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Analysis of wellbore instability in vertical, directional, and horizontal wells using field data

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Abstract

An old offshore field produced using vertical and directional wells is being redeveloped by drilling horizontal wells. The experience gained while drilling vertical and directional wells is not useful for drilling horizontal wells, as the failure rate is 1 in 3 holes. Quantification of drilling problems in sixty wells show that majority are tight holes. Stuck pipes and hole pack offs are also significant in number. The major loss of productivity is due to stuck pipes. A preliminary study of shale in sections where problems occur, show no chemical reactivity. Petrographic analysis confirmed the fissile and brittle nature of shale with presence of open, partially healed microfractures and partings. Rock mechanical simulation predicted the safe mud weight window for horizontal wells as 76–90 PCF, depending on azimuth. However, all the horizontal wells analyzed in this study were drilled using the same mud weight window. Therefore, field based parameters like initial mud weight used for drilling, mud weight increment and problems per well were used to analyze wellbore instability, identify different instability mechanisms and design safe mud weight window for drilling horizontal wells. These parameters were used first on the drilling data of vertical wells to develop the procedure for the analysis of wellbore instability and identify the mechanisms of instability. The developed procedure was then applied to the drilling data of directional wells to show the dependence of mud weight on the inclination and azimuth of the well. Finally, the procedure was applied to horizontal wells data along with the concept of critical washouts to infer the safe mud weight window as 77–80 PCF in East–West and 82–85 PCF in North–South directions. The safe mud weight window is validated on another set of drilling data showing 90% success rate. The analysis confirms the existence of anisotropy in horizontal stresses and is extremely useful in cases where there is significant variation in mechanical properties of different layers of reservoir rock.

Keywords: Wellbore instability; Drilling data analysis; Wellbore wall stabilization; Differential sticking; Mud invasion; Pore pressure penetration

1. Introduction

Wellbore instability manifests itself in different ways like hole pack off, excessive reaming, overpull, torque and drag, sometimes leading to stuck pipe that may require plugging and side tracking. This requires additional time to drill a hole, driving up the cost of reservoir development significantly. In case of offshore fields, loss of hole is more critical due to a limited number of holes that can be drilled from a platform.

Drilling an ingauge hole is an interplay of two factors: uncontrollable and controllable. Uncontrollable

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factors are the earth stresses (horizontal and vertical), pore pressure, rock strength and rock chemistry. Controllable factors include mud weight, wellbore azimuth and inclination. A proper drilling program optimizes the controllable factors with the knowledge of uncontrollable factors. The controllable factors are heavily dependent on rock mechanical behavior of rock. For example, it is well known in the rock mechanics literature that the change in mud weight with the angle of inclination depends on the in-situ stresses, if the rock anisotropy is negligible. If a normal stress regime is present, then the horizontal wells are more susceptible to instabilities and hence the most difficult to drill. The mud weight control plays a crucial role in instability management with the angle of inclination. Unfortunately, drillers traditionally depend on empirically derived “Rules of Thumb” rather than rock mechanic principles of rock stability and failure in designing mud weight.

1.1. Literature review

Design of wells using principles of rock mechanics is well reported in the literature (Wong et al., 1994; Morita and Whitebay, 1994). A case study of designing a horizontal well in Vlieland sand in the Dutch sector of North Sea is reported by Fuh et al. (1991). The rock mechanical parameters such as in-situ stresses, strength and pore pressure of the Vlieland sand and shale which overlies it were computed from the back analysis of drilling problems from previous eight vertical wells drilled in the area. A mud program was designed using these estimated parameters and a horizontal hole was drilled with few manageable instances of instability.

Drilling of overburden shales in offshore Nigeria resulted in several problems of stuck pipes and sidetracks. A detailed rock mechanics study was conducted to characterize the state of in-situ stress, rock strength, and formation pore pressure. These parameters were used to perform a geomechanical simulation and estimate safe mud weights. Use of these mud weights led to a marked improvement in wellbore stability (Lowrey and Ottesen, 1995).

Four wells drilled in Gulf of Suez and Mediterranean Sea, offshore Egypt, were analyzed for wellbore instability, to improve drilling performance in future wells (Hassan et al., 1999). A suite of logs, including DSI sonic, GR, and density were used as input to IMPACT-ELAN of Geoframe to predict rock strength, petrophysical properties, and safe mud weight windows. The weak shales in the overburden were failing due to inadequate wall support inspite of using oil based mud (OBM). The simulation predicted higher mud weight for adequate wall support. Use of predicted higher mud weights during drilling improved the hole condition and related instabilities. Therefore, OBM used of to drill shaly sections should be checked for correct mud weight.

Saidin and Smith (2000) discussed wellbore instability encountered when drilling through the Terengganu shale (K-shale), Bekok field, Malaysia. Due to the time dependency of the observed instability cases, K-shale was thought of as reactive and unstable due to shale–fluid interaction. Invert emulsion OBM was used to drill the wells. This, however, resulted in severe formation damage without any improvement in stability. Rock characterization and laboratory measurements of rock-mechanical properties indicated that K-shales had predominantly non-reactive weak clay. This information helped in improving the design of mud weight window leading to successful completion of a new well. To minimize differential sticking due to high mud weights, invert emulsion SBM was used.

In many cases, factors like magnitude of the maximum horizontal in-situ stress and variations in rock strength are not well known. These parameters are estimated using empirical or semi-empirical approaches. Under such circumstances, the safe mud weight window predicted using geomechanical simulation is often not realistic. For such cases, drilling data accumulated from previous problematic wells can be used to predict safe mud weight window. A brief review of studies using the above mentioned approach is given in the following paragraphs.

Santarelli et al. (1996) presented wellbore instability problems occurring in a developed field in Italy. The problems were back analyzed with respect to the mud types, mud weights, azimuths, and stress regime. More drilling problems like reaming and stuck pipe occurred in a particular azimuth. This proved the existence of anisotropic distribution of horizontal stresses, which was not known because of absence of any in-situ stress related data. The non-inhibitive water based mud gave better results compared to other mud system. In the light of new data, drilling practices which were planned during appraisal drilling phase were continued with necessary modifications.

Santarelli et al. (1992) presented a case study of drilling in highly fractured volcanic rocks at great depths. Use of OBM did not solve the problem since the instability was not due to clay. Analysis of the clay in those rocks showed that they were non-reactive. It was found that the main mechanism of instability was mud penetration in fractures which led to eventual erosion of the wellbore wall due to inadequate wall support. Appropriate mud weight was designed by simulating the fractured rock mass using discrete element modeling. Use of the new mud weight, lower than that being used, along with proper fracture plugging material in WBM proved successful. Classical method of solving the instability by increasing mud weight could have aggravated the problem.

In general, wellbore instability is caused by a combination of different reasons or presence of more than one mechanisms of instability. Wells drilled in complex geological areas encounter many layers of rock having different properties. Some layers could be weak, while others brittle, fractured, chemically reactive or rubble. There is no simple solution for wellbore instability in such cases. A collapsing weak layer needs high mud weight for stability, but increasing the mud weight could excite instability in fractured layers by mud invasion. Therefore, such cases require careful rock characterization and mud weight optimization.

In the past, fields were developed using vertical wells which did not exhibit any drilling trouble. The trend nowadays is to drill horizontal wells to enhance productivity. The experience of drilling vertical wells is carried forward without appropriate modifications to drill the horizontal wells resulting in wellbore instabilities.

Severe instability was encountered while drilling horizontal drains in Hamlah-Gulailah Formation, ABK field, offshore Abu Dhabi, though vertical wells were drilled without encountering any significant problem. To analyze the instability problem, a comprehensive rock mechanical study was carried out to characterize rock strength and in-situ horizontal stresses. The study suggested that the horizontal stresses were anisotropic in nature with strike–slip–thrust stress regime. The rocks were weak and fissured. The rock mechanical simulation predicted higher mud weights than those actually used in the field (Onaisi et al., 2000).

Al-Buraik and Pasnak (1993) discussed well plans, drilling fluids, casing and cementing liners, coring, logging, completions, and drilling problems encountered in more than a dozen horizontal wells drilled both in sandstone and carbonate reservoirs in Saudi Arabia. The wellbore, in sandstone reservoirs, passed through shale and shale–sand stringers before reaching TD (target depth). Because of the consolidated nature of the sand, these wells are completed with 7″ LNRs (liners). Three wells suffered from major wellbore instability problems such as borehole collapse leading to stuck pipe. The collapse due to the mechanical instability of shale was aggravated due to extended exposure time. Some of the shale layers needed a minimum mud weight of 92 PCF (12.3 PPG) in order to keep the borehole open. Several stuck liners and casings were experienced in holes drilled with motor. This problem was partially solved by reaming the motored hole with stiff, non-drilling reaming assembly before running the liner or casing.

Ezzat (1993) discussed different laboratory tests performed for suitable mud design for drilling Khafji and other reservoirs in Saudi Arabia. The petrophysical examination of Khafji cores revealed that the formation was basically sandstone with shale stringers, shaly sand, coal/lignite/amber (plant remains and fossilized tree resins) and iron rich shale/sand near the top of the reservoir. The shale was characterized as water-sensitive with kaolinite up to 49 wt.%, chlorite up to 19 wt.%, and mixed layer illite/montmorillonite up to 13 wt.%. This unstable shale caved in, if proper mud weight was not used during drilling. In some instances mud weights greater than formation fracture pressure had to be used to keep the hole open. Use of oil-based mud resulted in reduction of wellbore instability cases. Among the reasons that caused mechanical instability were erosion of unconsolidated sand, gas cut mud and hole fill after trip, pipe whip and drillstring sticking. Appropriate actions were taken to solve these problems.

Thus several studies have been conducted to design safe mud weight window using field drilling data. In this paper, wellbore instability as a function of shale–mud interaction, rock mechanical simulation, safe mud weight prediction, and analysis of drilling data has been studied. This paper proposes new parameters not used so far to develop a method of wellbore instability analysis and calculation of safe mud weight window. This method of analysis is very useful when in-situ stress data and rock strength data are not available or where there is significant variation in rock properties through different formation layers.

1.2. Reservoir geology and drilling experience

The field under study can be divided into three main lithological sequences. The upper part has predominantly shale with coal and sand stringers. The middle part has clean sand and the lower part has sand and shale stringers. The target zone for the development wells has clean sand. The trajectories of these wells in shale–coal–sand stringers of the upper zone are highly deviated and long. Since longer deviated trajectories have to be drilled, it takes more time to drill, giving rise to delayed problems like tight hole, hole pack off, and irremedial stuck pipe which require side tracking.

The initial development of the field was done by drilling vertical and directional wells. Drilling problems like tight holes, high torque and drag were common but manageable. Later, during infill drilling, highly deviated and horizontal wells were drilled. The drilling problems became severe leading to stuck pipes. Some of the holes had to be side tracked.

1.3. Characterization of borehole instability

Drilling data of sixty wells from the field was analyzed in this study. There were nine vertical, fifteen directional and the rest horizontal wells. As shown in Fig. 1, the compiled data of instability instances from the daily drilling reports (DDR's) show that tight-holes represent the majority of instability instances (65%), followed distantly by stuck pipe (13%) and hole pack-off (8%). Fig. 2 shows that 80% of these problems occurred during hole control. Typically hole control problems occur before or during the placement of casing, therefore they are time delayed.

The type of drilling problems indicate that the hole size is decreasing with time. This can happen due to many reasons such as presence of mobile formations, hydration of shales, presence of cavings and cuttings, and mud cake. A shale characterization study, described in the next section, was conducted to check if shale swelling is leading to tight hole and stuck pipe situations. Geomechanical simulation was also conducted to predict the safe mud weights. However, the range of mud weights predicted by goemechanical simulation was not compatible with field observations. The deficiency was mainly due to lack of enough rock mechanical data.

In view of the above, the huge amount of field data — from geology to DDR's was used to study the instability mechanisms and safe mud weights. This technique proved successful and was validated. It is described below after a brief account of shale and geomechanical simulation studies.

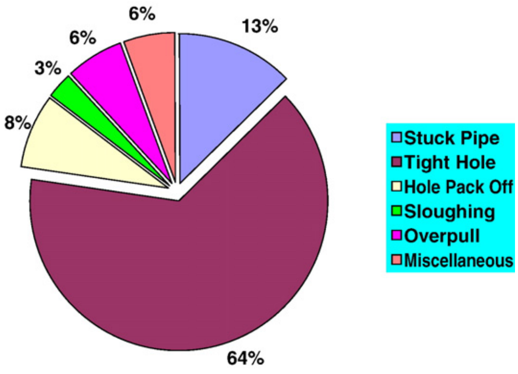

Fig. 1. Occurrence of wellbore instability problems.

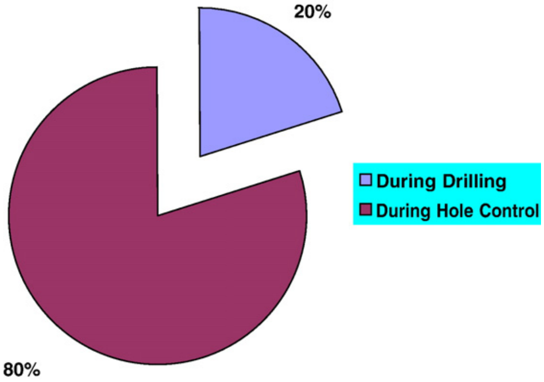

Fig. 2. Problems during drilling and hole control phases.

2. Shale study

The study of open hole logs showed large washouts at shale sections. There can be two reasons for these washouts, chemical and mechanical. Reactive shales can interact with water and fail leading to washouts. To check this, two pieces of shale were soaked for 3 weeks in two brine solutions, each having different salinity (1 K and 250 K ppm). No significant change was observed in both the samples indicating absence of chemical reactivity in the shale.

The shale samples were highly laminated with thin bedding planes. Core plugs perpendicular to the bedding planes could not be drilled because the shale sample disintegrated into flakes during drilling. However, few plugs could be cut parallel to bedding planes. The plugs were fissile, brittle and were black in color, indicating presence of organic material. They were highly heterogeneous with alternating layers of silt, sand, shale and organic matter. Coal seams and amber were visible to the naked eye whereas salt crystals were also visible under microscopic examination. The formation brine perhaps had high salinity leading to the deposition of salt in pores after evaporation of water.

The thin section and SEM-EDS analyses of the shale confirmed the presence of layers containing very fine sandstone and carbonaceous material. Partings occur in black carbonaceous material suggesting weak cohesion of this material. There is presence of open, partially healed and fully healed microfractures in some shale samples. This indicates that the failure of shale sections represented by washouts may have been caused by its brittle and fissile nature. Mud invasion through the open microfractures and partings may have led to the loss of overbalance leading to washouts.

3. Geomechanical simulation

The failure of the shale layers was simulated using a software called PBore-3D. Any geomechanical simulator needs the strength properties of rocks and in-situ stress magnitudes as input. The Poisson's ratio and Young's modulus of the shale layers were calculated using sonic logs and then calibrated with static core measurements. The strength parameters like cohesion and internal friction angle were estimated from empirical correlations for log data and then calibrated with available triaxial test results. The in-situ stress regime is a transition from normal to thrust type with the maximum horizontal stress slightly higher than the vertical stress, i.e., $\sigma_{\mathrm{Hmax}} \geq \sigma_{\mathrm{v}} > \sigma_{\mathrm{hmin}}$. Considering shear failure in compression and tensile failure as fracture limit, the safe mud weight window for horizontal wells is predicted from 76 to 90 PCF depending upon the azimuth of the well.

4. Development of field data analysis technique

4.1. Analysis of vertical wells

As seen in Fig. 3, a range of initial mud weights form 69 to 82 PCF was used to drill vertical wells. The data is used to evaluate the performance of mud weight with respect to the number of problems encountered. As shown in Fig. 3, there is a very weak correlation between initial mud weight used and number of problems encountered. But if the analysis is limited to the mud weight range of 70–75 PCF, the numbers of problems show a monotonous decrease from nine to zero. Only one point is before 70 PCF is not following the trend.

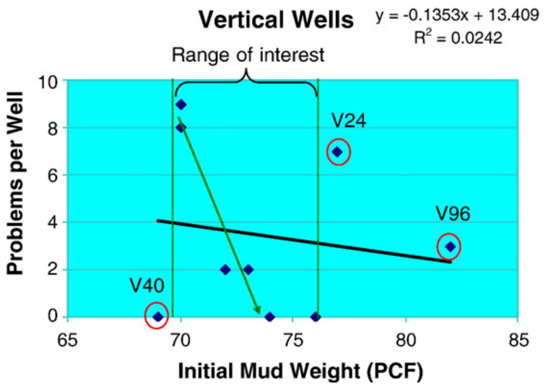

Fig. 3. Problems per well versus initial mud weight of vertical wells.

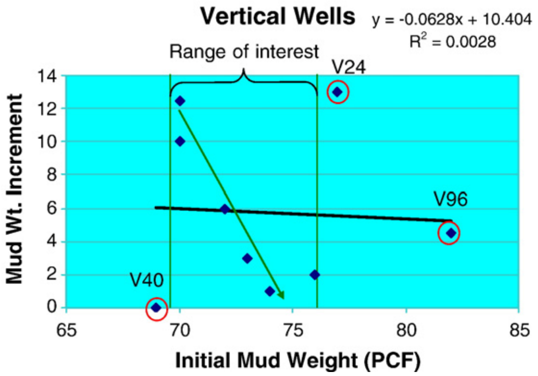

Fig. 4. Mud weight increment versus initial mud weight of vertical wells.

The analysis indicates that even though there were washouts in the well, no instability problems were reported perhaps because of efficient cleaning or slow drilling. Points beyond 75 PCF represent those cases where other instability mechanisms such as mud invasion were active.

Usually, instability is managed by increasing the mud weight. As observed in Fig. 4, in the range of 70–75 PCF, the maximum mud weight increment was applied for wells drilled with lower initial mud weights. The mud weight increment decreases monotonously in this range, confirming the observation that wells drilled with a starting mud weight of around 75 PCF were the most stable. The trend usually followed in industry is confirmed in Fig. 5. As shown in the figure, a strong correlation is observed between the number of problems encountered and the mud weight increment to counteract the instability. The initial mud weight was not high enough to support the wall resulting in washouts and the subsequent problems. The mud weight increments have significantly helped in decreasing these problems, as evident in the figure.

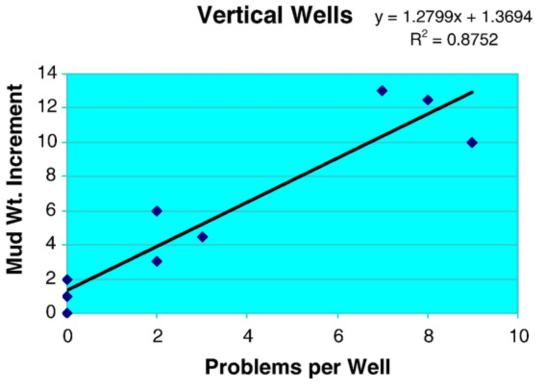

Fig. 5. Mud weight increment versus problems per well of vertical wells.

Fig. 6 shows the hole enlargement of vertical wells with initial mud weight. It is observed that the hole enlargement is decreasing with the increase in mud weight in the range of 70–76 PCF. Interestingly, contrary to the normal expected trend, the hole enlargement increased for the mud weight value beyond 76 PCF. Fig. 7 shows the relevant caliper logs of selected vertical wells. The wellbore wall stabilization as indicated by decreased washout with increase in mud weight is clearly evident. However, when mud weight is greater than 76 PCF, increase in hole size (washouts) at certain locations were observed. This increase in washouts could possibly be due to the mud invasion at high overbalance.

Fig. 8 shows the relationship of the number of problems per well with hole enlargement. For the wells in the range of 70–76 PCF, the problems per well increased with enlargement. The wells drilled with higher mud weight do not follow this trend, and show more problems per well at smaller enlargements. This is because these wells experienced drilling problems such as overpull and stuckpipe due to high overbalance. The origin of problems for wells drilled in the range of 70–76 PCF was the increased volume of cuttings and cavings in the hole. Hence the problems increased with increase in enlargement. It can readily be inferred from this information that the drilling difficulty was due to the extra amount of cuttings and cavings present in the hole. This can be controlled by the use of correct mud weight. If mud weight is high, it gives rise to problems due to differential sticking and mud invasion or pore pressure penetration. Hence, optimizing the mud weight to reduce the volume of cavings as well as avoid differential sticking or mud invasion is essential. Figs. 6, 7 and 8 also clearly show that it may not be possible to have a vertical well without washouts. However, these washouts can be minimized and the potential drilling problems better managed.

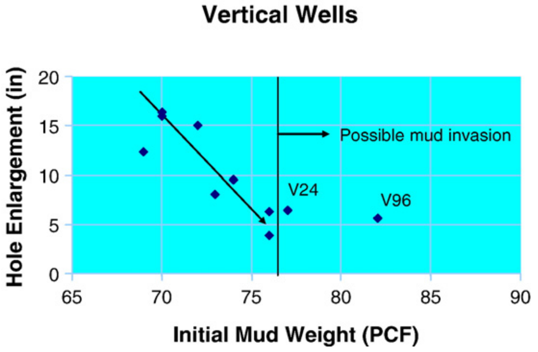

Fig. 6. Hole enlargement versus initial mud weight of vertical wells.

From the analysis of initial mud weight, mud weight increment, problems per well and hole enlargement of vertical wells, three instability mechanisms have been identified. If sufficient mud weight is not used, wellbore wall support is not available and the wellbore wall collapses. The instability due to wellbore wall collapse can be avoided by using appropriate mud weight that adequately supports the wall. Other instability mechanisms are mud invasion and differential sticking at higher mud weights. Therefore it is essential to drill vertical wells using an optimum mud weight that avoids the above instability mechanisms.

4.2. Analysis of directional wells

The mud weight increment and the problems per well decreased with higher initial mud weights for directional wells (Fig. 9). In general, the mud weight increment for this group of wells is less than vertical wells. This could be an indication of the ease of drilling. Also the change in mud weights and problems experienced are negligible when the well is drilled with a mud weight of 75 PCF or just above it. The range of mud weights used for this group of wells is smaller than the one used for vertical wells and falls within the range of interest. Therefore, we see only one type of behavior showing decrease in mud weight increment and problems per well with higher initial mud weight, but the scatter of points is more here. The possible reasons for this scatter could be due to a combination of several parameters such as inclination angle, azimuth, reservoir heterogeneity or exposure time for different wells, Santarelli et al. (1996). The following discussion also supports this view.

At this point, it may be pointed out that R^2 values for some of the graphs presented earlier are low. Due to nature of data coming from a huge field, the scatter is expected to be there. The objective here is not to develop equations but to see the trends. Therefore, the safe mudweights deduced from these graphs are valid for the given ranges only.

Fig. 10 shows the hole enlargement with initial mud weights for directional wells. A general trend of decrease in enlargement with increase in mud weight with a lot of scatter in the data points is observed. In the case of well D9, there is no washout. For the purpose of classification, wells having angle of inclination between 5–60° were called directional. In the following, the possibility of this scatter due to the change in inclination angle is explored.

It is observed that wells D97, D94 and D9, which have an inclination angle of 25° follow a trend. Well D61 with an inclination angle of 4–7° in the formation also follows

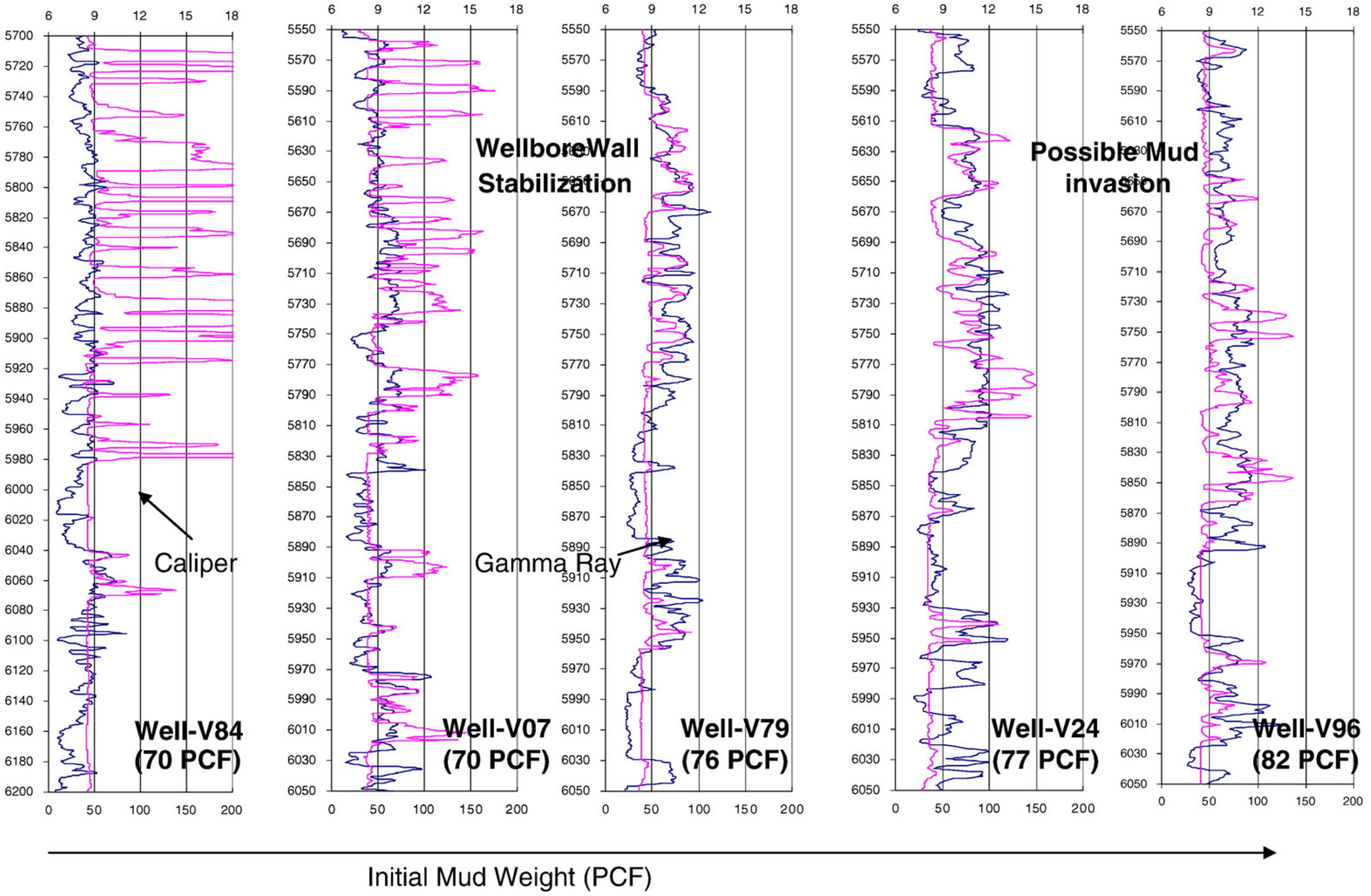

Fig. 7. Open-hole caliper log of selected vertical wells showing wellbore wall support and possible mud invasion.

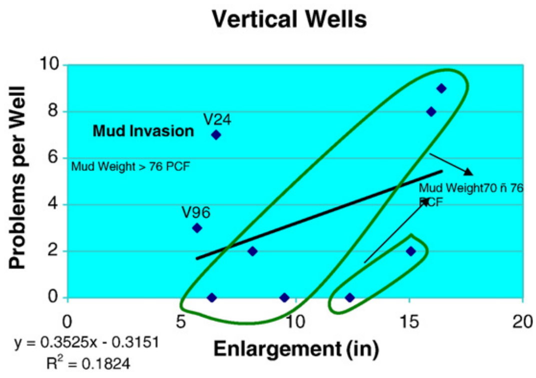

Fig. 8. Problems per well versus hole enlargement of vertical wells.

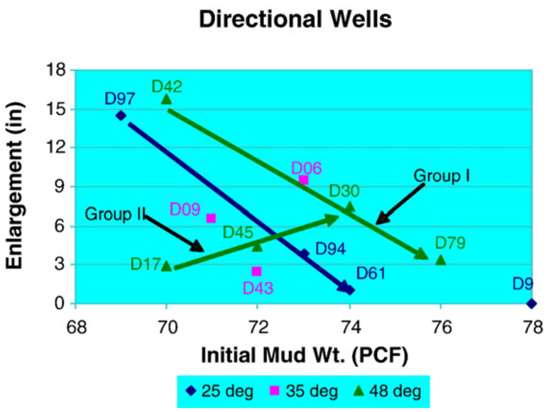

Fig. 10. Hole enlargement versus initial mud weight of directional wells studied with respect to inclination angle.

the same trend. Wells D17, D45, D42, D30 and D79 have an angle of inclination around 45° in the formation. These wells can be divided into two groups. For wells D42, D30 and D79 (Group I), the enlargement decreases with increase in mud weight. The other group of wells (D17, D45 and D30) has an opposite trend of increase in enlargement with mud weight. The remaining three wells namely, D09, D43 and D06 have an angle of inclination of 35° in the formation. This group of wells also does not follow a trend with mud weight. The enlargement decreases and then increases with mud weight. It is possible that the wells not following the trend of decrease in enlargement with mud weight lie in different azimuths. This aspect is also studied in detail as described below.

Fig. 11 shows the hole enlargement of directional wells drilled in similar azimuthal directions. For wells drilled North–South, the enlargement decreases with increase in mud weight. The upper line is for wells having inclination angle of 48° and lower line is for wells having 25° inclination angle. Wells drilled in NNE–SSW direction also follow a general trend of decrease in enlargement with increase in mud weight. Well D17, having an inclination of 50°, is an exception. It has small enlargement at a low mud weight of 70 PCF. Wells drilled East–West also follow the same trend of decrease in enlargement with mud weight. From the above analysis it is clear that the scatter in data in Figs. 10 and 11 is due to different inclinations and azimuth.

4.3. Anisotropy in horizontal stresses

If we compare wells drilled in North–South and East–West direction, we observe that there is more enlargement for the same mud weight for wells in North–South direction. It is to be noted that the North–South direction is closer to the direction of one of the horizontal stresses and East–West direction is closer

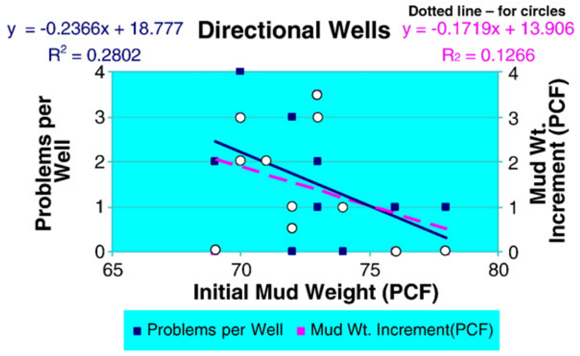

Fig. 9. Problems per well and mud weight increment versus initial mud weight of directional wells.

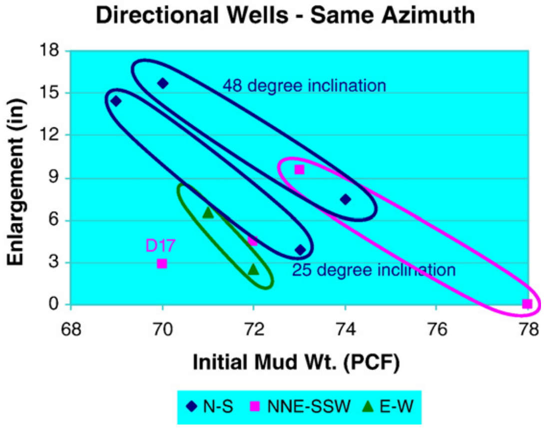

Fig. 11. Hole enlargement versus initial mud weight of directional wells studied with respect to azimuth.

to the other horizontal stress direction. This observation confirms that the formation under study has anisotropic horizontal in-situ stresses.

All the directional wells studied were drilled with mud weights in the range of 70–78 PCF. Mud weights above 80 PCF were not used. It is possible that mud invasion and differential sticking are not observed in directional wells because high mud weights were not used. Within the range of mud weights used wellbore wall stabilization is observed. One can drill a well without washouts if correct mud parameters are used for drilling.

5. Mud weight design based on field data analysis

The objective of designing a proper mud weight is to drill a well successfully with minimum drilling problems. This objective can be achieved by avoiding the active mechanisms of instability in the field. The proper mud weight should be able to provide maximum wellbore wall support without exciting the instabilities due to differential sticking, mud invasion, or pore pressure penetration. If it is not possible to avoid any of the instability mechanisms, then its affect on instability should be minimized.

5.1. Vertical wells

As shown in Figs. 6 and 7, the optimum mud density for drilling vertical wells is 75–77 PCF. At this mud weight range, there is a wellbore wall enlargement of around 2 in. Therefore, efficient hole cleaning must be designed to remove the cavings resulting from this hole enlargement.

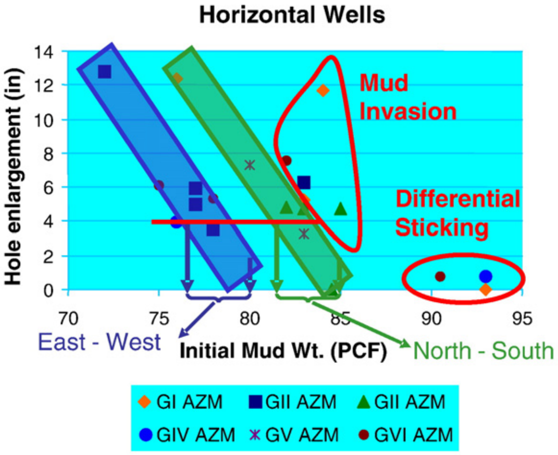

Fig. 12. Hole enlargement versus initial mud weight of horizontal wells — identification of mechanisms and design of safe mud weight window.

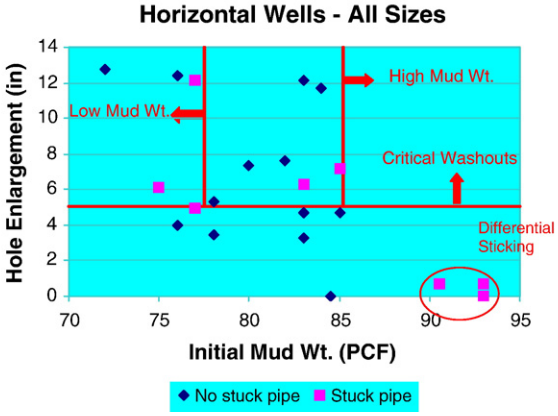

Fig. 13. Hole enlargement versus initial mud weight of horizontal wells showing stuck pipes — definition of critical washouts.

5.2. Directional wells

As shown in Figs. 10 and 11, the mud density depends on inclination and azimuth of the directional well to be drilled. In general, directional wells can safely be drilled with a mud weight range of 76–78 PCF with minimum wall failure.

5.3. Horizontal wells

In order to investigate the dependence of mud weight on azimuth and to recommend optimum mud weights, it is imperative to make use of all the data points available. For this purpose, all the horizontal wells with caliper logs were divided into six groups, each group spanning an azimuth of 60°. This data is plotted in Fig. 12. It is observed that the data points are falling in four distinct groups. The groups in which mud invasion and differential sticking was observed are clearly marked on Fig. 12. The other two groups show a trend of decrease in enlargement with increase in mud weight. The data points in the left strip represent groups of wells lying in the azimuth of 300–60 and 120–240°. Another group of data points lying in the right strip represent wells lying in the azimuth of 60–120 and 240–300. The two trends, representing the North–South and East–West directions, respectively, can be used to design the mud weights for horizontal wells. The maximum mud weights are designed such that mud invasion is not excited. The minimum mud weights can be designed considering the fact that stuck pipes have occurred in wells with more than 5 in. enlargement as shown in Fig. 13.

Considering the above two criteria from Fig. 12, the mud weights for drilling horizontal wells in the formation can be recommended. The East–West direction is easier to drill with a mud weight of 77–80 PCF. The North–South direction is more difficult to drill requiring a mud weight in the range of 82–85 PCF. It is important not to exceed this mud weight as it leads to hole enlargement due to mud invasion. Subsequently, hole enlargement leads to hole pack off or stuck pipe. Under higher overbalance conditions, differential sticking may also occur.

5.4. Validation of the designed mud weights

The effectiveness of the recommended mud weights can be measured by applying them to the available database of horizontal wells. The recommended mud weights were derived using a subset of this database for which the caliper logs were available. The occurrence of stuck pipes for wells drilled using mud weights falling within and outside the recommended ranges was counted. Among the wells drilled with mud weight outside the recommended range, 40% had stuck pipes. All the side-tracks fall in this group, whereas only 10% of the wells drilled with recommended mud weights experienced stuck pipes. Most of these were relatively simple events and were solved in comparatively less time.

6. Conclusions

The following conclusions can be made from this study:

- A new method of analyzing wellbore instability using field-based drilling parameters like initial mud weight, mud weight increment, and problems per well is developed.
- The analysis is used to identify three instability mechanisms — wellbore wall collapse, differential sticking, and mud invasion/pore pressure penetration.
- The analysis also confirms the anisotropy of in-situ horizontal stresses in the field. The approach is useful when there is lack of information about the magnitude and direction of horizontal stresses.
- This analysis is extremely useful where there is significant variation in mechanical properties of different layers of formation.
- Safe mud weight window for drilling vertical, directional, and horizontal wells is inferred. The window is validated using another set of data from the same field showing 90% success rate.

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