case, that the analysis is first focused on possible fluid invasion caused by osmotic effects.

2. Evaluation of Chemical Effects

Water activities are unknown in this case. Evaluation is performed by assuming that one water activity is slightly greater than the other to see the influence on wellbore failure. Mud weights that may offset this osmotic invasion are also evaluated for better understanding.

Figure 4 shows a simulation result for a case when the mud water activity is 0.84 and formation water activity is 0.85. This is a result after a two-day period. It does not show any instability at all for the entire two days. This simulation was done at a mud weight of 11.8 ppg. However, increasing the mud weight to 12.5 ppg shows no indication of wellbore instability, or the effect of differential pressure on fluid invasion is not detrimental in this case.

However, when the water activity in the mud is higher than that in the formation, the result is totally different. **Figure 5** shows a result of a simulation after a two-day period. In this situation, the mud water activity is 0.86 and the shale water activity is still 0.85. The orange color zone indicates the failure area. Together with simulation at other times, it shows that the chemical effect can cause a failed area around the wellbore when the formation chemical potential is not balanced.

When unfavorable osmotic effects exist, furthermore, natural fractures may be open during the osmotic process.[2] This would in turn worsen the situation. Therefore, it is clear that it is very important that a correct water activity of the non-aqueous drilling fluid is maintained according to what is in the formation. This analysis points out that knowing the exact formation water activity is of great significance. However, there has not been a universally accepted method for predicting the water activity in shale formations. Valuable discussion can be found in a reference paper.[3]

Conclusions

The wellbore stability analysis was performed without knowing critical information of the magnitude of S_{Hmax}. However, this was offset by an evaluation step with general knowledge of the area and other data aided by a special computer program.

The analysis points out wellbore trajectory (inclination and azimuth) should not be a critical factor without fluid invasion. Fluid invasion most likely is caused by osmotic effects and this can be controlled by the water activity of the non-aqueous drilling fluid when the shale water activity is known.

Since allowed increases in mud weights would not provide substantial offset on the fluid invasion caused by osmotic effects, the recommended mud weight is about 11.8~12.00 ppg without considering osmotic effects or the use of balanced water activity.

Due to the possibility of shale shrinkage caused by imbalanced water activities, a balanced water activity may be more critical for drilling in this kind of rock environment. Therefore, accurately predicting the shale water activity seems to be very critical.

Acknowledgments

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Nomenclature

Azi	*Azimuth*
deg	*Degree*
Dev	*Deviation*
ECD	*Equivalent Circulating Density*
ESD	*Equivalent Static Density*
ft	*Feet*
ID	*Identification*
lb/gal	*Pound Per Gallon*
MD	*Measured Depth*
md	*MiliDarcy*
Mini	*Minimum*
MW	*Mud Weight*
PPFG	*Pore Pressure Fracture Gradient*
ppg	*Pound Per Gallon*
PWD	*Pressure While Drilling*
SBM	*Synthetic Based Mud*
S_{Hmax}	*Maximum Horizontal Stress*
S_{hmin}	*Minimum Horizontal Stress*
ST	*Side Track*
S_v	*Vertical Stress*
TVD	*True Vertical Depth*
UCS	*Unconfined Compressive Strength*

References

1. Wang, H., Soliman, M.Y., Shan, Z., and B. Towler. "Geomechanics Modeling for Better Drilling Performance," *World Oil*, June 2008, pp 77-81.
2. Rojas, J.C., Clark, D.E., Greene, B., Zhang, J., "Optimized Salinity Delivers Improved Drilling Performance," paper AADE-06-DF-HO-11, presented at the AADE 2006 Fluids Conference held at the Wyndam Greenspoint Hotel in Houston, Texas, April 11-12, 2006.
3. Wang, H., "Rethinking of Shale Swelling Based on Interesting Test Results," paper ARMA 10-172, to be presented at the 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, held in Salt Lake City, UT June 27–30, 2010.

Tables

Table 1 Problems Encountered during Drilling on the Problematic Well

	ST00					
Zone	MD, ft	TVD, ft	Dev, deg	Azi, deg	Lithology	Observations
1	14999	13564	48.4	58	shale	tight hole, reaming
2	19833	16780	48.2	60	shale	packoff
	ST01					
3	18612	16200	31.4	126.6	shale	overpull 60,000 lbs
4	17786	15501	36	88.6	shale	backreaming

Table 2 Summary of the Pertinent Data for Wellbore Pressure

	ST00					
Zone	MD, ft	TVD, ft	Dev, deg	Azi, deg	Mini. MW, ppg	ECD, ppg
1	14999	13564	48.4	58	11.5	12.08
2	19833	16780	48.2	60	11.5	12.08
	ST01					
3	18612	16200	31.4	126.6	11.8	12.45
4	17786	15501	36	88.6	11.8	12.39

Table 3 Summary of UCS Tests for an Offset Well

Reservoir Intervals	Sample ID	Depth (ft)	Orientation	Pre-Test As-Rec'd Bulk	Compressive Strength (psi)	Poisson's Ratio	Young's Modulus (psi)
Lower Shale Section	BSA-15	17,035.80	45 °	2.368	1405	0.14	338,600
	BSA-24	17,035.80	45 °	2.585	8510	0.26	3,772,000
	BSA-8	17,035.60	60 °	2.372	1370	0.1	262,800
	BSA-4	17,035.60	Horizontal 90 °	2.34	4145	0.19	379,200
Upper Shale Section	BMA-2	17,002.20	Vertical 0 °	2.315	1230	0.13	91,510
	BMA-18	17,001.40	Vertical 0 °	2.406	3480	0.18	460,000
	BMA-9	17,002.00	45 °	2.409	3260	0.15	571,100
	BMA-3	17,002.30	Horizontal 90 °	2.375	1695	0.31	670,400

Table 4 Predicted Critical Mud Weights for the New Well (No Fluid Invasion)

Zone	MD, ft	TVD, ft	Pore Pressure, psi/ft	Shmin, psi/ft	Shmax, psi/ft	Overburden, psi/ft	Dev, deg	Azi, deg	Critical MW, ppg
1	16268	13564	0.61	0.68	0.69	0.69	58.4	63.6	11.75
2	21888	16780	0.55	0.70	0.72	0.75	30.0	63.6	11.16
3	21161	16200	0.53	0.68	0.71	0.74	45.0	63.6	10.86
4	19964	15501	0.56	0.70	0.71	0.73	58.4	63.6	11.32

Figures

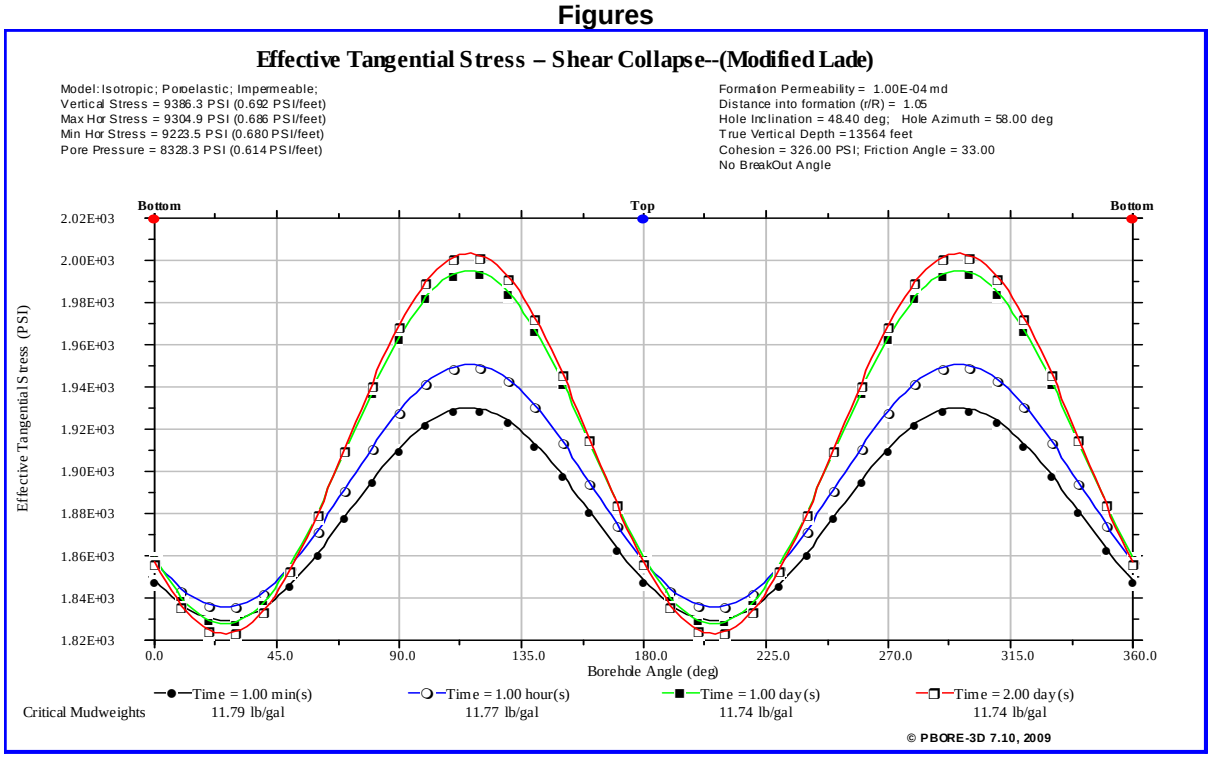

Figure 1 Tangential Stress and Critical Mud Weight Change with Time (Impermeable Boundary and Poroelastic Conditions)

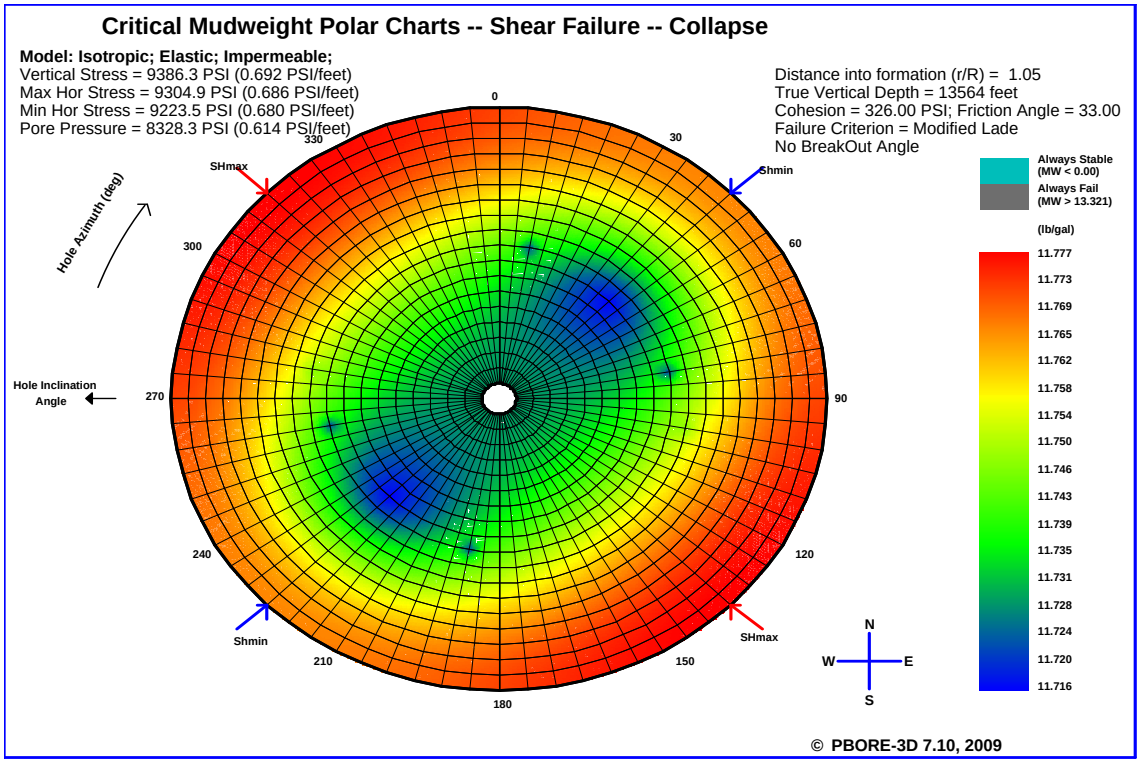

Figure 2 Critical Mud Weight for Various Drilling Directions when $S_{Hmax}=(S_V+S_{hmin})/2$

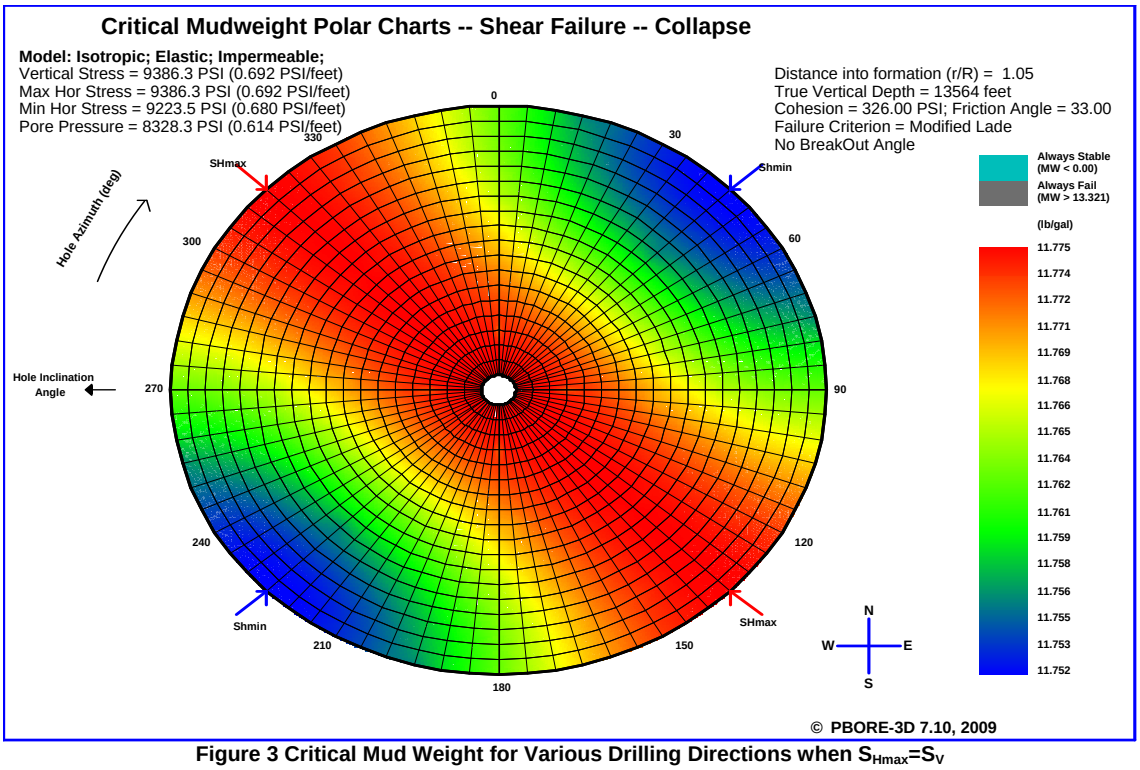

Figure 3 Critical Mud Weight for Various Drilling Directions when $S_{Hmax}=S_V$

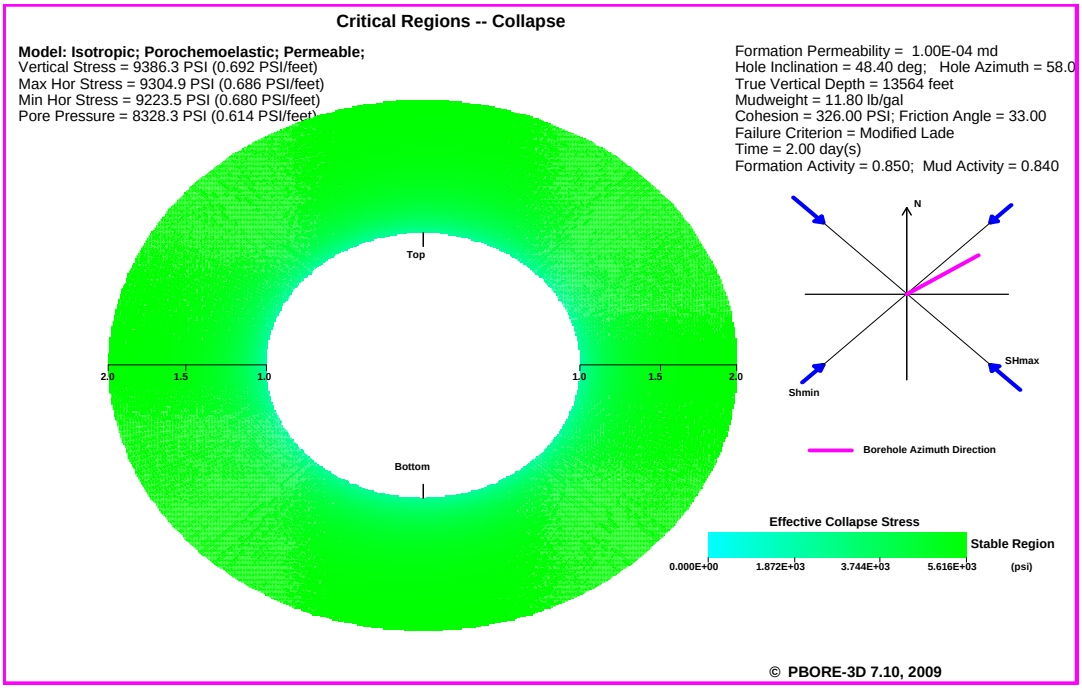

Figure 4 Stable Wellbore after Two Days with a Favorable Differential Water Activity

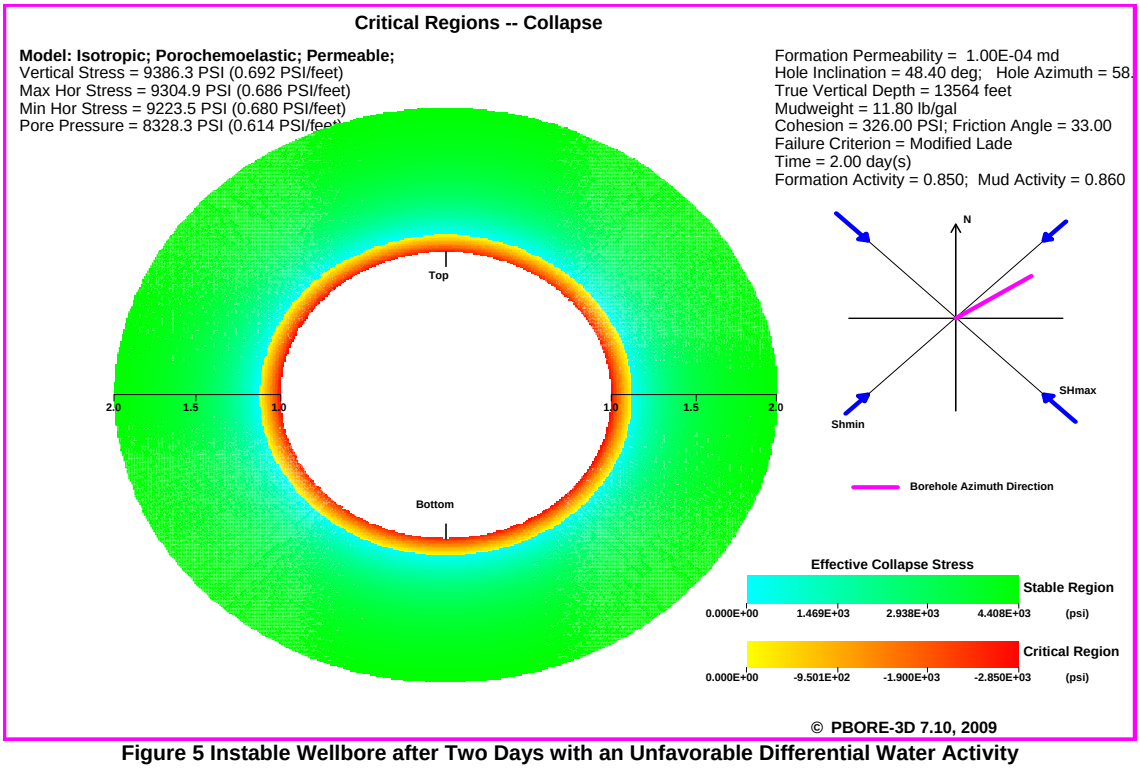

Figure 5 Instable Wellbore after Two Days with an Unfavorable Differential Water Activity