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The Concept of Mud Weight Window Applied to Complex Drilling

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Abstract

This paper deals with the concept of Mud Weight Window (MWW). In the first part, the classical case of passive basin is studied. It is shown that both impermeable shales and permeable reservoirs require overbalanced conditions, in the first case for stability reasons in the second to avoid a kick. It is then quickly explained how to determine *MWW* from logs in tight shales where direct measurements are not possible.

In the second part, some special complex cases are studied : unfissured and fissured formations, depleted fields, Extended Reach Wells, tectonic areas, deep water and HP/HT wells. In each case the specific *MWW* generates special problems. Several examples are discussed and operational solutions are proposed.

The concept of mud weight window

Three fundamental parameters govern the value of the density while drilling : the maximum pore pressure (*p*) of the considered phase, the minimum fracturing pressure (*FP*) of the considered phase and the critical stability density (*CSD*) of each formation. The Mud Weight Window (*MWW*) is the density range between pore and fracturing pressures. The global wellbore problem is summarised on **Fig. 1**. Theoretically, the mud static density (p_w) will always have to be larger than the pore pressure (to avoid a kick) and the ECD (Equivalent Circulating Density including effects of rotation and reciprocation) smaller than the fracturating pressure (to avoid mud losses). In a homogeneous formation, and an anisotropic stress field (the horizontal stresses are noted σ_h and σ_H with $\sigma_H > \sigma_h$), the fracture (that is losses) is generally initiated parallel to σ_H and at a well pressure quite often close to σ_h. Roughly speaking, *FP* can be considered as the sum of the minimal component σ_h of the stress tensor and the tensile strength of the rock *T*. For most shales and claystones, *T* is generally low compared to σ_h. However, for hard sandstones and limestones, *T* is nolonger negligible with respect to σ_h.

The *CSD* is controlled by numerous parameters among which the most relevant are in situ-stresses, pore pressure and rock strength[1,2,3]. 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 (assuming $\sigma_H = \sigma_h$), the pore pressure *p* and the mud pressure p_w. Stability limit is reached when the global mechanical state overcomes the compressive 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. However, pore pressure 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.

Finally, in an anisotropic stress field ($\sigma_H > \sigma_h$), the stability limit is first reached in the σ_h direction. For this reason, borehole caliper is often a good tool to determine the azimuth of the horizontal stresses (well bore breakout is parallel to σ_h).

How to determine the MWW?

Determination of the mud weight window normally requires a good knowledge of *p* and σ_h versus depth. As previously explained, *p* and σ_h are also the main ingredients to be injected in wellbore stability models.

Pore pressure is the pressure prevailing in the rock porous space. It exists in all rocks but it can only be directly measured

in sufficiently permeable rocks using RFT or MDT wire line tools. There is currently no possibility to perform such measurements while drilling. However, RFT while drilling is under development and could be available in the near future.
By contrast, in impermeable rocks (essentially shales and claystones), there is no direct access to pore pressure. The latter can be indirectly deduced from mud logging data and/or wireline logs. For instance, it is well known that, the ROP is higher when pore pressure increases. ROP provides therefore a useful tool for detecting underconsolidated overpressured formations. Many methods combining drilling parameters (ROP, RPM, torque, WOB) have been proposed in the past. The well known *"d-exponent"*[4] remains today the most commonly used method for detecting qualitatively abnormal pore pressures. However, the method is only valid when using rock bits and not PDC bits.
Another approach is to deduce pore pressure from wireline or MWD logs (sonic, density or resistivity). Several methods have been proposed in the litterature but, basically, the philosophy is always similar : the logging data allow the calculation of a true shale porosity from which the pore pressure is deduced via the effective stress concept. The most well known is the Eaton's method[5] proposed 25 years ago and mainly calibrated in the GOM. It is today widely used everywhere in the world.

By contrast to the pore pressure, the fracturation pressure can be measured in any formation via XLOT (Extended Leak Off test) or minifrac. However, a XLOT[6] always provides the lowest fracturing pressure of the exposed open hole and does not represent a local measurement. There are also some possible logging interpretation of the sonic in terms of stress and fracturing pressure based on the use of Poisson's ratio. Finally, measurements on core can be used as stress indicators. Among these methods, ASR (Anelastic Strain Recovery), D.S.C.A. (Differential Strain Curve Analysis) and core discing are the most common[7,8,9].

To improve pore and fracturing pressure forecasts, some companies propose integrated methods combining all the different methods. For instance, the DrillWorks/PREDICT software[10] developed in the scope of DEA59 predicts pore pressures and fracturing gradients by using a large number of data among which pre-drill seismic data, wireline log data (including GR, ILD, DT, RHOB, Neutron, Porosity, Caliper), drilling data (including MW, total gas, gas peaks, torque, kicks), pressure data (including RFT, LOT, RFT, MDT) and geological data (statigraphic column). The purpose of this approach is to force all the data to be consistent with a more general field (basin) model. The reliability of such forecasts are improved with time when the database is fed by new data (for instance a new well or a new seismic campaign).
On **Fig. 2** are presented the results of a single well. Pore pressure and fracturing pressures obtained using the PREDICT software fit very well both with RFT pressure data and LOT data.

The general case

Passive basin. In the classical scheme of a passive virgin basin (vertical stress equal to the overburden, two horizontal stresses equal, undepleted reservoir), the MWW is always sufficiently large for the mud density to be easily adjusted. Two cases are of interest depending on the rock fabric.
In hard limestones or sandstones (**Fig. 1**), rock cohesion is generally sufficiently high to support underbalanced conditions both in drilling and production. However, this type of rock being quite often permeable, during the drilling phase, the mud weight will be adjusted to balance the pore pressure (**Fig. 3**). In flowing conditions, the well pressure will be below the pore pressure but the well will remain stable (such a drain can possibly be produced open hole without hole deterioration and subsequent solid production).
By contrast, in shales, the cohesion is always too small (very often close to zero) for the hole to be stable in underbalanced conditions (**Figs. 1 and 3**). For stability reasons (and no longer for kick reasons as in the case of hard permeable reservoirs), the well cannot be drilled in underbalanced conditions and in most cases (especially for high inclinations), to ensure stability, the mud weight has to be much higher than pore pressure. However due to their plastic behaviour, shales generally exhibit much higher leak off limits than sandstones.
As a summary, in a passive basin and a permeable hard reservoir, the mud weight is nearly always governed by kick considerations whereas in shales, the mud weight is preferently driven by stability considerations.

Case history. Below, we present an interesting case history showing the catastrophic impact of underbalanced conditions on wellbore stability in shales. From a geological viewpoint, this 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. A detailed analysis of available logs (**Fig. 4**) have showed that the Eocene was underconsolidated with a pore pressure in the range of 1.35 to 1.40. The conventional drilling practice consists of setting the 18"$^{5/8}$ casing in the base of Oligocene sands (approximately 680mTVD), of performing a shoe bond test (leak off limit between 1.30SG and 1.35SG) and drilling the 17"$^{1/2}$ section in underbalanced conditions using a WBM maximum density of 1.25SG. With such a mud strategy, the well is highly overgauged and very large amounts of cavings are observed at the shakers during the whole phase (**Fig. 5**). Following three remedial side tracks experienced over the last two years (pack off, stuck pipes), a new mud strategy was implemented. It consists of 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 has 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). 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 this new mud strategy provided a perfectly in gauge well but also excellent tripping conditions (**Fig. 6**).

Some interesting complex cases

Unfissured and fissured formations. In an unfissured formation, a fracture can be initiated if the well pressure exceeds the fracturing pressure (equal to σ_h+T and normally largely above the pore pressure). Above the *FP*, a hydraulic fracture opens, propagates and large mud losses are experienced. However, if the well pressure is pushed back below the fracturing pressure, the drilling fluid back flows to the well and losses normally stop. In such a case, rock tensile strength can play an important role. In claystones, the tensile strength is low and, the fracturing pressure is very similar before and after fracture initiation. By contrast, in hard rocks, the tensile strength which can be several tens of bars will be lost after fracturation has been initiated.
Such an interesting case is presented on **Fig. 7**. The $8"^{1/2}$ phase of the considered well has been characterised by severe losses when entering into the reservoir. Drilling was initiated with a static mud weight equal to 1.62SG, a flow rate approximately equal to 1950 l/min and a rotation speed of 200 RPM. The resulting ECD (estimates using a PWD) during this first phase was in the range of 1.82SG. At the end of the considered stand, two quick reciprocation cycles were performed. As pointed out on **Fig. 7**, the surge pressure resulting from the first cycle reaches in terms of ECD 1.87SG. After adding a stand, the circulation was resumed (2000 l/min) but the ECD instantaneously dropped to 1.72SG and large mud losses (1000 l/min) initiated. The flow rate was then reduced to 1500 l/min but the losses did not stop. During phase 3 (the flow was further reduced to 766 l/min), the ECD stabilised at 1.71 SG. According to the PWD results, the origin of the losses is easily explained by the very high surge pressure (1.87 SG) associated with the first reciprocation cycle. The latter exceeding the leak off limit in the reservoir, a hydraulic fracture initiates. Given the high brittleness of the rock, this first peak can be considered as a breakdown pressure. When the flow is resumed, the fracture propagates at a much lower value (reopening pressure). The difference between breakdown (1.87SG) and reopening pressures (1.72SG) is due to the rock tensile strength, lost after the first cycle.

By contrast, in a naturally fissured formation, fractures which are never perfectly flat are hydraulically open and can be naturally flowed providing the mud pressure is larger than the pressure of the fluid filling the fracture (**Fig. 8**). Consequently, in a naturally fissured formation, the losses are initiated just above the pore pressure and the MWW is restricted to practically zero. It is always necessary first to plug the fractures either with cement or some plugging agent before resuming drilling.
The case history presented below is a mixed example of fissured and depleted formation[11]. The parent well is a classical J-shape well designed with a $8^{1/2}$" section covered by a 7". While drilling the $8^{1/2}$" section, large mud losses (up to $10m^3$/hr) were experienced both in static (mud weight initially 1.65SG decreased to 1.61SG to reduce the losses) and dynamic conditions. A total of $400m^3$ were lost. Open hole RFT showed a pseudo-virgin state in the whole reservoir (pore pressures between 1.53SG to 1.56SG). The well was then suspended without being perforated. After five years suspension, the parent hole was re-entered, cleaned, perforated and temporarily completed to be tested. The results of a new set of RFT logs showed a high depletion level (between 1.19SG and 1.22SG) due to production of nearby wells.
The main problem encountered while drilling the kick-off and the beginning of the lateral drain was again large losses ($700m^3$ of OBM were lost) exactly at the same vertical depth as five years earlier (3724mTVDBRT). However, this time, losses were initiated at a much lower mud weight (static mud weight was equal to 1.32SG) and, reducing the mud weight from 1.32SG to 1.25SG did not solve the problem at all. Furthermore, when stopping the pumps, no back flow was observed. All these considerations are very consistent with mud injection in a natural fracture and not within an induced hydraulic fracture, losses being clearly controlled by the current pore pressure and not at all by the fracturing gradient. The two points A and B where the losses occurred both in the parent hole and the lateral drain (**Fig. 9**) allow us to consider line AB as the trace of the fracture plane. To definitively cure the losses, a special stinger was RIH and a hi-vis pill followed by a high concentration LCM pill ($300kg/m^3$) was squeezed in the leaking fracture. This operation was very successful and no more losses occurred thereafter.

Depleted field. Decreasing the pore pressure in a reservoir strongly affects the global mechanical state. For obvious equilibrium reasons, fracturing pressures decrease with depletion. Consequently, risk of massive losses through a hydraulic fracturing process strongly increases in depleted reservoirs. For instance, numerous stress measurements performed on Ekofisk[12] (mainly stress and core tests – **Fig. 10**) show that the ratio between stress variation and depletion have the same order of magnitude (0.8 in the case of Ekofisk, 1 in the case of Alwyn). As pointed out in Table 1[13], stress/depletion ratios are more generally in the range of 0.5 to 0.6. Consequently, the *MWW* of a depleted reservoir which is shifted to the left very often becomes incompatible with that of a close formation integrated in the same phase. For instance, an overlying shale (**Fig. 11**) requiring a high mud weight will have to be disconnected from an underlying depleted reservoir to avoid either a catastrophic instability in the shales (mud weight only compatible with current reservoir pressure in the reservoir) or massive losses in the depleted reservoir (mud weight compatible with the *CSD* in shales but larger than the *FP* in the depleted reservoir). This new situation (in a virgin state the two *MWW* overlap), will require either a heavier casing strategy (covering the shales before drilling the reservoir with a lower mud weight) or specific trajectories (for instance a S-shape trajectory with a drop off to vertical in the shale -low inclinations requires lower mud weight for shales to be stabilised).

Very often, sequences of depleted reservoirs, undepleted reservoirs and unstable interbeds can make further drilling difficult. On **Fig. 12** is presented the well profile and the casing strategy of an ERD (4km departure) crossing successively a shale level (Cretaceous), a highly depleted reservoir (the Statfjord has a current pore pressure equal to 0.43SG) then a sequence of high (up to 1.60SG) and low (1.06SG) pressures in the Triassic reservoir. Given the very low value of the leak off in the depleted Stafjord, it is not possible to drill both reservoirs in a single phase. Consequently, the Cretaceous (shales) and the Statfjord are drilled with a 1.40SG mud weight but, to avoid differential sticking problems in the depleted Statfjord (see example below), the inclination is dropped off from 70° to 40° in the Stafjord. The $9"^{5/8}$ casing is set just at the top Triassic which is drilled in a single section with a 1.60 to 1.65SG mud weight.

Apart from losses, an overly high mud weight across a highly depleted reservoir strongly increase risks of differential sticking. Such problems in a highly depleted reservoir have been recently experienced in the Dunbar field (North Sea). To overbalance the virgin reservoir pressure in the Brent (1.65SG), the first wells were drilled with with a mud (oil based) 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 highest pore pressure, the Brent being generally drilled in highly overbalanced conditions. On the example shown on **Fig. 13**, 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 against 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). Bad control of the mud filtrate plays a major role on the cake building process.

In such a context, a stuck pipe has been experienced while drilling the top Brent of a highly deviated Dunbar well (72°). After completing the drilling of a stand, 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. During the double survey all the conditions were in favour of differential sticking: the tool was across a permeable reservoir with a highly overbalanced mud and pipe rotation was stopped during 15 minutes. Finally, the mud rheology was in bad condition (excessive mud filtrate, laboratory cake thickness equal to 7mm!).

In the 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) has to be minimised. For instance in case of a MWD failure, a short rotation should 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 disposed. 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 assumed to be virgin 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.

Extended Reach Drilling

Limitation and control of downhole ECD is one of the major problem while drilling and cementing ERDs. Even if the *MWW* is wide and, even if in static conditions the mud density is far from the leak off limit, when circulating and rotating at 200RPM, the total ECD can exceed more than 0.20SG above the static density and initiate mud losses. As already mentioned, the initiation of a hydraulic fracture can become a tremendous problem in high cohesion rocks where after fracturing, the tensile strength of the rock is definitively lost. A reliable calculation of ECDs when planning the well using temperature dependent models and care ful real time control of the ECD using a PWD sub can be of a great help to monitor ECD. In ERD wells, it is highly recommended to design the drill string according to a detailed hydraulic study and not only taking into account T&D consideration. It is particularly advised to avoid turbulent flow in the annulus by using reduced tool joints (for instance avoid too many $5"^{1/2}$ with $7"^{1/2}$ tool joints in a $8"^{1/2}$ well), to find a compromise between ECDs and hole cleaning, to avoid cumulated sources of ECD (for instance stop rotating when performing small trips at connection) and to adapt mud rheology.

Tectonic area.

Unlike passive basins, tectonic regions are characterised by a strongly anisotropic horizontal stress field (maximum horizontal stress very high and minimum horizontal stress quite low) and a vertical component which becomes intermediate (instead of major). Typically, stresses are in a ratio such that σ_h=0.65/σ_v=1/σ_H=1.4. Such values obviously have drastic consequences on the *MWW* : a situation in which the leak-off limit is lower than the *CSD* prevails. In other words, it is usually not possible in such a region to guarantee well stability by increasing the mud weight (the well would have to be drilled with total losses). However, a good choice of well azimuth and well inclination can strongly reduce instability problems

Located in the foothills of the Colombian Andin Cordilliera[14], the Cusianan field is a typical example of such a tectonic environment. The regional tectonics which trends NW-SE is mainly due to the subduction of the Pacific ocean plate under the South American continent. The direction of the tectonic thrust is well confirmed by wellbore ovalisation (**Fig. 14**) systematically aligned NE-SW. In addition to the main tectonic thrust, the area is characterised by large thrust faults and a dip lying SE-NW (**Fig. 15**). As the hydrocarbons are trapped in the central block, it is necessary to cross the Yopal fault before reaching the target. Numerical simulations of the whole structure show that in the superficial part of the Yopal block, the major stress remains pseudo-horizontal and parallel to the tectonic thrust whereas at a certain distance from the fault, a strong rotation of the principal stresses is observed[15] (it becomes perpendicular to the Yopal fault). To *"avoid"* the major stress, it is therefore necessary to cross the fault using an updip trajectory.

Fig. 16 shows results in terms of drilling performance[16]. Each well, located on the graph according to azimuth and mean deviation, is characterised by a vertical bar proportional to the number of unproductive hours. Depending on whether the well is deviated updip or crossdip and downdip, good or poor performances are systematically experienced. In a highly tectonic region, the dip of the layers and the orientation of the faults play a role which is at least as important as the tectonic thrust. As a conclusion, even if it is not always the optimised solution, drilling perpendicularly to the layers (updip quadrant) and more or less parallel to the tectonic thrust is probably the least risky strategy.

Deep water

Deep water is another complex case requiring a special monitoring of the mud weight in a narrow *MWW* particularly in surface formations just below the see bed. To better understand the process, we have compared on **Fig. 17**, similar pore and fracturing gradients for 200m and 1400m of water thickness. It is obvious that for the deep water case, the *"small opening"* of the window at 1400m makes very difficult mud weigh adjustment between the two bounds. This is mainly due to the mud column located in the riser : in a potential kick situation, one can be easily pushed to a losses situation with only a small variation of the mud weight. Apart from a good knowledge of the *MWW* and a care monitoring of the ECD using a real time PWD, the common technique in deep water wells is to multiply the casing points. An example issued from GOM is presented on **Fig. 18**. The water depth is 1206m. Just under the sea bed, the pore pressure quickly increases whereas the fracturing pressure remains moderate. For instance at 1500m, the MWW is less than 0.1SG. Consequently, a very heavy casing program has to be implemented (36" at 1292m, 26" at 1498m, 20" à 1805m, 16" at 2118m and 13"5/8 at 2480m). It can also be observed that the pre-estimated *FP* overestimates the *LOT* limit.

HP/HT well

Like deep water wells, HP/HT wells always exhibit very narrow *MWW*. HP/HT wells generally result from deep and quick sedimentation where high pore pressures are trapped in underconsolidated shales. All the problems already discussed can be experienced in HP/HT wells : wellbore instabilities, kick, losses. Predicting and monitoring precisely the downhole pressure appears particularly important. Some quite sophisticated hydraulic models[17] taking into account the effect of pressure and temperature both in static and circulating conditions are of course absolutely necessary. By contrast, the high pressure combined with the high temperature very often preclude the use of PWD tools.

Conclusion

For classical passive undepleted bassin, fracturing pressure is always much larger than pore pressure and Critical Stability Density is contained between the two bounds. Consequently, the mud density is easily monitored above *CSD* without any risk of kick, mud losses and catastrophic well bore instabilities. In hard permeable layers, the mud weight will be governed by kick considerations (mud weight just overbalanced) whereas in soft impermeable shales mud weight will be preferentially driven by stability considerations. For high inclinations, the required mud weight to stabilise unstable shales can be much higher than the pore pressure.

However, numerous cases are exceptions to this rule. In depleted reservoirs pore and fracturing pressures are strongly reduced with respect to their virgin values. Sequences of depleted and undepleted layers necessitates very often special heavy casing programs and specific trajectories.

In naturally fractured reservoirs, fractures are mechanically closed but hydraulically opened. In that case, kick and losses are observed nearly at a same value close to the pore pressure. The *MWW* is nearly nil and only the plugging of the natural fractures allows to resume drilling.

In tectonic regions the *CSD* is always much higher than the fracturing pressure. Well stability cannot be ensured but, stability problems can be improved by controlling the well trajectory with respect to dip and in situ stresses. Finally, in deep water wells and HP/HT fields, pore pressure can be very close to fracturing pressure which often imposes very heavy casing programs.

All these special cases require a good knowledge of pore pressure, *CSD* and fracturing pressure of all the drilled formations. The use of new *"integrated"* softwares mixing wireline and LWD logs, LOT, stress tests, mud logging data, rock mechanical properties and even large scale basin modelling will certainly be of a great help for the future. On the other hand, it is of major importance to monitor precisely down hole mud pressure (in static and dynamic conditions). For these reasons, the use of advanced ECD softwares (coupled with pressure and temperature, integrating rotation effects, swab and surge) for preparing well program and real time down hole pressure monitoring with PWD have become a general practice over the last three years.

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Nomenclature

MWW	Mud Weight Window
σ_h	minimum horizontal stress
σ_H	maximum horizontal stress
FP	fracturing pressure
p	pore pressure
CSD	critical stability density
p_w	mud weight
φ	friction angle
c	rock cohesion

Field	$\Delta\sigma/\Delta p$
Ekofisk	0.8
Magnus	0.68
Venture	0.56
Waskom	0.57
West texas	0.53
Wytch Farm	0.55
Basin	$\Delta\sigma/\Delta p$
Gulf coast	0.46
Lake Maracaibo	0.56
Brunei	0.486

Table 1 Minimum stress pore pressure relation. (after Addis et al, 1996)

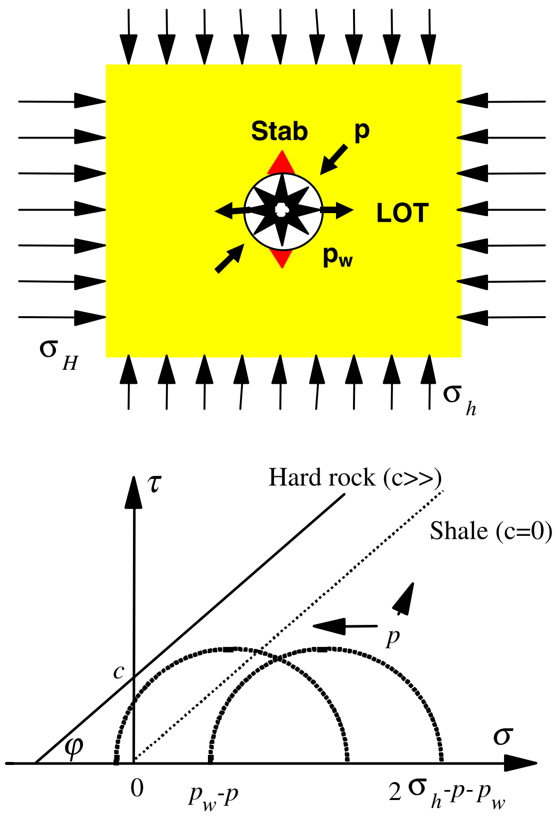

Fig. 1 The wellbore stability problem

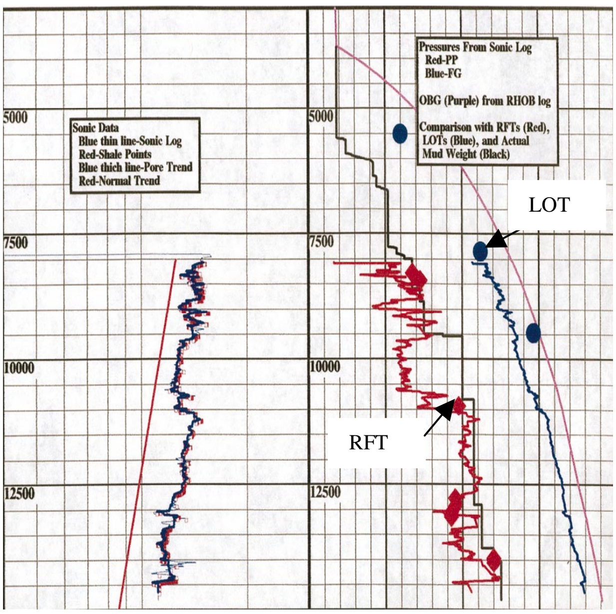

Fig. 2 Example of MWW issued from the software Drillworks/PREDICT

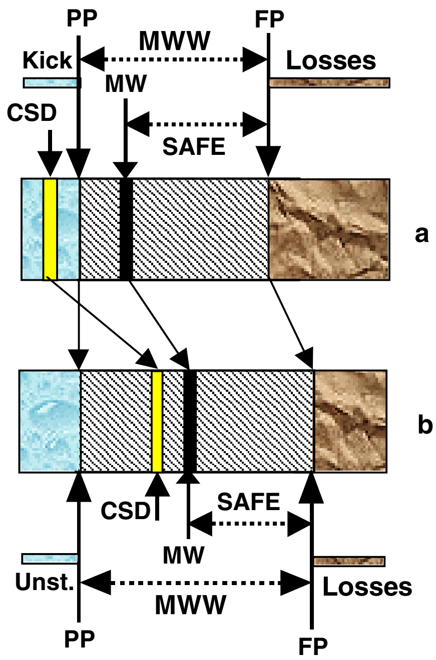

Fig. 3 Comparaison of MWW in a passive basin
a. Hard reservoir : stability limit smaller than pore pressure
b. Unstable shale : stability limit higher than pore pressure

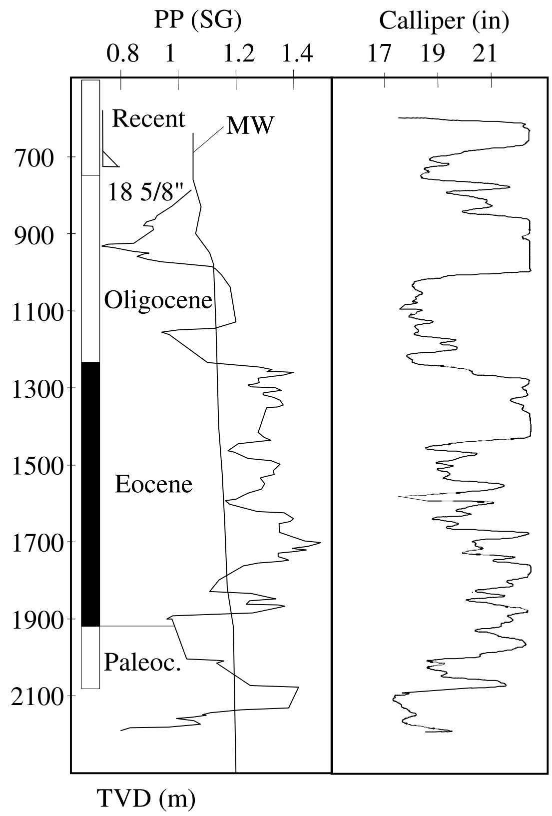

Fig. 4 Example of highly unstable shales when drilled in underbalanced conditions

Fig. 5 Large amounts of cavings following underbalanced conditions in highly unstable shales

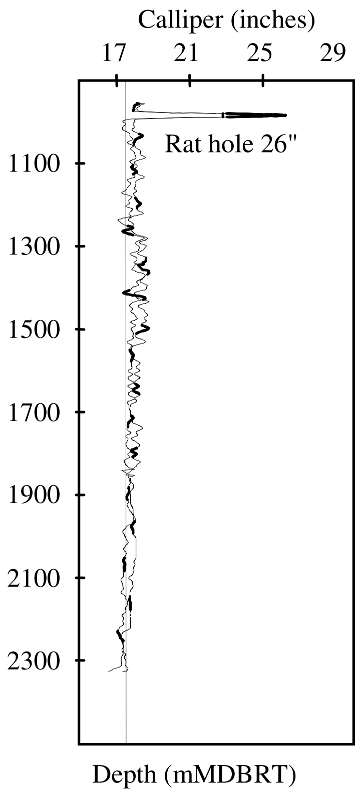

Fig. 6 - In-gauge well according to the new overbalanced mud weight strategy.

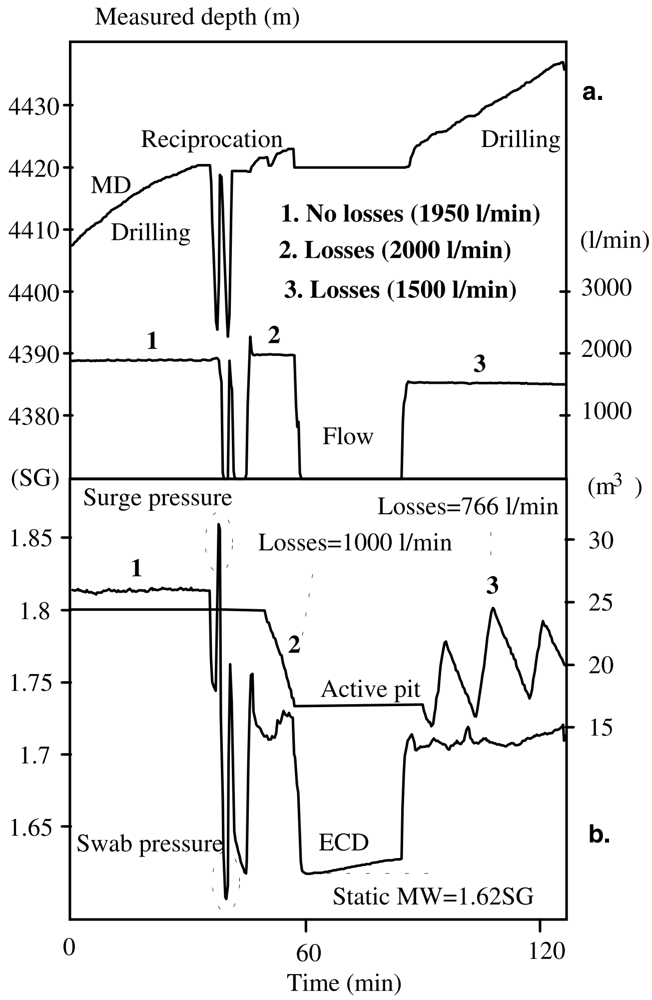

Fig. 7 Losses in an induced fracture following a surge peak

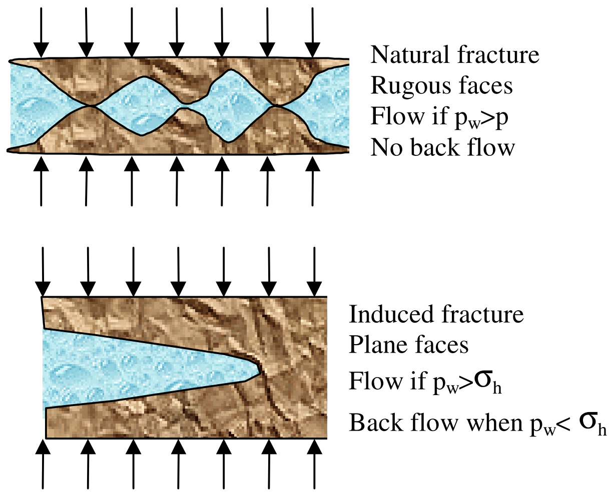

Fig. 8 - Comparaison between a natural (a) and an induced fracture (b)

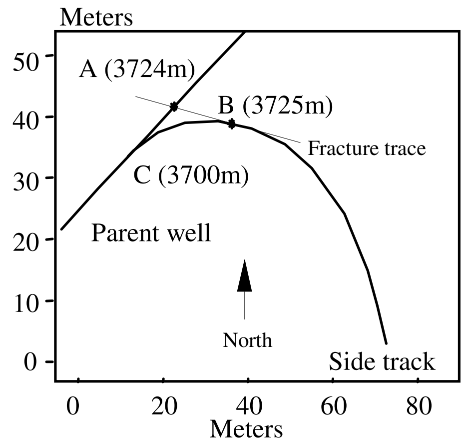

Fig. 9 - Losses in a natural fracture crossing both the parent hole and the re-entry.

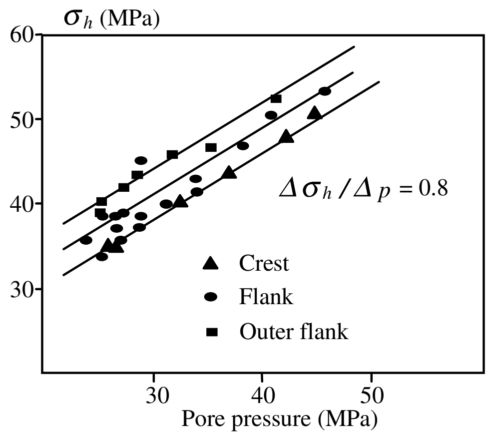

Fig. 10 - Strong dependence between pore pressure and minimal stress on the Ekofisk field (according to Teufel and al, 1991)

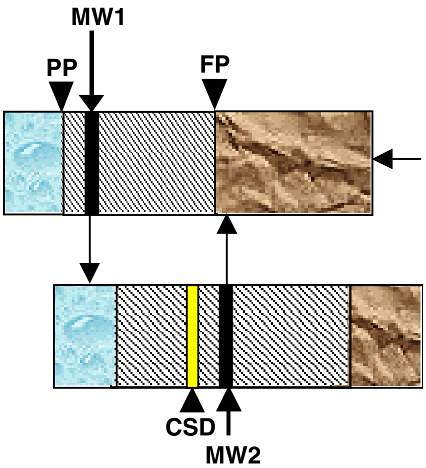

Fig. 11 Incompatibility between an unstable shale and a depleted reservoir.

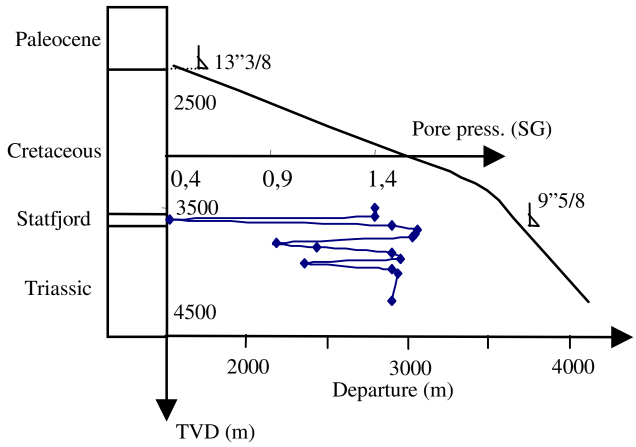

Fig. 12 Special casing design and trajectory when coupling depleted and undepleted reservoirs (Alwyn field - North Sea)

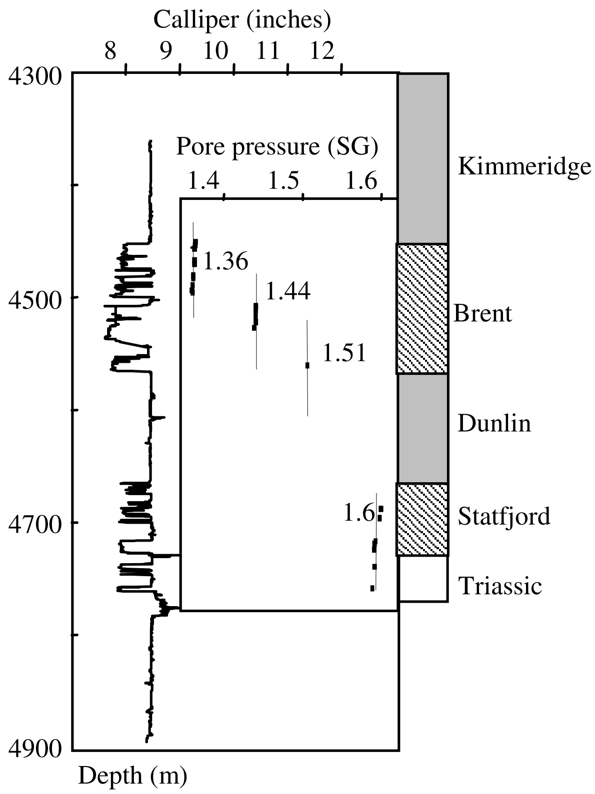

Fig. 13 Differential sticking and cake thickness face to a sucession of depleted and undepleted reservoirs

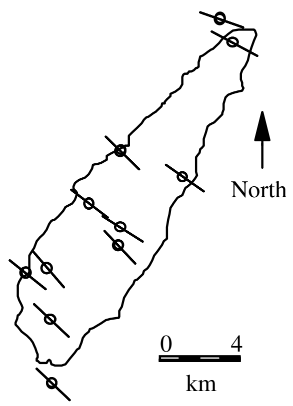

Fig. 14 Well ovalisation and direction of tectonic thrust in the Cusiana field

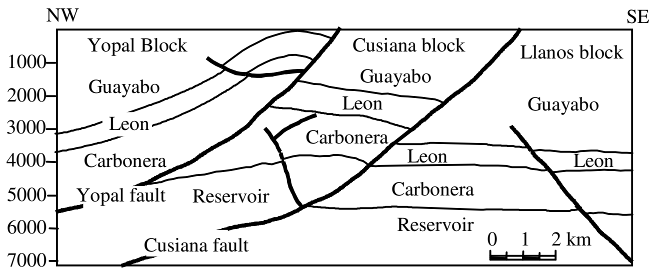

Fig. 15 Geological NW-SE cross section of the Cusiana field

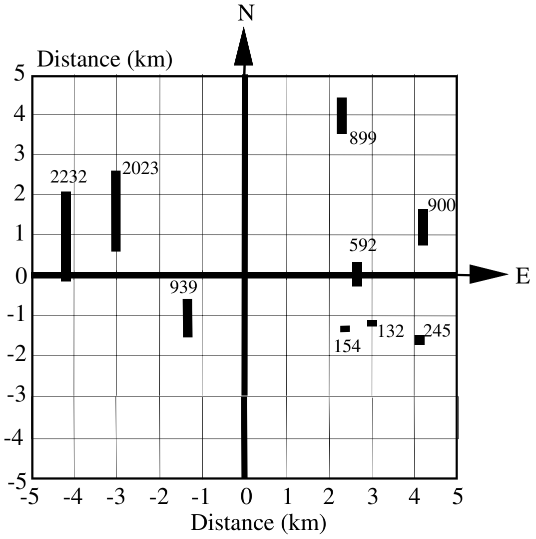

Fig. 16 Drilling performances depending on well trajectory

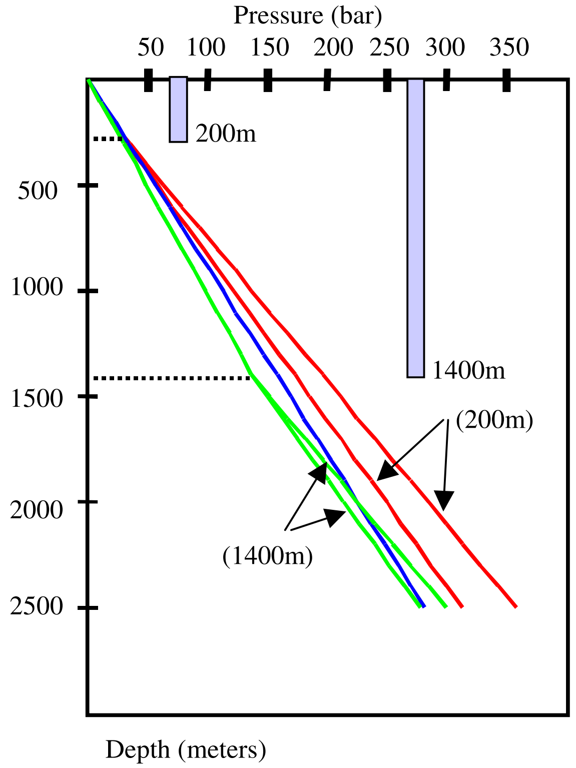

Fig. 17 Mud weight window in the case of a deep water well

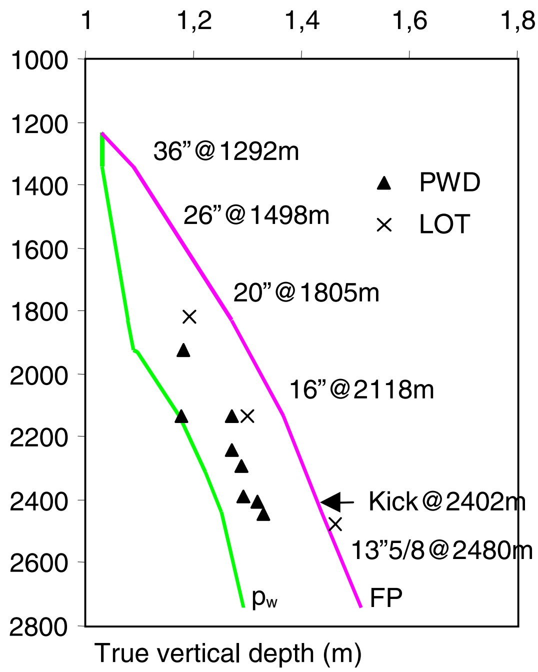

Fig. 18 Example of MWW of a deep water Well in the Golf of Mexico