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# Managing Borehole Stability Problems: On the Learning, Unlearning and Relearning Curve

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## Abstract

Borehole (in)stability while drilling shales is a continuing problem that results in substantial annual expenditure for the petroleum industry ($1.3 billion according to some estimates). The engineering problems of shale instability are closely connected with bulk properties of shales such as, strength and deformation. Other factors, like pore pressure, temperature, time in open hole, length of open hole interval, tectonics, etc., can directly impact drilling operations. Drilling a hole into a formation in equilibrium induces stress concentration in the vicinity of the borehole. A precondition for a stable wellbore while drilling is the existence of a balance between the near-wellbore stress concentration and the rock strength. In cases where the stresses considerably exceed the strength the resulting imbalance can lead to borehole destabilization.

A drilling fluid exposure related interaction might occur because parameters such as chemical potential, ionic concentration, etc., of the drilling fluid and the shale formation fluid are not in equilibrium. Differences in these parameters may alter near wellbore pore pressure, which in turn will influence the borehole stress-state and shale strength and thereby affect the stress-strength balance.

For a successful drilling operation all of the above, interconnected parameters, should be integrated into well planning, mud system selection criteria and/or new mud development. The work presented here discusses the influence of these parameters on borehole stability. Case history is provided where approaches have resulted in successes and where the lessons have been transferred into new drilling fluid developments. Results of ongoing efforts described here are aimed at developing a comprehensive approach for real-time wellbore stability resolution thereby helping to provide better management of stability problems in the field.


## Introduction

Shales make up over 75 percent of drilled formations and causes over 90 percent of wellbore instability problems. The drilling of shale can result in a variety of problems ranging from washout to complete collapse of hole. More typically, drilling problems in shales are experienced as bit balling, sloughing, or creep. (In)stability in shales is a continuing problem that results in substantial annual expenditure by the petroleum industry — $1.3 billion according to estimates. With the cost of drilling increasing, the need to drill extended-reach wells with long open hole intervals has also increased. In the past, oil-based muds (OBM) have been the system of choice for difficult drilling. Their application has been typically justified on the basis of borehole stability, thermal stability, fluid loss, lubricity, etc. As environmental concerns restrict the use of oil-based muds, innovative means are needed to obtain OBM performance without negatively impacting the environment. Water-based muds (WBM) are attractive replacements from a direct cost viewpoint. But, conventional WBM systems have failed to meet key performance measures met with OBMs, especially while drilling high-angle, extended-reach well trajectories going through water-sensitive shale formations.

Past efforts to develop improved WBM for shale drilling have been hampered by a limited understanding of the drilling fluid/shale interaction phenomenon. This limited understanding has resulted in drilling fluids designed with inadequately optimized properties that are required to help prevent the onset of borehole instability problems. Historically, wellbore (in)stability problems have been approached on a trial-and–error basis, going through a costly multiwell learning curve before arriving at reasonable solutions for optimized operations and systems. Recent studies[1,2] of fluid-shale interactions have produced fresh insights into the underlying causes of borehole (in)stability, and these studies suggest new and innovative approaches as to the design of water-based drilling fluids.

Since the identification of chemical-potential related instabilities in shales, a complex analytical model has been proposed to describe the physio-chemical interaction. Furthermore, the chemical-potential borehole stability analytical model, derived for an arbitrary borehole orientation, has been successfully implemented to address borehole (in)stabilities[3].

There are increasing economic demands on reducing rig downtimes associated with borehole instability problems. Thus, the anticipation and resolution of instabilities in the field using MWD/LWD data in conjunction with prior geophysical and shale/fluid interaction knowledge is becoming more critical.

With enhanced understanding and proper diagnosis of wellbore instability problems in the field and an efficient implementation of novel technology, adequate resolution and management of wellbore instability can be achieved. Novel technology like new membrane efficient water-based drilling fluids have been developed as a result of an enhanced understanding of the key issues affecting wellbore instability.

## Wellbore Instability Problem Background

At any given time during the drilling process, borehole stability is controlled by the relationship between the near-wellbore stress-state and the rock strength. The first stage of wellbore stability analysis consists of identifying and interpreting the problems observed in the field. Correct identification and classification of the wellbore instability at hand is of utmost importance for any additional analysis. Wellbore instability observed while drilling can be grouped into five basic types:

§ washout or hole enlargement,
§ tight hole or creep,
§ altered, damaged or plastic zone,
§ lost circulation; and
§ wellbore breathing.

The first three types of instability are associated with the near wellbore region; and they are sometimes collectively referred to as near wellbore collapse. In contrast, lost circulation and wellbore breathing are attributed to mud invading the far field as a result of either hydraulically induced tensile fractures or losses occuring to permeable formations or thief zones[4].

Drilling problems and wellbore instability is interrelated. It is important to understand the possible connections, first to diagnose the problem and, second to take appropriate remedial actions.

**Washout or hole enlargement**. While drilling, evidence of washout is given by several observations including excessive cuttings return at surface, excessive hole fill after tripping, mud volumes in excess of calculated amount, oversize hole from LWD calipers, etc. Washouts can be explained primarily by two mechanisms, borehole collapse of a portion of the wellbore due to insufficient mud weight and/or hole erosion due to improper mud chemistry design.

**Hole convergence or tight hole**. This reduces annular clearance and can be observed directly from calipers as undergauge hole. Other indirect observations while drilling are, increased torque and drag, increased swab and surge pressures, stuck pipe and an increase in overpull (hook load) during tripping operations. Although indirect drilling observations can often be associated with other factors such as solids loading that can also reduce annular clearance. Tight hole is expected to show time-dependency for formations prone to creep (e.g., salts).

**Altered, damaged or plastic zone.** This corresponds to near-wellbore zone of shale altered as a result of hydration or swelling. Improperly designed water-based muds can lead to shale hydration or swelling. Main problems associated with sticky hole are increased torque and drag and key seat, especially in high angle holes.

**Mud losses.** These can be classified as total losses (lost circulation) or partial losses with some gains (wellbore breathing). In an intact formation, a hydraulic fracture is initiated by too high a mud weight. The high mud pressure causes tensile failure. Following fracture initiation, the fracture may propagate depending on the maximum borehole pressure and take in drilling fluid. When the borehole pressure is reduced the initiated fractures close and may give mud back (often associated with a build-up in annular pressure)[4].

## Parameters Influencing Borehole (In)stability

While drilling borehole instability problems may arise solely due to inadequate or too high mud weight (mechanical problem). As a function of drilling fluid exposure during the drilling process alterations of the near-wellbore stresses, formation properties and rock strength may arise leading to time-dependent borehole instability (physico-chemical problem). Factors influencing borehole (in)stability are presented in Table 1. Mud weight predictions required to mechanically stabilize the borehole are heavily influenced by parameters like in-situ stresses, pore pressure, strength, well trajectory, hole angle, etc. Near-wellbore pore pressure, effective stresses and strength can alter due to drilling fluid exposure and influence time-dependent borehole instability. The following parameters in addition to pore pressure primarily influence mud weight predictions (mechanical problem):

**In-situ Stresses.** The loads acting on the borehole region consists of the far field in situ stresses, the wellbore mud pressure and the formation pore pressure. The onset and severity of borehole collapse is determined by the magnitude of the in situ effective stresses (i.e., total stress - pore pressure), and the mud overbalance relative to rock strength. Borehole collapse increases as the effective stress increases. Borehole fracturing becomes less likely as the minimum in situ stress increases. Borehole fracturing increases as the total minimum in-situ stress decreases and/or mud weight exceeds the breakdown pressures for intact rock or mud weight exceeds the fracture extension pressures for fractured rocks.

**Rock Strength and Ductility.** The strength of rock material is described by strength parameters such as the unconfined compressive strength and/or triaxial compressive strength. However, strength is not the only rock property controlling stability. First, strong intact rock may behave weak when fractured. In that case the (weak) fractures rather than the (strong) intact material determine the strength of the rock. Second, borehole stability also depends on the ductility i.e. the degree to which rock can plastically deform without losing load-bearing capacity. Plastic deformation results in delay of failure due to transfer of excess load to rock located away from the borehole wall. A ductile rock remains intact under more severe loading than a brittle material of similar strength. Strength and ductility depends on lithology. The most important lithological parameters are mineral composition and porosity. The strength and ductility of shales is influenced by water content.

The increase in the water content in the shale due drilling fluid exposure can lead to an increase in near-wellbore pore pressure and subsequent changes in the effective stress-state. In many cases, borehole instability arises from insufficient mud column support on the borehole wall from an inadequate mud weight or a time-dependent increase in near-wellbore pore pressure (physico-chemical problem). A brief discussion on near-wellbore direct and coupled flow phenomena that influence fluid (water) transport in and out of shale are presented below.

**Alteration of Near-Wellbore Pore Pressure.**

In the case of an oil-based mud (OBM) a continuous oil phase exerts a confining pressure on the borehole wall. This is because the mud-column pressure in most cases exceeds the formation pressure and does not exceed the threshold capillary entry pressure. While in the case of water-based mud (WBM), the net radial support offered by the continuos phase may be altered over a period of time due to mud pressure penetration. In addition to the above the difference in the molar free energies of water in the oil-based mud and the shale provides the mechanism for hydration or dehydration of the shale. In the case of a water-based mud however the molar free energies of all the constituents within the shale and the water-based mud provide the driving forces for ionic and water transport into and out of the shales.

The interaction process and the mechanisms for water transport for WBM-shale can be complex. Differences between shale and drilling fluid hydraulic pressure, chemical potential, electrical potential and temperature influence fluid (water) transport.

The sum of all the flow phenomena mentioned above can result in a net flow. Equilibrium conditions will be dictated by the sum of these driving forces. The difficulty is in the mathematical treatment of this coupled physio-chemical interaction between the WBM and shale. Several investigators have used the non-equilibrium thermodynamic approach in the treatment of the transport process in shales[1, 2 and 5]. Non-equilibrium thermodynamics allows the incorporation of cross effects between different phenomena, such as flux of a solution with different ionic species caused by the hydraulic gradients and/or chemical potential gradient of that species, as well as thermal and electrical gradients.

In most cases however, the two most relevant mechanisms for water transport in and out of shale are the hydraulic pressure difference between the wellbore pressure (mud weight) and the shale pore pressure, and the chemical potential difference i.e., activity, between the drilling fluid and the shale pore fluid.

A mathematical representation to describe the driving force for the movement of water by an osmotic mechanism is shown in the following equation:

$$\left(\frac{RT}{V}\right)\times\ln\left(\frac{A_{wdf}}{A_{wsh}}\right)=\pm(\sigma\times\Delta P_p)=\pm\sigma\times(P-Pp)\quad\text{..........(1)}$$

where $A_{wdf}$ and $A_{wsh}$ are the water activity of the drilling fluid and shale pore fluid respectively; $P_O$ is the far-field pore pressure; $P$ is the near wellbore pore pressure and σ is the membrane efficiency term, or "reflection coefficient", specific to a shale and drilling fluid system.

The concept of "reflection coefficient" (i.e., membrane ideality) first proposed by Staverman[6] was introduced in Ref. 1 to handle "leaky systems" including WBM/shale type systems used for borehole stability applications. Ref. 2., further explains the concept and provides a detailed theoretical analysis on the use of membrane efficiency in modeling chemical potential effects.

**Drilling-Fluid Exposure Related Alteration of Shale Strength.**

Laboratory data and field observations have clearly demonstrated modification of rock strength as an inverse function to changes in water content, in that when the water content was reduced, the rock strength increased or when water content was increased, the rock strength decreased relative to a control untreated native shale.

Several mechanisms, listed below are used to explain the influence of moisture content on shale strength. The reader is referred to Ref. 7 for a detailed discussion on the subject and how these factors affect shale strength. None of these mechanisms can be discounted outright; but some are more likely than others for certain shale type, loading, and geologic conditions:

- Pore pressure change using the concept of effective stress law.
- Change in rock frictional characteristics.
- Chemical and corrosive effects based on cementing minerals in the shale.
- Change in capillary tension.
- Fracture energy alteration using the classical Griffith fracture criterion[7, 8, and 9].

## Evaluation of Time-Dependent Shale Property Alterations

A Pore Pressure Transmission (PPT) experiment is designed to study time-dependent alterations in shale properties as a function of exposure to drilling fluid. The test is also used to develop novel drilling fluid systems that enhance shale stability. The experiment consists of confining well-preserved shale cores or outcrops under geostatic stress and then circulating (under confined dynamic conditions) test fluids at the upstream side of the sample (Fig. 1). Change in the downstream pressure is measured simultaneously. The upstream pressure may be increased to simulate overbalance conditions. The downstream pressure changes indicate changes in the sample pore pressure. During the experiment the transient pressure, sonic compression and shear travel times, radial and axial deformation, temperature, and circulation rate are monitored.

Fig 2 indicates the three stages of the PPT test; in this example the shale (Pierre II) is first saturated with 8% w/w NaCl (simulated pore fluid). This is followed by circulating the 8% w/w NaCl continued to equilibrium and finally the shale is exposed to the test fluid (sodium silicate solution with 20% w/w sodium chloride salt solution).

The change in the downstream pressure (pore pressure) is monitored. Once the downstream pressure stabilizes the change in pressure is recorded. Based on the observed pressure drop and utilizing Eqn. 1 the membrane efficiency for the Pierre II/sodium silicate with 20% w/w NaCl system is estimated to be 60%. For reference the membrane efficiency for an oil-based mud has a theoretical membrane efficiency close to 100%.

Simultaneous acquisition of acoustic data in the PPT tests (Figs. 3) provides useful data to calculate dynamic changes in the rock properties. Observing changes in the dynamic Young's modulus as a function of transient pore pressure in Fig. 3 assists in understanding changes in rock properties. Similar computations can be made for dynamic Poisson's ratio and other rock properties derived from sonic data. Observations of inherent changes in the effective stress can be made from the velocity data. For example, comparison of velocity data when the shale is exposed to 8% w/w NaCl solution to that obtained when the shale is exposed to the test solution (Fig. 3) shows a change in the magnitude of compressional and shear wave sonic velocity ratios. Similar experiments done with other drilling fluids and salt solutions have helped to quantify changes in shale properties and pore pressure as a function of drilling fluid exposure[10, 11] .

## Borehole Stability Analysis

Several analytical solutions have been derived for an arbitrary borehole orientation assuming elastic rock behavior[12, 13]. These are generally considered to make conservative predictions. More sophisticated models based on viscoelastic, elastoplastic and non-linear approaches have been proposed[14-16]. These new models are thought to be more realistic than a simple elastic analysis, since rocks rarely behave in a purely elastic manner until ultimate failure. In cases where laboratory testing of cores is possible and well-defined rock properties can be obtained, contemporary rigorous non-linear modelling techniques can be applied. However, in most practical circumstances, the poor definition of key input parameters (i.e., in-situ stresses and rock strengths) justifies at best, a simplistic conservative elastic analysis. In these cases the rock strength is determined by utilising a peak-strength criterion[1,17] (e.g., von Mises, Drucker-Prager, Mohr-Coulomb failure criterion).

Once the type and degree of borehole instability has been identified, the next step is to recommend means of improving the situation. Mitigating borehole instability involves changing some of the operational parameters involved, usually mud weight and mud composition. The optimum corrective action depends on a proper assessment of the cause of borehole instability and of the effect of the measures contemplated. The following case study demonstrates the general approach.

## Case History

An extended-reach-drilling (ERD) well was drilled in the North Sea with an oil-based drilling fluid. The 17 1/2-in. shoe was set at 4,900-ft true vertical depth (TVD) at a 75 degree angle. Then, a 12 1/4-in. hole was drilled smoothly to 14,924-ft measured depth (MD) (5,826-ft TVD) with no problems using a 12.5 ppg static mud weight (13.5 - 13.8 ppg equivalent circulating density range). At this point, hole packoff incidents were experienced and the decision was made to make a trip to condition the hole. The packoff and tight-spot problems continued throughout drilling and tripping operations for the 12 1/4-in. open hole until 16,008-ft MD (5,997-ft TVD). A wiper trip out of the hole proved difficult with continuing packoff problems. While attempting to re-enter the original hole, a ledge was encountered at 7,350-ft MD. Attempts were made to drill through this ledge but despite drilling several stands, the original wellbore was not found. At this point drilling was halted and borehole-stability modeling was performed to improve planning for the mud program for the sidetrack.

Three scenarios were modeled.

§ The case that neglected chemical and mud-penetration effects involved the traditional impermeable elastic-type modeling approach and predicted mud weights required to drill the formation initially.

§ The case including chemical effects optimized internal water-phase salinity and incorporated time-dependent osmotic effects that tended to change mud-weight requirements to drill the 12 1/4-in. interval.

§ The case including mud pressure penetration effects modeled the effect of hydraulic conductivity of an oil-based mud (OBM) with a microfractured shale and the influence of this phenomenon on mud-weight requirements.

Shale pore fluid water activities were predicted with a proprietary model. On the basis of existing information, internal water phase salinity of the invert emulsion OBM was optimized. Optimized salinity of the 80:20 oil/water ratio (OWR) was calculated to be 20% for this shale and drilling conditions. Once this information was obtained, a borehole-stability analysis was performed for 5,000-ft TVD. The majority of hole problems were encountered at this depth, which is also the depth at which the shales were thought to be weak in compressive strength and naturally micro-fractured.

Fig. 4 shows the upper and lower limit of safe mud weight for modeled depths as a function of hole inclination angle. The upper limit is the mud weight above which formation breakdown would occur resulting in total drilling-fluid losses. Formation pore pressure or minimum mud weight required to prevent borehole collapse determines the lower limit.

Low-permeability shales lack filter-cake protection because they do not experience normal fluid loss from WBMs at overbalanced conditions. Instead, slow fluid-filtrate invasion gradually equilibrates the mud pressure and the near-wellbore pore pressure, so effective mud-pressure support is lost. An identical phenomenon may be observed in microfractured shales exposed to OBMs if the threshold capillary entry pressure is exceeded. Shale material may yield in shear or tensile mode due to this pore pressure elevation. The elevation reduces the near-wellbore effective stresses that hold the material together, thus resulting in delayed failure.

For the case where mud pressure penetration effects are considered (Fig. 5) using a 13.8 lbm/gal ECD, a poroelastic analysis[18, 19] shows the alteration of near-wellbore tangential stress as a function of drilling fluid exposure (12 days of drilling). Excessive swab forces can cause the rock in the mud pressure invaded critical region to fail in circumferential tensile mode[4]. This failure can then result in fill on bottom and cause severe hole packoff problems. As the near-wellbore pore pressure increases changes in the effective stress distribution eventually leads to time-delayed near-wellbore deterioration.

Mud pressure penetration effects are time-dependent effects that come into play when the drilling fluid has been in contact with shales for an extended time period. On the basis of the analysis, the side-track was drilled to depth with very few borehole-stability problems with a 12-lbm/gal static mud weight. For future operations a comprehensive shale testing program was implemented that lead to the development of an alternative water-based drilling fluid to the oil-based drilling fluid system.

## Summary

Important factors that contribute to wellbore instability were briefly discussed. Key parameters that influence wellbore instability are pore pressure, rock properties including strength, in-situ stresses, well trajectory and the drilling fluid. The time-dependent nature of the stress and pore pressure distributions influenced by drilling fluid exposure, manifests as time-dependent wellbore stability. Details were provided about the Pore Pressure Transmission (PPT) test. The results of a PPT test were discussed and membrane efficiency of a sodium silicate drilling fluid system was calculated. Based on the simultaneous acquisition of acoustic data, estimates of dynamic rock properties were presented. The time-dependent nature of the wellbore instability problem was presented in a North Sea case study. In the example case study time-dependency was observed in the failure analysis, in estimations of critical regions around the wellbore, and mudweight-window analyses. The study shows that time-dependency in wellbore stability can be critically examined with the help of contemporary analytical solutions.

To better manage wellbore instability problems in the field an in-depth understanding of the fundamental physics and chemistry of drilling fluid/shale interaction can be critical as they take place down hole. The same is true for designing novel membrane efficient water-based drilling fluid systems. More importantly this technology should be translated into simple practical terms so that field personnel can apply these principles to solve practical problems.

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**Table 1- Field and Operational Parameters Influencing Borehole (In)stability.**

| Drilling Fluid | Rock Properties | Drilling Operations | In-Situ Stresses | Drill String |
|---|---|---|---|---|
| Composition | Strength | Hole Orientation | Overburden & Horizontal stresses | Bottom Hole Assembly |
| Pressure | Permeability & Porosity | Open Hole Time | Pore Pressure | Vibrations |
| Flow Rate and Rheology | Mud - Rock Interaction | Tripping | | |
| Temperature | | | | |

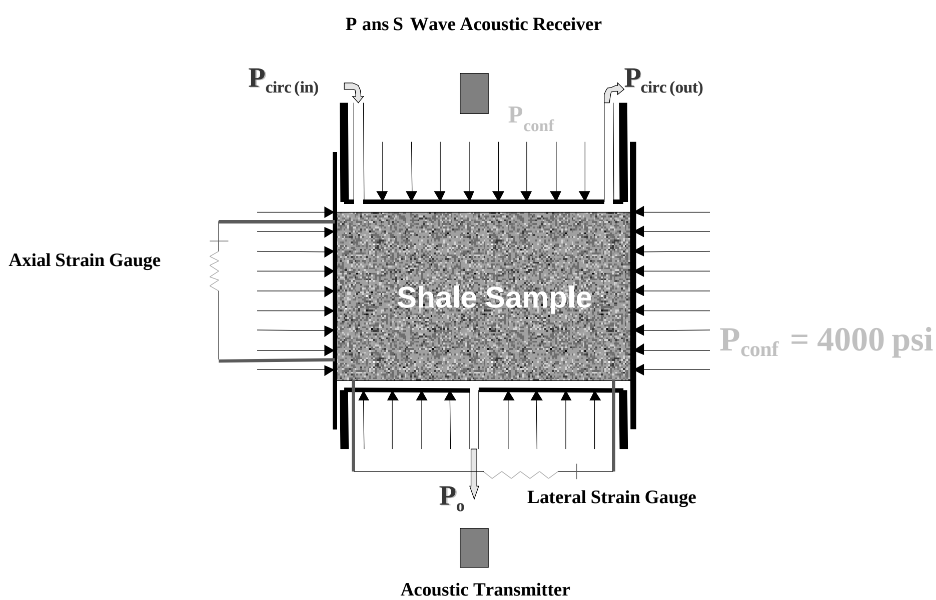


**Fig. 1- Schematic of the Pore Pressure Transmission (PPT) Test.**

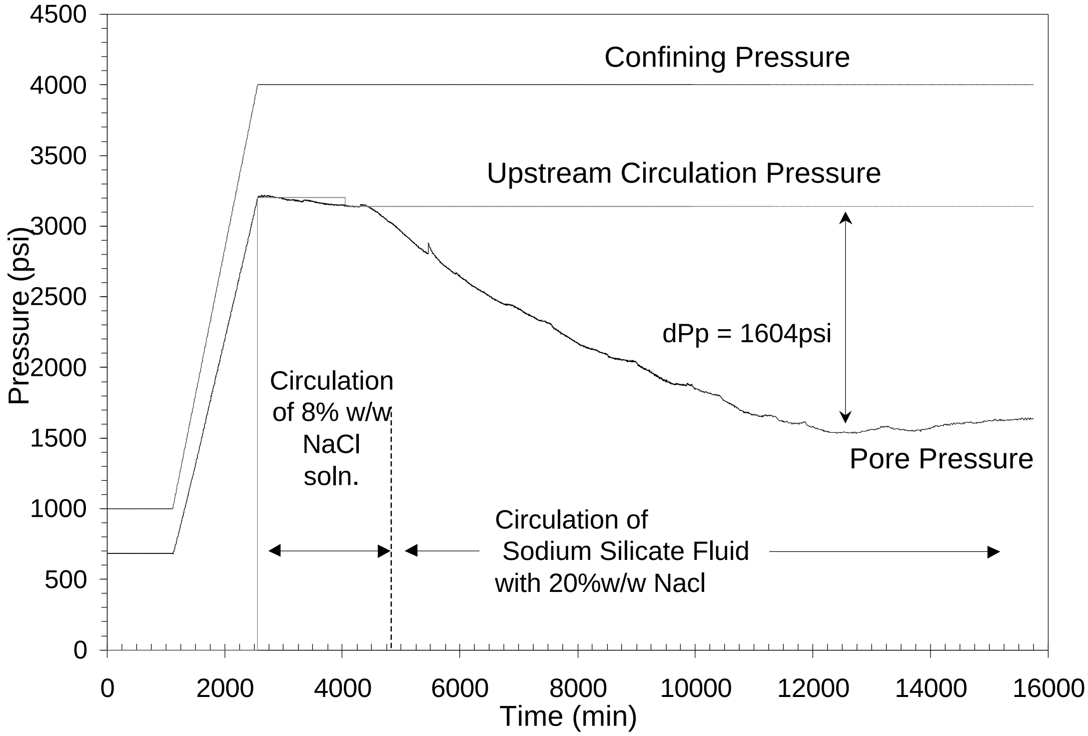


**Fig. 2- Pierre II shale pore pressure response when exposed to a sodium silicate solution with 20% w/w NaCl in a PPT test.**

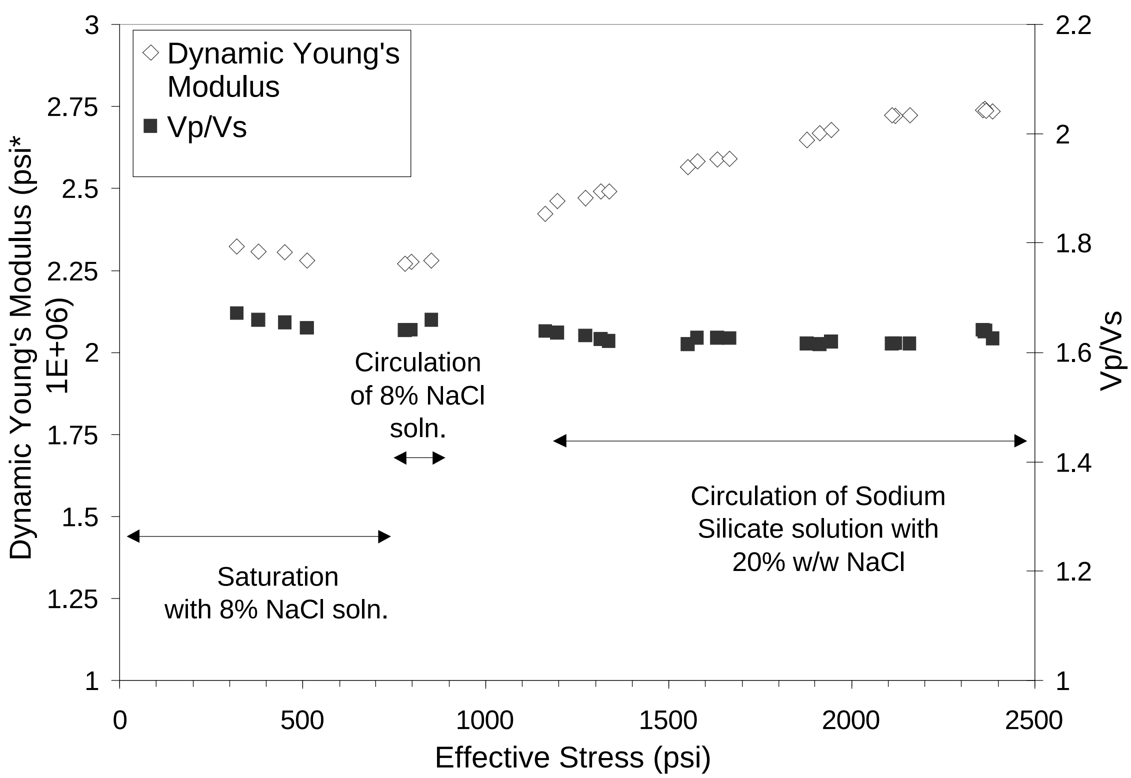


**Fig. 3- Dynamic Young's modulus derived from sonic data and P wave/S wave velocity ratio for Pierre II shale exposed to a sodium silicate solution with 20% w/w NaCl.**

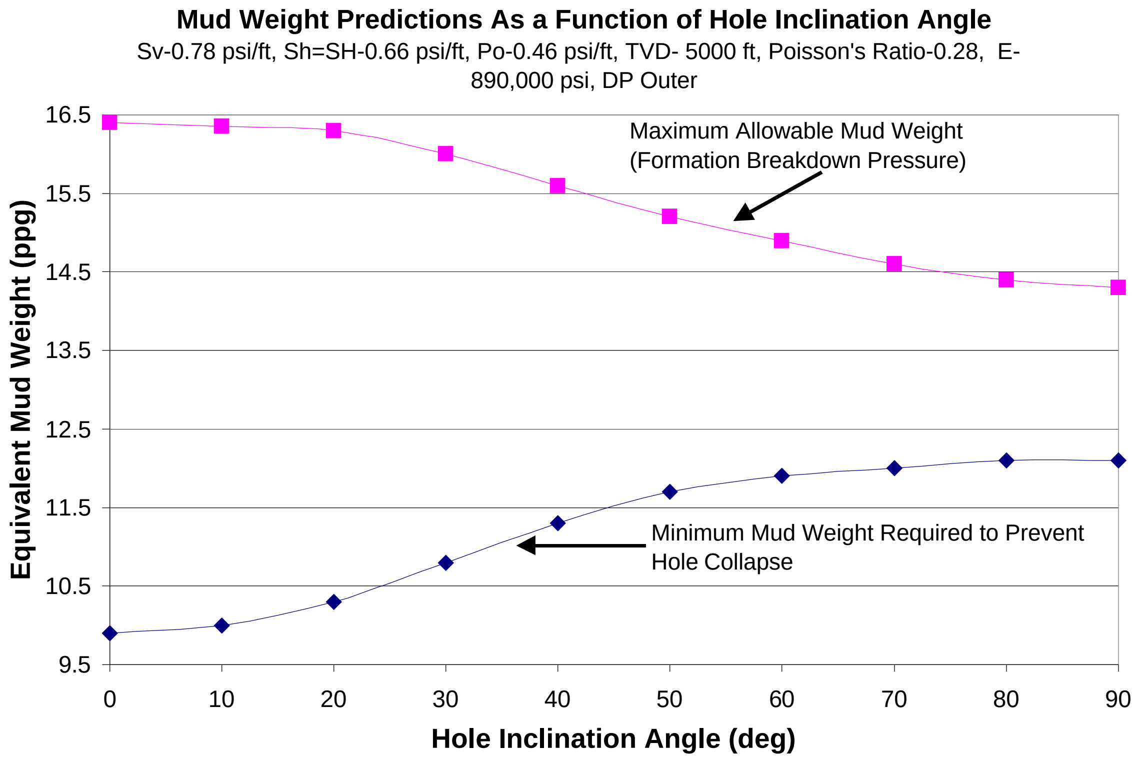


**Fig. 4- Case study 12-1/4 inch hole section, mud weight window as a function of increasing hole angle.**

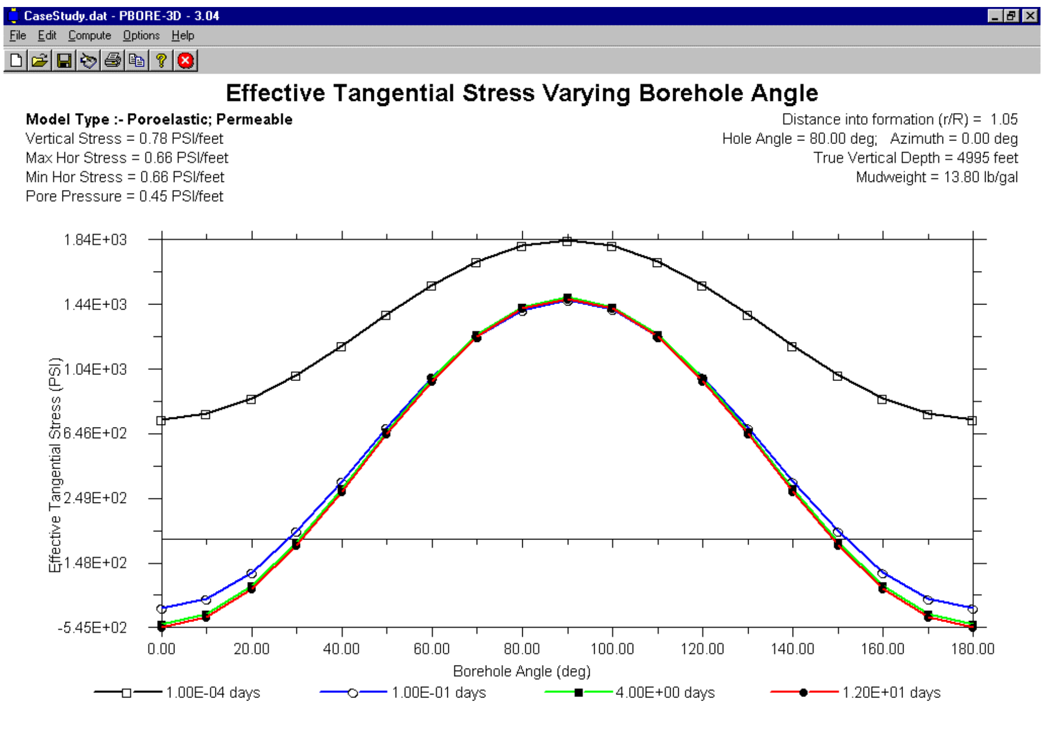


**Fig. 5- Effective tangential stress near the wellbore varying with time for mud weight of 13.8 lb/gal. (Note: Portions of the curve below the x-axis will fail in tensile (fracturing) mode).**