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Field Based Criteria For The Design of Safe Mud Weight Window

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Abstract

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 mechanism 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. The safe mud weight window is validated on another set of drilling data showing 90% success rate.

Background

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 significantly the cost of reservoir development. In case of offshore fields, loss of hole is more critical due to the 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 factors are the earth stresses (horizontal and vertical), pore pressure and rock strength. Controllable factors include mud weight, wellbore azimuth and inclination. A proper drilling program optimizes the controllable factors with the knowledge of uncontrollable factors. 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 a normal stress regime is present, then the horizontal wells are the most difficult to drill, hence the mud weight has to be increased with the angle of inclination. However, for other stress regimes, the same is not true.

In many a cases factors like magnitude of the maximum horizontal insitu stress and rock strength variations are not known. Under such circumstances, the safe mud weight window predicted using estimated parameters and available commercial software is often not realistic. If the wellbore instability is encountered, the drilling data accumulated for the previous wells can be used to predict the safe mud weight window. Some pertinent studies using drilling data and laboratory evaluated rock strength are reviewed here.

Santarelli et al., (1996) presented the wellbore instability occurring in a developed field in Italy. The drilling problems were back analyzed with respect to the mud system used, azimuth, and stress regime. More drilling problems like reaming and stuck pipe occurred in one particular azimuth which corresponded with the maximum horizontal stress. In the absence of stress direction and magnitude for the field, the anisotropic distribution of stress field came to knowledge. The non inhibitive water based mud gave better results compared to other mud system. The standard drilling practices planned during appraisal drilling were continued with few 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 as reactive clays were not present in the problematic rock. The main mechanism of instability was found to be mud penetration in fractures and 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 predicted mud weight which was lesser than the currently being used and proper fracture plugging material in WBM proved successful. Classical method of solving the instability by increasing the mud weight could have aggravated the problem.

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 measures 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 dig deep into 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 the 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 like borehole collapse leading to stuck pipe. The collapse due to the mechanical instability of shale was aggravated due to extended shale 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 has shown that it is 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 RSVR. 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 were 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. 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 insitu stress data and rock strength data are not available or where there is significant variation in rock properties through different formation layers.

Definition of terms used

Initial mud weight – It is the mud weight used at the start of drilling a formation. If problems are encountered during drilling, the mud weight is increased to ease the difficulty of drilling.

Mud weight increment – The difference between the minimum and maximum mud weights used to drill a formation is called mud weight increment. In industry, it is a common practice to increase the mud weight by a few PCF (pounds per cubic foot) whenever wellbore instability is encountered. Therefore, the mud weight increment defined above is also a measure of the instability experienced while drilling a well.

Problems per well – Total number of problems in study wells divided by the total number of wells.

Hole enlargement – The difference between the maximum caliper reading and the bit size.

Critical washout – The threshold value of hole enlargement above which stuck pipe occurs.

Vertical Wells

As seen in Figure 1, a range of initial mud weights form 69 to 82 PCF was used to drill the vertical wells. This provides a platform to evaluate the performance of mud weight used with respect to the number of problems encountered. As shown in Figure 1, there is a very weak correlation between initial mud weight used and number of problems encountered. But if we limit our analysis to the mud weight range of 70 – 75 PCF, we observe that the number of problems show a monotonous decrease from a maximum of nine to zero. Points lying before 70 PCF and after 75 PCF on the X-axis do not follow the trend.

Usually, the instability is managed by increasing the mud weight. As observed in Figure 2, in the range of 70 – 75 PCF, the maximum mud weight increase was done for wells drilled with lower mud weights. The mud weight increment decreases monotonously in this range, confirming our 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 Figure 3. We observed a strong direct correlation between the number of problems encountered and the mud weight increment to counteract the instability.

Figure 4 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. Figure 5 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.

Figure 6 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. They 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 is 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 is 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. Hence, optimizing the mud weight to reduce the volume of cavings and to avoid differential sticking and mud invasion is essential. The above figures 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.

From the analysis of initial mud weight, mud weight increment, problems per well and hole enlargement of vertical wells, two 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. Another instability mechanism is the possible mud invasion and differential sticking at higher mud weights. Therefore it is essential to drill the vertical wells using an optimum mud weight that avoids the above two instability mechanisms.

Directional Wells

The mud weight increment and the problems per well decreased with higher initial mud weights for directional wells (Figure 7). 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 one or the combination of several parameters such as inclination angle, azimuth, reservoir heterogeneity or exposure time for different wells.

Figure 8 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 D09, there is no washout. For the purpose of classification, wells having angle of inclination between 5 – 60 degrees 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 D09, which have an inclination angle of 25 degrees follow a trend. Well D61 with an inclination angle of 4 - 7 degrees in the formation also follows the same trend. Wells D17, D45, D42, D30 and D79 have an angle of inclination around 45 degrees 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 degrees in the formation. This group of wells also do 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.

Figure 9 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 degrees and lower line is for wells having 25 degrees inclination angle. Wells drilled in NNE-SSW direction also follow a general trend of decrease in enlargement with increase in mud weight. Well D17 is the exception, though its inclination is 50 degrees, 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 Figures 8 and 9 is due to different inclinations and azimuth.

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

All the directional wells studied were drilled with mud weights in the range of 70 – 78 PCF. High mud weights above 80 PCF were not used. It is possible that mud invasion is 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.

Mud Weight Design

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 and mud invasion or pore pressure penetration. If it is not possible to avoid any one of the instability mechanisms, then its affect on instability should be minimized.

Vertical Wells

As shown in Figures 4 and 5, 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.

Directional Wells

As shown in Figures 8 and 9, 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.

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 degrees. This data is plotted in Figure 10. 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 Figure 10. The other two groups show a trend of decrease in enlargement with increase in mud weight. The data points between blue lines represent groups of wells lying in the azimuth of 300 – 60 and 120 – 240 degrees. Another group of data points lying between green lines 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. These mud weights should be 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 inch enlargement as shown in Figures 11.

Considering the above two criteria from Figure 10, 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 and stuck pipe. Under higher overbalance conditions, there is a danger of drilling problems due to differential sticking too.

Validation Of The 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 were 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.

Conclusions

The following conclusions can be made:

- 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 the two instability mechanisms – wellbore wall collapse and possible mud invasion and differential sticking.
- This analysis also confirms the anisotropy in insitu 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 horizontal wells is inferred. It depends on azimuth and inclination of the well. For horizontal wells, it is 77-80 PC in East-West direction and 82-85 PCF in North-South direction.
- The safe mud weight window is validated using another set of data showing 90% success rate.

Acknowledgement

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References

Al-Buraik, K.A., and J.M. Pasnak (1993). Horizontal Drilling in Saudi Arabian Oil Fields: Case Histories. Paper SPE 25592 presented at the *SPE Middle East Oil Technical Conference and Exhibition*, Bahrain, April 3-6, 1993, pp. 609-617.

Ezzat, A.M. (1993). Horizontal Drilling and Completion Fluids Design Criteria. Paper SPE 25595 presented at the *SPE Middle East Oil Technical Conference and Exhibition*, Bahrain, April 3-6, 1993, pp. 645-654.

Onaisi, A., J. Locane, and A. Razimbaud (2000). Stress Related Wellbore Instability Problems in Deep wells in ABK Field. Paper ADIPEC-0936 presented at the *9th Abu Dhabi International Petroleum Exhibition and Conference*, Abu dhabi, UAE, Oct. 15-18, 2000, pp. 1-8.

Santarelli, F.J., D. Dahen, H. BaroudI, and K.B. Sliman (1992). Mechanisms of Borehole Instability in Heavily Fractured Rock Media. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* Vol. 29, No.5, pp. 457-467, 1992.

Santarelli, F.J., S. Zaho, G. Burrafato, F. Zausa, and D. Giacca (1996). Wellbore Stability Analysis Made Easy and Practical. Paper IADC/SPE 35105 presented at *1996 IADC/SPE Conference*, New Orleans, Lousiana, March 1996, pp. 523-532.

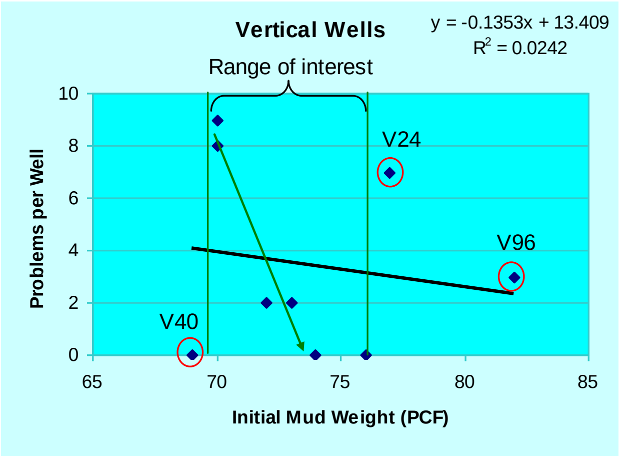

Figure 1. Problems per well versus initial mud weight of vertical wells.

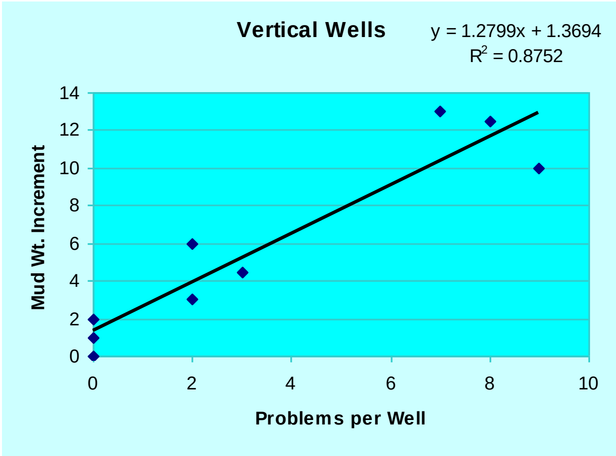

Figure 3. Mud weight increment versus problems per well of vertical wells.

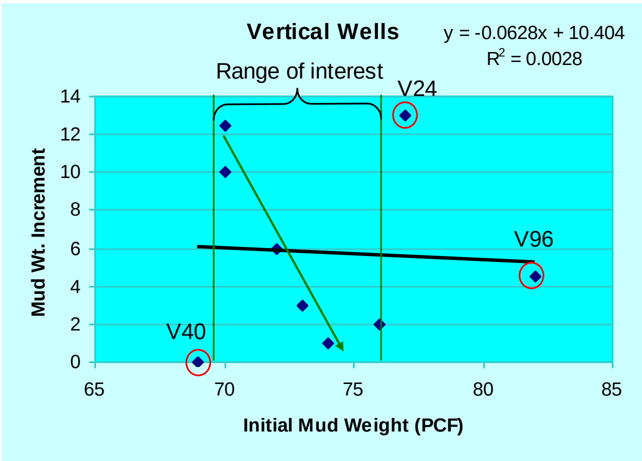

Figure 2. Mud weight increment versus initial mud weight of vertical wells.

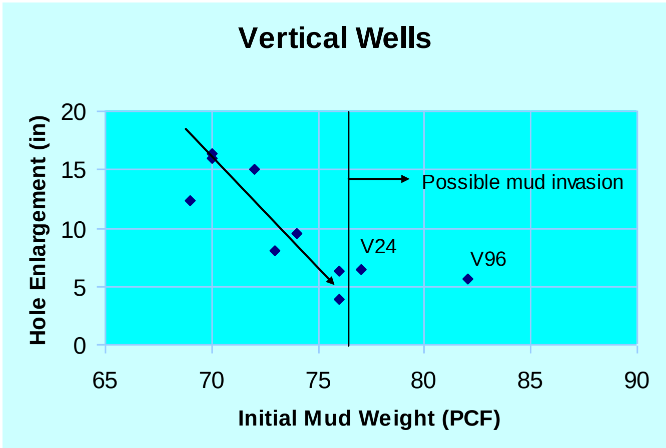

Figure 4. Hole enlargement versus initial mud weight of vertical wells.

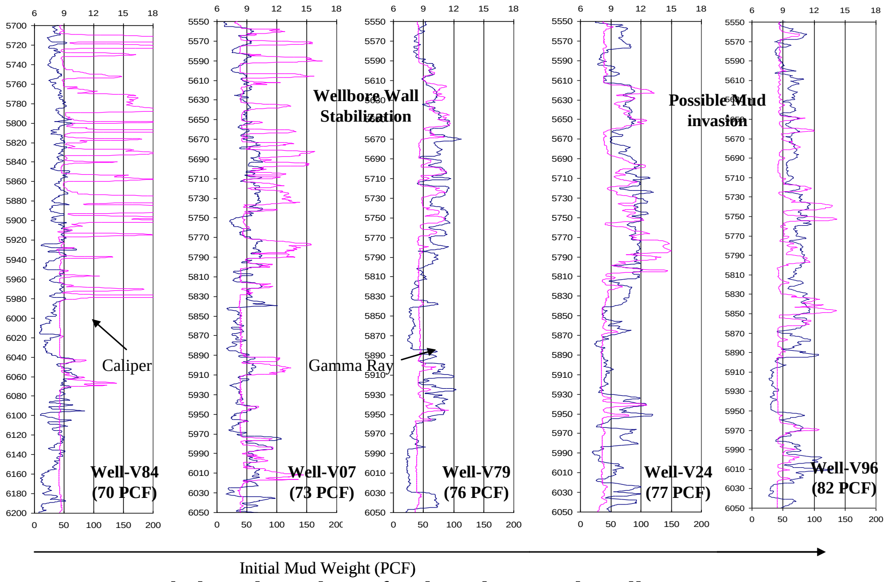

Figure 5. Open hole caliper log of selected vertical wells showing wellbore wall support and possible mud invasion.

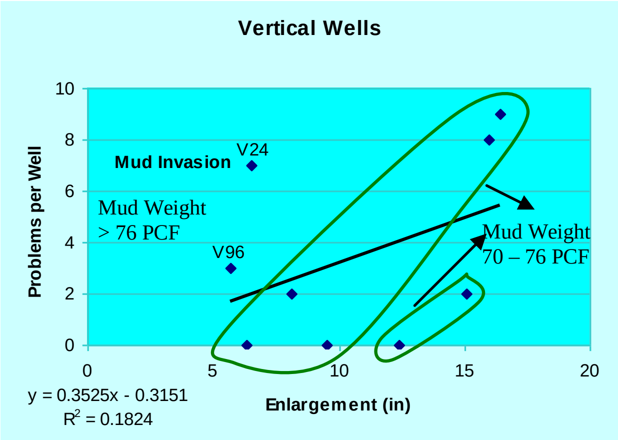

Figure 6. Problems per well versus hole enlargement of vertical wells.

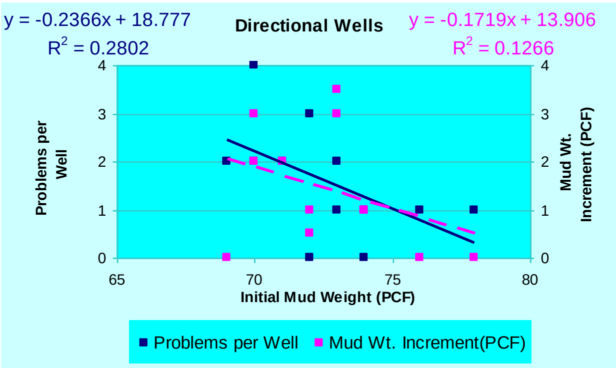

Figure 7. Problems per well and mud weight increment versus initial mud weight of directional wells.

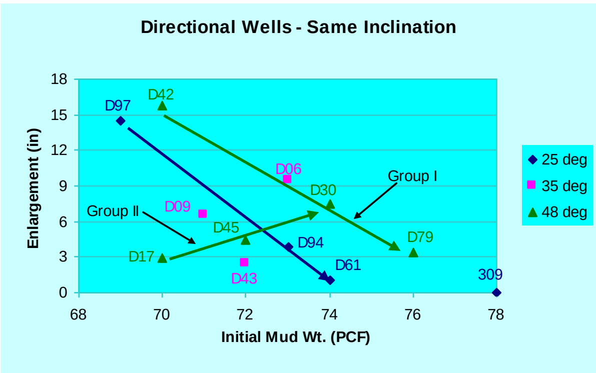

Figure 8. Hole enlargement versus initial mud weight of directional wells studied with respect to inclination angle.

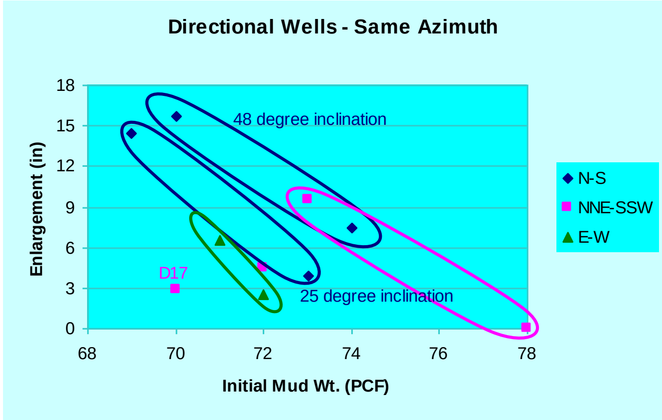

Figure 9. Hole enlargement versus initial mud weight of directional wells studied with respect to azimuth.

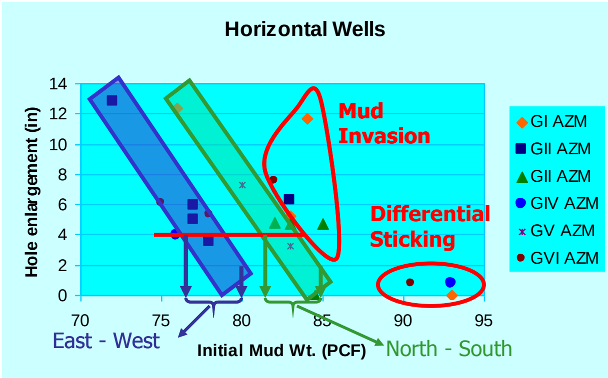

Figure 10. Hole enlargement versus initial mud weight of horizontal wells – identification of mechanisms and design of safe mud weight window.

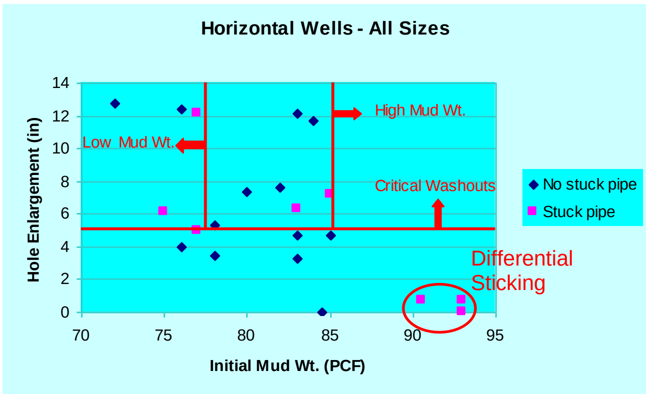

Figure 11. Hole enlargement versus initial mud weight of horizontal wells showing stuck pipes – definition of critical washouts.