Analysis of the potential conditioning factors for pipe sticking in well drilling through active faults.

Wire-line boreholes FAM-1 and FAMSISIGN, Alhama Fault, Murcia, Spain.

J. M. Moratalla

ABSTRACT

Failures related with borehole drilling are a very common problem when the drilled area is a fault zone. Through this work will be analysed the hypothetical causes that produced a pipe sticking in two scientific boreholes drilled through the fault plane of the Alhama fault, Murcia, Spain. Concretely in a transitional contact between the main fault rock, called "Fault Gouge" and a very fractured phyllitic formation.

Several potential types of pipe sticking could have produced the failure in the borehole, being the main causes: differential pressures, swelling formations, unconsolidated and unstable formations, plastic-flowing formations, cuttings packoff and key seating. These causes have been defined properly in this work, with the purpose of evaluating the materials and technical characteristics that are related with each cause.

Several analysis have been developed and discussed, starting with in-situ test and continuing with laboratory test, thus, permeability test, free swelling test, X-Ray diffraction, plastic limits, caliper analysis, borehole deviations, dipping angles of the formations, recovery indexes and finishing with muds concentrations.

The analysis results, many of them negative, drove this work to conclude that the pipe sticking was produced by a cuttings packoff at the bottom of the borehole. This failure was generated by the oversaturation in the drilling muds due to an incorrect planification of the mud´s viscosity and density, and, in addition, the presence of unstable formations with inclinations of their weakness planes in the risk limits while drilling a vertical borehole.

Some recommendations for future boreholes are exposed in the last chapter of this work.

KEY WORDS: ***Scientific borehole, pipe sticking, fault zone, drilling stability.***

KEY WORDS: Scientific borehole, pipe sticking, fault zone, drilling stability.

1. INTRODUCTION

The aim of the present work is the evaluation of the different hypothetical causes that produced a pipe sticking failure, in two boreholes drilled directly in the fault of Alhama, Murcia, Spain.

In order to investigate in detail the architecture of the fault zone and to collect unaltered core samples of fault rocks (principally a black "fault gouge" generated from the Paleozoic schists of the Alpujárride complex), a first borehole, FAM-1, was drilled until 175 meters depth. One year later, a second borehole, the FAMSISIGN was drilled in the same area. The selected section of the fault is a zone where the deformation is concentrated, several trenches were firstly excavated in order to have an approximated idea of the structure of the fault zone.

The boreholes have provided a large amount of core samples of fault rock; due to the movement of the fault, these rocks were probably generated several kilometers deep, near to the hypocentral region of large earthquakes.

The character of the fault zones often leads to drilling problems. The scientific boreholes FAM-1 and FAMSISIGN had a stuck in the machinery, the drilling strings were blocked at a depth coincident with a “Fault Gouge” formation and a transitional zone between this formation and a blue-phyllitic material.

This work will go through different hypothesis that will try to reach an approximation to the real causes of the failure that stuck the drilling strings, different analysis of the materials and the drilling parameters will be developed.

1.1 GEOGRAPHICAL LOCATION

The study area is situated in Murcia, a region in the South-East of Spain with seismic activity due to the presence of the Alhama de Murcia fault. The boreholes were located in an area 3 km to the SW of Lorca, close to La Torrecilla ramble (figure 1.1.2) where the fault zone is dominated by well-developed clay rich fault gouge with a clear lithological banding.

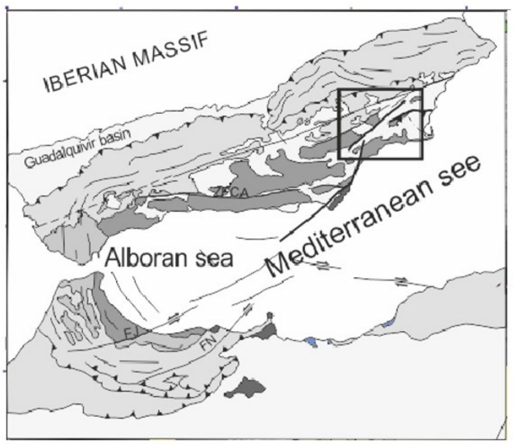

Figure 1.1.1 Location of Alhama de Murcia fault (Martínez-Díaz et al., 2016).

1.2 FAILURE PROBLEMATIC IN THE BOREHOLES

Borehole FAM-1 drilled without any problem until 155 meters depth, where recovering percentages decreased and the rig started to have difficulties to continue drilling. At 174 meters depth, the machinery could not continue drilling and the last three meters of drilling string remained stuck in the bottom of the well. The problems started in the last 20 meters of fault gouge formation, where there is a progressive transition from this material to a blue-phyllites formation.

The same failure occurred in borehole **FAMSISIGN** The drilling strings had an obstruction at 43 meters depth where there was no possibility to extract the barrels, or to continue drilling, the obstruction impeded the rotation and extraction of the strings, a progressive stop in the circulation of the drilling fluids worsened the situation.

An analysis of the materials that could potentially cause sticking problems in the borehole is the main objective of this work, thus, the presence of swelling clays, the plasticity of the materials where the failure occurred, grain size analysis, frictional angles formations tilts and other studies will be developed.

2-GEOLOGICAL CONTEXT

Alhama de Murcia Fault (AMF) is a strike-slip shear fault with reverse component, located in the eastern Betic Cordillera and crossing it with a NE-SW direction.

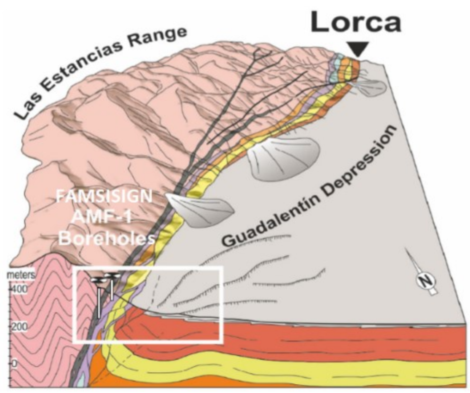

Figure 2.2.1 Geomorphological representation of the fault of Alhama and the associated materials.

The fault, with a length of 85 km, is generated due to the convergence between the Nubian and the Eurasian plates, and is one of the longest faults in the South-West of Spain.

The Fault of Alhama puts into contact the metamorphic rocks from the Betic basement that emerge in this associated elevations, with the Miocene and post-Miocene deposits that are deposited in the Cenozoic basins. In the contact zone, the FAM presents a mixture of all these materials, (figure 2.2.1) due to that, the fault presents a very heterogeneous zone that locally can reach more than 150 meters of thickness.

3. 3. BOREHOLE PARAMETERS AND CORE TESTIFICATION

Boreholes FAM-1 and FAMSISIGN drilled using wire-line with triple tube methodology. Fam-1 drilled t The first 119.55 meters where drilled using PQ-3 diameter (83mm), and the rest with HQ-3 diameter (63mm), until the drilling string stuck at 174.75m, The drilling mud used is AMC CR 650, a no contaminant polymer that acts as substitute of the bentonite. This polymer is destined to the perforation and stabilization of shales and clays. The optimal concentration for its use is 0.75 kg per 1000 liters of fresh water FAMSISIGN drilled using PQ-3 diameter. The strings used in the borehole are steel tubes with high elastic limit, nitrated threads and post-welding thermic treatments. Each tube has 3 meters length and inner diameter PQ-3.

Principal materials cored:

-Quartz-schists and phyllites:
Graphitic quartz schists with fine-medium grain sizes, there are continuous alternations with levels of phyllites along all the borehole. (Figure 3.2.1-B). Generally with well-developed foliation. The formation present high grade of oxidation in the first 16 meters, and last until 63.60 meters. (Figure 3.2.1-A)
Abundant presence of levels of quartz mm to cm.
RQD test results (see annexes A-RQD results for quartz-schists). The degree of fracturing increases from the top of the damage zone towards the gouge zone.
Discontinuities type S1, with rugosity level from II-V, there is no presence of filling material in the fractures.
Dipping angle variations from 20 to 80 degrees, with predominant dip angle of 75º (see annexes A-Dip angles for the quartz-schists).

-"Fault gouge":
Black silty clayey material with angulous debris and blocks of quartz-schists and phyllites of different sizes, from mm to decimetric. Pulverized quartz fragments are included, with sizes from mm to centimetric, the external structure is remained. (Figure 3.2.1-C).
At this section of the fault, the fault gouge presents an exceptional thickness, with more than 60 meters, from 81.70 to 171 meters depth. It is not continuous, having intercalations of blocks of the protolitic quartz-schists, claystones and phyllites (Alpujjárride system). This fault gouge forms the nucleus of the fault where it is concentrated the major part of the strike-slip deformation. The structure of the original schistosity is remained and can be observed in the cores, but it is re-oriented. Presence of sigmoidal structures very well defined, sub vertical orientation of the schist planes, 60-70º.

-Blue-phyllites:
Blue-violaceous phyllites with high grade of fracturation. Silvered tonalities due to the presence of graphite. Clayey matrix giving soapy feel due to the presence of talc and other phyllosilicates. (Figure 3.2.1-D)

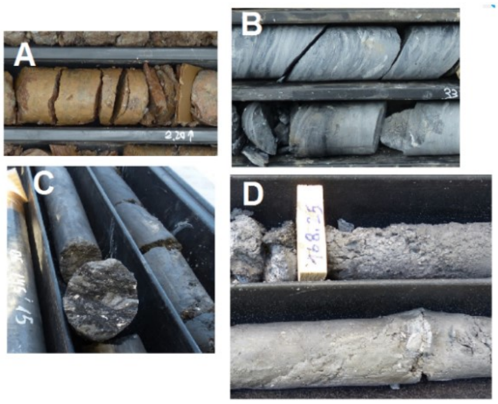

Figure 3.2.1 Appearance of the cores obtained in boreholes FAM-1 and FAMSISIGN. A) Altered schists, B) quartz-schists, C) Fault Gouge, D)Blue phyllites.

The quality of the cores recovered is very low, the extremely low cohesion of the material forced it to remain in the drilling mud in suspension. It is observable in the recovering percentages in the last meters.

4. PIPE STICKING

Pipe sticking is a common failure that has been a problem since borehole drilling began. When the pipe is stuck, means that the strings cannot be freed and pulled out of the hole without damaging the pipe or exceeding the maximum hook load of the rig. In the case of boreholes FAM-1 and FAMSISIGN, the pipes were stuck at the bottom of the well, impeding rotation, extraction and muds circulation.

Pipe sticking can be produced by several causes, thus, it is divided in three main types: Differential sticking, formation related sticking and mechanical sticking.

4.1 DIFFERENTIAL STICKING

Differential sticking occurs in permeable zones where drill collars, drill pipes or casing, get imbibed in mud cake and pinned to the borehole wall by the difference between the mud´s hydrostatic pressure and a lower formation pressure. The pipe is held in the cake by a difference in pressures between the hydrostatic pressure of the mud and the pore pressure in the permeable zone. The force required to pull the pipe free can exceed the strength of the pipe (figure 4.1).
A permeability study is going to be developed in this work with the purpose of evaluate this characteristic in the materials that could have caused the failure, fault gouge unaltered samples will be used to elaborate the tests.

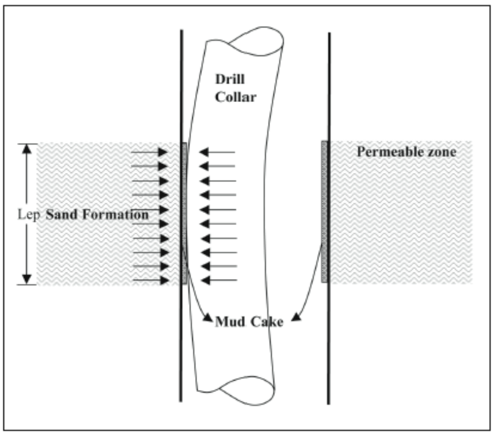

Figure 4.1 Differential pressure stuck pipe. (J.J.Azar and Samuel ,2007)

4.2 FORMATION-RELATED STICKING

Formation-related sticking occurs when unstable formation constricts the drilling string, this occurs in presence of swelling clays, unconsolidated rocks and flowing formations such as salt and plastic shales.

4.2.1 Swelling clays sticking:

When drilling reaches unstable shales or phyllites that, in presence of water-base mud, tend to swell, sticking failure can be produced due to the reduction in the diameter, constricting the hole and gripping the drilling strings.
The utilization of water-base muds in reactive formations can cause clays hydration, creating a rough borehole wall that could grip the strings, or its particles could fall on the BHA (bottom hole assembly) and bit, possibly packing them off.
In the present work, some laboratory analysis will be made with the objective of determining the presence of swelling clays in the fault gouge, at the transition levels with the blue phyllites. The fluid circulation through the faulted and fractured rocks could reasonable produce neo-formed minerals that belong to the group of the phyllosilicates, and probably contain montmorillonite or smectite. Thus, X-ray diffraction will be developed to determine this.

Once the presence of swelling clays in the samples is probed, will be performed free swelling test to determine the capacity of the material to swell in presence of water

4.2.2 Unconsolidated formations sticking:

The formation that are commonly involved in this type of failures are unconsolidated sands, gravels, bolders and conglomerates. Especially if water is being used in the drilling fluid, the materials often fall into the hole and pack off around the drill string.
This failure is closely related with the muds saturation, another problem related with accumulation of material in the drilling fluids.

An analysis of the core-recuperation percentage and the drilling muds characteristics will be done with the purpose of find a section in the borehole where a washout could have happened

4.2.3 Unstable formations:

Before the formation is drilled, the rock strength at any depth is in equilibrium with the in-situ rock stresses.
The hole collapse in mechanical failures is generally related to an increment of the borehole diameter of the hole due to brittle failure and caving of the wellbore wall. If the cuttings are not transported anyway, it is a potential source to stuck the pipe.
Probed results (Aminul Islam, 2009), in wellbores drilled 45º to weak bedding planes in artificial shale formations show the potential instability of drilling at this angles.
In addition, it is important to note that in all types of formations, using too low of a mud weight can lead to the collapse of the hole, possibly causing mechanical pipe sticking.

Thus, to observe the possibility of unstable formations in the borehole, a study of the core-recuperation percentage and the orientation of the weak planes of the formations will be made. This result are discussed in section 5.4.

4.2.4 Flowing formations, plastic shales:

Plastic shales can potentially cause stuck failures in boreholes. If the mud weight used has low viscosity, some shales can behave plastically flowing inward the borehole and generating pipe sticking

Plastic flowing shales are often sticky, and contain considerable amounts of swelling minerals (smectite, montmorillonite), thus, plastic shales failures are closely related with swelling shales failures

In the Attenberg Limits chapter, we are going to evaluate the plastic limits with the purpose of determine if the material could behave plastically in the natural conditions that exist in the fault.

4.3 MECHANICAL STICKING

Mechanical sticking cover several cases, the most important are the cuttings accumulations due to a poor hole cleaning, key seating due to a deviation in the hole and a collapsed casing produced by an incorrect casing planning. This last case will not be treated in this work due to the absence of casing in the boreholes.

4.3.1 Hole pack off (Cuttings accumulations)

When cuttings are not totally removed from the borehole, they tend to accumulate in the well, eventually causing the hole to pack off, often around the Bottom-Hole Assembly (BHA) and sticking the drill string.
Poor hole cleaning would result in overloading the annulus with cuttings, potentially sticking the drill string.This problem is encountered often in over gauge sections, where annular velocities of the fluids are reduced (washouts of cavities).
To try to demonstrate the effect of the hole pack off in the boreholes FAM-1 and FAMSISIGN, chapter 5.6 is dedicated to the muds quality, density and saturation.

4.3.2 Key seating

Key seating is a very common mechanical failure produced in boreholes where there is a large deviation of the strings.

Generally, this failure is related with doglegs or washouts in the borehole wall. Soft to medium hard formation, as the drilled materials in boreholes FAM-1 and FAMSISIGN, have a great tendency to get key seat, also, the dipping angles of the formations is a very determinant factor in hole deviations
Generally, this effect is produced in long bit runs, and it is not produced in the bottom of the well, generally occurs in the middle part of the strings, and the deviation normally coincide with a change in the lithology or in the dipping of the layers.

An evaluation of the borehole deviation resulting from the geophysical testification will be done in the correspondent chapter (see 5.7 borehole deviation).

5. DISCUSSION

5.1 PERMEABILITY TEST

The permeability of the fault gouge and the intact porotolite rock has been determined with a triaxial cell in the laboratory of the company Geotecnia-2000.
This core is not formed with intact fault gouge, instead of this, it has been disaggregated and compacted to observe it without considering the schistosity of the material.
Being the humidity an important factor in the behaviour of the material, it has been conserved as much as possible to observe the behaviour of the rock in the closer natural conditions.

Taking the results into consideration (0.0263 and 0.0192 Darcys), the low resulting permeabilities are the key of demonstrating that the pipe sticking was not produced by differential pressures between the formation and the drilling fluids. To produce this effect, it is necessary the presence of fluids within the formation and large values of permeability. Thus, differential pipe sticking is neglected as a possible cause of the failure.

5.2 EXPANSIVE CLAYS: OEDOMETER LABORATORY TEST (OR LAMBE TEST)

The mineralogical composition of the fault gouge has been studied by X-ray Diffraction (DRX). The results show potasic and sodic micas (Paragonite), abundant presence of quartz, feldspar and sporadic presence of chlorite. In several sections has been observed minerals from the group of the carbonates (calcite, ankerite and dolomite). (Tsige et al, 2016). The fraction < 2μm, presents a predominant composition of illite and presence of kaolinite, graphite and smectite.

Previous to the swelling test, sieving at 0.075mm was developed to separate the fine particles in order to use only larger amount of the fraction < 2μm, where the swelling clays have been observed. Thus, the possible expansion would be quantified easily and more precisely.

The free swelling test result were negative, the content of the fault gouge in swelling clays is real but too low. The total swelling of the sample was zero.

Thus, as was supposed with the mineralogical tests, the failure was not caused by volume expansion of the material due to water hydration of the clays by inclusion of H2O molecules in their interlaminar spaces.

5.3 CALIPER RESULTS

Analysing the calliper results we reached to the next conclusions:
-There is no presence of diameter reduction until 139 meters depth, thus, the presence of expansive clays or plastic flowing shales was not produced until 139m.

-The borehole wall is regular from 27.5 to 65m, these depths correspond with the quartz-schists formation.

-Irregularities in the borehole wall start with the fault gouge and continue until practically the end of the logging, except an interval of 5 meters from 132.5 to 137.5m. that is supposed to have better rock quality.(figure C-02)

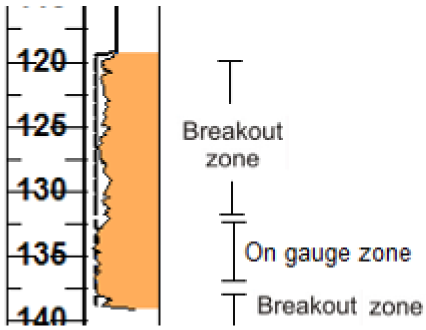

Figure C-02: Caliper log

Due to the small size of the breakouts, the cavings created can be supposed to be produced due to the eccentric movement of the drilling bit while drilling. This movement can be produced in zones where the rate of penetration (ROP) is low.

Thus, the final conclusion observing the calliper results is that there is presence of breakouts in the borehole walls but not caused by washouts or formation instability, at least until 139 meters depth. The corresponding fragments of the cavings created will be included in the drilling fluids and have to be evacuated anyway.

Therefore the generation of cavings in the borehole wall lead to cuttings accumulation in the annular space.

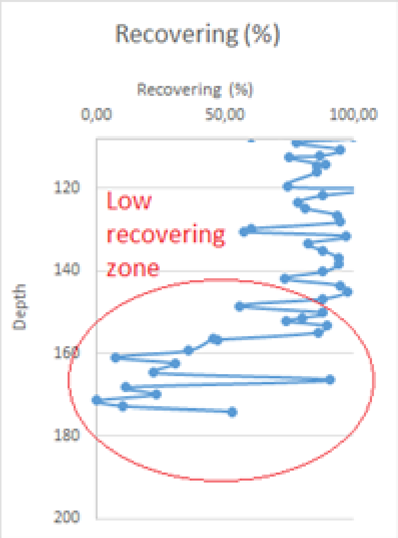

Figure 5.4.3, recovering percentages for the last 20 meters of borehole FAM-1.

5.4 DIPPING ANGLES OF THE FORMATIONS, CORE-RECUPERATION PERCENTAGES FOR THE BOREHOLES AND ROCK QUALITY INDEX (RQD).

5.4.1 Dipping angles of the formations

The measurements have been taken with respect of the vertical axis of the borehole, that coincides with the vertical plane
The results for FAM-1 show a 45º tendency of the dip angles along the last meters of the fault gouge, where the transition between this formation and the blue phyllites is produced

Thus, the inclination of the formations in borehole FAM-1 show that a vertical borehole has the maximum risk of a failure related with a borehole wall collapse. The zone with maximum probability of failure is reached from 135 to 174 meters depth, being larger in the last 20 meters.

In the case of borehole FAMSISIGN a tendency of 40-45º is observed all along the borehole, increasing to 50º in the last five meters, where there is transition from the fault gouge to the blue phyllites (figure 5.2.2).

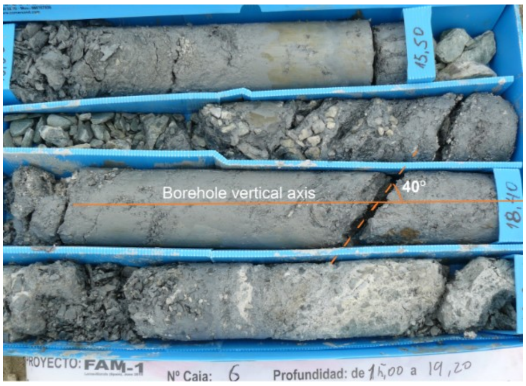

Figure 5.2.2 Dipping angles of the weak planes of the formation with respect of the vertical axis of the borehole FAM-1

In conclusion, the angles of most susceptibility that can produce a collapse of the borehole wall coincide with the last meters in both boreholes, depths were the failures were supposed to be produced.

5.4.2 Core recovery percentage

Observing the results of recovering represented (figure , it is possible to observe that along the first 156 meters, the borehole was having very high recovering percentages, varying from good to excellent qualities after that a reduction in the recovering at the last 20 meters, from 156.60 to 174m, show poor-fair recovering qualities, see figure 5.4.3 and Appendix-B.

5.5 ATTERBERG LIMITS

The limits reached in the laboratory for this study are the following:

Liquid Limit (%)	25.84
Plastic Limit (%)	21.2
Plasticity Index(P)	4.64

Figure 5.5.2 Atterberg Limits for the formation

Observing the results we can confirm that the plasticity index of the soil is very low, being 4.6% of humidity. Also, while the test realization was possible to observe that the material losses humidity very rapidly if it is exposed to the ambient conditions and it disaggregates and dries extremely quickly.

Thus, the plastic behaviour of the material is not plastic except in a very small range of humidity, once the plastic limit is crossed, the material behaves as a liquid, and it should not cause sticking pipes.

5.6 DRILLING MUDS

The used polymer, AMC CR 650must follow the following specifications while fabricating the drilling mud:

-Must be added to fresh water, under normal conditions in a proportion of 0.5 to 0.75 kg / 1000 l of water.

-To stabilize swelling clays and shales a proportion of 0.75 to 1.0 kg / l of water must be used.

-It should be mixed by adding it slowly through a jet funnel of high speed stirrer.

Polymer seems to be correctly selected for the purpose of the boreholes, thus, the concentrations used must be calculated observing the amount of water and polymer used, to guarantee that the muds had the correct density and viscosity.

The polymer concentration was 12,7148 kg/21560 litres of water; what means 0.59 kg/1000liter of water.

This polymer concentration is above the minimum limits (0.5 kg/1000L) but it is below the limits stablished for clays and shale stabilisation (from 0.75 to 1kg/1000L of fresh water) (according to the ADG Code, Approved Criteria for Classifying Hazardous Substances, see references).

Thus, muds could have not worked properly due to the low polymer concentrations used, the viscosity and density of the muds probably were not large enough to develop a correct hole cleaning and the cutting could have remained at the bottom of the well.

Evaluation of the recovery percentages and particles surrounding the cores:

The recovering percentages can be evaluated reversely, thus, will be possible to observe the percentage of extra material that is included in the drilling mud, and must be evacuated through the annular space

There is an observable increment of particles included in the mud in the last 20 meters in the borehole FAM-1, zone where the core recovering percentage decreases.

Another relevant factor that should be taken into account is the cores obtained in borehole FAMSISIGN, as can be appreciated in the figure 5.6.4, the samples are surrounded of particles of different materials and sizes.

In conclusion, the low concentration of the polymer in the drilling muds produced an inefficient hole cleaning that, added to the low core recovering percentages observed in the last meters, produced the cuttings accumulation at the bottom of the borehole. This hypothesis is also corroborated with the presence of cuttings surrounding the cores, figure 5.6.4.

5.7 BOREHOLE DEVIATION

The objective of the present chapter is to evaluate the geophysical testification where a clinometer introduced in the borehole registered the tilt angles for the first 140 meters of borehole FAM-1.

The dipping angles of the formations that were drilled reached the 70º dip, this inclinations normally tend to deviate boreholes if there is no directional controlling-

Despite this, in the case of the boreholes of this study, a stuck caused by key seating was not the cause of the failure, the maximal deviation reached by the well was 2.66º, this deviation is not large enough to produce a key seating.

Also, another reason is that the machinery was not capable to continue drilling, the stuck related with key seating generally does not impede to continue perforating.

6. CONCLUSION

First of all, it is important to remark that the zone that was implicated in the failure is a transitional area of around 20 meters between the main fault rock, called “Fault Gouge”, and its following contact formation, a blue-phyllitic material with similar characteristics.

The fault gouge is rock with a low grade of metamorphism that behaves as a soil, but conserves its original weak planes and schistosity, being this characteristic an essential feature for the development of this final conclusion.

The final conclusion, based in the results obtained from the several studies developed, is a pipe sticking probably caused by unstable formations with critical angles in their weakness planes with respect to the vertical axis of the borehole, in addition, the transitional zone between the “Fault gouge and the blue-phyllites formation had more instability potential due to the transitional contacts. The materials that collapsed from the borehole walls passed to the annular spaces, sticking the drilling strings.

The incorrect concentration of the drilling muds drove to an incomplete hole cleaning of these overcharged annular spaces, the low viscosity and density of the drilling fluids probably induced to cuttings accumulation at the bottom of the borehole. That accumulation finally produced the failure, impeding the strings to rotate and the muds to continue flowing and cleaning the borehole.

Boreholes FAM-1 and FAMSISIGN were stuck at different depth, but the geological correlation of the materials due to the emplacement of the rigs, made coincide the failure depths with the transitional zone between the “Fault gouge” formation and the blue-phyllites.

7. RECCOMENDATIONS FOR FUTURE BOREHOLES

The future planning should take into account the potential risks that drilling a fault zone, directly in the fault plane, brings.

Thus, the following recommendations would be helpful for future boreholes in areas with similar characteristics:

-Dipping angles of the weakness planes of the formations:
Angles equal and above 45º are risky for the stability of the borehole wall. If it is possible, a directional drilling should be developed, with the objective of crossing the formations as perpendicular as possible to these planes.

-Drilling muds characteristics:
In presence of shales and fault rocks with lower grades of metamorphism, we would advise using high polymer concentrations, as larger as the rates permit it.

Mud additives:
Treatments with seepage-loss material, such as M-I-X-IIE fiber, will help seal these formations and provide a base for the filter cake.

-Casing plan:
Casing design assures the stability in the different stages of drilling and production. The correct estimation of the different casing characteristics will assure the correct behaviour of the pipes in different conditions. Casing prevents the hole from caving in, avoids water migration to the formations and helps to the hole cleaning.

8.REFERENCES

Azar J.J and Samuel, 2007, Drilling Engineering

Deere, D U 1964. "Technical description of rock cores", Rock Mechanics Engineering Geology, 1 (16-22).

Islam A. 2009, Underbalanced Drilling in Shale (UDB) - Perspective of Factors Influences Mechanical Borehole Instability

Martinez-Díaz etal 2001, Evidence for coseismic e vents of recurrent prehistoric deformation

along the Alhama de Murcia fault, southeastern Spain.

Martinez-Diaz etal 2012, Alhama de Murcia fault.

Naraghi etal 2013, Prediction of drilling pipe sticking by active learning method (ALM)

Rodríguez Soto, 2016, Caracterización Geotécnica y Geomecánica de la “Fault Gouge” de la falla active de Alhama, Murcia

Reinecker, M. Tingay and B. Müller, Borehole breakout analysis from four-arm caliper logs

Tsige etal 2016, Composición mineralógica y micro-fábrica de la fault gouge de la Falla de Alama de Murcia FAM. en prensa.