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How to manage wellbore stability in the Vicking Graben tertiary shales by using mud systems environmentally friendly?

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Abstract

This paper deals with the drilling of the 17$"^{1/2}$ section of the Dunbar field (Viking Graben - North Sea). In the past, this formation was systematically drilled with a conventional WBM in underbalanced conditions (mud weight less than formation pore pressure estimated at 1.4SG). With such a mud system, the well was highly unstable particularly in the Eocene shales (very large amounts of cavings were produced, calliper was very overgauged) and the final trip was particularly tight. Following three remedial side tracks experienced over the last two years, an extensive study has been carried out. The main recommendations were to drill the Eocene in overbalanced conditions (MW>1.4SG) with a Silicate Mud. The results obtained on two wells slightly inclined (20° and 35° inclination at the 13$"^{3/8}$ casing shoe) were very encouraging. By contrast to previous underbalanced experience, the hole was perfectly in gauge and trips much easier (regular wiper trips to be performed). However, even in the case of a perfectly stable rock and to ensure a good hole cleaning, the wells had to be circulated at a high rate and a sufficiently thick rheology.

These results have then been confirmed on a third well (64° at the 13$"^{3/8}$ casing shoe) with a maximum mud weight equal to 1.45SG. However, this MW was not sufficient for 72° inclination (the well was too unstable and had to be abandoned).

Introduction

Legislation of certain countries is becoming increasingly strict regarding the dumping of drilling cuttings at sea when using OBM. In many cases, however (particularly when crossing reactive shales), use of WBM is not advised. Several solutions have been proposed to solve this ecological problem.

The first possibility consists in shipment and surface treatment[1] for land disposal. Offshore, this method can be very costly particularly when drilling extended reach wells. A second method is to reinject the oil contaminated crushed and slurried cuttings[2, 3] by hydraulic fracturing in the overburden. Considering the large volumes involved (several thousand m^3), control of the fracture extension is essential, both to protect the integrity of the reservoir and the surface environment.

Another alternative consists in using WBM systems designed to provide similar advantages to Oil Base Mud that is protecting shales from filtrate invasion.

Role of pore pressure on wellbore stability

Main parameters affecting stability. Stresses, pore pressure and rock strength are recognised as the major parameters influencing wellbore stability[4, 5, 6].

In the Mohr diagram (**Fig. 1**), the rock strength can be represented by a straight line (the Mohr Coulomb line) with two material constants (cohesion C and friction angle φ) whereas the mechanical state around the well is graphically represented by a circle (the Mohr circle) the size of which depends on the horizontal stress σ_h, the pore pressure p and the mud pressure p_w. Stability limit is reached when the global mechanical state overcomes the rock strength that is when the circle tangents the straight line.

As pointed out on **Fig. 1**, the diameter of the Mohr circle depends on stress and mud pressure. The higher the stress, the larger the circle, the higher the mud pressure, the smaller the circle. Pore pressure however which plays on both points of the circle does not change the diameter but can move the centre to the right if it decreases, to the left if it increases. Consequently, the higher the pore pressure, the higher the risk of instability.

Over and underbalanced conditions. One speaks about overbalanced (underbalanced) drilling conditions when the mud pressure is higher (lower) than the pore pressure. In hard limestones or sandstones, rock cohesion is generally sufficiently high to support underbalanced conditions. However, in shales the cohesion is always too small (very often close to zero) for the hole to be stable in underbalanced conditions (**Fig.1**)

Diffusion processes. Any mechanism which is inclined to increase the pore pressure in the well vicinity acts against stability. During the drilling process, two main diffusion processes can modify pore pressure.

The first one is the hydraulic gradient. Even if the permeability k of shales is small (in the range of a few nanoDarcies), depending on the direction of the hydraulic gradient a flow occurs between well and formation. Consequently, in overbalanced conditions and providing that there is no barrier to flow, pore pressure quickly equilibrates with mud pressure ($p_w=p$ at the wall) and initial overbalanced condition is broken down in an extended zone where pore pressure has been elevated.

The second one is the chemical gradient. Shales act as a semi-permeable membrane and depending on the chemical activities of the two fluids (mud filtrate and formation fluid), an osmotic water flow occurs from the fluid with the higher water activity (i.e. the lower salt concentration) to the fluid with the lower water activity (i.e. the higher salt concentration). From a general viewpoint, the total flow between drilling fluid and formation can be written[7]

$$Q = \frac{k}{\mu}\left(\Delta p - \nu \Delta \Pi\right) \quad with$$

$$\Delta p = p_w - p_p \qquad \Delta \Pi = \frac{RT}{V_w}\left[\frac{a_{sh}}{a_w}\right]$$

μ and ν being respectively the filtrate viscosity and the efficiency of the semi permeable membrane. According to those relations, two possible mechanisms can be used to reduce Q (in overbalanced conditions only) :

1. reduce the shale mobility (ratio between shale permeability and mud filtrate viscosity)
2. create an osmotic flow towards the well by reducing the mud filtrate activity.

Comparison between different mud systems - Main features of silicate mud

General. When drilling shale formations, conventional WBM does not allow to decrease the shale mobility (**Fig. 2a**). As previously mentioned, at the wall, shale pore pressure reaches equilibrium with mud pressure and overbalanced conditions are immediately broken down. The only way to stabilise the flow process (and consequently the rock) is to balance Δp by an osmotic back flow $\Delta\Pi$ which implies that $a_w<a_{sh}$.

The main advantage of OBM is to build at the wall a *"one way"* capillary barrier (relative permeability) preventing any fluid movement from mud (oil) to formation (water). At the wall, a pressure discontinuity between mud and formation fluid prevails and, the mud support remains effective with time. Furthermore, this interface acts as a semi-permeable membrane allowing osmotic exchanges between the pore fluid and the water phase of the OBM. An overbalanced OBM (**Fig. 2b**) with a chemical activity lower than that of the formation fluid allows therefore to the combination of mechanisms 1 and 2. For this reason, OBM is the best drilling fluid guaranteeing wellbore stability.

Silicate mud[8] is made of a silicate solution obtained by dissolving silica (SiO_2) in sodium (Na_2CO_3) or potash (K_2CO_3) carbonates i.e.

$$Na_2CO_3 + nSiO_2 \rightarrow Na_2O, nSiO_2 + CO_2$$
$$K_2CO_3 + nSiO_2 \rightarrow K_2O, nSiO_2 + CO_2$$

where n identifies the molecular ratio [i.e. the number of SiO_2 molecules relative to one Na(K) molecule]. It is typically in the range of 1.5 to 3.3 for commercial products. Let us note that depending on n, such a solution can have a very high pH (between 11 and 12). Silicate solutions react almost instantaneously with dissolved polyvalent cations such as Ca^{++} or Mg^{++} to form insoluble precipitates. Formation fluids generally offer this type of cation to the silicate mud allowing an impermeable precipitate to form at the wall which is then squeezed into the pores by the overbalanced pressure. Furthermore, it is recognised[9] that the silicate precipitate also works as a semi-permeable membrane so allowing a decline in pore pressure, providing a proper osmotic gradient be applied. However, the membrane efficiency ν is normally lower than that prevailing with an OBM.

Laboratory tests. To validate the process, pressure transmission experiments have been carried out in a special laboratory device (**Fig. 3**). The rock sample is placed in a metal sleeve and submitted to a vertical load (oedometric conditions). The sample is first consolidated (top circuit) under a given pressure P1 (equal to the formation pore pressure) then, the mud filtrate (bottom circuit) is flowed at a higher pressure P2 (equal to the mud pressure). To appreciate the importance of the diffusion processes, P1 is then recorded versus time.

Results of such tests are presented for WBM (**Fig 4a**) and Silicate Mud (**Fig. 4b**). In both cases, the sample is first consolidated under a pore pressure of approximately 100 bars then, mud filtrate is flowed at the base of the sample at a pressure of 150 bars (valve V2 is closed). In the case of WBM (pore fluid and mud filtrate have similar chemical compositions), pore pressure equalises with mud pressure after 20 hours whereas for the silicate mud, no hydraulic diffusion is observed. Furthermore, the higher salinity of the mud (lower chemical activity) allows an inversion of the diffusion process. Consequently, the pore pressure has a tendency to slightly decrease versus time.

The Dunbar field

The Dunbar field is located in the northern part of the North Sea (Viking Graben - **Fig. 5a**). The three main targets (below

3500mTVD) are in the middle and bottom Jurassic (respectively Brent and Statfjord reservoirs) and in the Triassic (Lunde reservoir). Depending on the location they can be oil bearing, gas bearing or both.

Typical well design is presented in **Fig. 5b**. After batch setting a conductor pipe (26") 80 meters below the sea bed (140 m water depth), drilling is initiated in $23"^{1/2}$, the $18"^{5/8}$ casing shoe being set in the bottom of the recent (mainly sandy) sediments. The $17"^{1/2}$ phase (Oligocene, Eocene and Palaeocene) is resumed with a WBM. Depending on the well profile, deviation at the $13"^{3/8}$ casing shoe (set in the top Cretaceous) is classically between 20° and 45°. The $12"^{1/4}$ phase is drilled with a SBM (Synthetic Base Mud), the $9"^{5/8}$ being set just above the reservoir section in the Kimmeridge shales (top Jurassic). Finally, the reservoirs are drilled in $8"^{1/2}$ diameter and covered with a $4"^{1/2}$ cemented liner providing full bore access to the $4"^{1/2}$ tubing.

The 17 1/2" section

Wellbore stability in Eocene shales. From a geological viewpoint, the $17"^{1/2}$ section is made up of alterning sequence of sands and clay associated (from top to bottom) with Oligocene, Eocene and Palaeocene levels (**Fig. 6b**).

The conventional drilling practice (used since the beginning of the Eighties) consisted of setting the $18"^{5/8}$ casing in the base of Oligocene sands (approximately 680mTVD), in performing a shoe bond test (leak off limit between 1.30SG and 1.35SG - **Fig. 7**) and drilling the $17"^{1/2}$ section using a WBM maximum density of 1.25SG. With such a mud system, the well is highly unstable (**Fig. 6a**) particularly in the Eocene shales where very large amounts of cavings are observed at the shakers during the whole phase. These instabilities are clearly confirmed by the calliper of **Fig. 6b**, with a hole very overgauged at the bottom of the Oligocene and the whole of theEocene. Faced with these difficulties, hole cleaning (flow rates in the range of 4000 l/min, regular viscous pills) and tripping procedures (pump out, back reaming) are of strategic importance in avoiding pack off problems**[10]**. Following three remedial side tracks experienced over the last two years, an extensive study has been carried out to better understand these instability problems.

Pore pressure regime in Eocene shales. Determination of pore pressure regimes in impermeable rocks is a difficult problem since direct measurements (RFT) are not possible. The only method consists in translating sonic log in terms of pore pressure via the effective stress concept (*Eaton's method*[11]). As pointed out on **Fig. 6b**, the Eocene clays which exhibit pore pressures in the range of 1.35SG to 1.40SG (underconsolidated formation), were systematically drilled in underbalanced conditions (the maximum mud weight used for this phase was equal to 1.16SG). We should note that in some parts of the Eocene where the pore pressure locally decreases and becomes close to the mud weight, the caving is systematically reduced.

Interpretation of log data are confirmed on one hand by the high rate of penetration, on the other by the shape of the cavings (**Fig. 6v**). If low permeability shales are drilled in under balanced conditions, large shale fragments spall off the side of the borehole. Spalling shales are generally long and thin and have concoïdal fracture pattern apparent under a microscope**[12]**. In the Eocene pore pressure plays a strategic role and, only overbalanced conditions (mud weight larger than the pore pressure) could improve the situation.

Mud weight calculations. Cohesion c and friction angle φ have been estimated on caving blocks using an indentation technique**[13,14]**. With respect to pore pressure and cohesion (**Table 1**) the Eocene can be divided into two different zones. Above 1500mTVD, Eocene is only slightly undercompacted (pore pressure is in the range of 1.2SG) but rock cohesion is low (1.6 bars). However, below 1500mTVD, pore pressure rises to 1.4SG but rock cohesion is much stronger (6 bars). However, friction angle φ is constant over the whole stratigraphic column.

Critical mud weight versus well inclination has been calculated using a fully coupled finite element model both for WBM and Silicate Mud. The rock is assimilated to a Cam-Clay material**[15]**. In the calculations, the difference between the two mud systems is integrated in the hydraulic boundary conditions : for the WBM, the rock is considered as fully permeable at the wall whereas for the silicate mud, the deposited membrane does not allow any fluid exchange between well and formation. Water osmotic exchanges are not taken into account in the process.

As pointed out in **Fig. 8**, in the lower Eocene, the mud weight required to stabilise the well at high inclination is much lower with silicate mud (no increase of the pore pressure in the well vicinity - maximum of 1.50SG) than with conventional WBM (maximum of 1.63SG). However, at low inclinations, the critical mud weight is close to the pore pressure (1.4SG) and consequently similar whatever the type of mud used.

New mud strategy. According to these results, a new mud strategy was implemented on two Dunbar wells (D19 and D20) slightly inclined (20° and 35° at the $13"^{3/8}$ casing shoe). It consists first in increasing the mud weight above 1.40 SG (to balance the 1.35SG pore pressure) and using a Silicate Mud preventing any fluid exchange between well and formation. For this solution to be adopted, the $18"^{5/8}$ casing shoe had to be moved down into the middle Oligocene (1000 m instead of 680m) to obtain a higher LOT (in the range of 1.55 SG - **Fig. 7**). In any case, to keep a sufficient margin with respect to the leak off limit, the mud weight was limited to 1.45SG.

By contrast to the conventional light WBM (**Fig. 9)**, this new mud strategy provided a perfectly in gauge well but also excellent tripping conditions. However, given the mineral coating deposited, it is necessary to perform wipers trips (with no back reaming and no pump out) every 500 meters to remove the cake from the section freshly drilled. As pointed out on **Fig. 9a**, overpull which was experienced during the wiper trip is no longer observed afterwards for the final trip.

Hole cleaning

As already mentioned hole cleaning is of a strategic importance to avoid pack off and/or stuck pipe problems[10] particularly in highly deviated wells. Such a pack off has been experienced with Silicate Mud on well D20 while POOH the string after drilling the Eocene (**Fig. 10**). The ECD (measured real time with a Pressure While Drilling sub[16, 17]) showed an initial "smooth" increasing trend (ECD grows from 1.45SG to 1.48SG for a 1.42SG mud) then roses sharply with loss of circulation and initiation of mud losses. The pack off also obviously appears on torque (a maximum of 3000kg*m was recorded). Consequently, the string had to be run in hole to recover both normal circulation conditions (extra ECD due to circulation are in the range of 0.03SG) and normal torque.

The poor hole cleaning while drilling the Eocene was first of all attributed to an insufficient flow rate (due to pump failure, part of the section was drilled at 2500 l/min) but also to a low initial rheology. Even in the case of a perfectly stable well it is therefore necessary to maintain flow rates above 4000l/min and to use sufficiently thick rheologies (sufficient carrying capacity) to properly lift the cuttings.

Impact of inclination on stability

Two other wells (D21 and D22) were drilled with the same mud strategy. With respect to D19 and D20), they were highly deviated in the Eocene (52° for D21 and 64° for D22). D21 was successfully completed (64° at the $13''^{3/8}$ casing shoe) but for the extreme case of D22 the maximum allowable mud weight (1.46SG) was not sufficient to properly stabilise the well. As pointed out on **Fig. 11**, while tripping out the string, big pieces of cavings were observed at the shakers for several hours and given the high inclination, the enlarged hole could no longer be cleaned. Consequently, the string packed off and well had to be side tracked with a less aggressive trajectory similar to that of D21.

Conclusions

Among the different parameters influencing wellbore stability, formation pore pressure has to be recognised as a major one. In a permeable reservoir, the response to drilling in underbalanced conditions is a kick. In low permeable shales the response is wellbore instability. However, as shales generally exhibit a very low cohesion (less than 5 bars), overbalanced conditions are not generally sufficient to ensure stability. With a conventional WBM, equilibrium between well and formation is quickly achieved breaking down overbalanced conditions. Consequently, the mud system has to play as a *"one way"* semi-permeable membrane preventing any fluid movement from the well to the formation but allowing water exchange towards the well providing a proper osmotic gradient be installed. Diffusion laboratory tests have shown that Silicate Mud acts as such a *"one-way"* semi permeable membrane and can possibly replace OBM to drill reactive shales.

In the undercompacted Eocene shales of the Dunbar field such a mud system proved its capability to manage wellbore instability at low inclinations (less than 35°). By contrast to previous "underbalanced" experiences (three side tracks over the last two years), wells were perfectly in gauge and trips much easier (providing regular wiper trips be performed). However, even in the case of a perfectly stable rock and to ensure a good hole cleaning, the well has to be flowed with high flow rates (above 4000l/min in $17^{1/2}$") and sufficiently thick rheologies.

However, even with a heavy silicate mud program (MW<1.45SG), 55° at the bottom Eocene and 65° at the $13''^{3/8}$ casing shoe can be considered as a limiting case.

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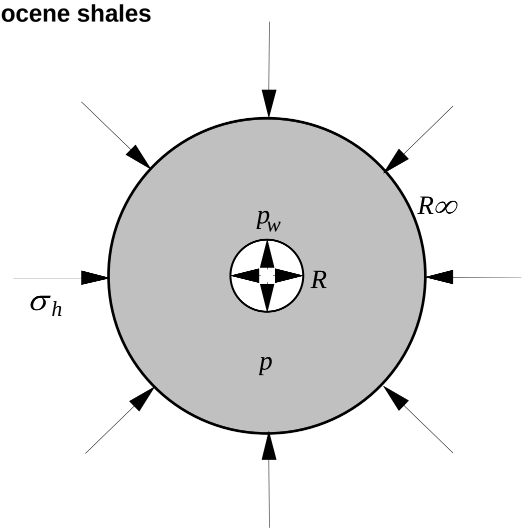
Depth" (mTVD)	σ_v (SG)	σ_h (SG)	p (SG)	c (bars)	φ(°)
1300	1.91	1.7	1.2	1.6	37
1500	2.02	1.71	1.4	6	37
1800	2.04	1.72	1.4	6	37

Table 1 Mechanical parameters and loading parameters in theEocene shales



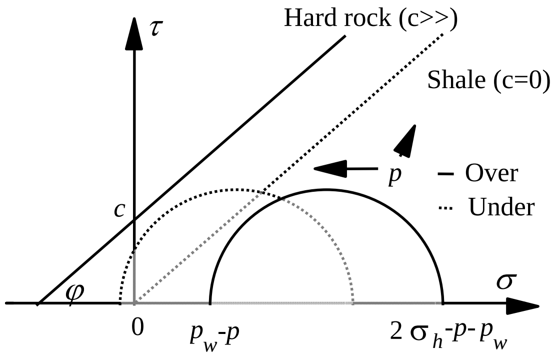


Fig. 1 Mohr diagram showing how the interstitial pressure can influence wellbore stability

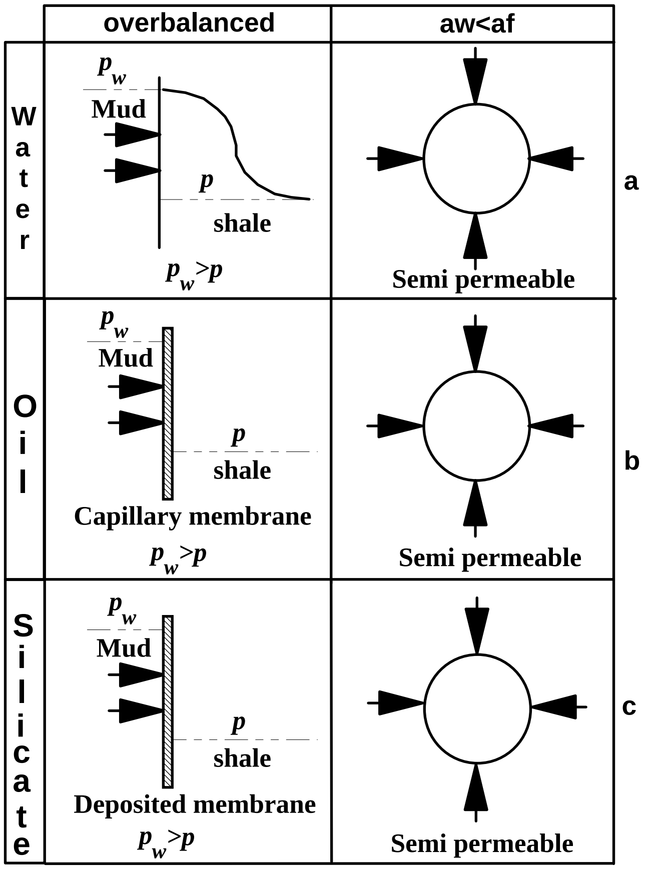


Fig.2 Fluid exchanges between mud and formation depend on hydraulic and osmotic gradients

a. **Water base mud b. Oil base mud c. Silicate mud**

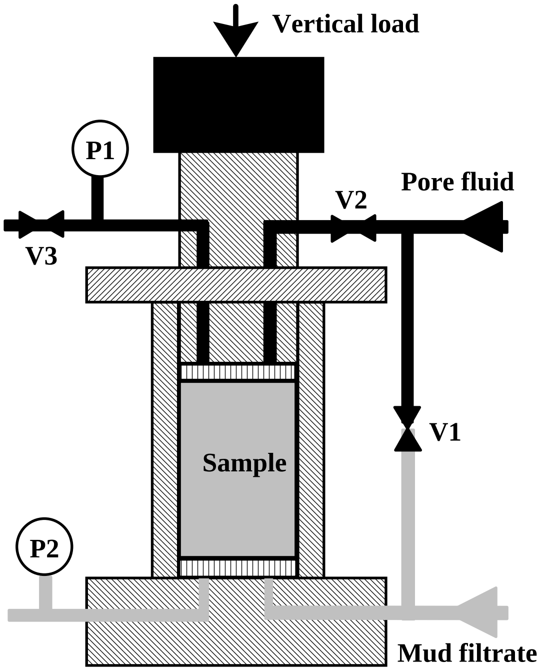


Fig. 3 Laboratory filtration device.

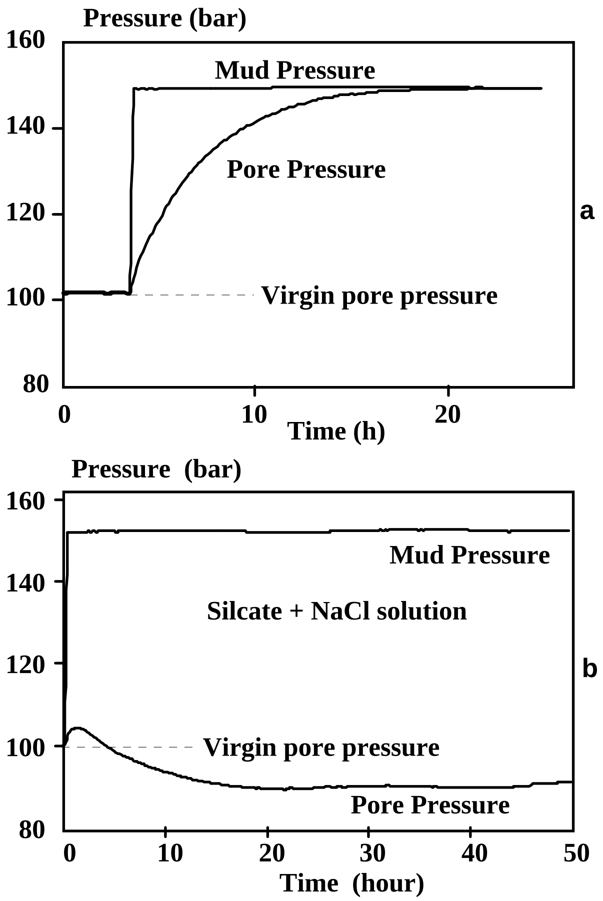
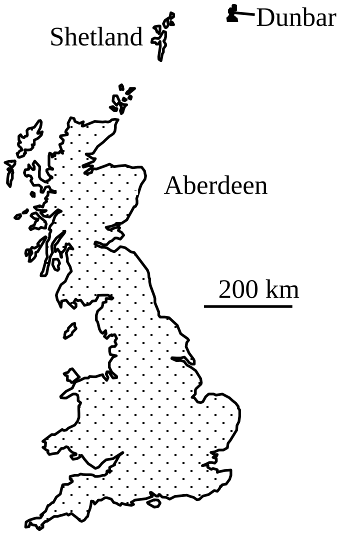
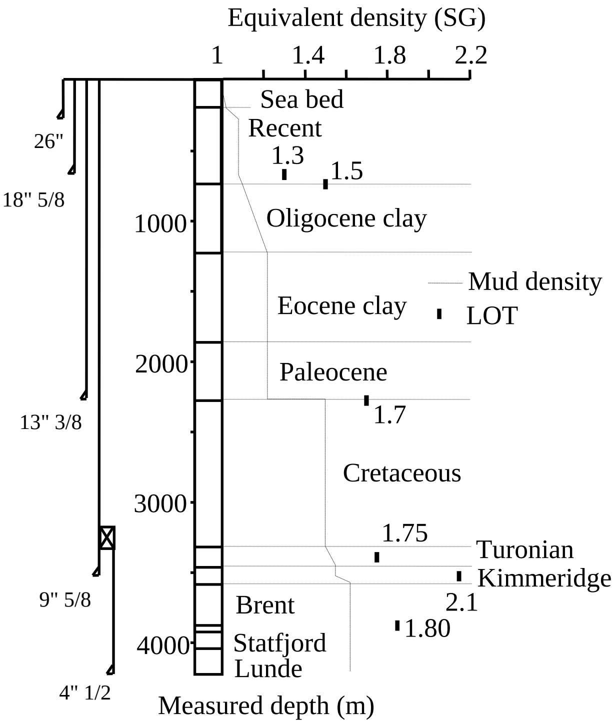


Fig. 4 Laboratory tests comparing
a. Conventionnal WBM
b. Silicate mud



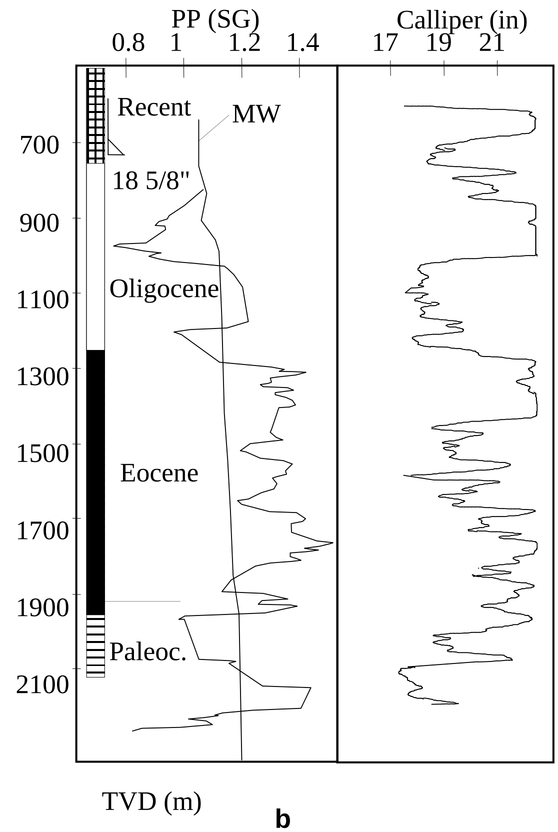
a.



b.

Fig. 5 The Dunbar field
a. Location
b. Typical well design

a



b

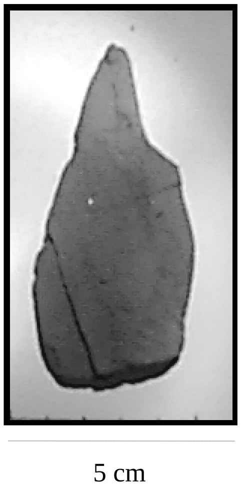


Fig. 6 a. 12kg caving recovered at the shakers while drilling the unstable Eocene shales
b. Results of Eaton's method and calliper
c. Typical spalling shale in Eocene

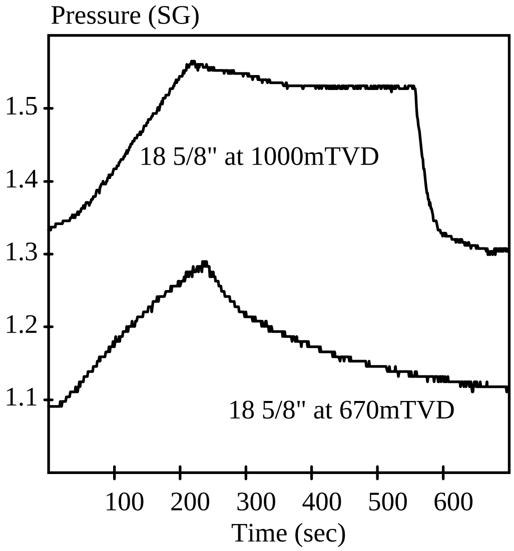


Fig. 7 Comparaisont of LOT between 18 5/8" shoe set in Oligocene sands and in Oligocene shales

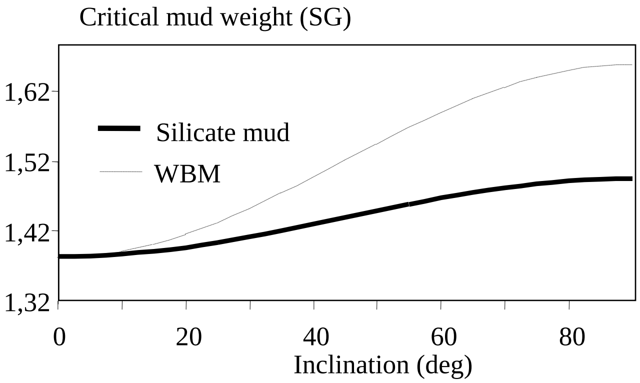


Fig. 8 Calculated mud density in the overpressured Eocene for conventionnal WBM (perfect filtration) and Silicate mud (no filtration)

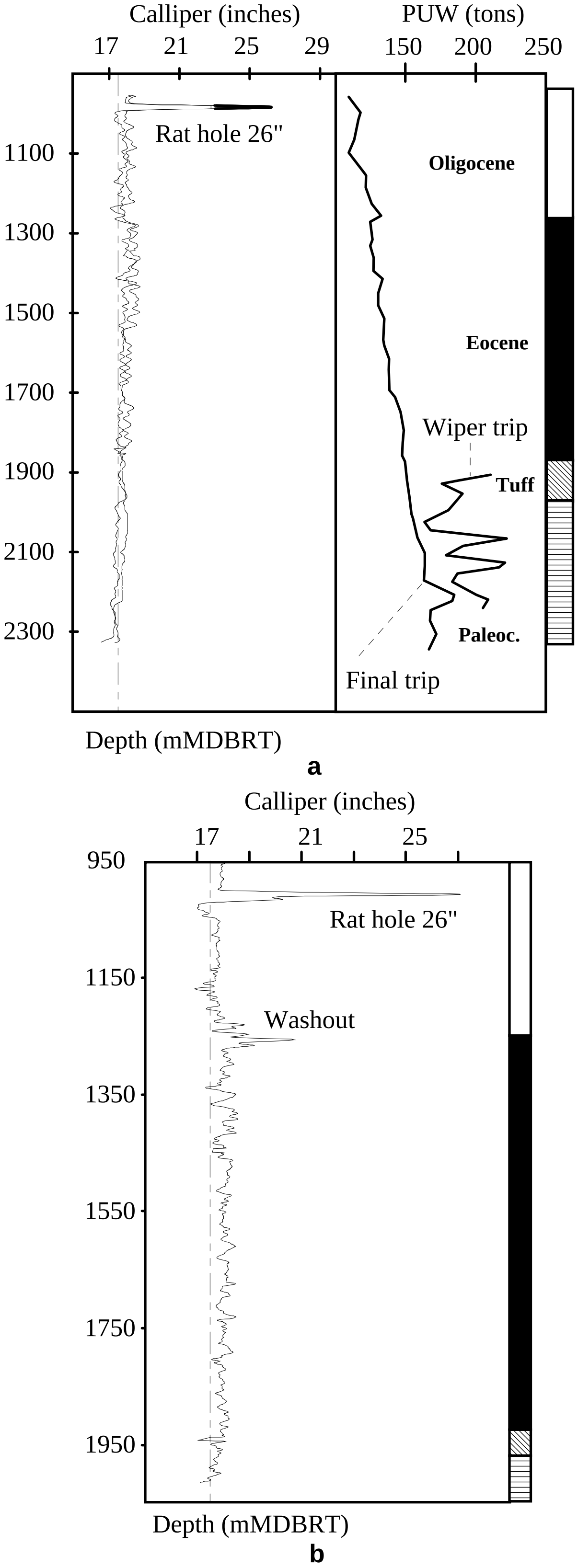


Fig. 9 - Calliper on well D19 (20° - MW=1.40SG) and D20 (34° - MW=1.42SG)

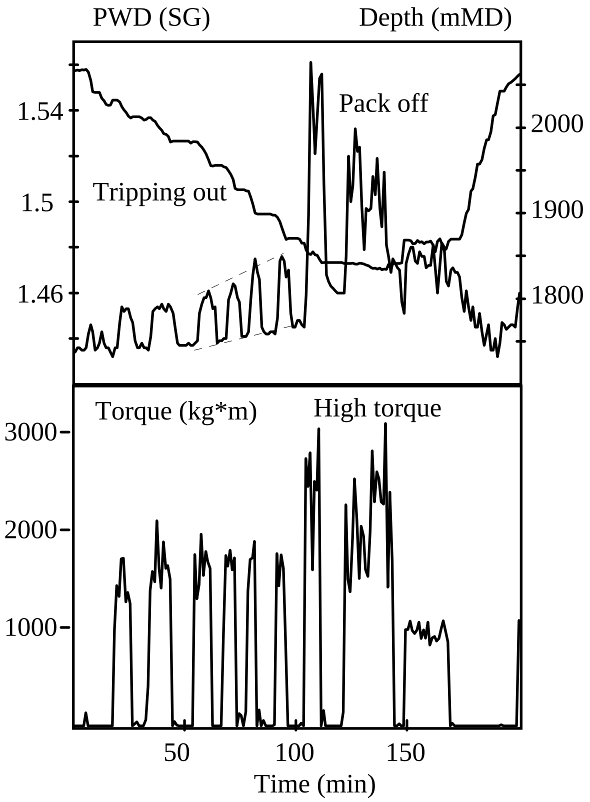


Fig. 10 Pack off experienced while tripping out

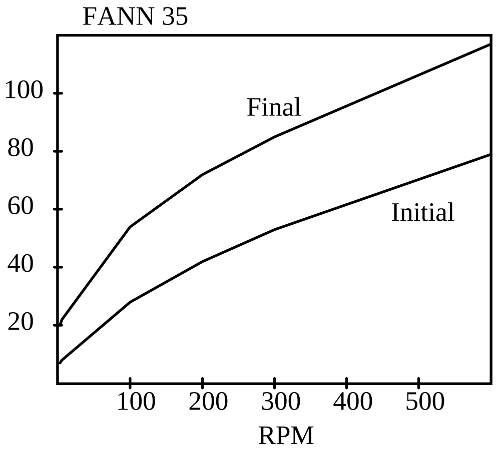


Fig. 11 Initial and final rheograms

Fig. 12 Big pieces of cavings observed at the shakers due to high inclination (72°)