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PRODUCTION ENHANCEMENT PRODUCTS & PROCESSES

PROJECT REPORT

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Title: **Towanda Core Mohr's Failure Envelope**

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Company: Anadarko Petroleum Corporation
Field: Hugoton Field, Kansas
Well: Younggren J 1-H
Formation: Towanda
Depth: 2,609' - 2,656'

Summary

Mechanical property and formation strength tests were performed on core plugs taken from a high porosity streak between 2,634' and 2,638' and an average porosity area at 2,621' within the Towanda formation of well Younggren J 1-H. Young's modulus, Poisson's ratio, and the Mohr-Coulomb failure envelope were determined for each set of core plugs. Results of these tests are shown in Table 1.

Using the Mohr-Coulomb failure envelope and the expected formation stresses, the stability of a horizontal wellbore drilled and completed open-hole in the Towanda formation was evaluated. The following conclusions were reached:

- Under the expected formation stresses, the borehole will not collapse in the Towanda formation.
- In the high porosity streak, some spalling is likely to occur at the lateral sides of the borehole. After a certain amount of spalling the borehole will stabilize at a new, elliptical geometry.
- No spalling will occur in average porosity intervals.

Mechanical Properties

Mechanical property tests were performed to evaluate wellbore stability and to measure the mechanical properties needed to design stimulation treatments in the Towanda formation of the Hugoton Field, Kansas. To assess the s bility of the Towanda formation, Mohr-Coulomb failure envelopes were prepared for cores from a high porosity (Figure 1) and an average porosity (Figure 2) section. The high porosity region was suspected to be the weakest area of the pay interval.

The evaluation of wellbore stability using the Mohr-Coulomb failure envelopes requires in-situ stress and reservoir pressure data. For this study, a minimum horizontal formation stress gradient of 0.375 psi/ft and a pore pressure of 90 psi were provided. An overburden gradient of 0.9 psi/ft, an intermediate horizontal formation stress gradient of 0.66 psi/ft, and a bottomhole wellbore pressure of 100 psi were assumed.

Borehole Failure Analysis

While drilling a well, three potential borehole failure mechanisms are of concern. These are:

- Borehole spalling or sloughing,
- Fracturing, and
- Complete wellbore collapse.

To determine if, under a given set of conditions, one of these mechanisms is active, the stresses at the borehole wall need to be calculated and the strength of the formation has to be determined in intervals of interest. Stresses at the borehole wall are calculated using Kirsch's[1] solution for a circular borehole in an infinite medium. Assuming that the axis of the borehole coincides with one of the principal stresses, the effective principal stresses at the borehole wall are:

$$\begin{aligned}
\sigma_{rr} &= P_w - \alpha P_p && \text{(radial stress)} \\
\sigma_{\theta\theta-\max} &= 3S_1 - S_2 - P_w - \alpha P_p && \text{(maximum tangential stress)} \\
\sigma_{\theta\theta-\min} &= 3S_2 - S_1 - P_w - \alpha P_p && \text{(minimum tangential stress)} \\
\sigma_{axial} &= S_{axial} + 2\nu(S_1 - S_2) - \alpha P_p && \text{(axial stress)}
\end{aligned} \quad (1)$$

where

S_{axial}, S_1, and S_2 are the total principal formation stresses (Table 2),

P_p = formation pore pressure immediately adjacent to the wellbore,

P_w = wellbore pressure,

α = Biot's constant, and

ν = Poisson's ratio.

To evaluate stability under drilling conditions it is assumed that equilibrium has been established between the wellbore fluid pressure and the pore pressure in the near wellbore region. In other words, in the immediate vicinity of the wellbore, $P_w \approx P_p$. Under this conditions and for a Biot's constant $\alpha = 1$, equations 1 reduce to:

$$
\begin{aligned}
\sigma_{rr} &= 0 \\
\sigma_{\theta\theta-\max} &= 3S_1 - S_2 - 2P_w \\
\sigma_{\theta\theta-\min} &= 3S_2 - S_1 - 2P_w \\
\sigma_{axial} &= S_{axial} + 2\nu\left(S_1 - S_2\right) - P_w
\end{aligned}
\tag{2}
$$

To evaluate the effects of a sudden change in wellbore pressure (i.e., an abrupt change in drawdown), equations 1 have to be used since P_p and P_w will not be equal. For this case, P_p is the wellbore pressure immediately prior to the sudden drawdown.

Borehole Spalling or Sloughing

To determine if borehole spalling will occur, the combined stress state at the borehole wall has to be evaluated using a failure criterion in conjunction with experimentally determined rock strength parameters. The standard failure criterion applied to borehole stability problems is the Mohr-Coulomb failure criterion. The appropriate Mohr-Coulomb failure envelopes are determined in the laboratory.

To apply the Mohr-Coulomb failure criterion, the minimum and maximum effective normal stresses at the borehole wall are calculated using equations 1 or 2 above. Generally, these are σ_{rr} and $\sigma_{\theta\theta}$ respectively. Only if $2S_1 < S_{axial}$ will the axial stress (σ_{axial}) be the maximum principal stress acting at the borehole wall.

The calculated maximum and minimum effective normal stresses at the wellbore wall are then plotted on the effective stress axis of the Mohr-Coulomb failure diagram (Figure 3). A semi-circle centered at the average of the two stresses is drawn such that both σ_{rr} and $\sigma_{\theta\theta}$ (or σ_{axial} if $\sigma_{\theta\theta} < \sigma_{axial}$) are the endpoints of the semi-circle. The formation will be stable if the complete semi-circle falls within the failure envelope. If a portion of the semi-circle is outside of the failure envelope, borehole spalling or sloughing is likely to occur.

Spalling by itself will not lead to complete borehole collapse. Following a certain amount of spalling, the borehole will stabilize at a new, elliptical geometry.

Borehole Fracturing

To initiate a fracture at the borehole wall, the minimum tangential stress ($\sigma_{\theta\theta\text{-min}}$) has to be negative (tensile) and it's absolute value has to exceed the tensile strength (σ_T) of the formation. There are two conditions under which this can occur. Depending on the nature of the radial stress (σ_{rr}), either borehole fracturing or borehole collapse will occur.

First consider the case where $\sigma_{rr} \geq 0$ (i.e., $P_w \geq \alpha P_p$). Under this condition the borehole will break down and a fracture will initiate when the wellbore pressure exceeds the formation breakdown pressure (P_{bd}). For a non-penetrating fluid, fracture initiation will occur if

$$P_w \geq \alpha P_p \quad \text{and}$$
$$P_w = P_{bd} = 3S_2 - S_1 - \sigma_T - \alpha P_p \qquad \text{for} \qquad S_1 > S_2 \tag{3}$$

For a penetrating fluid, the initiation pressure is given by

$$P_w = P_{bd} = \frac{3S_2 - S_1 - \alpha \frac{1-2\nu}{1-\nu} P_p + \sigma_T}{2(1-\nu)} \qquad \text{for} \qquad S_1 > S_2 \tag{4}$$

Once initiated, the fracture will continue to propagate as long as $P_w > S_2$.

Conditions can exist under which a fracture may initiate and propagate only a small distance out from the wellbore. Once the fracture has grown far enough away from the wellbore, fracture growth will stop if the pressure within the fracture is below the fracture opening pressure or the least principal formation stress.

Borehole Collapse

Complete collapse of the borehole is likely when both the radial stress (σ_{rr}) and the tangential stress ($\sigma_{\theta\theta}$) at the borehole wall are tensile. This will occur when

$$P_w < \alpha P_p \quad \text{and}$$
$$3S_2 < S_1 + P_w + \alpha P_p$$

Implications for Towanda Formation

Using these results the stability of the Towanda formation can be evaluated. Based on the stress gradients presented earlier, the stress state within the Towanda formation at a depth of 2,630' is as follows:

S_V	= 2,367 psi	P_p	= 90 psi
$S_{H\text{-min}}$	= 986 psi	$S_{H\text{-max}}$	= 1,736 psi

Since the well is being air drilled and to be conservative, the bottom hole pressure was assumed to be approximately 100 psi.

Under these conditions one finds that wellbore collapse will not occur since the formation is consolidated and since the wellbore pressure exceeds the pore pressure. To determine if spalling will occur, the following two cases need to be considered:

a. Well drilled in direction of $S_{H\text{-}min}$, and

b. Well drilled in direction of $S_{H\text{-}max}$.

The wellbore stresses for each case are shown in Table 3 and plotted, relative to the Towanda formation failure envelopes, in Figure 3. For each case we find that borehole spalling should be expected in the high porosity streaks at the sides of the wellbore (90° from top and bottom). No spalling will occur in the stronger, average porosity rock.

Laboratory Test Summary

Mechanical Property Testing

Purpose: To measure the elastic properties and strength of submitted core samples.

Procedure: A 1-inch diameter by 2-inch long plug is drilled horizontally from a core and is placed in a load cell. Once within the cell, a predetermined hydrostatic stress is applied to the sample. The axial load applied to the plug is then increased at a constant rate. The resulting axial and lateral deformations are measured using linear variable displacement transducers (LVDTs).

Using the applied loads and the measured displacements, a stress-strain curve showing the applied stress (axial load/sample cross sectional area) as a function of axial strain (axial deformation/original sample length) is drawn. From the initial, straight-line portion of this stress-strain curve, Young's modulus is determined. The ratio of the lateral strain to the axial strain during the initial, linear portion of the stress strain curve is defined as Poisson's ratio. All displacement data are obtained prior to the rock sample undergoing any appreciable plastic deformation or failure.

Compressive strength is measured by increasing the axial load applied to the test plug under a constant confining load until the plug fails or the maximum load frame capacity is reached.

Results: Young's modulus (the ratio of stress to strain for values of stress not exceeding the elastic limit of the test plug), Poisson's ratio (the ratio of lateral strain to axial strain below the elastic limit of the test plug), and the compressive strength under different confining loads for the tested Towanda cores are reported in Table 1.

Brazilian or Indirect Tensile Tests

Purpose: To measure a rock sample's tensile strength.

Procedure: A 1-inch diameter by 0.75-inch long plug is drilled horizontally from a core. This plug is placed on the lower platen of the load frame such that the flat, circular ends of the plug are parallel to the loading direction. Once in place, load is applied to the sample across a single diameter perpendicular to the rock's bedding planes. The load is increased until the sample fails.

Results: From the load at failure the tensile strength of the rock sample is calculated using the following equation:

$$\sigma_T = \frac{2F}{\pi D t} \tag{5}$$

In this equation,

σ_T = tensile strength in psi,

F = applied load in lbf,

D = specimen diameter in inches, and

t = specimen thickness in inches.

The Brazilian Tensile strengths for the two Towanda core samples tested are given in Table 1.

Mohr-Coulomb Failure Envelope Testing

Purpose: Determine the Mohr-Coulomb failure envelope for core samples of interest.

Procedure: To determine the Mohr-Coulomb failure envelope for a specific formation, four or five standard mechanical property specimens from a specific depth are loaded to compressive failure under different confining loads.

The Mohr-Coulomb failure envelope is constructed by plotting each compressive stress at failure and confining stress pair on the effective stress axis of a shear stress versus normal stress plot. For each data pair a semi-circle is drawn with end points at the confining pressure (minimum principal effective stress) and failure stress (maximum principal effective stress) and centered at the average of these two normal stresses.

Using the Mohr's circles, the failure envelope is constructed either by drawing a straight line tangent to all the semi-circles or by drawing individual tangent lines between adjacent Mohr's circles.

The intercept of the resulting failure envelope with the shear stress axis is called the cohesion which defines the strength of the bond between individual grains in the matrix. The cohesion depends on two factors, the amount and type of cementing material present in the formation and the capillary forces exerted by the pore fluid on the formation grains.

The angle of the Mohr-Coulomb failure envelope relative to the normal stress axis is referred to as the "angle of internal friction."

Cohesion and internal friction angle for the Towanda formation are shown in Table 4. The actual Mohr's circles and the resulting Mohr-Coulomb failure envelopes for the Towanda cores are shown in Figures 1, 2, and 3.

DATA

Table 1

Towanda formation mechanical property data determined on cores retrieved from Younggren J 1-H, Hugoton Field, Stevens County, Kansas.

Core Box	Depth (feet)	Confining Pressure (psi)	Formation Strength: Compressive (>0) or Tensile (<0) (psi)	Young's Modulus (psi)	Poisson's Ratio	Porosity
7-6	2,621	0	11,940	3,560,000	0.25	13 %
		500	14,565	2,360,000	0.21	13 %
		1000	18,659	3,143,000	0.24	13 %
		n/a	-1,023	n/a	n/a	13 %
7-12	2,636	0	2,354	1,500,000	0.24	31 %
		750	6,112	1,730,000	0.27	31 %
7-13[1]	2,637	1,500	8,101	2,300,000	0.23	25 %
		2,250	7,451	1,980,000	0.14	25 %
	2,638	3,000	8,325	1,940,000	0.29	25 %
	2,637	n/a	-250	n/a	n/a	25 %

[1] Depths shown in table are based on the core box numbering sequence. Assuming that the core boxes were numbered sequentially, the depths are as shown in the table above. Cores from 2,633.5' to 2,636.5' were in box 7-12. The actual depth interval marked on core box 7-13 is 2,536.5' to 2,539'. Core box 7-13 was the only one of the 7-xx core boxes that appears to have been marked with an incorrect depth.

DATA (Continued)

Table 2

Principal stresses referred to in equations 1 and 2 as a function of borehole orientation.

Borehole Orientation	S_1	S_2	S_{axial}
Vertical	$S_{H\text{-}max}$	$S_{H\text{-}min}$	S_V
In $S_{H\text{-}min}$ direction	S_V	$S_{H\text{-}max}$	$S_{H\text{-}min}$
In $S_{H\text{-}max}$ direction	S_V	$S_{H\text{-}min}$	$S_{H\text{-}max}$
In the above, $S_V > S_{H\text{-}max} > S_{H\text{-}min}$ and S_V = Overburden $S_{H\text{-}max}$ = maximum horizontal formation stress $S_{H\text{-}min}$ = minimum horizontal formation stress			

Table 3

Stress state at the wall of a horizontal borehole penetrating the Towanda formation at 2,630'.

	Case A	Case B
Wellbore Direction	$S_{H\text{-}min}$	$S_{H\text{-}max}$
S_1	2,367 psi	2,367 psi
S_2	1,736 psi	986 psi
σ_{rr}	≈ 0 psi	≈ 0 psi
$\sigma_{\theta\theta\text{-}min}$	2,841 psi	591 psi
$\sigma_{\theta\theta\text{-}max}$	5,365 psi	6,115 psi

Table 4

Cohesion and internal friction angle for Towanda formation.

	Cohesion	Internal Friction Angle
High porosity interval	820 psi	23°
Average porosity interval	2,500 psi	47°

DATA (Continued)

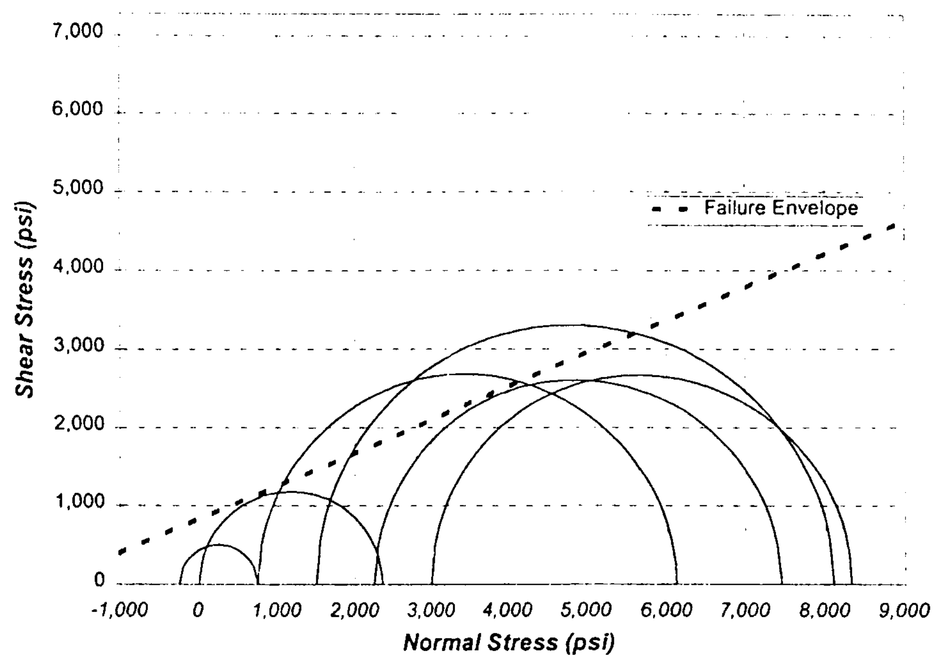

Figure 1: Mohr-Coulomb failure envelope for Towanda cores from high porosity interval (2,636' to 2,638').

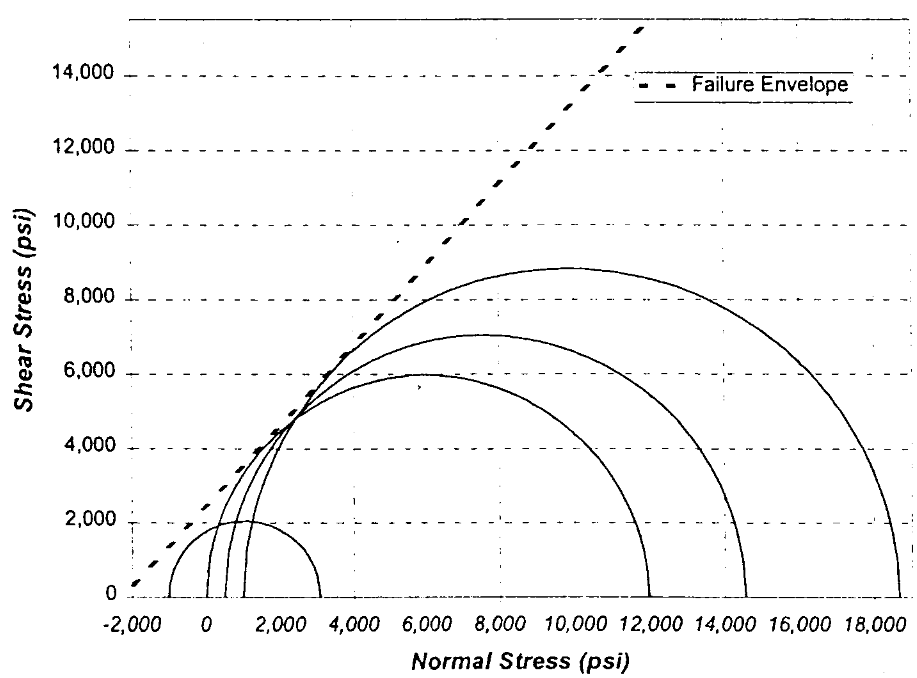

Figure 2: Mohr-Coulomb failure envelope for Towanda cores from average porosity interval at 2,621'.

DATA (Continued)

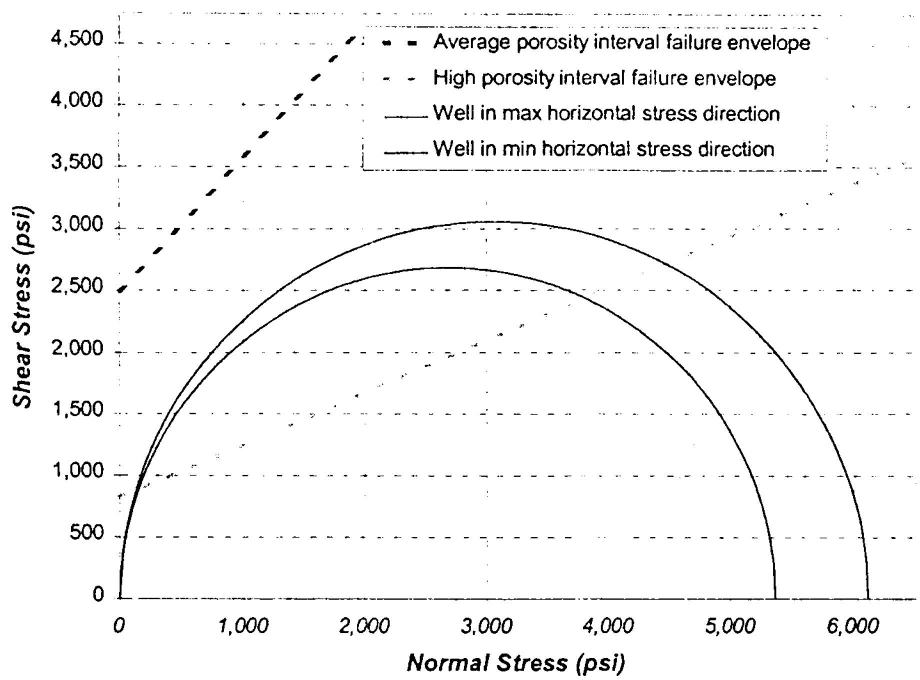

Figure 3: Failure envelopes and Mohr's circle for horizontal wellbore penetrating the Towanda in a high porosity and an average porosity interval.

REFERENCES

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