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Three History Cases of Rock Mechanics related Stuck Pipes while drilling Extended Reach wells in North Sea.

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Abstract

Stuck pipes have three different origins : hole geometry (excessive dog legs in highly deviated wells), pack off (wellbore instability or bad hole cleaning leading to a plugging of the annulus) and differential sticking (drill string embedded into the mud cake due to an excessive difference between mud weight and reservoir pressure). This paper presents three different examples of stuck pipes directly related to rock mechanics problems.

The first one results from a typical pack off in a highly unstable under compacted shale formation drilled in under balanced conditions.

The second stuck pipe is quite untypical since it occurred while drilling a 9 5/8" cemented shoe track.

Finally, the third one occurred while drilling the reservoir section of a highly deviated well (72° inclination) and during a directional survey. The analysis of the surface data clearly showed that differential sticking was the cause of the stuck pipe.

In the three cases, the well had to be side tracked where each time the cost was in the range of 1M£.

Introduction

Stuck pipes represent more than 75% of the problems experienced while drilling. In many cases a stuck pipe leads to remedial side tracks greatly increasing the cost of the well. Drill strings can get stuck in a borehole because of a variety of reasons. However, three of the most common are pack off, differential sticking and hole geometry.

Pack off. Pack off (**Fig. 1a**) consists of a sealing of the annulus space due to an abnormal accumulation of cuttings around the drill pipe. This accumulation can be either due to a poor hole cleaning (especially in highly deviated wells) and/or to wellbore stability problems (large amounts of cavings fall down and seal the annulus).

Pack off primarily occurs when the drill pipe is static (drill pipe connection or drilling in sliding mode with a downhole motor), or moving up and down (tripping), but rarely when rotating the string. Due to the plugging of the annulus, mud circulation is always affected by pack off (circulation restricted or impossible).

Differential sticking While drilling permeable formations and to prevent any gas influx, well pressure p_w is usually higher than formation pore pressure p_R (drilling is said to be *"overbalanced"*). Consequently there exists a positive differential pressure Δp between well and formation (**Fig. 1b**). If rotation and reciprocation are stopped, the drill collars can be embedded in the filter cake. The latter forming good seals, drill collars get stuck against the borehole wall. Differential sticking always occurs when the drill string is static. The annulus is not affected, therefore circulation after differential sticking is generally unrestricted.

The intensity of the sticking force can be estimated using the simple model[1,2] described in **Fig. 1b**. The mud cake is represented by a ring of constant thickness e. The pipe (of external radius R_p) is completely imbedded in the cake (the pipe has a single point of contact A with the formation) over a distance DB. The distance d between the two sealing points can be estimated by writing the equations of the pipe and that of the mud cake i.e. :

$$d = 2\sqrt{(R_w - e)^2 - \left[R_w - \frac{e(2R_w - e)}{2(R_w - R_p)}\right]^2}$$

The problem consists of calculating the normal force F_n resulting from the application of the mud pressure p_{mud} over BCD and of the reservoir pressure p_R over BAD. After integration, we get :

$$\frac{F_n}{h} = d\,\Delta p$$

h being the reservoir height. Assuming a pipe/mud cake friction coefficient equal to f, the net overpull $OVPL$ (upwards pulling force necessary to move the pipe) is written

$$OVPL = f F_n = f d h \Delta p$$

which is proportional to the differential pressure. Apart from differential pressure, mud cake appears to be the primary driving force of differential sticking. With a thick mud cake the sealing area as well as the risk of differential sticking quickly increase.

Hole geometry. Several types of geometrical anomalies can induce a stuck pipe. The most common are key seating (drill string producing a groove when rotating against the formation), dog legs (change of borehole direction over a short distance - **Fig. 1c**) and well convergence (decrease of wellbore diameter in plastic and viscous rocks - soft clay or salt for instance). By contrast to pack off and differential sticking a hole geometry stuck pipe can occur while rotating the string. After sticking, down vertical motion and rotation are generally restricted but rarely impossible, whereas the circulation remains free and unrestricted.

Stuck Pipe Worksheet (SPW). To perform quick diagnostics, Ramsey and Robinson[3] have proposed a Stuck Pipe Worksheet (SPW - **Table 1**) which has to be used as follows. In each main item (written in bold letters), chose the option corresponding to your current situation and write the corresponding number (0, 1 or 2) in the score column. For example if you was rotating up prior to sticking you will write in the empty rectangles of the *"rotating up line"* 0 for pack off, 0 for differential sticking, 2 for well geometry. Do the same for the other items (only one option can be selected in each main item) and calculate the three total scores. The higher the score the most probable the stuck pipe origin.

The Dunbar field

The Dunbar field is located in the northern part of the North Sea (Viking Graben). 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, mud weight strategy, and leak of test values are presented in **Fig. 2**. After batch setting a conductor pipe (26") 80 meters below the sea bed, drilling is initiated in 23 1/2" with a 1.08SG water base mud. The 18 5/8" casing shoe (where a LOT in the range of 1.30SG to 1.35SG is classically obtained) is set in the bottom of these recent (mainly sandy) sediments. The 17 1/2" phase (Oligocene, Eocene and Paleocene) is resumed with a water base mud 1.10SG in the Oligocene then raised to 1.22SG just before reaching the Eocene. Depending on the well profile, deviation at the 13 3/8" casing (set in the top Cretaceous) is classically between 20° and 45°. A minimum LOT of 1.70SG is required before beginning the 12 1/4" phase. The latter is drilled with a synthetic oil base mud in the range of 1.50SG to 1.60SG. The 9 5/8" is set just above the reservoir section in the Kimmeridge clay (top Jurassic) where a very high LOT value (up to 2.15SG) is obtained. In case of ERD wells, well inclination sometimes goes up to 70° at the 9 5/8" casing shoe and, to ensure stability of the Kimmeridge, the mud weight has to be raised. 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.

We analyse below three major stuck pipe incidents which have occurred on three different wells respectively in 17 1/2", 12 1/4" and 8 1/2" phases. They have all lead to remedial side tracks.

Example 1 : pack off in the Eocene/Oligocene shales (17 1/2" section)

In a classical casing design, the Oligocene/Eocene/Paleocene series are drilled in 17 1/2", the 13 3/8" casing shoe being set in the top Cretaceous. According to the LOT value at the 18 5/8" casing shoe (1.30 SG in most cases), the phase is drilled with a water base mud between 1.10 SG (Oligocene) and 1.22SG (Eocene/Paleocene). With such a mud system, the well is highly unstable and very big amounts of cavings are observed at the shakers during the whole phase particularly while drilling the Eocene clays but also while tripping out the drill string (a 12 kg caving has been recently recovered).

Log analysis. A detailed analysis of available logs (gamma-ray, resistivity, sonic, calliper) is presented on **Fig. 3a**. On one hand the calliper confirms very large cavings particularly at the top Oligocene clay (it is more sandy at the base) and in the whole Eocene. On the other hand, the well known Eaton's method[4] (translation of sonic log in terms of pore pressure via the effective stress concept) has been used to determine pore pressure regimes. As pointed out on **Fig. 3a**, Eocene appears as an under consolidated formation with a pore pressure up to 1.35 SG. According to these values, the Eocene is thus drilled in under balanced conditions. We should note that in some parts of the Eocene where the pore pressure locally decreases and becomes close to the mud weight, the borehole ovalisation is systematically reduced.
The conclusions issued from the interpretation of the log data are confirmed on one hand by the high rate of penetration, on the other by the shape of the cavings (**Fig. 3b**). If low permeability shales are drilled in under balanced conditions, large shale fragments spall off the side of the borehole. Spalling shale are generally long and thin and have concoidal fracture pattern apparent under microscope[1].

Analysis of drilling data. The incident occurred while pulling the drill string out of hole. The bit was approximately at 1000 m (**Fig. 4** - phase 1) and the drilling parameters were normal : PUW=100 tons, surface torque=1000 kg*m, SPP=140 bars for a flow rate equal to 3500 l/min.
Beginning of the stuck pipe process is signified by a small increase in the SPP (**Fig. 4** - phase 2) at a reduced flow rate then by a regular increase in hook weight (overpull) and high torque (up to 2500 kg*m) indicating a progressive plugging of the annulus.
In spite of increasing overpull (**Fig. 4** - phases 4 and 5), a further three stands were POOH. In parallel with the final WOH (above 200 tons), one totally looses circulation. After jarring 12 hours, the string was backed off and the well side track. A fish including bit and MWD (more than 300k£) was abandoned in the hole. Applying these drilling data to the SPW (**Table 2**) clearly allows identifying pack off as the origin of the stuck pipe.

Proposed solution The problem was cured in next wells by increasing the mud weight up to 1.40 SG (to balance the pore pressure) and by using a silicate water base mud preventing from any fluid exchange between well and formation (silicate mud builds a chemical cake by deposing a mineral coating on the wall). For this solution to be adopted, the 18 5/8" casing shoe had to be moved down in the Oligocene clay (1000 m instead of 680m - **Fig. 2**) where a higher LOT (in the range of 1.55 SG) can be obtained. This new mud weight strategy provided a perfectly in gauge well (**Fig. 5**) and 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. 5**, overpull which is experienced during the wiper trip is nomore observed afterwards during the final trip.

Example 2 : pack off in the Kimmeridge clay while cementing the 9 5/8" casing

Once the 13 3/8" casing has been cemented (LOT at the 13 3/8" casing shoe in the range of 1.70SG), the 12 1/4" phase (the whole Cretaceous sequence) is drilled with a synthetic oil base mud the density of which is between 1.50SG and 1.60SG. The main part of the section is performed without any problems. Nevertheless the top Jurassic formation (the Kimmeridge - source rock of the main Jurassic reservoirs) can become unstable for high deviations and long open hole times. As shown on **Fig. 6**, the critical mud weight (calculated under undrained conditions according to a Mohr Coulomb criterion) required to stabilise the Kimmeridge (pore pressure 1.6SG, LOT 2.15SG) is only 1.40SG for a vertical well but increases up to 1.67SG at 90° inclination. The data base presented on **Fig. 6** clearly confirms the forecasts of the model (all side tracked wells are clearly located below the curve). The stuck pipe discussed below appears quite atypical since it occurred while drilling the cement of the 9 5/8" shoe track. However, we will see that it results from wellbore stability problems in the Kimmeridge.

Analysis of cementing data before the stuck pipe. The 12 1/4" phase (TD at 4903 mMD, top Kimmeridge at 4883mMD) was drilled below the critical stability curve (mud weight equal to 1.51SG for a 66° inclination) without any problem. The 9 5/8" casing was then RIH (shoe at 4897m) and the cement job carried out. The cement slurries were displaced with an initial SPP of approximately 25 bars but after 5 minutes, the SPP suddenly raised up to 250 bars (**Fig. 7a**). Simultaneously, large losses initiated (no return) and the flow (initially at 2000 l/min) had to be reduced to 1400l/min, then 950l/min and finally 710 l/min. The well was then displaced to 1.59SG mud weight to initiate the 8 1/2" section. While finishing drilling the cement in the shoe track (4903m), the string stalled (bit stuck into the rat hole), the annulus was packed off and the circulation was lost. It was consequently decided to cut the string and to side track the well.

Interpretation. The sudden increase in pressure associated with large losses experienced while displacing the cement are clearly due to a pack off of the annulus. As already observed on previous wells, instability of Kimmeridge occurs with a certain delay. It is not surprising therefore that in spite of an insufficient mud weigh (1.51SG used against 1.66SG) drilling was achieved without problems and that the major pack off occurred later while cementing. With a completely packed off annulus, cement was injected above the fracturing regime in the Kimmeridge (**Fig. 7b**) as confirmed by the equivalent density at fracture initiation (2.25SG) which corresponds quite well to the leak off limit in the Kimmeridge (2.15SG to 2.20SG) and not at all to that of the upper formations where a leak off limit in the range of 1.75SG prevails. Finally, a CBL performed afterwards confirmed uncemented casing over the whole section.
The stuck pipe occurring while redrilling the cement in the shoe track can be understood as follows (**Fig. 8a**). Due to the pack off, the cement was squeezed and thickened at very high pressure (**step a**) under fracturing regime at 2.25SG (in a normal job, cement is placed in the annulus at 1.75SG). Due to this high pressure, the cement in the shoe track was externally over stressed (**step b**). When the cement plug was drilled, it became less and less stable (**step c**) the final picture being a cement hollow cylinder loaded by an internal pressure 1.60SG and an external pressure 2.25SG. The stability of such a cylinder is studied using the elastic Lame's solution and a Tresca criterion assuming for the cement an UCS (Unconfined Compressive Strength) equal to 5000psi. As pointed out on **Fig. 8b**, for a 1.60SG mud weight, the cement ring is clearly stable in classical circulating conditions (1.75SG) but for a squeezing situation (above 2.10SG), it becomes quickly unstable and instantaneously collapses when reaching the bottom of the shoe track [all the points below the

dashed line (cement resistance) remain stable whereas the points above are unstable].

Proposed solutions. The key to success is first and foremost to follow the stability curve (particularly at high deviation) but also to minimise open hole time in the Kimmeridge.
Depending on the inclination of the well, the casing shoe has to be set either in the bottom Kimmeridge, or in the bottom Cretaceous. For deviation up to 50°, the mud weight required to stabilise the Kimmeridge (1.57SG) remains compatible with the LOT both at the 13 3/8" casing shoe (1.7SG) and in the Turonian (1.75SG). It is consequently advisable to drill the major part of the Kimmeridge in 12 1/4" phase minimising the open hole time but determining quite accurately the Kimmeridge/Brent transition (using a LWD-gamma ray) to avoid penetrating in the Brent (possible virgin pressure).
By contrast for inclinations above 55° which requires heavier mud weights (up to 1.68SG), Kimmeridge has to be decoupled from the Cretaceous, the 9 5/8" casing being set in the very bottom of the Turonian. Two situations can prevail.
If the reservoir pressure is close to its virgin value the fracturing gradient in the Brent (above 1.9SG) is generally sufficient to support the required mud weight without losses and the Kimmeridge/Brent sequence can easily be drilled in a single 8 1/2" section. However, if the Brent is highly depleted (leak off value in the range of 1.8SG), ECDs while drilling[5] can induce large losses in the Brent. It is therefore necessary to cover the Kimmeridge by an intermediate 7" liner before resuming drilling.

Example 3 : differential sticking in the Brent reservoir.

To overbalance the virgin reservoir pressure in the Brent (1.65SG), the first wells of the Dunbar field were drilled with with a mud (oil base) weight in the range of 1.65SG. Depletion being quicker than expected, the pore pressure in the Brent is today much lower (between 1.15SG and 1.30SG in most wells currently drilled). However due to the very complex drainage of the structure, geologists and reservoir engineers can never guarantee an homogeneous depletion, some isolated sand layers possibly remaining undepleted. Furthermore, depletion being different in Brent, Stafjord and Lunde, when the three reservoirs are drilled together, the mud weight strategy has to be aligned on the largest pore pressure. Consequently, in most cases, the Brent is drilled in highly overbalanced conditions. Consequently, with very permeable reservoirs (permeability in Brent is in the range of 40 mD) the mud builds thick cakes particularly when the filtrate is badly controlled. On the example shown on **Fig. 9**, the three reservoirs (Brent, Stafjord and Triassic) are all oil bearing. The pore pressure in the Brent is quite depleted (1.36SG at the top, 1.43SG at the bottom) but in the Statfjord and in the Triassic, it is quasi virgin (in the range of 1.60SG). Very thick cakes (in the range of 1 inch over the diameter) are observed face to the reservoirs. By contrast, in the Kimmeridge and the Dunlin (shales), the well is perfectly in gauge. The cake cannot therefore be interpreted as a single consequence of the differential pressure (small in Stafjord and Triassic). The bad control of the mud filtrate plays a major role on the cake building process.

Analysis of drilling data before the stuck pipe. We present below the drilling data of a stuck pipe which occurred while drilling the top Brent of a highly deviated Dunbar well (72°). According to this deviation the 9 5/8" was set in the bottom Cretaceous and the Kimmeridge drilled according to the mud weight required by the mud weight curve (1.69 SG - **Fig. 6**).
After completing the drilling of a stand in the top Brent, a directional survey was carried out. The first measurement being unsuccessful a second one had to be carried out. Between the two surveys, circulation was reinitiated (to send the data up to the surface) but the drill pipe was not rotated. Consequently a 15 minutes period was spent without rotating the string.
The stuck pipe was notified after the second survey (overpull up to 290 tons, no rotation possible but unrestricted circulation - **Fig. 10a**). In spite of several attempts to unstick the BHA, the drill string had to be backed off and the well was side tracked. The back off point confirmed that the string was stuck in the Brent but free in the Kimmeridge. Applying these data to the SPW (**Table 3**) clearly shows that the stuck pipe is related to a differential stuck pipe in the Brent. During the double survey all the conditions were in favour of a differential sticking : the tool was in front of a permeable reservoir probably with an overbalanced mud, pipe rotation was stopped during the double survey (15 minutes) while circulating (the downhole density inducing the differential sticking was not the static density but the ECD estimated at 1.8SG). Finally, the mud rheology was in bad condition (excessive mud filtrate, laboratory cake thickness equal to 7mm!). If one uses the stuck pipe model (assuming a friction coefficient equal to 0.3 and 8" drill collars stuck over 55m - 75% of the drilled Brent), for a 7 mm mud cake, the required overpull to unstick the BHA would have been approximately equal to 200 tons (**Fig. 10b**).

Proposed solutions. In case of potential differential sticking problems (permeable reservoirs, inaccurate knowledge of the pore pressure, high deviation), the duration of the non rotating periods (surveys, connection) have to be minimised. For instance in case of a MWD failure, a short rotation will be carried out between the two surveys.
As previously explained, and given the importance of the cake thickness, mud plays a strategic role in the differential sticking process. The mud will have to be properly conditioned before the beginning of the phase and the filtrate frequently controlled by the mud engineer. In case of unacceptable properties, part of the mud has to be dumped. An excessive mud filtrate can possibly be decreased by charging the mud with polymers. However, filtrate reducer an/or plugging agent (baracarb, barafiber) which can

efficiently stop mud losses play no real role on mud filtrate and reduction of cake thickness.
Finally, when preparing the drilling program, pore pressure is commonly assimilated to virgin pore pressure and does not take into account the depletion of nearby wells. A closer collaboration between reservoir engineers, geologists and drilling engineers with a shared risk in case of problems is also one of the key issues.

Conclusion

Three examples of Rock Mechanics related stuck pipes while drilling Extended Reach wells in the Dunbar field have been presented in this paper. The two first cases are obviously related to wellbore stability problems. In the underconsolidated Eocene clay the main source of instability is the under balanced situation between the pore pressure and the mud weight. Increasing the mud weight above the pore pressure solved the problem for the next wells and allowed to obtain a perfectly *"in gauge"* well. The second one is also due to wellbore instability but this time, well deviation plays a major role. Following the theoretical stability curve is here the key issue. When drilling above the critical mud weight, no more problems were observed.
Finally the third case is of a differential sticking origin and due to the conjugate association of a thick cake, a large differential pressure and a too long static time between two directional surveys. Better conditioning the mud and reducing the overbalanced mud weight alleviated the problem in future wells.
These three examples clearly show that Rock Mechanics plays a major role in stuck pipe problems particularly while drilling complex ERW. In the future, it should be fully integrated in Drilling Engineering practice.

Acknowledgements

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	Pack off		**Diff. sticking**		**Hole. geom.**	
Questions	1		2		3	
	Value	Score	Value	Score	Value	Score
Prior to sticking was the pipe						
Moving up	2		0		2	
Rotating up	0		0		2	
Moving down	1		0		2	
Rotating down	0		0		2	
Static	2		2		0	
After sticking was down motion?						
Free down	0		0		2	
Restricted down	2		0		2	
Impossible down	0		0		0	
After sticking was rotation?						
Free rotation	0		0		2	
Restricted rotation	2		0		2	
Impossible rotation	0		0		0	
After sticking was circulation?						
Free and unrestricted	0		2		2	
Restricted but possible	2		0		0	
Impossible	2		0		0	
Total points						

Table 1 - Stuck pipe worksheet (*after Ramsey and Robinson*)

Questions	1		2		3	
	Value	Score	Value	Score	Value	Score
Prior to sticking was the pipe						
Moving up	2	2	0	0	2	0
After sticking was down motion?						
Impossible down	0	0	0	0	0	0
After sticking was rotation?						
Impossible rotation	0	0	0	0	0	0
After sticking was circulation?						
Impossible	2	2	0	0	0	0
Total points		4		0		0

Table 2 - Stuck pipe worksheet (example 1)

Questions	1		2		3	
	Value	Score	Value	Score	Value	Score
Prior to sticking was the pipe						
Static	2	2	2	2	0	0
After sticking was down motion?						
Impossible down	0	0	0	0	0	0
After sticking was rotation?						
Impossible rotation	0		0		0	
After sticking was circulation?						
Free and unrestricted	0	0	2	2	2	2
Total points		2		4		2

Table 3 - Stuck pipe worksheet (example 3)

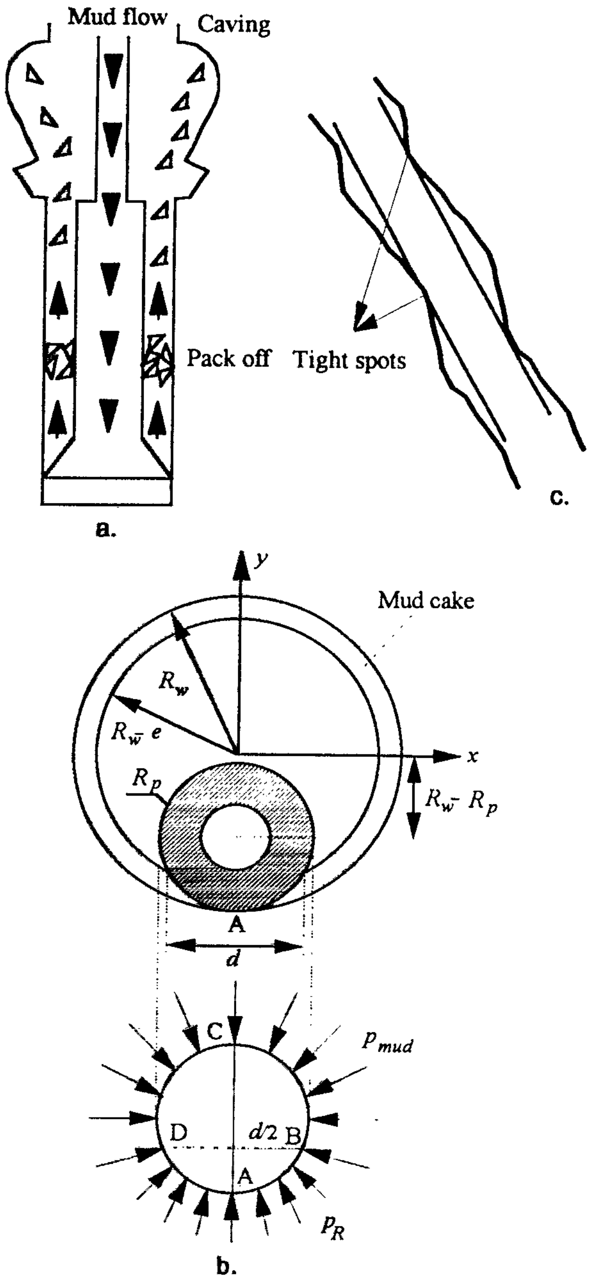


Fig. 1 - Three main origins of stuck pipes
a. Pack off following an upper well bore stability problem
b. Differential sticking
c. Hole geometry (severe dog legs)

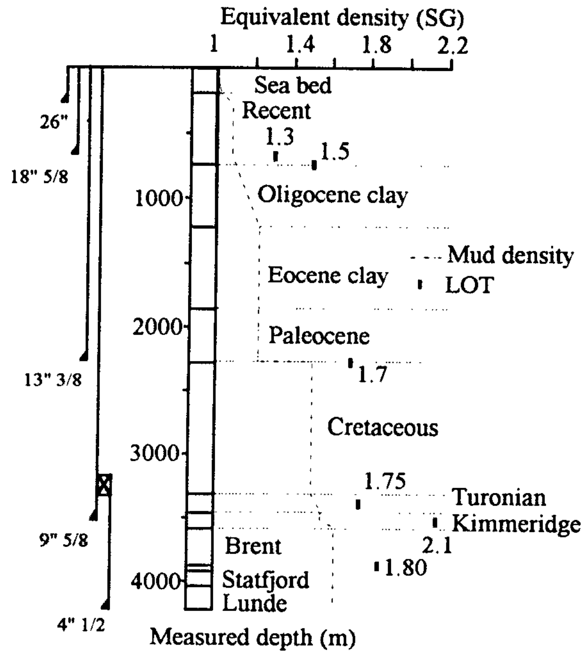
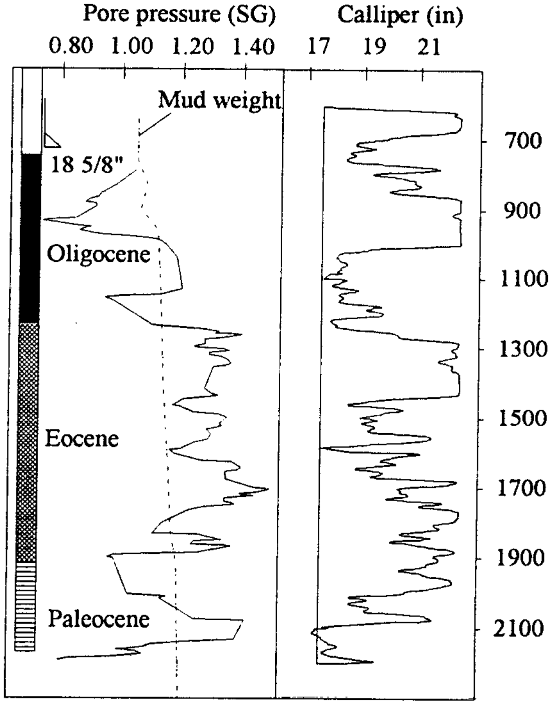
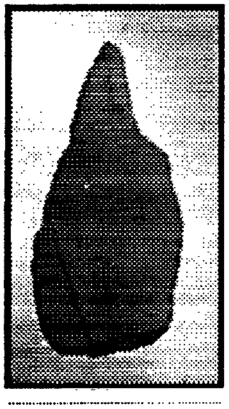


Fig. 2 The Dunbar field.
Typical stratigraphic column and casing points



a



5 cm

b

Fig. 3 Log analysis in 17 1/2" section
a. Calliper and sonic (Eaton's interpretation
b. Typical spalling caving from the Eocene

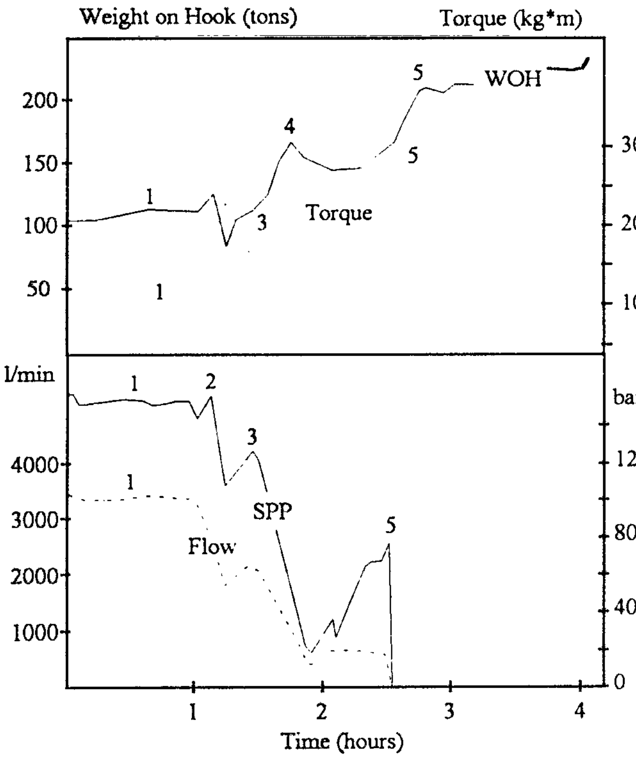


Fig. 4 - Example 1 : drilling parameters prior and during the stuck pipe

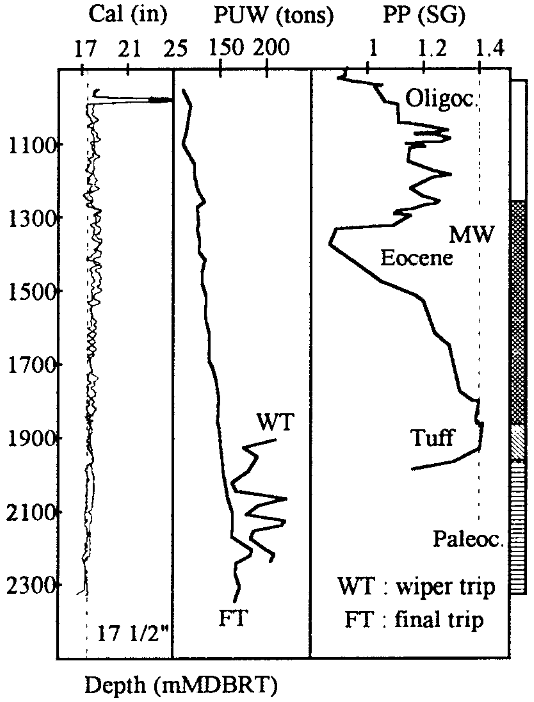


Fig. 5 - 4 arms calliper obtained after using 1.40SG silicate base mud

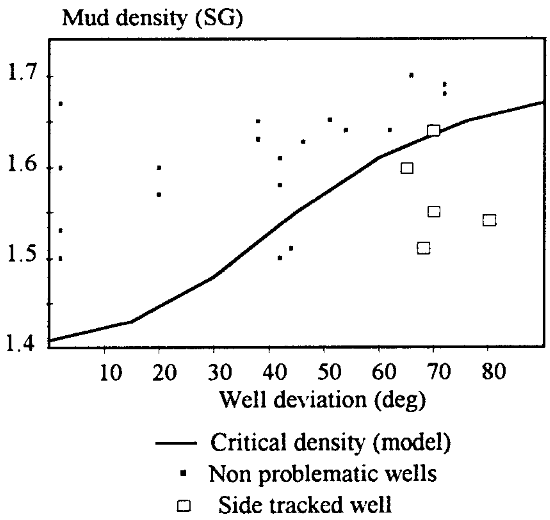
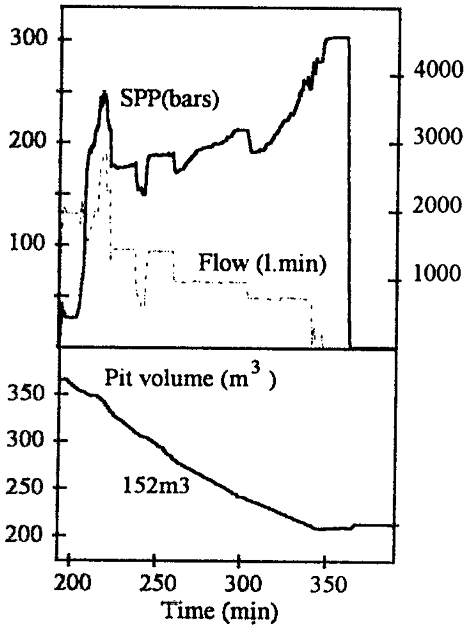
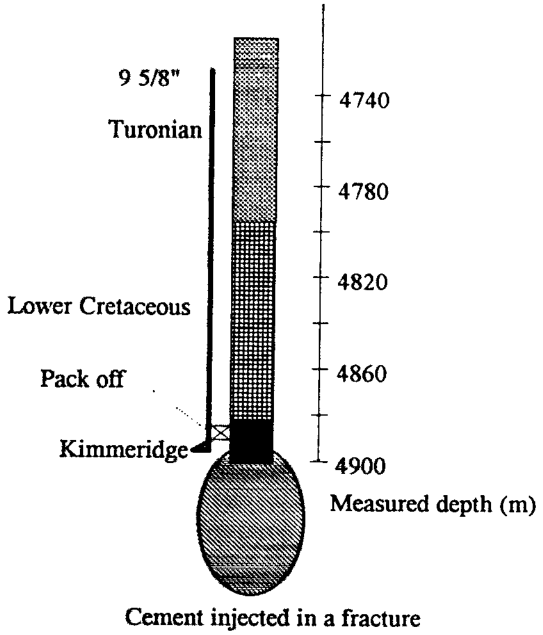


Fig 6 - Wellbore stability in Kimmeridge clay

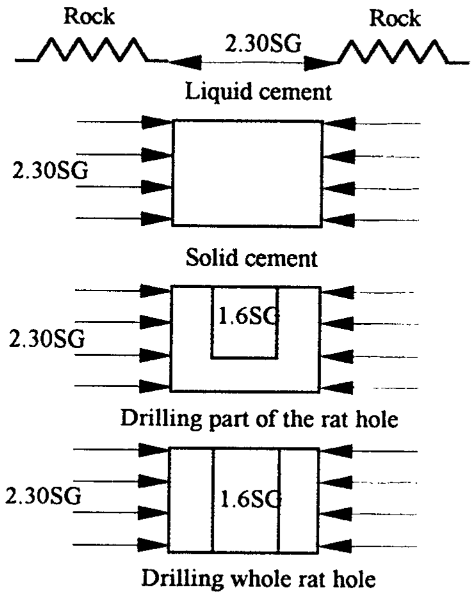


a.

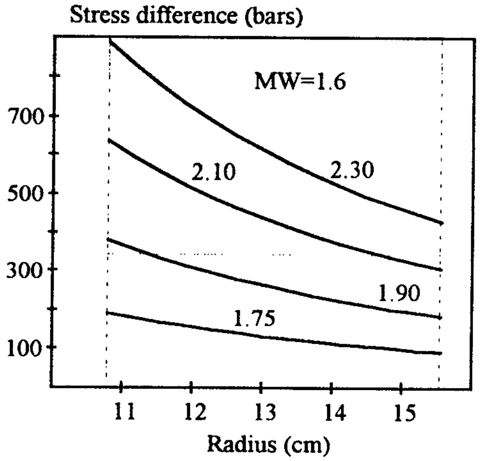


b.

Fig. 7 - Pack off in the Kimmeridge while cementing the 9 5/8 casing.
a. Drilling parameters
b Proposed mechanism



a.



b.

Fig. 8 Stuck pipe in the shoe track
a. Envisaged collapse mechanism
b. Mechanical stability of the cement shoe track

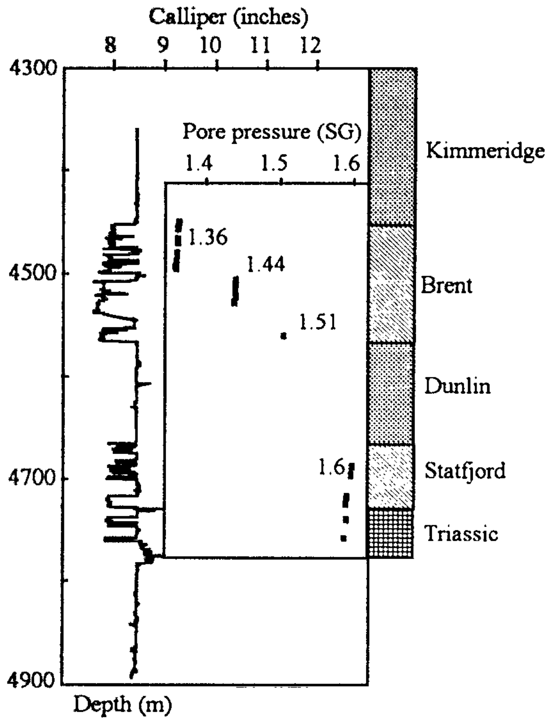


Fig 9 - Mud cake face to various depleted reservoirs

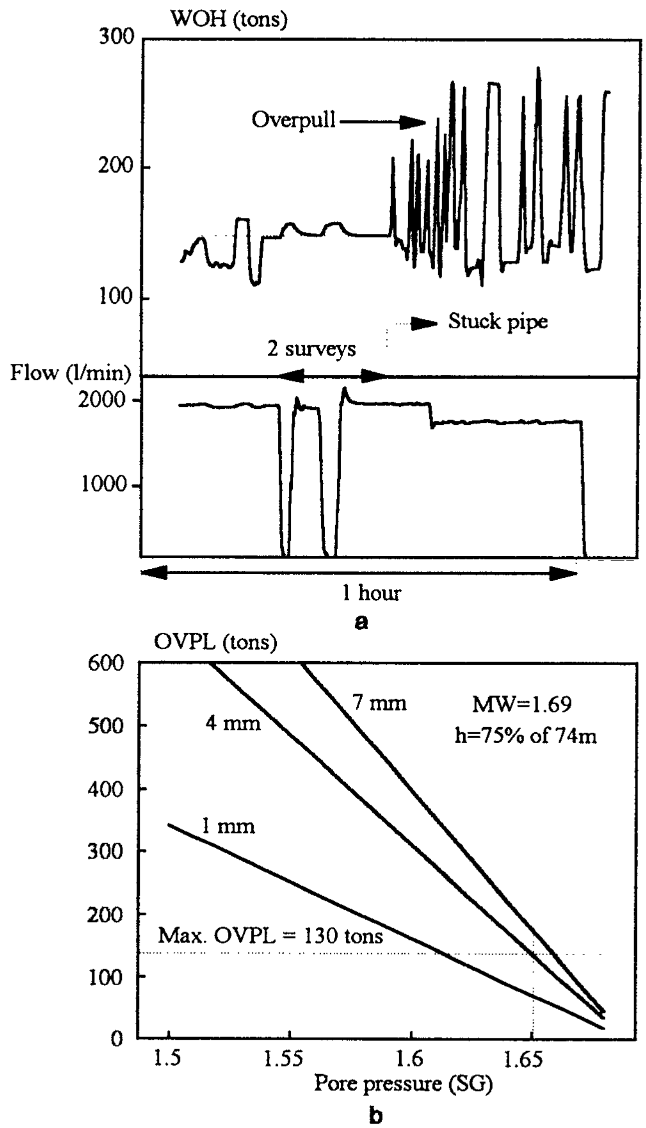


Fig. 10 Differential sticking in the Brent
a. Drilling parameters
b. Overpull required to unstick the string