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EFFECT OF DRILLING INDUCED STRESSES ON FORMATION PRODUCTIVITY

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ABSTRACT

A new stress state around the borehole will be initiated during drilling operations. When the rock around a borehole is loaded beyond its elastic limit (due to excessive drilling mud pressure) it will fail and a zone of failed rock will surround the borehole and will remain in place supported by its residual strength. Drilling induced stresses are localized within a radial ring around the borehole wall. These induced stresses will cause a mechanical formation damage around the borehole leading to an additional restriction to hydrocarbon production. In this study in-situ stress state, well geometry and formation failure criteria are integrated into the poro-elastic stress solution and the yield-zone concept and optimum mud weights are predicted for three sandstones. Furthermore, the effect of stress increase on permeability of synthetic sandstone cores was investigated and the results were supported by thin sections examination of the yielded cores. Therefore, the proposed method presented in this paper can be used to predict the optimum mud weight required to drill stable borehole with no mechanical damage in the drilled formation.

INTRODUCTION

Mud weight required to drill a stable borehole with no mechanical damage (skin) may be predicted by coupling of the yield-zone concept and the stress solution for poro-elastic material. In this paper the optimum mud weight predicted is based on the concept of preventing the rock from failure and hence avoiding the formation of a zone of failed rock which is the major reason for the permeability mechanical damage around the borehole. This can be done by avoiding the use of excessive or insufficient mud weights during drilling. Excessive mud weight may cause the borehole to fail in tension while the insufficient mud weight may cause the borehole to fail in compression. Both modes of failure can contribute to the formation of the mechanically yielded zone of rocks around the borehole. It has been postulated [1, 2] that when a hole is drilled into a sub-surface rock, the horizontal stresses are released and the load is transfered to the circumference of the hole as a tangential (hoop) stress and the hole contracts until the radial stress at its walls equals the pressure acting within the borehole. If the strain does not reach the elastic limit of the rock, the reduction in hole diameter will be negligible. If the strain exceeds the elastic limit, the deformation will be plastic because of the high confining stresses prevailing at great depths. Hence, high mud weights are required to maintain the rock surrounding the borehole in an elastic condition. Otherwise a zone of plastically yielded rock would form around the borehole reducing the localized stress concentration as shown in **Fig. 1**.

MODEL FORMULATION

From the classical elastic theory, a circular opening in a hydrostatic stress field will have a tangential stress around its circumference (σ_θ). In soft rocks at depth, the value of this stress generally is greater than the in-situ compressive strength of the rock and the opening will fail.

If the failed rock at the boundary is held in place by a restraining (confining) force, friction within the failed rock will allow the pressure to build up as the distance from the opening increases. Wilson [3, 4] developed a relationship for the behaviour of yielded rock in circular opening under hydrostatic conditions. Somerville [5] modified Wilson's equation to account for mud weight and pore pressure as follows:

$$r = r_w * \left[\frac{\left(\sigma_\theta - \sigma_o\right) + \alpha \bar{\sigma}_o}{\left(P_m - P_p\right) + \alpha \bar{\sigma}_o} \right]^{\frac{1}{k-1}} \qquad \text{...[1]}$$

$$\alpha = \frac{k+1}{\bar{k}-1} \qquad \text{...[2]}$$

In order to investigate the stability of inclined boreholes the in-situ principal stresses should be transformed into the frame coordinates of the inclined borehole as follows[6]:

$$\sigma_{\theta} = \left[\sigma_x + \sigma_y - P_m\right] - 2\left[\sigma_x - \sigma_y\right]\mathrm{Cos}2\theta - 4\tau_{xy}\mathrm{Sin}2\theta \qquad \text{...[3]}$$

$$\left.\begin{aligned} \sigma_x &= \sigma_H \mathrm{Sin}^2\beta + \sigma_h \mathrm{Cos}^2\beta \\ \sigma_y &= \mathrm{Cos}^2\alpha\left[\sigma_H \mathrm{Cos}^2\beta + \sigma_h \mathrm{Sin}^2\beta\right] + \sigma_v \mathrm{Sin}^2\alpha \\ \tau_{xy} &= \mathrm{Cos}\alpha\ \mathrm{Sin}\beta\ \mathrm{Cos}\beta\left[\sigma_H - \sigma_h\right] \end{aligned}\right\} \qquad \text{...[4]}$$

EVALUATION OF MODEL PARAMETERS

The parameters appearing in Eqs. 1 and 2 are evaluated from the failure criteria of both the intact and the failed (broken) rocks [5]. This is done by testing the rock until failure is initiated then the load is increased under controlled strain rate until residual strength is reached as shown in **Fig. 2**. Based on Mohr-Coulomb failure theory the failure criteria for intact rock will be as follows:

$$\sigma_1 = \sigma_0 + k\sigma_3 \qquad \text{...[5]}$$

and for the failed rock will be as follows:

$$\bar{\sigma}_1 = \bar{\sigma}_0 + \bar{k}\,\bar{\sigma}_3 \qquad \text{...[6]}$$

Two types of sandstone, high and medium strength as well as an unconsolidated sand were used to verify this method. Laboratory measured failure criteria [5] for the rocks used in this study are shown in **Table 1**. The in-situ principal stresses are transformed to the coordinates frame of the borhole (see **Fig. 3**) in the case of inclined boreholes using Eq. 4.

LABORATORY INVESTIGATION OF MECHANICAL DAMAGE

Artificial sandstone cores were used to investigate the effect of yield stress on the permeability and productivity of stressed formations . Clean sand (washed with HCl and distilled water) with a grain size distribution as shown in **Fig. 4** was mixed with 40 percent by weight silica powder and an optimum amount of sodium silicate solution. The mixture was then thoroughly mixed and poured into a compaction cell (see **Fig. 5**) and a specific load was applied for 1.5 hour. The sample then was extracted and left to dry at room temperature for 24 hours after that it was further dried in an oven at 110°C for one hour then permeability and mechanical tests were performed. To investigate the effect of yield stress on permeability three samples were mechanically stressed above their uniaxial compressive strength (**see Fig. 6**) using the compaction cell shown in **Fig. 5** and a compression machine. Then the applied load was released and permeability was measured using air permeameter. **Fig. 7** shows the effect of yield stress on the permeability of tested cores. Immediately after the termination of permeability measurement each sample was cut to three sections and each section was examined under a stereo microscope. **Fig. 8** presents photographs of thin sections cut from the tested samples before and after the induction of mechanical skin.

RESULTS AND DISCUSSION

The proposed method presented herein was applied for three different rocks. For the unconsolidated sand higher mud weight is required to prevent borehole collapse as well as to prevent any yielding (grain damage) for the formation as shown in **Fig. 9**. Moderate mud weight is required for the medium strength sandstone. The high strength sandstone has high frictional properties which can help in maintaining stability, thus lower mud weight is required to drill a stable borehole in this rock as shown in **Figs. 9**. From the previous results it can be seen that horizontal boreholes require higher mud weights to maintain stability and to prevent rock yielding compared to vertical boreholes. **Figs. 10** shows the effect of borehole orientation in unequal (anisotropic) in-situ horizontal stresses. It was found that higher mud weights are necessary to stabilize boreholes drilled parallel to the maximum horizontal in-situ stress due to the initiation of shear stresses in that direction which is supported by the experimental results obtained by Adiss et al [7] . Thus care should be taken when selecting orientation of inclined boreholes as well as the selection of proper mud weights in order to maintain borehole stability and to prevent mechanical damage (skin) which may reduce the permeability of the drilled formation and minimize its productivity. As seem from **Figs. 9 and 10**, the yielded rocks around the borehole can be destabilized if a confining force is provided (mud pressure). Permeability of a stressed sand is decreased when the yielding stress is increased as shown in **Fig. 7**. This reduction is believed to be due to the damage occurred on sand grains. When sand grain is fractured it generates small debris which will block pore throats initially present in undamaged portion of the sample. Therefore decreasing the available passages for fluids. This process is clearly illustrated in thin section photographs shown in **Fig. 8**.

CONCLUSIONS

- The model presented in this paper provided an excellent method to predict mud weight required to drill stable boreholes with no mechanical damage.
- Mechanically induced stresses may load the formation above its elastic limit and cause permanent mechanical skin which will restrict the productivity of such formation.
- The reduction in permeability of yielded rock is due to the fracturing of sand grains and the generation of debris.
- Artificial sandstone plugs can be easily made using the developed technique and used in various testing procedures.
- Borehole orientation have a great effect on mud weight selection criteria.
- Using the presented model it was found that, higher mud weights are required to drill inclined and horizontal wells compared to vertical wells.
- Boreholes drilled parallel to the minimum horizontal principal in-situ stress was found to be more stable than those drilled parallel to the maximum horizontal principal in-situ horizontal stress.

NOMENCLATURE

k = Triaxial stress factor for intact rock.
$\bar{k}$ = Triaxial stress factor for failed rock.
P_p = Formation pore pressure.
P_m = Mud hydraulic pressure (wellbore pressure).
r_w, r = Wellbore and yield zone radii respectively.

σ_x, σ_y = Transformed principal in-situ stresses.

σ_θ = Induced tangential (hoop) stress.

σ_o = Unconfined compressive strength of intact formation rock.

$\overline{\sigma}_o$ = Unconfined compressive strength of broken formation rock.

$\overline{\sigma}_1, \overline{\sigma}_3$ = Normal and lateral stresses at failure for broken rock.

σ_1, σ_3 = Normal and lateral stresses at failure for natural intact rock.

σ_H = Maximum Horizontal in-situ principal stress.

σ_h = Minimum Horizontal in-situ principal stress.

σ_v = Vertical principal in-situ stress.

τ_{xy} = Shear stress.

θ = Angular position around the borehole.

α = Borehole inclination (w.r.t. vertical).

β = Borehole orientation (w.r.t azimuth).

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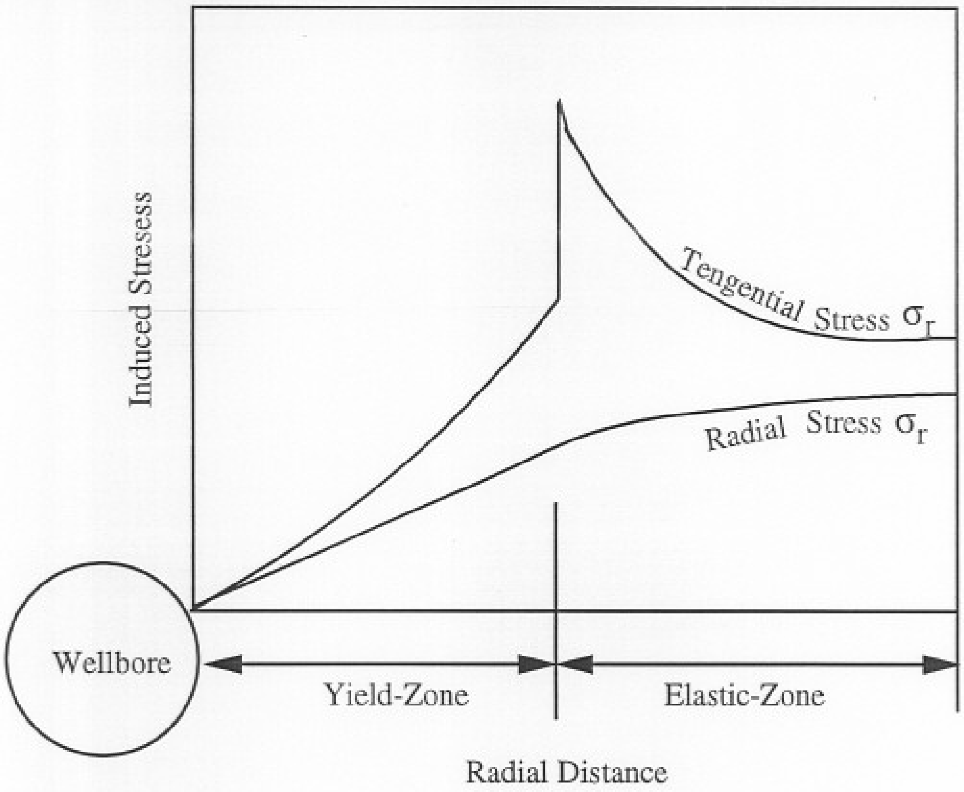


Fig. 1 Stress Distribution Around a Borehole.

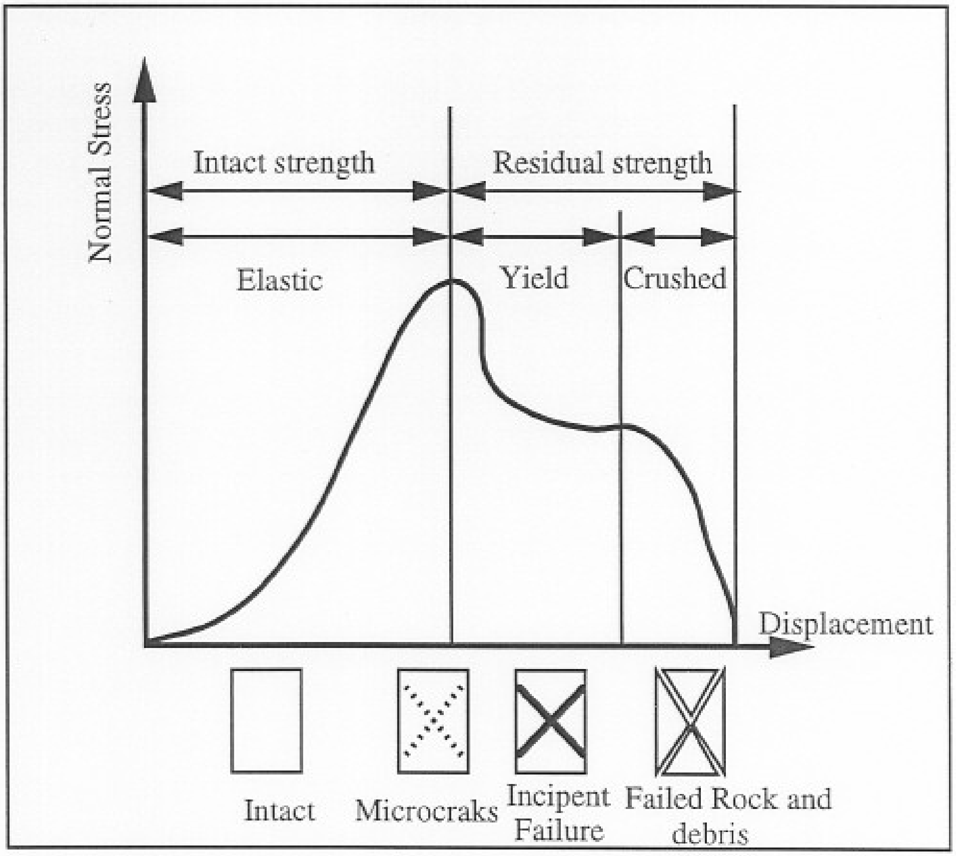
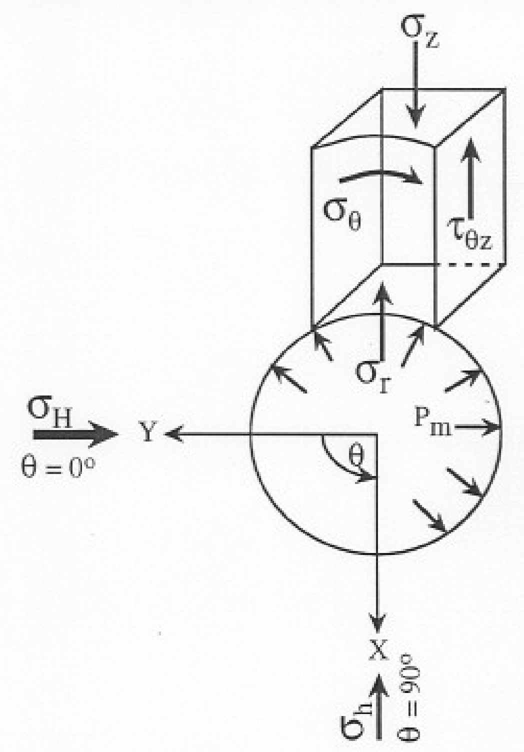
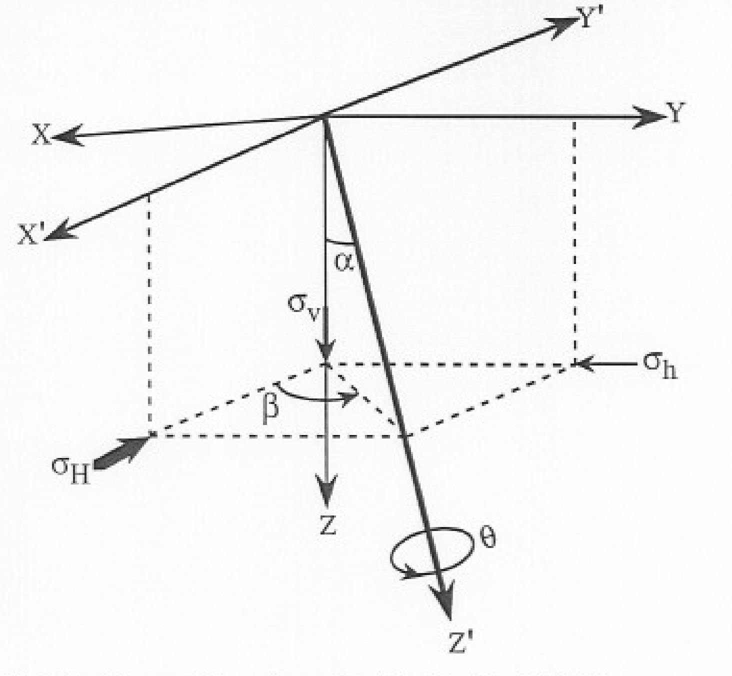


Fig. 2 Typical Load-Displacement Curve for Brittle-Ductile Rocks



(A) Stress State at the Wall of Vertical Wellbore.



(B) In-Situ Stresses Transformation for Deviated Wellbore.

Fig. 3 Induced Stresses at the Wall of an Inclined Borehole and its Transformation to Borehole Frame.

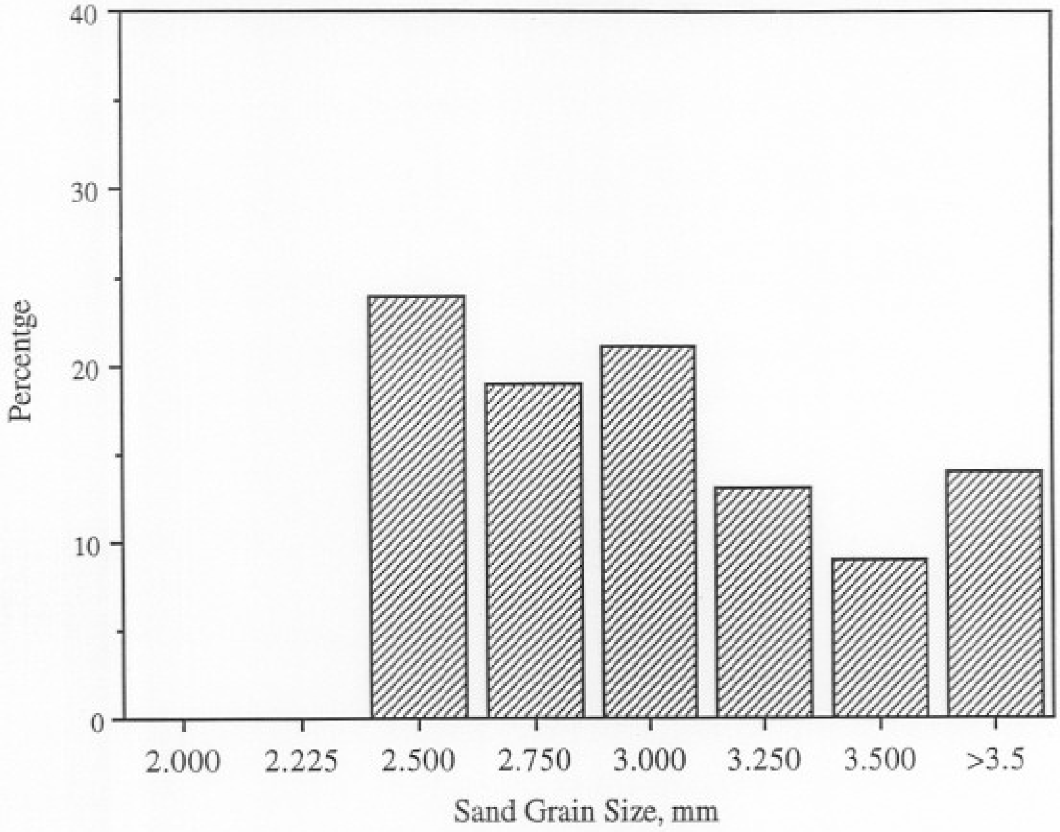


Fig. 4 Grain Size Distribution of Sand Used in this Study.

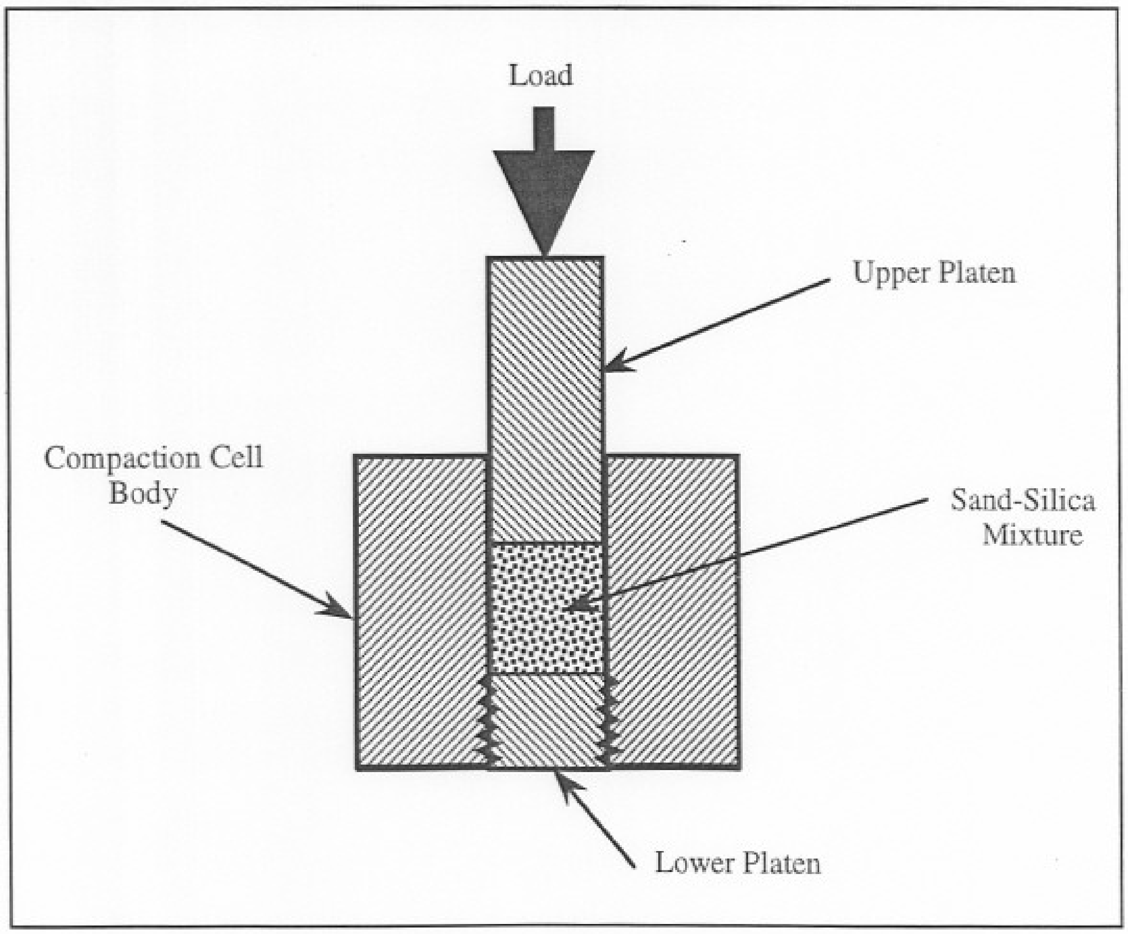


Fig. 5 A Schematic Diagram Showing the Compaction Cell.

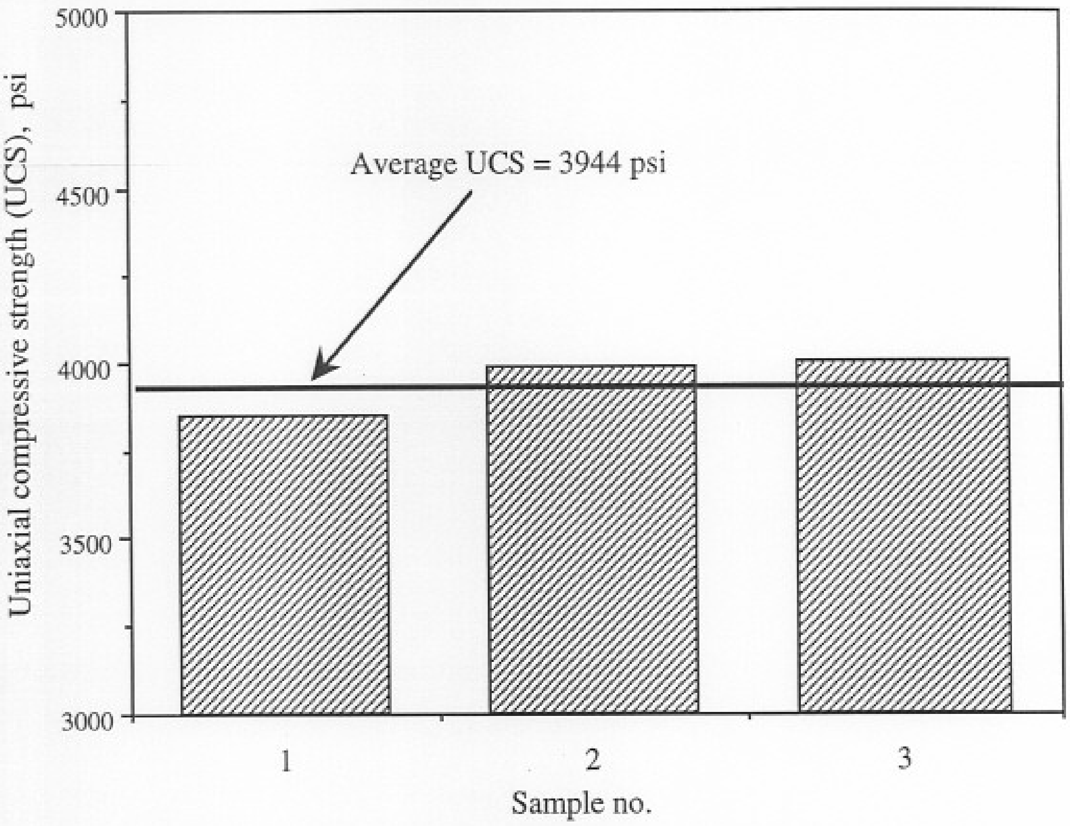


Fig. 6 Uniaxial compressive strength of artificial sandstones.

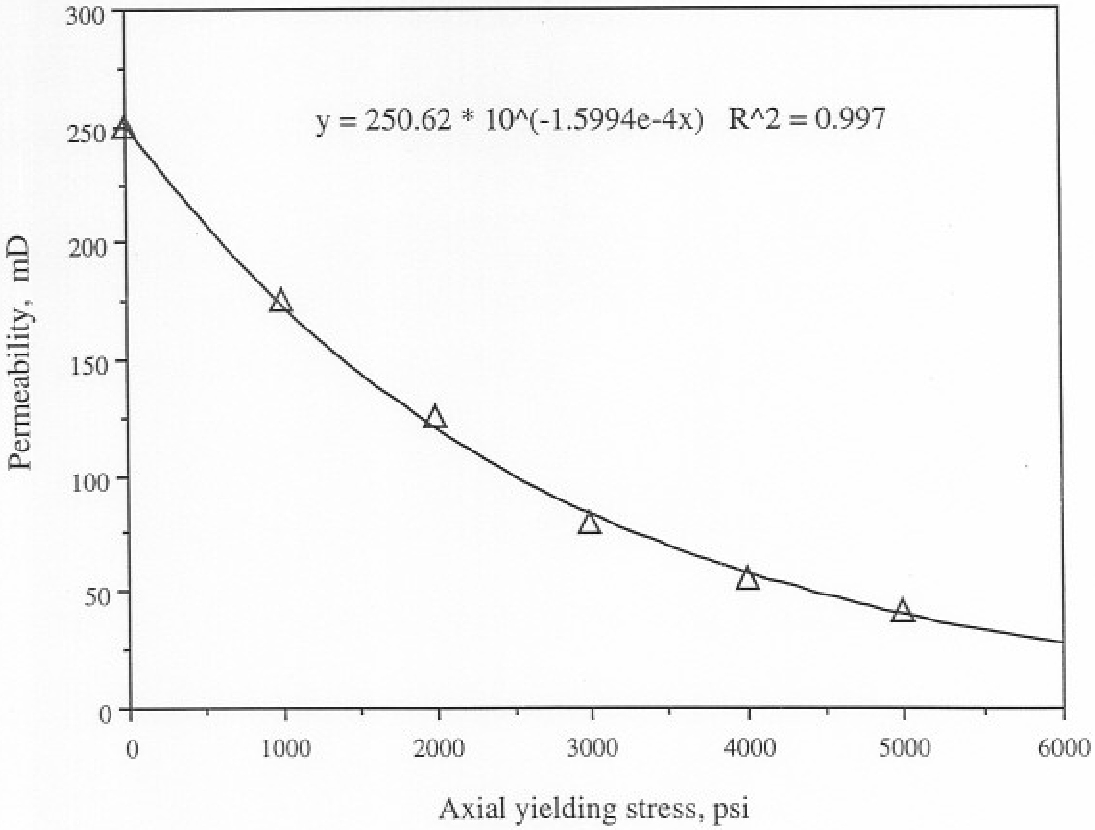
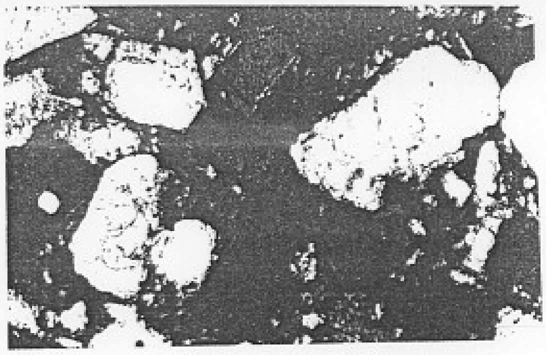
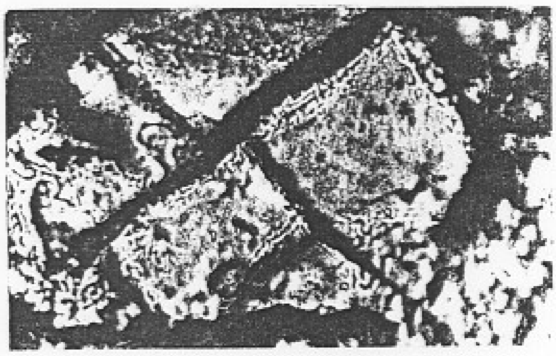


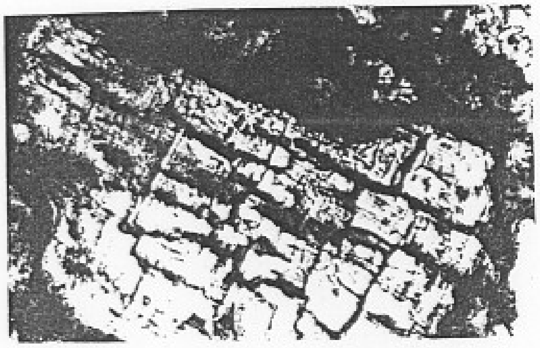
Fig. 7 Variation of permeability with applied yielding stress (mechanical skin).



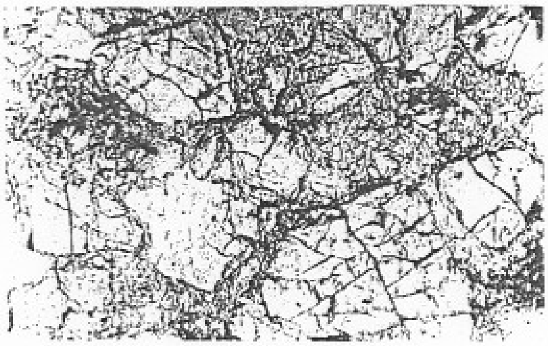
(A) Initial State (No Yielding Stress)



(B-i) Mechanical Damage After the Application of 3000 psi Yielding Stress.



(B-ii) Mechanical Damage After the Application of 4000 psi Yielding Stress.



(B-iii) Mechanical Damage After the Application of 5000 psi Yielding Stress.

Fig. 8 Thin Sections Examination photographs of Artificial Sandstone Cores Before and After the Induction of a Mechanical Damage.

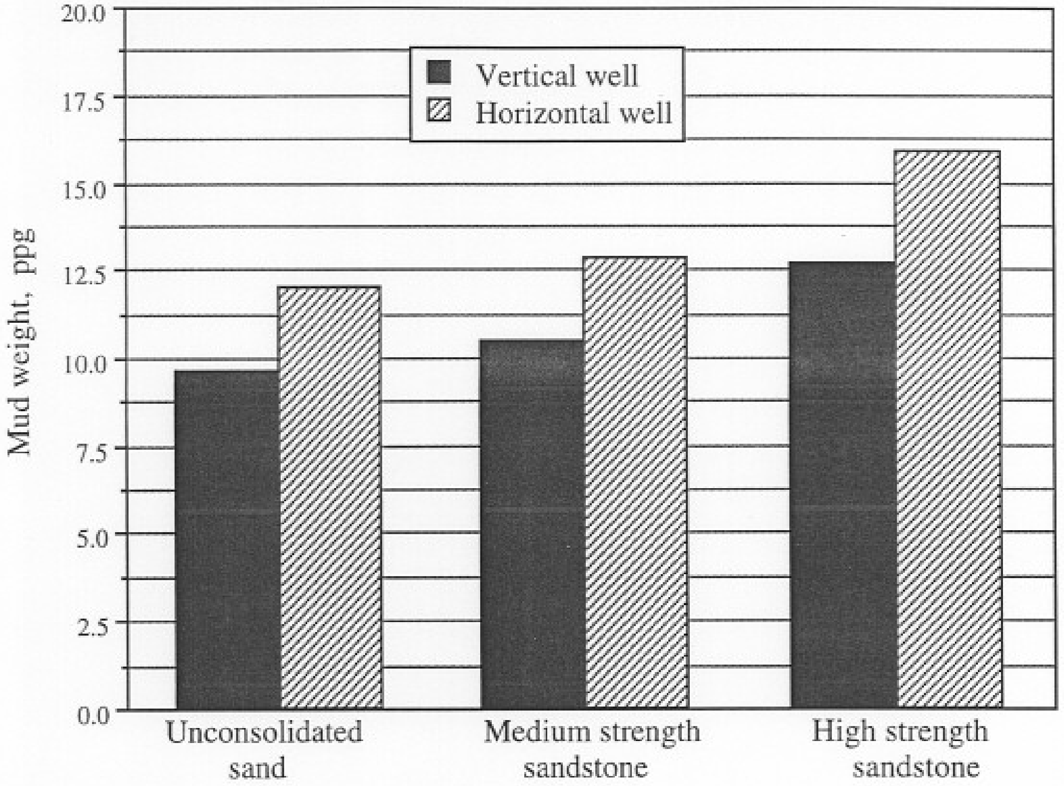


Fig. 9 Maximum mud weight required to prevent mechanical skin generation.

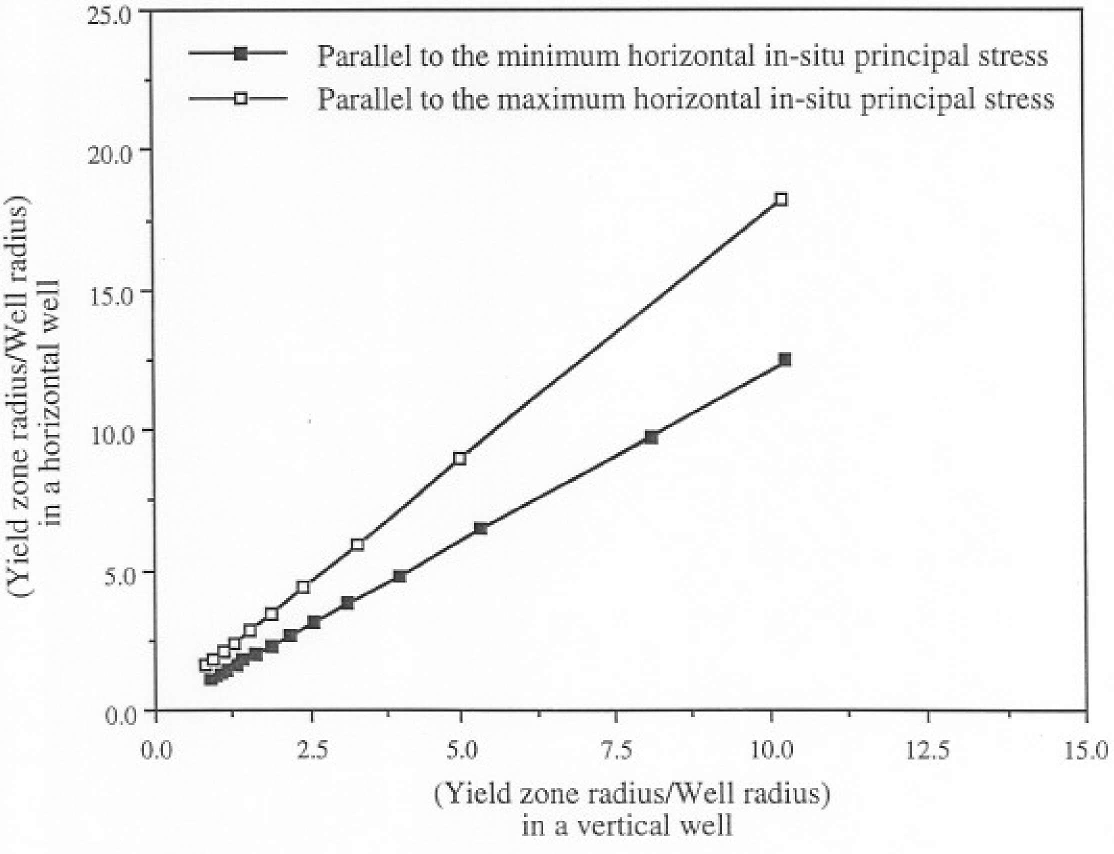


Fig. 10 Relationship between yield zone radius, well inclination and orientation.