[Analysis of the potential conditioning factors for a stuck pipe through the active fault of Alhama.]

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

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Thesis to obtain the Master of Science Degree in

Petroleum Engineering

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ABSTRACT

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

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

Several analysis were undertaken and discussed, including in-situ test and laboratory test, namely, 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 of the results, allowed to eliminate most of the causes evaluated.This work concluded 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 planning 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 drillings are proposed in the last chapter of this work.

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

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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 measured 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 characteristics of the fault zones often leads to drilling problems. Due to the abrasive nature of faults, the bit may break, or more likely wear on the face of inner and outer gauges. Bits may also plug with a piece of core, or their nozzles may become blocked by clay or rock fragments in addition, cores may jam in the bit or core barrel due to small shifts along fractures during the drilling process.

The scientific boreholes FAM-1 and FAMSISIGN had stuck pipe problems, the drilling strings were blocked at a depth coincident with a “Fault Gouge” formation and a transitional zone between this formation and a following blue-phyllitic material.

The objectives of the scientific project Intergeo for the borehole were widely reached, but an explanation of the failure in the machinery was still pending.

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

1.1 GEOGRAPHICAL LOCATION

The study area is located in Murcia, a region in the South-East of Spain with seismic activity due to the presence of the Alhama de Murcia fault, an active strike-slip fault that produced recent destructive earthquakes (figure 1).

The boreholes were located in an area 3 km to the SW of Lorca, close to La Torrecilla ramble (figure 2) where the fault zone is dominated by well-developed clay rich fault gouge with a clear lithological banding.

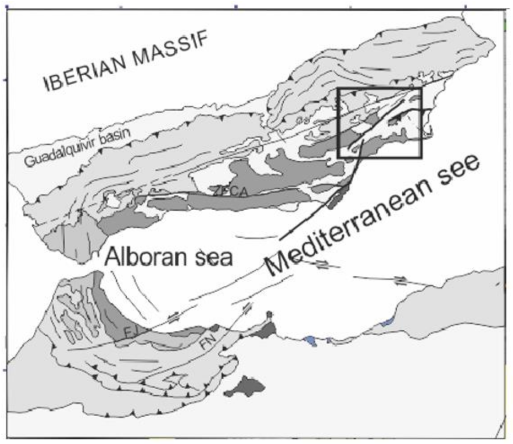


Figure 1 Location of Alhama de Murcia fault (Martínez-Díaz et al. 2016).

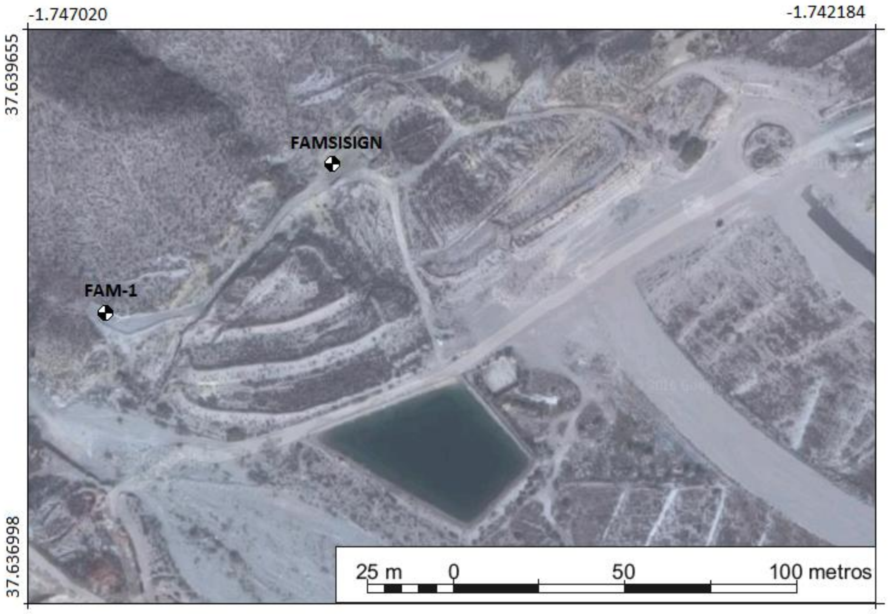


Figure 2 Location of boreholes FAM-1 and FAMSISIGN.

	LATITUDE	LONGITUDE
FAM-1	37.638405	-1.746662
FAMSISIGN	37.639119	-1.745355

Table 1 Coordinates of the boreholes in decimal degrees.

1.2 SCIENTIFIC BOREHOLES FAM-1 AND FAMSISIGN, OBJECTIVES

With the purpose of an accurate characterization of the fault of Alhama, on July 2015, the scientific borehole FAM-1 was drilled directly in the fault plane, starting the perforation in the hanging wall of the fault. The objective of this first borehole was to obtain the maximum amount of information of the fault rock and the associated materials.
Using a wire-line system, a large amount of samples were obtained (mainly cores of the fault gouge, a very representative fault rock generated by seismic efforts), the borehole intersected different materials with different characteristics, at 174.00 a failure related with a stuck in the drilling strings was produced, while trying to trip out the hole (extract the pipes), the last meters of drilling strings were locked at the bottom of the well.

On July 2016, a second borehole, FAMSISIGN, was drilled at 150 meters from the FAM-1, the purpose of the well was to introduce a seismograph at 50 meters depth, directly in the fault rock. The borehole was also used to observe the drilled materials, as the figure 3 shows it was located in more recent materials, closer to the footwall block of the fault.

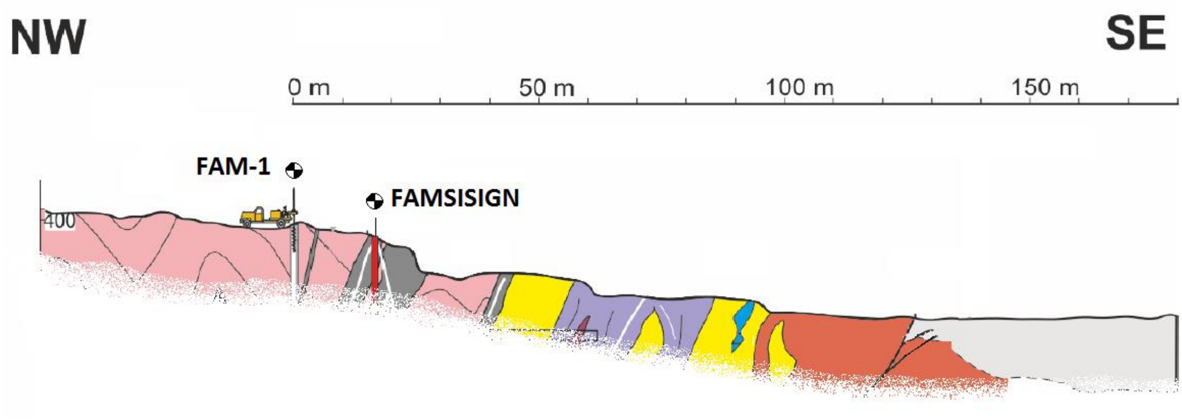


Figure 3 Location of boreholes FAM-1 and FAMSISIGN.

1.3 FAILURE PROBLEMATIC IN THE BOREHOLES, description

Borehole FAM-1 was expected to reach a depth of 200 meters, the operation ran fast and without any technical problem along the first 165 meters. The borehole drilled perfectly through quartz-schists and phyllites (hard rocks with a high grade of fracturing) and through the first 80 meters of fault rocks (breccias and gouges).
The borehole ran perfectly until the 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 at 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.
This failure is known as "stuck pipe", is a very common failure that can be produced by several causes that will be evaluated in this work.

The drilling rig was not capable to rotate, extract the strings or continue drilling, the failure was produced progressively, starting with a large energy demand to produce rotation that finished with the non-possibility to rotate, push or pull the drill strings.
Once the stuck pipe phenomenon initiated, the mud flow also started to decrease progressively, and finally stopped completely, the mud circulation could not be re-started once the pumping rate was reduced to zero.

As occurred in the FAM-1, and to corroborate that the failure is associated to a change in the lithology, the machinery of FAMSISIGN had a failure when the drilled materials started a transition between the "fault gouge" to the blue phyllitic formation. 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.

After some significant efforts, the strings were recovered, but was impossible to reach the objective of 50 meters to install the seismograph. The final decision was to install the seismograph at a depth of 35 meters.
This coincidence of the failure in both boreholes led us to think that the failures could be related with the drilled materials and the perforation methodology.

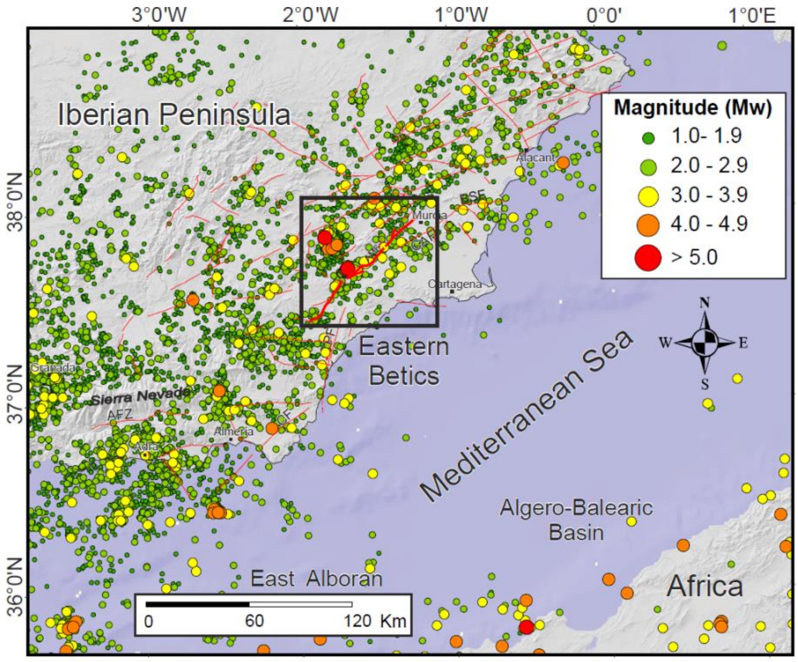
An analysis of the materials that could potentially cause sticking problems in the borehole is the main objective of this work, thus, the presence of swelling clays, the plasticity of the materials where the failure occurred, grain size analysis, frictional angles formations tilts and other studies will be developed in this work. The decision of the cores selected will be explained in the corresponding chapter, as well as the results of each test. Taking into account the different results (positive and negative), a final conclusion will be exposed considering these results.

2-GEOLOGICAL CONTEXT

2.1 FAULT OF ALHAMA

The Alhama de Murcia Fault (AMF), where the boreholes are located, is a strike-slip shear fault, with reverse component, located in the eastern Betic Cordillera and crossing it with a NE-SW direction. 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 major part of the important earthquakes that occurred in the area of the Betic Cordillera are related with the AMF (figure 4, *Martinez-Diaz etal., 2012).*

As can be appreciated in the figure, the major earthquakes in the zone (Mw>4) have epicenters in the nearby areas to the AMF.



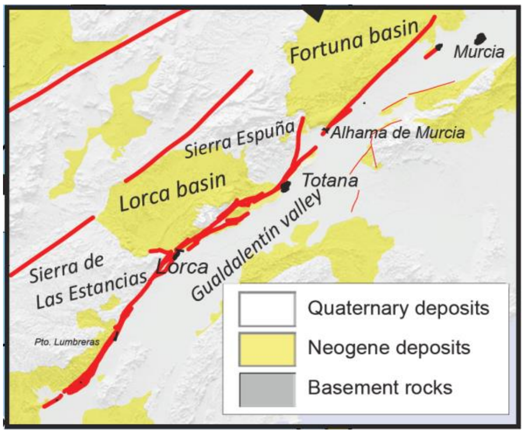


Figure 5: Location of the Alhama fault and the associated basins. . (Martínez-Díaz etal 2001)

Figure 4: Seismicity related with the fault of Alhama, expressed in moment magnitude, the fault is framed by the square. (Martínez-Díaz etal 2012)

Since Upper Miocene, the fault of Alhama is considered as a left-lateral strike slip fault, until that time, the fault behaved as a normal fault. The sinking of the hanging wall favored the formation of depressed basins associated to the fault, the main basins are Lorca and Fortuna basins, the extensional phase finished in Middle-late Miocene (Tortonian).*(Montenat etal.,1987).* Since Tortonian, the behavior of the area is a horizontal shortening under a compressive stress field with a NNW-SSE to NNE-SSW direction. There are some recent studies that evidence Quaternary activity under the same compressive stress.
Neotectonic analysis divided the fault into four main sections, each section has specific strike and structural features, (*Silva etal., 1992), the four sectors are, from north to south:* Murcia-Orihuela,

Alhama-Alcantarilla, Lorca-Totana and Overa-Lorca. The area of study of this work is located in the Lorca-Totana segment. Several studies inform that this segment is the one with higher reverse component, the evidences are the wide number of earthquakes with intensity I >VI linked to this section (Lorca, 1579, 1674, 1818 y 1977).

2.2 MATERIALS IN THE AREA ASSOCIATED WITH THE FAULT.

The objective of the borehole FAM-1 was to perforate through the materials present in the fault, obtaining samples along the borehole.

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 6) due to that, the fault presents a very heterogeneous zone that locally can reach more than 150 meters of thickness.

It is possible to observe a tectonic layering sub-parallel to the fault plane, the reologic behavior of the different materials is very diverse, and it is possible to observe brittle deformation in the more competent materials and ductile deformation around them of the less competent materials. (*Rodriguez-Escudero etal 2014*).

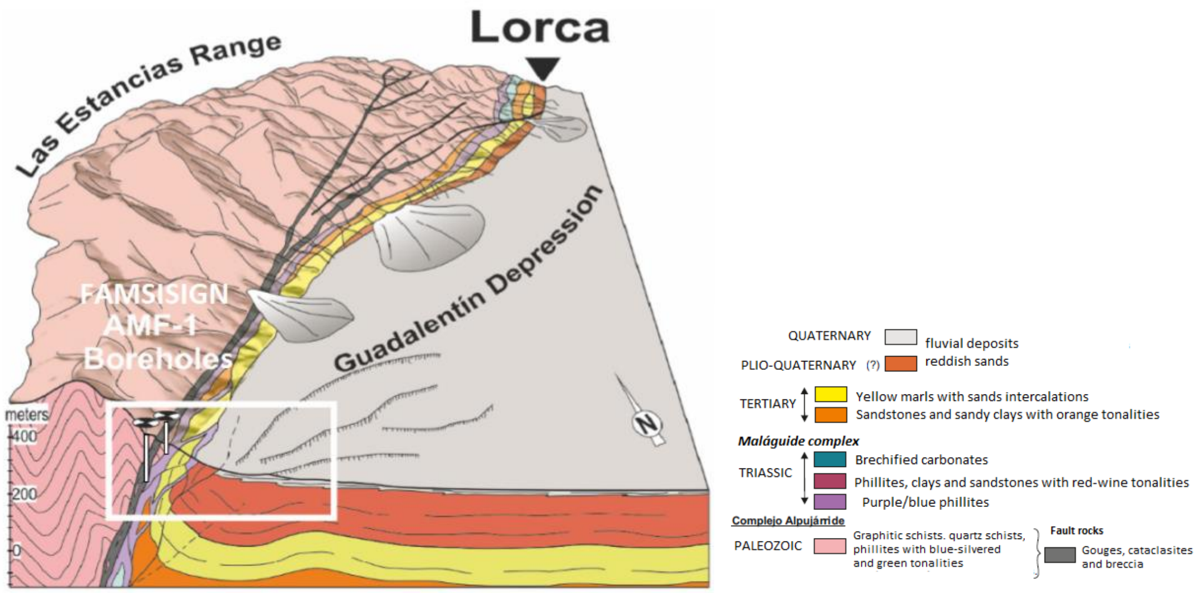


Figure 6 Geomorphological representation of the fault of Alhama and the associated materials. (Martínez-Díaz etal.,2016)

2.2.1 Materials present in the geological cartography

A detailed geological cartography was created before the perforation of the well. The purpose was to locate the borehole in an optimal position, and be able to cross the major number of formations, or, at least, the totality of the fault gouge, a wide layer of fault rock that was the objective of the project.

A preliminary description of the materials was first made, using the field data obtained during the cartography, the observation of trenches and the previous general studies that exist (Magna 975,1971 and Magna 953,1972).

Borehole FAM-1 was located in the hanging wall of the fault. And it is pretended to cross the sub-vertical formations associated to the fault (figure 7).

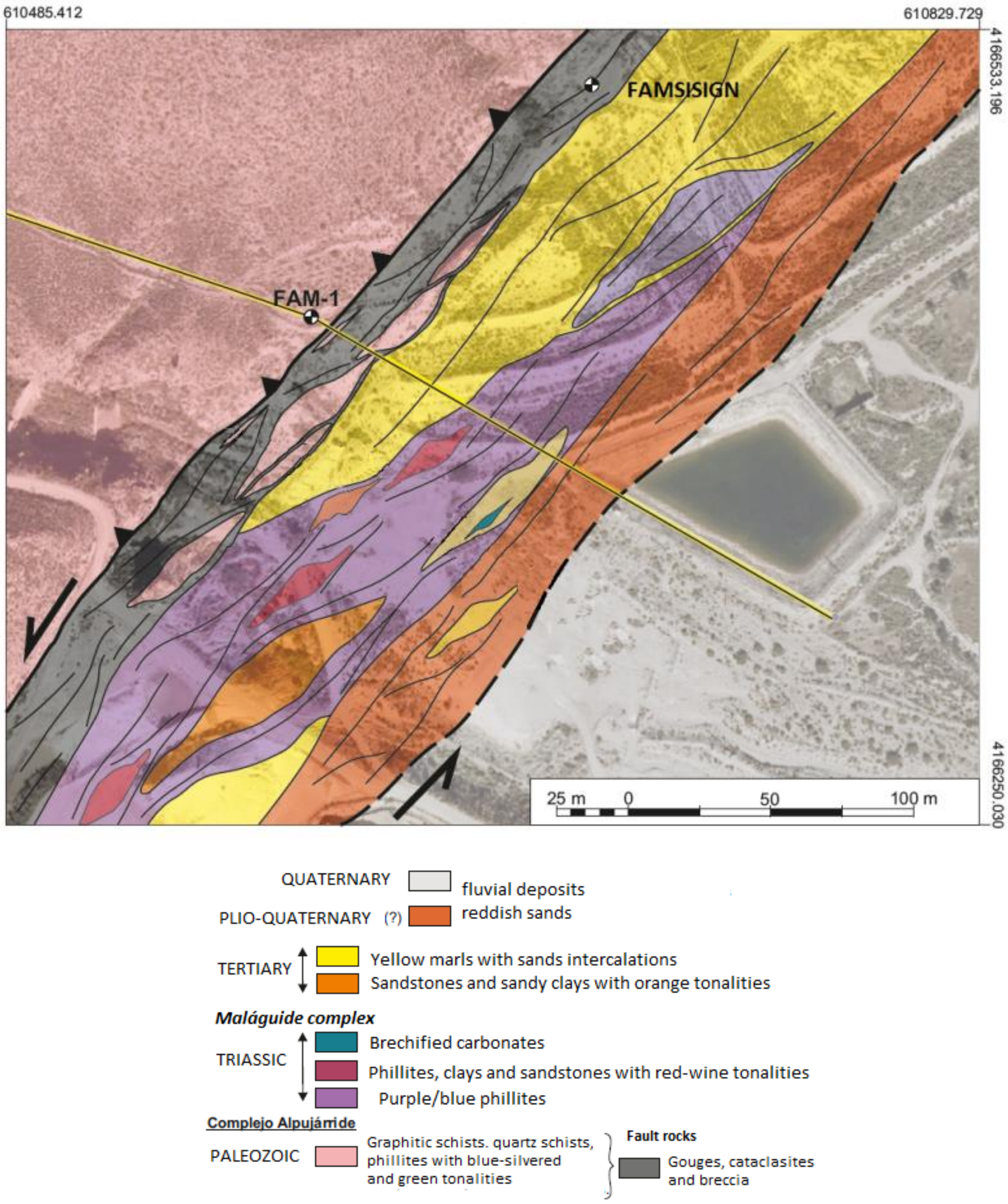


Figure 7 Geological cartography of the area.

The main materials that were predicted to be drilled are the next :

Paleozoic:

Alpujárride Complex:

- Schists and phyllites: Very weathered superficial level, with altered schists and phyllites. With depth increment changes to unaltered schists and quartz-schists. Phyllites and quartzites crossed by veins of quartz.

In alternance with the following materials, very fractured blocks of schists and quartz-schists of metric to decametric thickness (in some cases decimetric blocks). High content of graphite giving black-grey-silvered tonalities.

- Fault rocks: gouges, cataclasites and breccia derivated from the schists. Formed by a cataclastic matrix with high content in limes and clays that includes milimetric to decimetric fragments of schists. Presence of fragments of quartz very fractured. Black tonalities due to the presence of graphite.

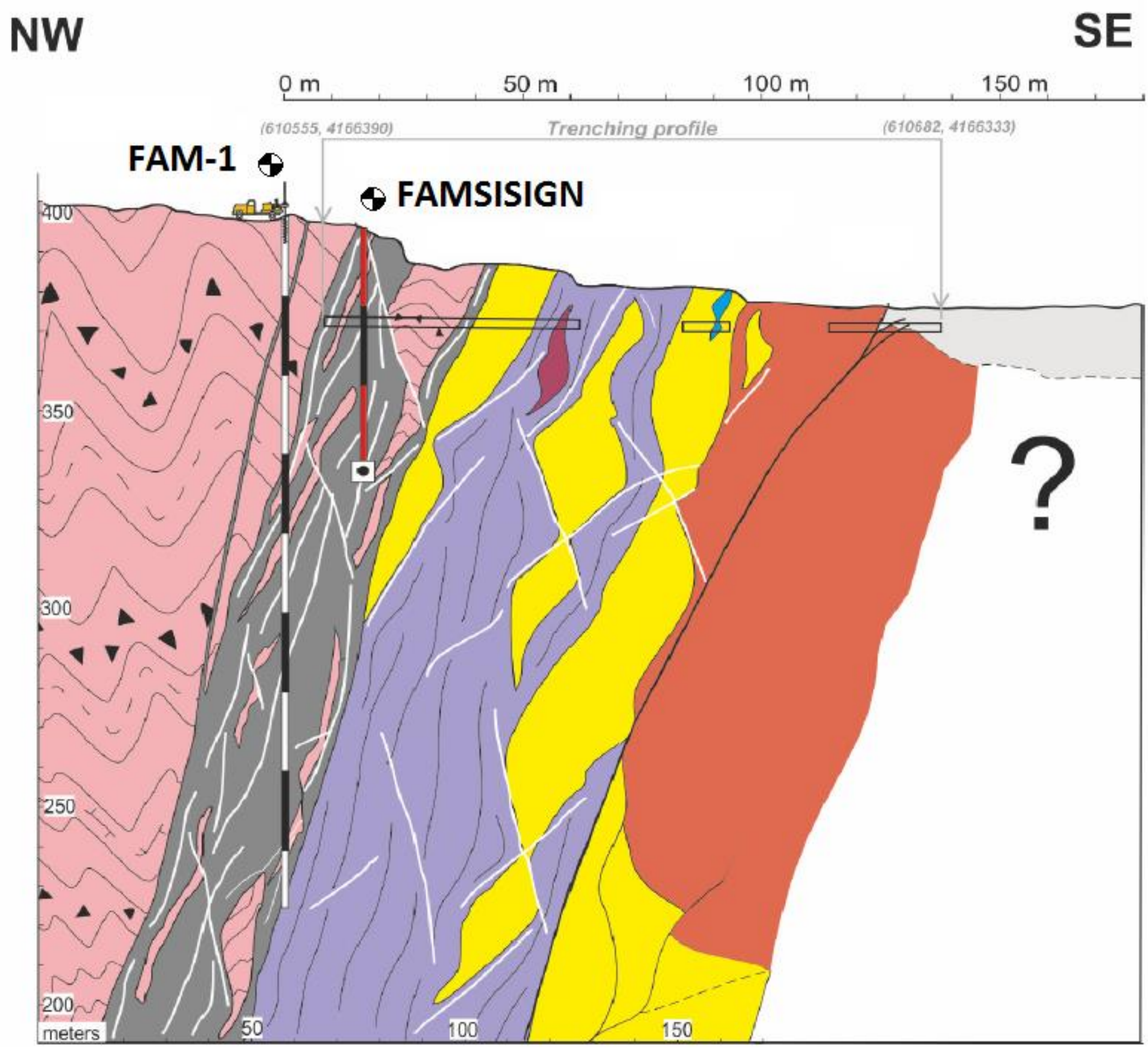


Figure 8 Schematic geological cross-section of the boreholes. (Martínez-Díaz etal., 2016)

Triassic:

Maláguide Complex:

-Purple/blue phyllites: sheared phyllites that appear into the fault zone with a cataclastic matrix of very fine grain (lime or clay).

-Phyllites, clays and sandstones with red-wine tonalities.

-Brechified carbonates: Not present in the surface but locally have enough importance to be considered.

Tertiary:

-Yellow marls with sands intercalations: Included in the fault zone, very sheared, could contain inclusions of purple phyllites and limes with orange tonalities.

The location of the borehole FAMSISIGN was some meters closer to the footwall of the AMF, the purpose of this location was to obtain more information than what FAM-1 reached (figure 8). Due to the dipping of the semi-vertical layers of the fault, the borehole reached the blue phyllites at a shallower depth than FAM-1. This relationship between the cross sections and the position of the boreholes will be explained more accurately in the following chapter.

3. BOREHOLE PARAMETERS AND CORE ANALYSIS

3.1 TECHNICAL CHARACTERISTICS OF THE BOREHOLES

For the present work, it is interesting to evaluate the technical conditions of a wire-line borehole with triple tube drilled directly in an active fault zone. Generally, this coring method has less penetration rate than other techniques, and the cost/meter is relatively high. However, the sample is generally superior to that collected using a conventional barrel.

Larger diameters may be more beneficial in the sampling of the faulted rock, using a triple tube where the core is collected into a metal or plastic liner that is placed within the core-barrel. The core is slightly smaller (PQ3=83.0mm, HQ3=61.1mm), but there is so much less sample disruption.

The used wire-line sampling systems are designed to core a telescoped hole where smaller standard sizes are designed to core through larger sizes (PQ>HQ). Therefore, if penetration is stopped, rods can be left in the hole as casing, and the next smaller size system can be used to continue coring.

Boreholes FAM-1 and FAMSISIGN used wire-line core catching method to obtain samples along the well.

BOREHOLE	OBJECTIVE	COORDINATES		DATES		DRILLING RIG	DEPTH	DIAMETER
		X	Y	start	end			
FAM-1	Scientific	-1.746662	37.638405	10/07/2015	25/07/2015	Segoqui-09	174	PQ-HQ
FAMSISIGN	Scienfic	1.745355	37.639119	13/07/2016	22/07/2016	Segoqui-06	35	PQ

Table 2 Technical characteristics of the boreholes.

3.1.2 -FAM-1, technical characteristics

The borehole FAM-1 was drilled using a machine Segoqui-09, and with a wire-line core recuperation method.

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 machine uses 75Kw of maximum power at 1800 rpm. The maximum torque is 800 kgm, a maximum pull of 10 000 kg and a maximum push of 4500kg.

The water necessary for the drilling was obtained from a nearby artificial water reservoir destined to agricultural uses. That water was pumped from the reservoir to the mud pits.

The core recuperation along the borehole was very high, reaching a final average of the 80% of the total depth of the well. 31 core boxes where filled, reaching around 155 meters of cores.

Also unaltered samples where obtained (9 paraffined and 18 encapsulated), these cores will be used for laboratory analysis and will give relevant information to justify the several hypothesis that are exposed for the final work.

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.

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 diameters PQ-3 and HQ-3.

3.1.3 FAMSISIGN, technical characteristics

The borehole FAMSISIGN was drilled using a drilling rig Segoqui-06 with a wire-line core recuperation method.

The diameter used was PQ-3 (83mm).

The water necessary for the perforation was brought in a water tanker truck and stored in auxiliary water pits before passing to the mud pit.

The drilling machine uses 57kw (78 H.P) of maximum power at 800 r.p.m. The maximum torque is 600 kgm, a maximum extraction of 5000kg and a maximum push of 2500 kg.

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, according to the manufacturer.

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.

3.2 MATERIALS DRILLED

Due to the location of the boreholes, the materials drilled were exactly the same. Borehole FAM-1 was located further in the hanging wall of the fault (figure 8) thus it crossed a larger amount of materials in comparison with FAMSISIGN, which was located closer to the footwall of the fault. The resulting analysis from FAM-1 was performed more accurately, due to the purpose of the borehole. FAMSISIGN drilled exactly the same materials but reaching a shallower depth.

In relation with well inclination and orientation, a fault can influence directional control, hole inclination, and doglegs (rapid changes in direction). In general, holes tend to curve into a fault, particularly when the core hole and the fault are both at steep angles that was our case, the fault was dipping 70º (30º from the axis of the vertical well). Due to this circumstances, the drill bit can become "trapped" within a fault and wander down a soft component, unable to scape. In most cases, and if it is possible, it is better to plan crossing the fault at as high an angle as possible, that was not possible to realize in the boreholes FAM-1 and FAMSISIGN.

The wells were drilled practically vertical, with a maximum deviation of 3º from the vertical axis, this conclusion was justified by geophysical analysis in the borehole using a clinometer.

Altered schists and phyllites:

Schists with fine-medium grain size, presence of levels with crystals of quartz mm to cm. The alteration by oxidation is very notable, giving reddish tonalities. (Figure 9-A) Folded factory. Alteration lasts until 16.90 m depth, below this depth it is not remarkable. There is presence of phyllites that share the same characteristics.

Weathering grade from III to V, being reduced with depth.

-RQD test results from poor to very poor rock quality (see annexes *A-RQD results for altered schists*).

-Discontinuities type S1, with rugosity level II-III, there is no presence of filling material in the fractures (see appendix-A, JRC results for altered schists).

Dipping angle variations from 35 to 60 degrees, with predominant dip angle of 65º *(see annexes A-Dip angles for the altered schists).*

Quartz-schists and phyllites:

Graphitic quartz schists, there are continuous alternations with levels of phyllites along all the borehole. Generally with well-developed foliation (Figure 9-B).

Abundant presence of levels of quartz mm to cm, the quartz structures presents the peculiarity of maintaining apparently the crystalline structure, but it is pulverized due to the effect of the impact of the seismic wave (Escudero etal 2014). The amount of quartz varies along the borehole apparently without a particular trend, it is observed due to variations in the color of the schist/phyllite.

Except two lenses of fault rock of around 1 meter thick located at 20.6 and 63.60, and a level of black limestones 1.5 m thick at 41.70 meters, the alternation schists - phyllites is the predominant lithology until the 68.60 meters, where the fault gouge starts its presence.

-RQD test results gives qualitys from very poor to fair (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 (see annexe-A, JRC results for quartz-schists).

Dipping angle variations from 20 to 80 degrees, with predominant dip angle of 75º *(see annexes A-Dip angles for the quartz-schists).*

Black limestones:

Black limestones located in alternation with the quartz-schists and phyllites, from 41.70 to 43.10 meters. There is presence of milimetric veining of calcite. The dipping structure of the phyllites and schists is conserved. Isoclinal folding with stilolitic joints parallel to S1.

Fault Breccia:

Black graphitic sandy clay with angled fragments of schists with a length of . Centimetric debris of quartz, very fragmented, eventually pulverized. Debris from mm to centimetric from the protolite (original schists).

Very high concentration of graphite, giving the dark-grey – black colour.

S1 discontinuities disappear and a sub vertical schistosity appears with 70-90 dipping angles. There are observed lenticular and sigmoidal geometries with inverse cinematic criteria.

This material is a transition between the quartz-schists and the fault gouge, described next. In alternation with this material, there are observed metric blocks of schists. The thickness of this transition material goes from 68.60 to 81.70m.

"Fault gouge":

Black silty clay 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 9-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.
There are observed intercalations of clays in the quartz but remaining the structure.

Around the 135 meters, some variations in the grain size are observed, sand grain size lenses are present, and it coincides with a very low recuperation, this variations difficult very much the description of these materials.

Blue-violaceous phylliltes:

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 9-D)

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

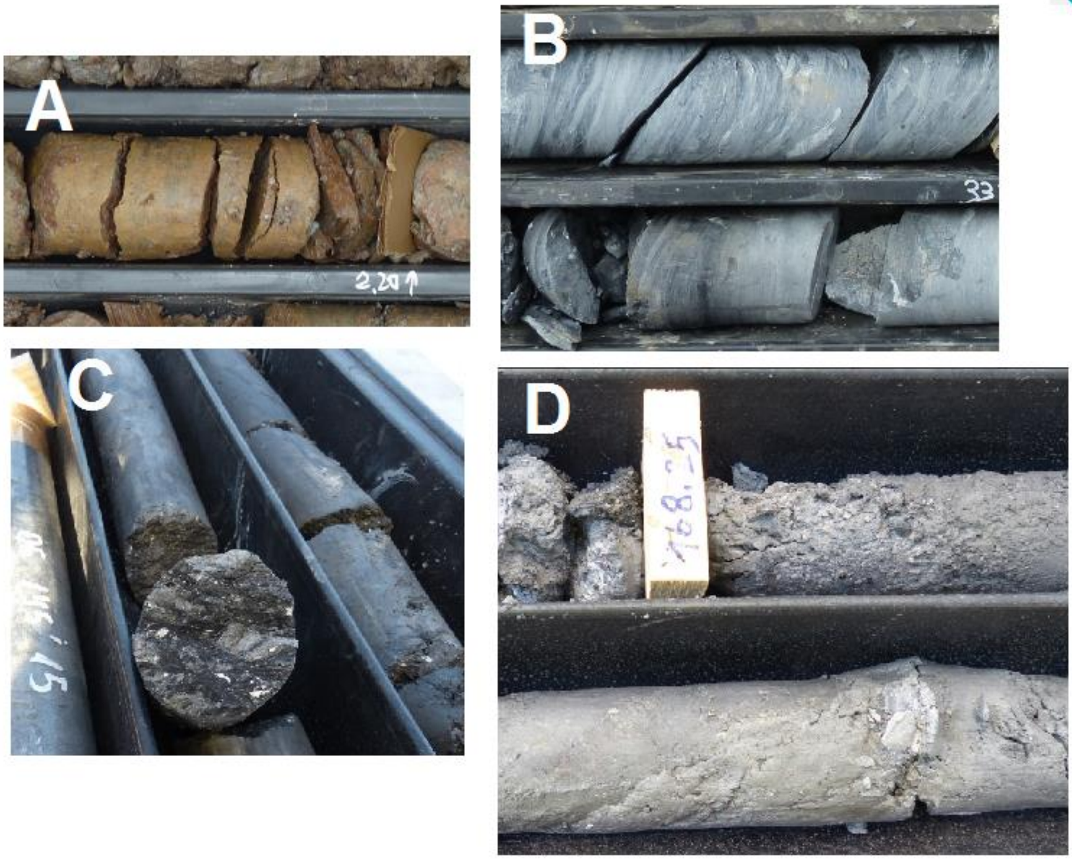


Figure 9 Appearance of the cores obtained in boreholes FAM-1 and FAMSISIGN. A) Altered schists, B) quartz-schists, C) Fault Gouge, D)Blue phyllites.

4. STUCK PIPE

Stuck pipe is a common failure that has been a problem since borehole drilling began started, almost a century ago. 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.

In this chapter, we are going to go deep in the three main types of pipe sticking in relation with the cases of pipe stuck in boreholes FAM-1 and FAMSISIGN. The objective is to analyse the possible causes that could have produced this type of sticking with the purpose of analyse and demonstrate, if it is possible, the different reasons that could have produced the failure. Analysing the drilled materials and the technical properties of the boreholes we will try to reach an explanation for the sticking pipe failures that occurred in both boreholes.

It is important to note that in this chapter we are going to make reference to shales in many times, instead of the materials drilled, many metamorphic materials as phyllites and schists can be considered shales in terms of drilling engineering (Azar and Samuel, 2009). In this work we are going to consider the fault gouge and the blue phyllites materials as shales with low grade of metamorphism.

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.

When the differential pressure between mud and formation is large enough, the strings are pushed towards the borehole wall, (figure 10) reaching enough pinning force to impede rotation and pulling the strings. This happens when the pipe is not rotating.

The pinning force is the pressure difference times the contact area between drill collar or pipe, and the mud cake. According to coulomb friction model, the over pull required to free the drill string is the pinning force times the friction factor.

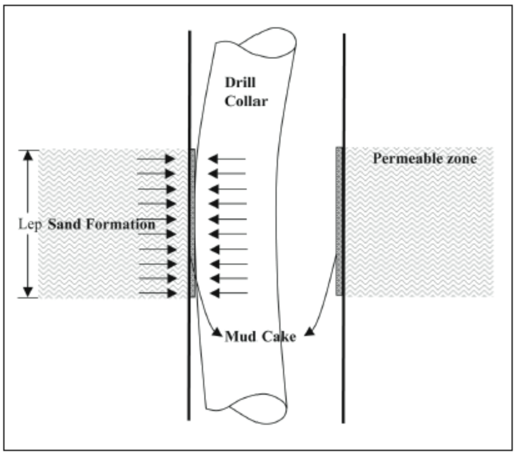


Figure 10 Differential pressure stuck pipe. (J.J.Azar and Samuel ,2007).

The differential pressure acting on the portion of the drill pipe that is embedded into the mud cake can be expressed as follows:

$$\Delta P = Pm - Pff. \qquad 4.1.1$$

As higher is the differential pressure, larger will be the probability pf having a sticking pipe in this section (figure 11)

The pull force, Fpull that is required in order to free the stuck pipe is a function of the differential pressure, ΔP; the coefficient of friction, μ; and the total contact area, Ac, between the pipe and mud cake surfaces:

$$Fpull = \mu Ac\Delta P \qquad 4.1.2$$

The coefficient of friction, μ, can vary from less than 0.04, for oil-based muds, to as much as 0.35, being generally 0.3 or 0.4 for weighted water-based muds with no lubricants added. The contact area, Ac, can be expressed in terms of the arc length, Ψarc, and length of the pipe body portion, L_{ep}, that are embedded in mud cake. The arc length is given as follows:

$$\Psi_{\mathrm{arc}} = 2\sqrt{\left(\frac{D_{\mathrm{h}}}{2} - t_{\mathrm{mc}}\right)^2 - \left(\frac{D_{\mathrm{h}}}{2} - t_{\mathrm{mc}}\frac{D_{\mathrm{h}} - t_{\mathrm{mc}}}{D_{\mathrm{h}} - D_{\mathrm{op}}}\right)^2} \qquad 4.1.3$$

D_{op} must be equal to or greater than 2tmc and equal to or less than (Dh – t_{mc}) where Dh is the hole diameter D_{op} is the outer pipe diameter tmc is the mud cake thickness.

D_{op} must be equal to or greater than 2tmc and equal to or less than Dh – t_{mc}.

Thus, the contact area can be expressed as follows:

$$Ac = \Psi arcL_{ep} \qquad 4.1.4$$

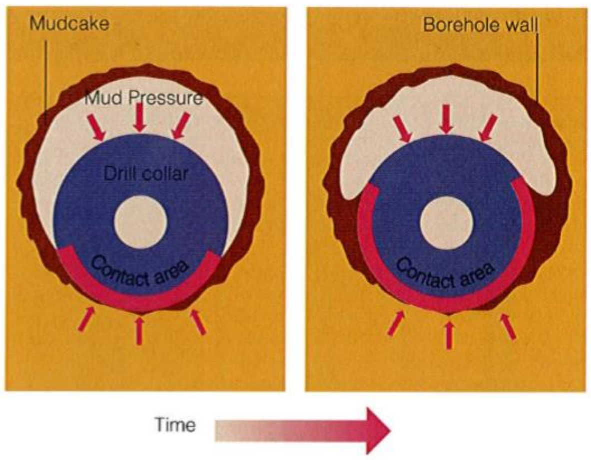


Figure 11 Annular space in differential sticking. (Bailey etal 1991)

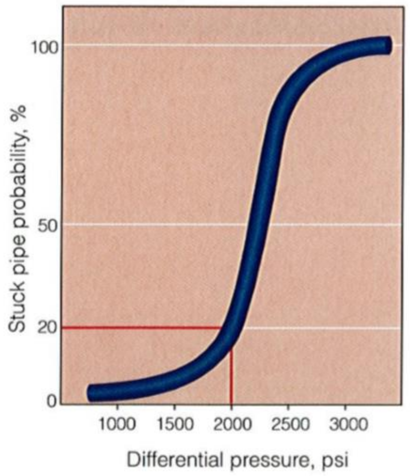


Figure 12 Probability of sticking pipe in relation with ΔP. (Bailey etal 1991)

Some indicators of differential pressure stuck pipe while drilling permeable zones or known depleted-pressure zones are:

- Increase in torque and drag.
- Inability to reciprocate the drill string and, in some cases, difficulty in rotating it.
- Drilling-fluid circulation is not interrupted.

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.

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. Through this chapter, we are going to evaluate the possible formation-related failures that would have constricted the strings.

4.2.1 <u>Swelling clays sticking:</u>

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. (Figure 13)

The reason of swelling is the presence of clays in their structure that react with water; a process called hydration which results in formation swelling. All swelling clays are potential causes of stuck pipe their concentration within a large magnitude in the formation, generally, when the formation contains montmorillonite or smectite the probability increases a lot. If the rock wall does not reach the pipe when it swells, it also reduced the annular space and avoids the correct evacuation of solids.

The utilization of water-base muds in reactive formations can cause clays hydration, creating a rough borehole wall (figure 14). This rough wall 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 a free swelling test to determine the capacity of the material to swell in presence of water.

If the results are positive and large enough, the failure could have been produced by a hole diameter reduction caused by reactive formations.

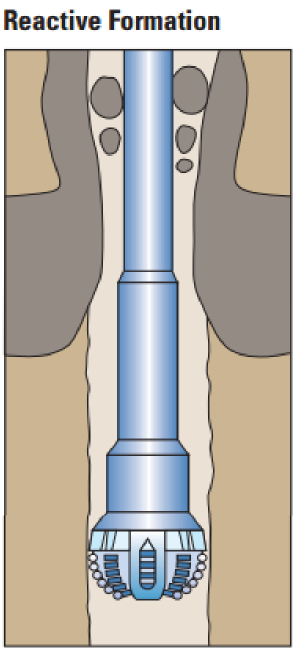


Figure 13 Pipe sticking due to clay swelling. (Lake, 2005)

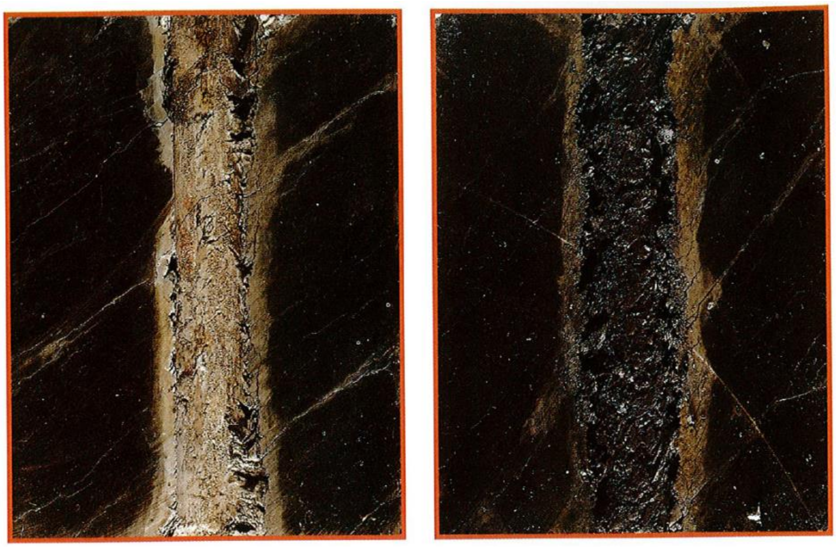


Figure 14 wall produced by clay swelling (right) in comparison with no swelling formation (left). (Bailey etal, 2008)

4.2.2 <u>Unconsolidated formations</u>

This type of failure id generally produced in zones that cannot support the hydrostatic overbalance alone. When this occurs, the material often falls into de hole and pack off around the drilling strings (see figure 15).

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. To drill these formations, the mud should provide a good- quality filter cake to consolidate the formation and prevent it from washouts, an excessive hole enlargement caused by erosion due to the high mudflow intensity near the drill bit, or due to the low cohesion of the materials drilled.

This failure is closely related with the muds saturation, another problem related with accumulation of material in the drilling fluids.

Problems also occur if insufficient filter cake is deposited on loose, unconsolidated sand to prevent it from "flowing" into the wellbore and packing off the string.

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.

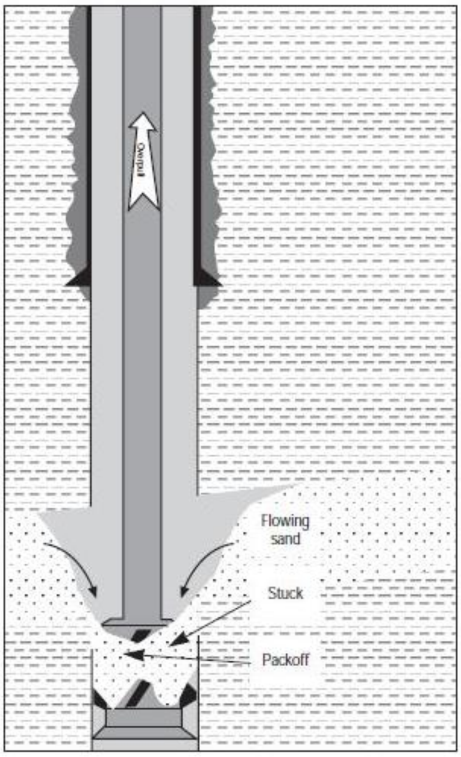


Figure 15 Pack off caused by unconsolidated formations (J.J.Azar and Samuel ,2007)

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 (effective overburden stress and effective horizontal confining stresses). While the borehole is being drilled, the balance between the rock strength and the in-situ stresses starts being disturbed. This perturbation, and the additional action of the drilling fluids, can contribute to this perturbation of the equilibrium. These factors can contribute to potentially cause an instability problem in the walls of the borehole.

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, (figure 17) it is a potential source to stuck the pipe. This normally takes place in brittle rocks, but it also can occur in weak rocks.

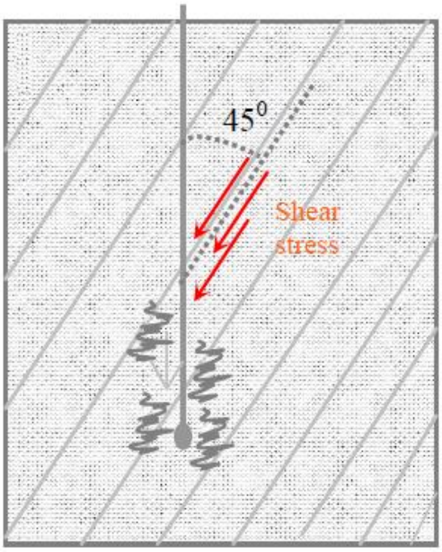
Mainly brittle formations are responsible of this type of failure, these formations cause brittle shear failure generating cavings.
The shape of the cavings will vary depending of the failure mode that is acting, it can be shear or radial tensile failure mode.
Shear failure may occur when the shear stress is maximum at the borehole wall, and failure will be initiated when it is maximized. Such situations can be found when pressure increases and effective stress decrease quickly near the wellbore wall.

On the other hand, tensile failure occurs when the tangential stress is equal to the tensile strength of the rock, which occurs more commonly in sedimentary and unconsolidated rocks, in these conditions, only a few MPa can produce a failure.

Effect of bedding plane and lamination

The dipping angles of the formations is a very important criteria to analyze the potential instability while the borehole is being drilled. The orientation of the weak planes of the material should be taken into account if we want to avoid problematic drillings.

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.(figure 4.8) The maximum shear stress direction will follow the bedding plane and the material is weak in this direction. Thus, shear stress failure could be a potential reason for failure. An induced failure direction will be developed if the borehole is drilled at 45º (or closer angles) to the weak planes. So, drilling a well in such conditions is considered the highest risky possibility for mechanical borehole instability.



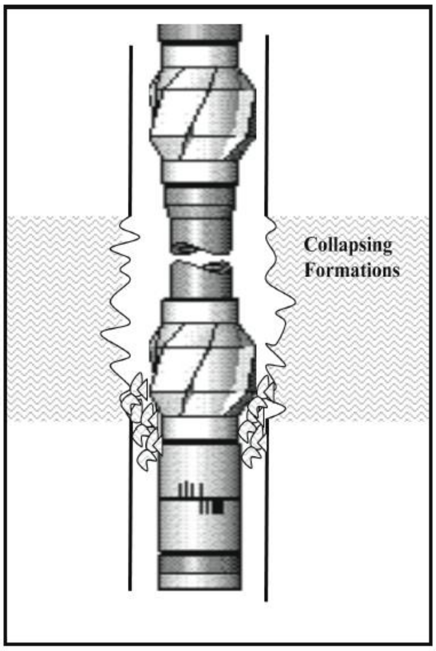


Figure 16 Direction of shear stress in the maximum failure probability of wall collapse. (Aminul Islam, 2009)

Figure 17 Borehole wall collapse caused by mechanical failure. (Qadir Tunio etal, 2011)

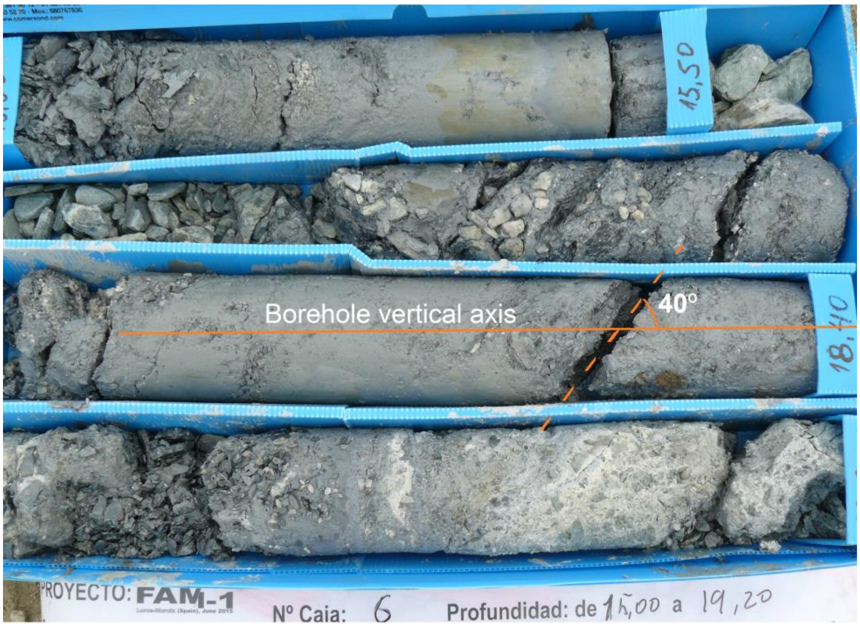


Figure 18 Dipping angles of the formation with respect of the vertical axis of the borehole

An 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. Borehole collapse occurs when the drilling-fluid pressure is too low to maintain the structural integrity of the drilled hole, the mud in use may not bring the altered stresses to the original state; consequently, shale may become mechanically unstable.

In the case of rock formations, the rock quality factor (RQD) must be taken into account in parallel with the orientation of the weak planes of the formations, it leads to think the presence of unstable formations in the boreholes. A study of the RQD has been developed, but only along the first 65 meters, after that depth, the material drilled has the behaviour of a soil and cannot be evaluated by RQD.

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.

The materials fill the annulus impeding the extraction of the strings, reducing the drilling fluids flow. The flow velocity reduction could produce the more fine particles to precipite at the bottom of the well, obstructing progressively the muds flowing and finally stucking the strings.

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. Sometimes it is referred as creep, and it is produced when the potentially plastic formation is liberated from its overburden pressure. With a low mud density, the drilling fluid is not capable to compensate the inward pressure caused by the flowing shale, and a sticking failure can be produced.

This problem is generally related to plastic shales and salt formations, and it is not commonly produced as shallower depths, thus would be very rare that the failure of boreholes FAM-1 and SISFAM-1 were related with inward flowing of plastic shales.

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. Although plasticity and swelling properties are going to be evaluated in separated chapters in this work.

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)

If cuttings are not totally removed from the borehole, they will accumulate in the well, eventually causing the hole to pack off, often around the Bottom-Hole Assembly (BHA) and sticking the drill string (Figure 19).

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).

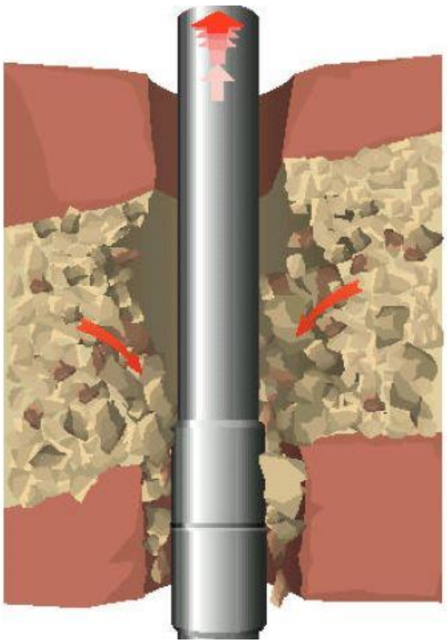


Figure 19 Hole pack off caused by a formation washout. (Larry W. Lake, 2005)

A common field practice is to circulate bottom up several times with the drill bit off bottom to flush out any cuttings bed that may be present before making a trip. Increases in torque/drag, and sometimes in circulating drill pipe pressure, are indications of large accumulations of cuttings in the annulus and of potential pipe-sticking problems.

Hole pack off can be generated by several reasons, being the most important the following:

-Drilling at excessive Rates of Penetration (ROP) for a given circulation rate. This generates cuttings faster than they can be circulated mechanically from the annulus.

-Inadequate annular hydraulics.

-Failure to suspend and carry cuttings to the surface with adequate mud rheology.

-Highly deviated well paths. High angle wells are more difficult to clean, since the drilled solids tend to fall to the low side of the hole. Beds of cuttings will form, which are not easily removed.

-Formation sloughing and packing off around the drill string.

-Not circulating enough to clean then hole before tripping out or making connections. When circulation is interrupted, cuttings may settle around the BHA and pack off, sticking the pipe.

-Drilling blind (without mud returns) and not adequately sweeping the hole periodically with a viscous mud.

-Few cuttings returning at the shakers relative to the drill rate and hole size.

-Formation washouts, where annular velocity decreases and cuttings accumulate.

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 <u>Key seating</u>

Key seating is a very common mechanical failure produced in boreholes where there is a large deviation of the strings (figure 20). 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. The optimal orientation should be crossing the formations perpendicularly, as closer is the dipping angle of the materials to the axis of the borehole, easier will be the well to deviate. In the boreholes of this study, formations were dipping 70º, what is 30º from the vertical axis of the borehole.

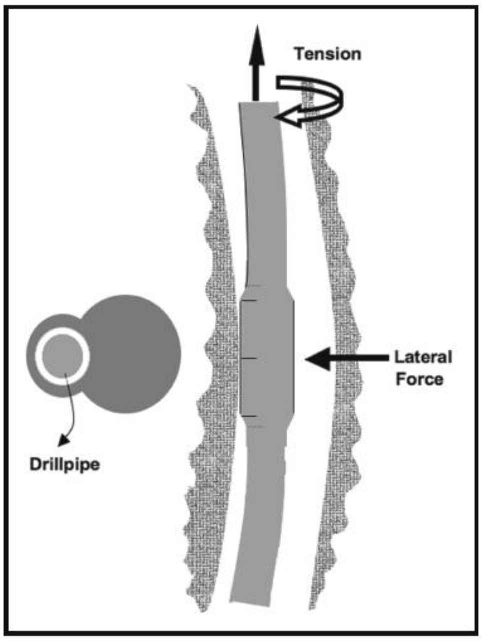


Figure 20 Pipe sticking caused by key seating.

A large lateral force produced by the deviation pushes the pipe against the wall, causing mechanical erosion. The lateral force is expressed by the next equation:

$$Fl = T \sin\theta_{dl} \qquad 4.3.2.1$$

Where Fl is the lateral force, T is the tension in the drill string just above the key seat area, and θ_{dl} is the abrupt change in the hole angle (commonly referred as the hole angle).

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 pipes, and the deviation normally coincide with a change in the lithology or in the dipping of the layers.

<u>Identification signs for Key Seating</u>

-This situation occurs when pulling out of the hole only.
-Circulation is not restricted.
-High over pull is suddenly seen when the BHA is pulled into the key seat.
-Tripping back is possible.

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, naming the fault gouge core as sample “reshaped-1” and the protolite core as “sample V-T”.

It has been determined the permeability 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.

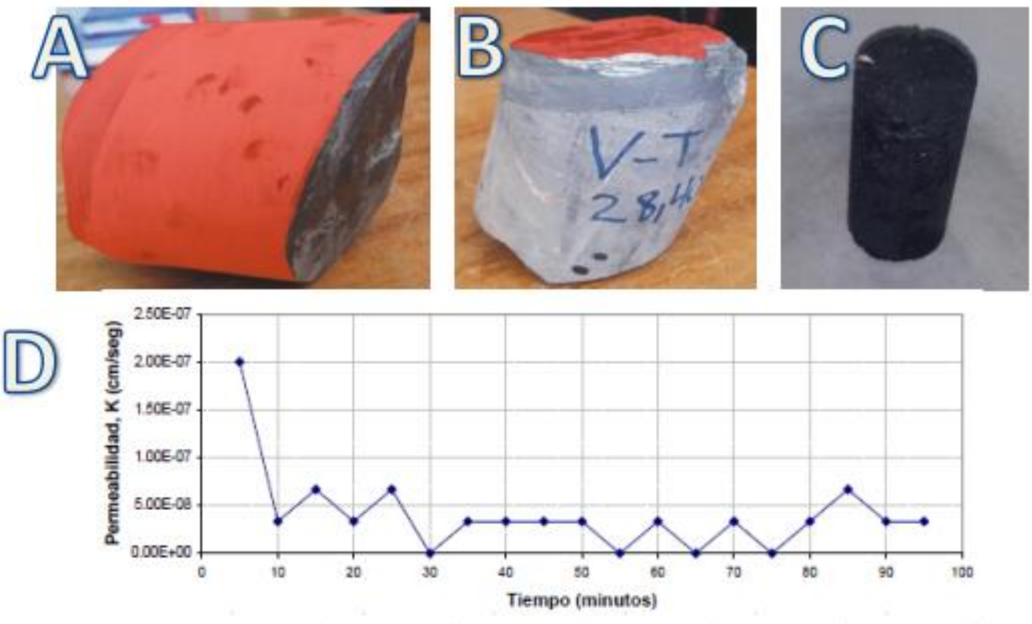


Figure 21 (Rodriguez Soto 2015-2016) A) sample V-T of the protolite where the test is made in the schistosity direction. B) Sample V-T where the test is made normal to the schistosity. C) Reshaped-1 sample of fault gouge where the test was made using triaxial cell. D) Resulting graph for permeability test of Reshaped-1 sample.

The sample has been compacted according to the standard regulations and the final density has closer values to the original values of the intact rock, the procedure consisted in 5 layers compacter by 15 hits of minipróctor in the Harvard mould.

The protolite core was tested using the air permeability test in two different directions in the Petrophysics lab of Geological Sciences at Complutense de Madrid University.

The first direction follows the foliation planes (schistosity), and the second in the normal of these planes.

SAMPLE	PERMEABILITY(Darcy)
V-T	2,63E-02
RESHAPED-1(following schistosity)	1,92E-02
RESHAPED-1(normal to schistosity)	2,28E-02

Table 3 Permeability results for the samples.

Taking the results into consideration, 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)

5.2.1 MINERALOGY OF THE FAULT GOUGE

The mineralogical composition of the fault gouge has been studied by X-ray Diffraction (DRX). The results show potasic and sodic micas (Paragonite), there is abundant presence of quartz, accompanied with 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. There is presence of kaolinite in all the samples but with large variations in the content, being always small amounts in comparison with the total of the sample. Also there was observed a small amount of graphite and smectite.

Also, using Electronic scanning microscopy (MEB), there is evidence of a cataclastic structure where appear a mixture of laminar minerals englobing the grains of quartz.

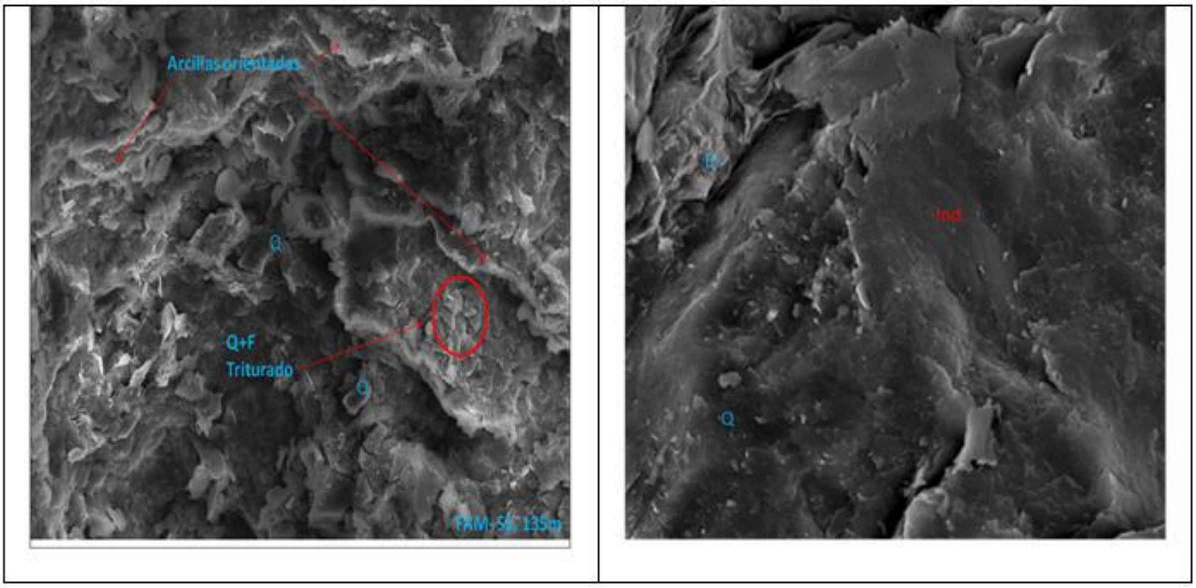


Figure 22: Microphotography of the simple of fault gouge.

<u>Formation of smectite in fault rocks due to the presence of fluids circulation:</u>

Fault rocks generated in shallow fault zones with brittle fracture generally contain rock fragments and a variable proportion of neo-formed minerals that, in many cases belong to the group of the clay minerals.

The results from x-ray diffraction revealed presence of clay minerals, between others, in the fault gouge, the results showed presence of smectite, a clay with swelling properties in presence of water.

This clay mineral has a fundamental role in the geotechnical behavior of the rocks. By this way, the plasticity, compressibility and swelling capacity are increased when the percentage of smectite is increased. (Grim, 1949, Seed etal., 1962, Terzaghi & Peck, 1967).

The amount of smectite and other swelling minerals will probably be very small to produce any type of swelling, nevertheless free expansion tests have been developed in this work to assure this. A negative result of this test will definitely neglect the possibility of a failure caused by reactive formations.

5.2.2 EXPANSION OF SMECTITE IN PRESENCE OF WATER

Clay minerals, such as smectites and mixed-layer illites, have the capacity to swell 20 times their original volume due to the incorporation of water molecules to their laminarstructure. These phylosillicates have this capacity because there is no hydrogen bonding between the octahedral layers of the unit cells.

The explanation of this is driven primarily by the balance between electrostatic and van der Waals forces between the layers of clay.

Swelling is known to occur in three steps. In the first step, referred to as crystalline swelling, layers of water enter the interlayer space in the clay mineral, resulting in an increase in the C spacing of the clay mineral in steps. The size of these steps is observed to be approximately equal to the diameter of the water molecule. Extremely large swelling pressures can be generated through such an expansion of the clay lattice. The next stage in swelling is referred to as hydration swelling. This is thought to occur through the hydration and dehydration of ions entering the interlayer region. (Anderson et al., *2010).*

<u>Prevention of clays swelling:</u>

It has been demonstrated that smectite and other swelling clays, reduces its expansion if the drilling is made in presence of KCl. Specifically, including this component in the drilling fluids the expansion will be reduced considerably.(Gdanski etal.1997).

Smectite and mixed-layer clays (illite and smectite) are the most water-sensitive, ion-exchanging clays and, hence, are most prone to swelling after ion exchange, thus, are the minerals that need a higher concentration of KCl if it is wanted to avoid the swelling. Several experimental analysis showed that a 7% KCl (1Molar) presence in the drilling fluids is enough to prevent the clays to swell.

This method is the most common in the oil and gas industries, used to prevent the borehole obstruction in presence of swelling clays, and also to avoid the clays to swell in the reservoir and reduce the fluids circulation.

5.2.3 SWELLING CLAYS IN SCIENTIPHIC BOREHOLES: THE IMPORTANCE OF THE DRILLING MUDS

Water-based drilling fluids, as the polymer used in boreholes FAM-1 and FAMSISIGN, are generally considered to be more environmentally acceptable than oil-based or synthetic-based fluids. However, the former type of drilling fluid facilitates clay hydration and swelling, which can lead to increase the problems in drilling operations.
For this reason, minimizing clay swelling is an important field of research. In order to reduce the extent of clay swelling effectively, its mechanism needs to be understood, so that efficient swelling inhibitors may be developed. Suitable clay swelling inhibitors must significantly reduce the hydration of the clay, and must also meet increasingly stringent environmental guidelines.
In the case of this study, the drilling mud used is planned to prevent clay swelling if it is correctly applied and in the correct concentrations in the mud pits.

The presence of clays swelling has been determined with the purpose of establish a hypothetical situation if the water-based mud did not reach its function.

In the hypothetical causes of the failure, the presence of swelling clays could reduce the diameter of the hole, gripping the pipe. Observing the failure characteristics, the pipe remained blocked in the bottom of the well, if the material had swelling properties, the diameter of the well would be reduced, sticking the barrels.

5.2.4 FREE SWELLING TEST RESULTS

-<u>Procedure</u>.

1-Sieving:

The objective is to separate the fine particles in order to use only the larger amount of clays in the oedometric tests, or at least the fraction < 2μm, where the swelling clays have been observed. Thus, the possible expansion would be quantified easily and more precisely. It is supposed that clays will pass the 0.075mm sieve, and the major part of the other materials that contain the core will remain in the previous sieves.

The samples that are going to be sieved must be dry, the sample was dried in an oven at temperatures of 50ºC for 48 hours, with the objective to accelerate the drying process.

The sieve used is 0.075 mm. Once the sample is sieved (figure 5.2.2, A and B), two swelling tests will be made, in order to quantify the expansiveness of the clays.

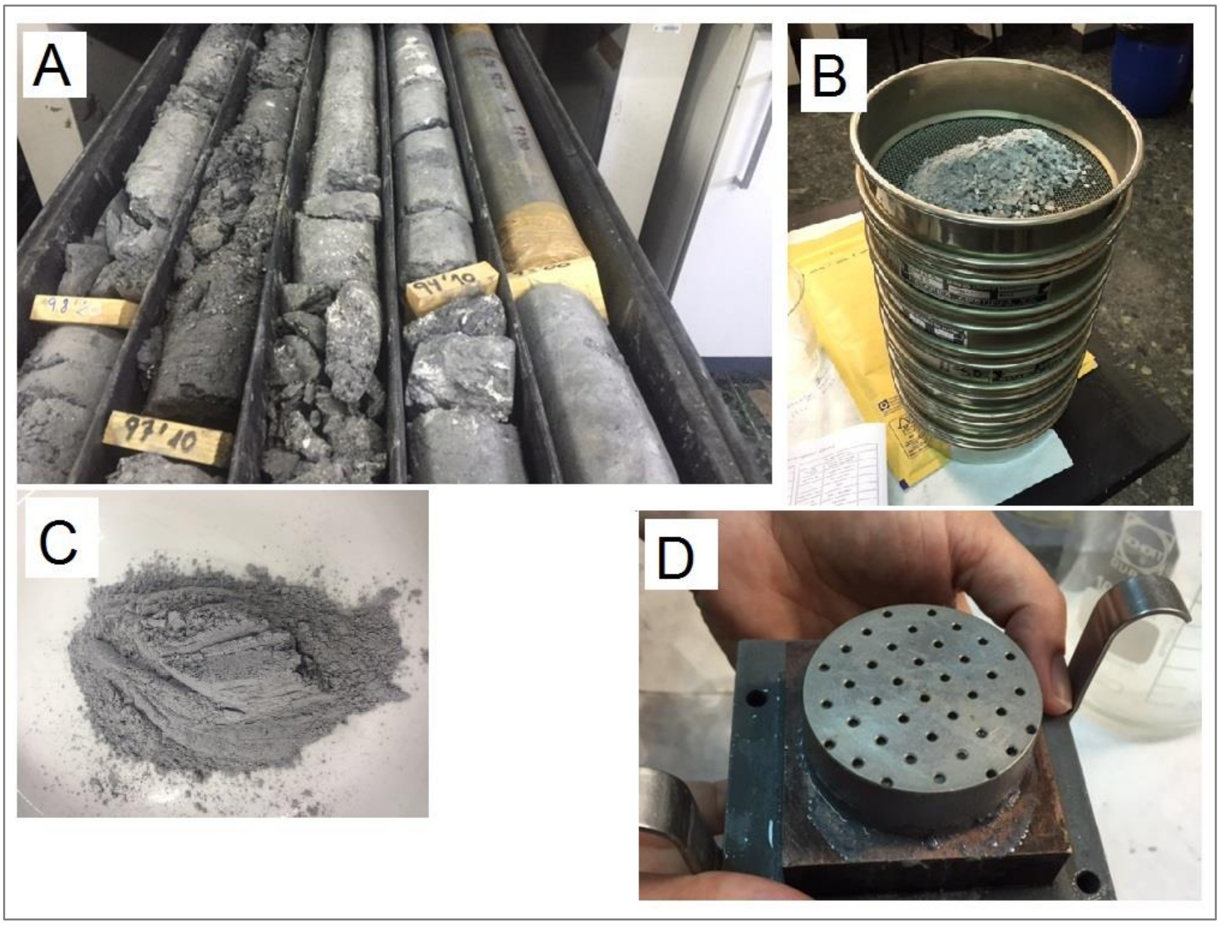


Figure 23 a) Core box containing part of the samples used in swelling test analysis. B) Sieving C) Sample fraction < 2µm D) Sample used in free swelling test.

2-Swelling test:

The target of this test is to determine the expansiveness or increment in volume of a sample of rock in cohesive soils. In expansive materials, the observed swelling depends of the compaction conditions. As drier is the sample, higher is the possibility for it to swell.

Free swelling test:

Allows the sample to swell when it in saturated with water. The sieved sample is placed in an oedometer (figure 24), the deformation indicator is turned to zero, and afterwards it is saturated with fresh water, until a level where the water only penetrates through the porous stone (with this we avoid the air to remain trapped inside the sample).

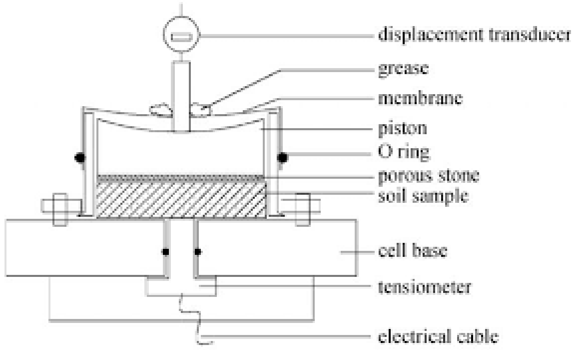


Figure 24 Oedometer.

The final swelling is measured and expressed in percentage in comparison if the initial thickness of the sample.

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.

In addition, the test was useful to corroborate the low plasticity index of the material, behaving practically as a fluid when the sample was hydrated, and flowing when it was liberated of the confining box.

5.3 CALIPER RESULTS

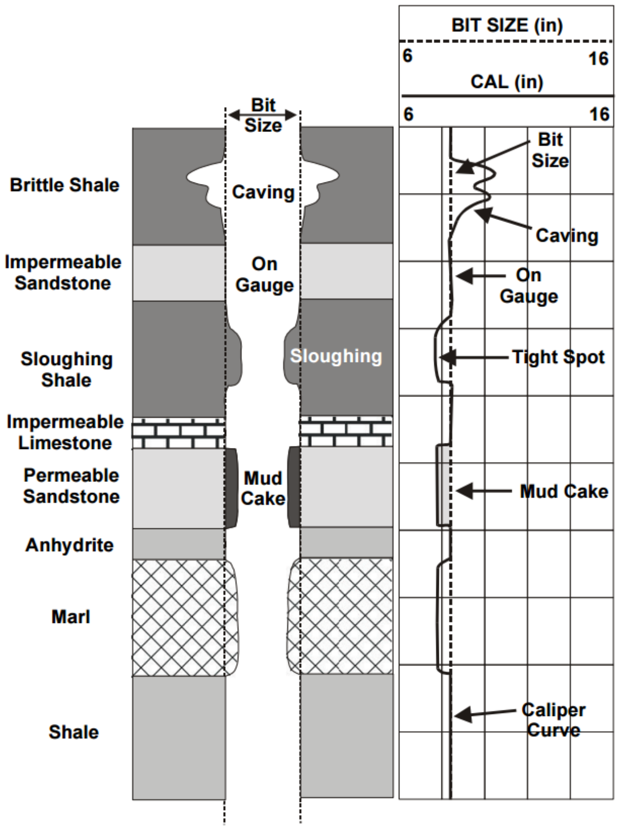
The Calliper Log is a tool for measuring the diameter and shape of a borehole. It uses a tool which has 2, 4, or more extendable arms. The arms can move in and out as the tool is withdrawn from the borehole, and the movement is converted into an electrical signal by a potentiometer.

The calliper can observe three main situations in function of the hole diameter registered:

<u>1. On Gauge</u>: Produced in well consolidated formations and non-permeable formations. Main examples are massive sandstones, calcareous shales, igneous rocks and metamorphic rocks.

<u>2. Larger than Bit Size</u>: in formations soluble in drilling mud, formations weak and cave in. Generally produced in salt formations drilled with fresh water, unconsolidated sands, gravels and brittle shales.

<u>3. Smaller than Bit Size</u>: in formations that tend to swell and flow into borehole, and where there is development of mud cake for porous and permeable formations. Produced in presence of swelling shales and porous-permeable sandstones.



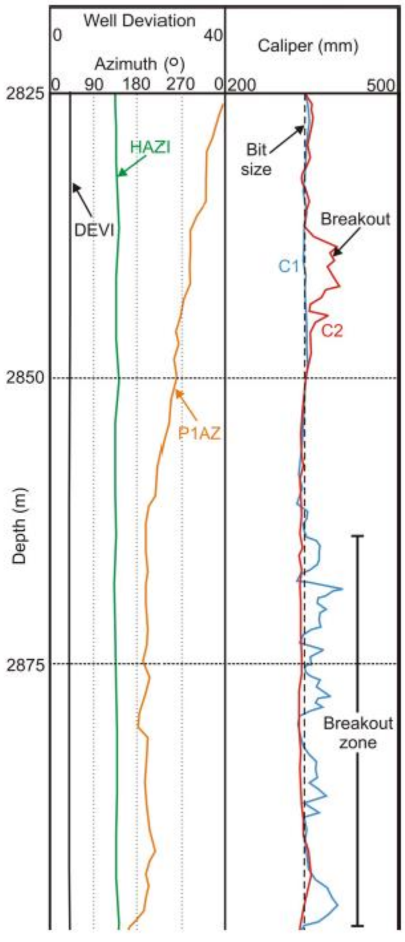


Figure 25 Formation conditions using calliper logging. (Reinecker etal. 2003)

Figure 26 Breakouts determination Guidelines calliper logs) (Reinecker etal. 2003)

Observing the results for borehole FAM-1 in Annex-C, it is possible to observe three main tendencies in the formations from 0 to 139 meters depth.

DEPTHS		**Relation calliper-bit size**	**Situation**
Top	**Bottom**		
0	27.5	Larger that bit size	Caving
27.5	65	On Gauge	Borehole wall stable
65	107	Larger that bit size	Caving
107	119	No logs	-
119	132.5	Larger that bit size	Caving
132.5	137.5	On Gauge	Borehole wall stable
137.5	139	Larger that bit size	Caving

Table 4 Calliper results for borehole FAM-1

It is important to note that the results do not reach the bottom of the well, where the blue phyllites appeared, thus, we cannot determine the behaviour of the formations at depths from 139 to 174m. But it is possible to have an approximation due to the continuity of the materials until 164.70m, the fault gouge is supposed to have a similar dynamic behaviour until this depth.

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.

Criteria for interpreting borehole breakouts from four-arm calliper data. (*Reinecker etal.*)

1. Tool rotation must cease in the zone of enlargement.

2. There must be clear tool rotation into and out of the enlargement zone.

3. The smaller calliper reading is close to bit size. Top and bottom of the breakout should be well marked.

4. Calliper difference has to exceed bit size by 10 %.

5. The enlargement orientation should not coincide with the high side of the borehole in wells deviated by more than 5°.

6. The length of the enlargement zone must be greater than 1 m.

Taking these considerations into account, the increment in the calliper observed in the boreholes are considered to be breakouts, they are well defined and exceed in more than a 10% the drilling bit size (enlargement of around 20mm in each breakout zone, which is more than a 10% considering the drilling bits used, PQ and HQ).

Figure C-02 in Annex-c shows the breakout zones present in the borehole.

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.

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

A measurement of the inclinations of the dipping angles in the boreholes have been done with the purpose of reaching a zone with more susceptibility to be unstable. As is showed in figure 4.8, the orientation and dip of the weak planes of the formations is a determinant factor of instability. An observation of the dipping angles of the weak angles of the formations in both boreholes has been developed, and it is showed in appendix-C.

The measurements have been taken with respect of the vertical axis of the borehole, that coincides with the vertical plane, deviation of the borehole have been neglected here, due to its small values (see chapter 5.7).

The results 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, see Appendix-c.

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 wider in the last 20 meters, see Appendix-C, figure C-03 and figure 27.

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, see Appendix-C, figure C-03.(figure 28).

Figure 27 Dipping angles of the weak planes of the formation with respect of the vertical axis of the FAM-1

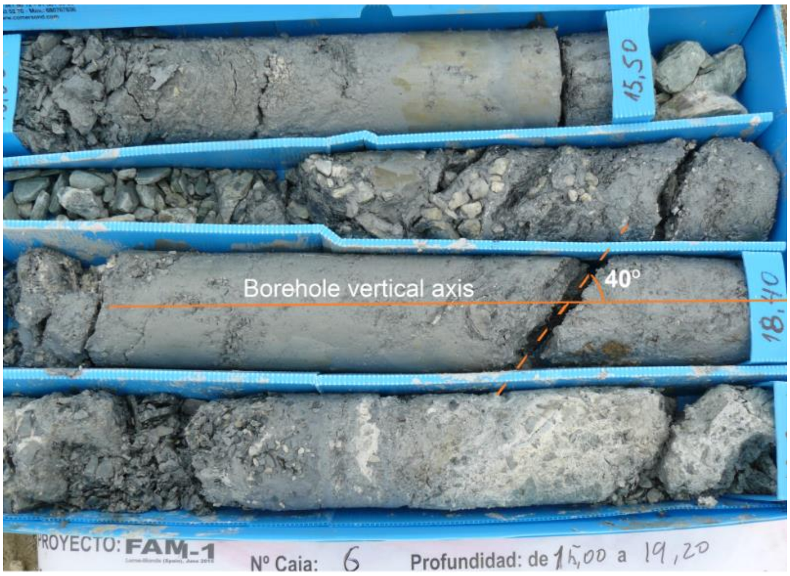


Figure 28 Dipping angles of the weak planes of the formation with respect of the vertical axis of the borehole FAM-1

In conclusion, what we can obtain from the evaluation of the dipping angles is that 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

With the purpose of evaluate the quality and stability of the formations, we have evaluated the core recovery percentages along the boreholes.

Core recovering gives information about the area that is being drilled, and has lower values in soft seams, fractures with edges that don't match, zones of decay, etc. (Geotechnical Engineering Bureau 2015).

Total core recovery is the total length of core recovered from a borehole as a percentage of the length of the borehole, it has been calculated using the next expression:

$$\text{TCR} = \frac{Lsum\ of\ pieces}{Ltotal} x\ 100$$

CORE RECOVERING (%)	QUALITY
0-25	POOR
25-50	FAIR
50-75	GOOD
75-100	EXCELLENT

Table 5 Core recovering percentages and quality of the rock based on the TCR.

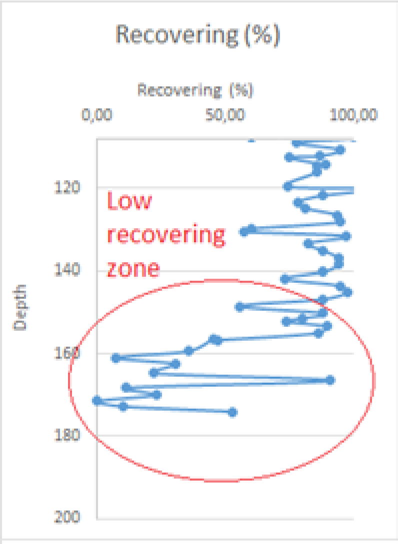


Figure 29, recovering percentages for the last 20 meters of borehole FAM-1

Observing the results of recovering represented using WellCad specific software, 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.

This information, matching with the increment in the dipping angles of the formations in the last meters, could imply more unstable zones in the borehole, where the cuttings and collapsed walls obstructed the annular space, producing the failure.

5.4.3 ROCK QUALITY DESIGNATION INDEX (RQD)

The Rock Quality Designation Index (RQD) is generally used to observe the rock quality of rock formations, is the only rock mass classification index available. To determine the engineering properties of rock masses, it is important to consider the effect of discontinuities.

RQD was proposed by Deere (1964) as a measure of the quality of borehole core. The RQD is defined as the ratio (in percentage) of the total length of sound core pieces that is 0.1 m (4 inch) or longer to the length of the core run. Besides the direct method for determining RQD from coring, different indirect methods are also available for evaluating RQD.

For determination of RQD using core boring, the International Society for Rock Mechanics (ISRM) recommended a core size of at least NX (size 54.7 mm) drilled with double-tube core barrel using a diamond bit. Artificial fractures can be identified by close fitting of cores and unstained surfaces. All the artificial fractures should be ignored while counting the core length for RQD. The correct procedure for determining RQD from coring is shown in Figure 30 (Zhang 2016).

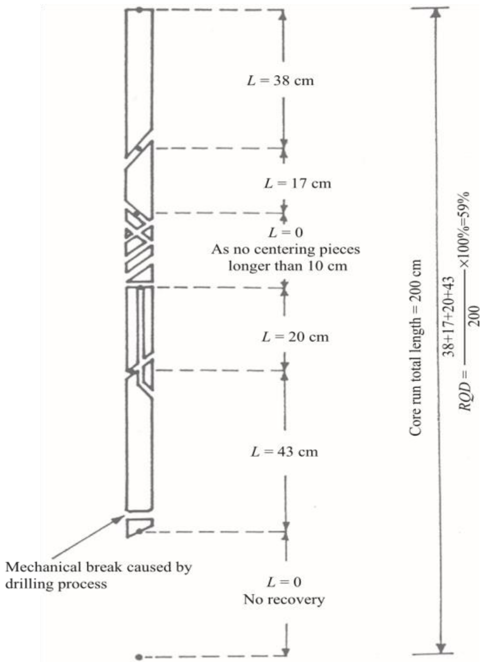


Figure 30 RQD calculation. (Zhang, 2016)

In the case of the present work, RQD can only be calculated in the first rock formations, once the material changes from the quartz-schists to the fault gouge, RQD cannot be calculated due to the soil behaviour of the fault gouge.

Thus, results of RQD are not very relevant due to hypothesis that in the boreholes, the failure was produced in the last meters of the boreholes, matching with the final meters of fault gouge and the transition between this material and the following blue-phyllites formation.

Elsewhere, RQD´s have been computed with the purpose of characterize the upper zones of the boreholes, mainly FAM-1, which have more longitude of schists drilled. FAMSISIGN was placed directly in the fault gouge materials and does not have coring of schists or other rocks.

The results of RQD for the altered schists and the quartz-schists are showed in Appendix-A, the rock formation existent from 0 to 68 meters depth show materials from poor to very poor qualities, with a reduced number of fair-good quality zones. Results are shown in appendix-A.

5.5 ATTERBERG LIMITS

Depending of the water content of a soil, it can change its behaviour. Atterberg limits are water contents at critical stages of soil behaviour. Evaluating the Attenberg limits will be possible to analyse the behaviour of the formation within the fault, when it is liberated from the confining pressure while the borehole is being drilled.

In the order of increasing moisture content, a dry soil will exist into four distinct states: from solid state, to semisolid state, to plastic state, and to liquid state. Between the solid and semisolid states is *shrinkage limit*, between semisolid and plastic states is *plastic limit*, and between plastic and liquid states is *liquid limit*.

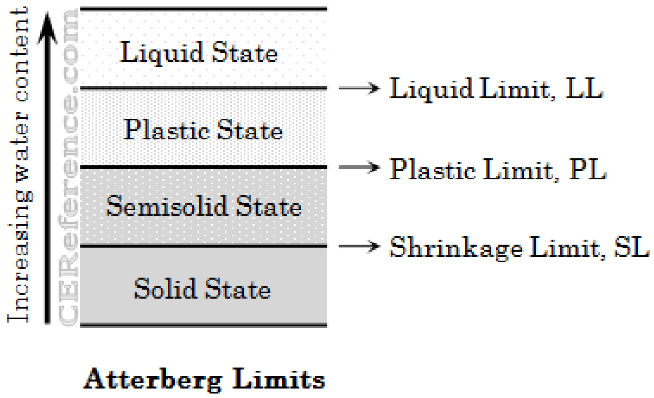


Figure 31 Atterberg limits (Mani etal. 2002)

Liquid Limit, LL: Liquid limit is the water content of soil in which soil grains are separated by water just enough for the soil mass to loss shear strength. A little higher than this water content will tend the soil to flow like viscous fluid while a little lower will cause the soil to behave as plastic.

Plastic Limit, PL: Plastic limit is the water content in which the soil will pass from plastic state to semi-solid state. Soil can no longer behave as plastic; any change in shape will cause the soil to show visible cracks.

Shrinkage Limit, SL: Shrinkage limit is the water content in which the soil no longer changes in volume regardless of further drying. It is the lowest water content possible for the soil to be completely saturated. Any lower than the shrinkage limit will cause the water to be partially saturated. This is the point in which soil will pass from semi-solid to solid state.

The purpose of the present analysis is to evaluate the amplitude of the plastic limit of the formation that potentially caused the stuck pipe with the purpose of determining if the material can behave plastically in the natural conditions within the fault.

Casagrande´s cup Method

Following the ASTM D 4318-84, Casagrande´s cup plastic limits laboratory test has been developed, using this criteria, the plastic limits are described as follows:

Liquid Limit, LL: The water content, in percentage, of a soil in a limit between liquid and solid states. The water content is defined as the amount of water where a small portion of soil with a cut in the middle and collocated in the Casagrande cup, will flow in the base of the cut a distance of 13mm (1/2 inches). When the cup it is hit by 25 hits falling 10mm in a standard apparatus of plastic limit operating 2 hits per second.

Plastic Limit, LP: The content of water, in percentage, of a soil between the plastic and shrinkage limits. The water content in the soil where it cannot be more deformed when it is rolled as a tube of 3.2mm (1/8 inches) of diameter without creating fractures on it.

Plasticity Index (IP): The water content range where the soil behaves plastically, numerically it is the difference between the liquid and the plastic limits.

Results:

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

Table 6 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

5.6.1 Accumulation of drilled materials in the annular space: cause of pipe sticking

Excessive drilled-cuttings accumulation in the annular space caused by improper cleaning of the hole can cause mechanical pipe sticking, particularly in directional-well drilling. The settling of a large amount of suspended cuttings to the bottom when the pump is shut down, or the downward sliding of a stationary-formed cuttings bed on the low side of a directional well can pack a bottom hole assembly (BHA), which causes pipe sticking. (Qadir Tunio etal 2011)

Excess solids of any type are the most undesirable contaminant of drilling fluids, because they affect all mud properties. It has been shown that fine solids, of micron and submicron size, are the most detrimental to the overall drilling efficiency and must be removed if they are not a necessary part of the mud makeup.

-Shape of the cuttings:

The size and distribution, the shape, and the specific gravity of cuttings affect their dynamic behavior in a flowing media. The specific gravity of most rocks is around 2.6 and therefore can be assumed as a nonvarying factor in cuttings transport.

The cuttings size and shape are functions of the bit types (roller cone, PDC, or diamond matrix), of the regrinding that takes place after they are generated, and further of breakage by their own bombardment and bombardment with the rotating drill string. Thus, it is impossible to control the size and shape of cuttings, even if a specific bit group has been selected to generate them. *(Azar and Samuel, 2009).*

Thus, the size and shape of the materials in suspension in the drilling mud cannot be determined, however, there are other factors that can be evaluated with the objective of stablish a relation between the failure and the drilling muds, this factors are the drilling polymer concentration in the mud pits and the recovering percentages.

5.6.2 <u>Drilling muds:</u>

The selection of the drilling mud can be determinant in avoiding failures in the borehole. There is a large variety of components that can be included in the drilling mud in function of the materials that are supposed to be drilled. The drilling mud acts as an stabilizer in the borehole wall, and also, due to its density, evacuates the cuttings that result from the perforation of the drilling bit, this process is called hole cleaning.

The two mud properties that have a direct impact on hole cleaning are the viscosity and the density.

The main functions of density are mechanical borehole stabilization and prevention of the intrusion of formation fluids into the annulus. Any unnecessary increase in mud density, beyond fulfilling the aforementioned two functions, will have an adverse effect on the ROP and, under the given in situ stresses, may cause fracturing of the formation. Importantly, mud density should not be used as a criterion to enhance hole cleaning. Viscosity has as its primary function the suspension of added desired weighting materials, such as barite. Only in vertical well drilling and high-viscous pill sweep is viscosity used as a remedy in hole cleaning*. (Azar and Samuel, 2009).*

In the case of the boreholes of this study, an intermediate polymer to create the drilling mud was used (figure 32).

Figure 32 Polymer used in the boreholes.

The used polymer, AMC CR 650must follow the <u>following specifications</u> 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.

The 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.

5.6.3 Polymer concentration in the muds

The mud pits built for the boreholes (figure 33) were filled totally, and during the water filling, the polymer was added at the same time:

Figure 33 Mud pit filling, borehole FAMSISIGN.

The volumes used to create the drilling mud are the next:

MUD PITS VOLUME(m^3)	21.56
POLYMER VOLUME(cm^3)	15844

Table 7 Volumes used in drilling mud mixture.

A density test of the polymer have been developed, giving a value of 0.8025 g/cm^3

Thus, the polymer concentration was 12,7148kg/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 cuttings could have remained at the bottom of the well.

This hypothesis will be corroborated in the next chapters, being observed evidenced of an inefficient cutting evacuation.

5.6.4 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, this result can be observed in figure C-04, Appendix-C.

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 34, the samples are surrounded of particles of different materials and sizes.

Figure 34 Cores surrounded by particles not evacuated by the drilling mud.

This particles are cuttings that probably could not be evacuated by the drilling mud and are deposited at the bottom of the borehole. This fact is an evidence of an incorrect hole cleaning in the boreholes.

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 non-cleaned cuttings surrounding the cores, figure 34.

Cuttings concentration in the bottom of the borehole is a strongly supported hypothesis that will be taken into account in the final conclusion of this work.

5.7 BOREHOLE DEVIATION

A large deviation of the borehole could produce a stuck in the drilling strings, this phenomenon is called dog-leg or key-seating.
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 clinometer was introduced in the borehole two times, firstly in open hole conditions, and secondly when the casing was introduced and placed, thus two separated measurements were realized in borehole FAM-1, the results can be observed with accuracy in Appendix-C, figure C-01.

-<u>Open hole tilt progression:</u>

Until the geophysical results reach, the borehole started with 0º of deviation, and it increased progressively until 2.38º, at 102.815 meters depth. Having several variations between this ranges.
After 102.815 meters, the deviation was slightly corrected until 1.58º at 139.313 meters, the maximum depth with open hole deviation data.
There is missing information in an interval between 107.242 and 117.998 meters depth due to the diameter reduction in the drilling pipes from PQ-3 to HQ-3.

-**<u>Casing tilt progression:</u>**

Measurements with placed casing reached 2.66 degrees at 137.927 meters depth. Very low variations of the tilt were produced in the casing. Measurements reached 155.929 meters depth with a tilt angle of 1.40º, thus, the deviation was corrected once it reached its maximum.

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 drilling.

An additional reason is the fact that in key seating failures, the drilling fluids continue circulating, in the case of study, a stop in the flow occurred in both FAM-1 and FAMSISIGN boreholes.
Thus, key seating has been rapidly eliminated as a possible cause of the failures, thanks to the clinometer data obtained in the testification and the additional evidences showed.

6. CONCLUSION

Drilling fault systems has always been a problematic issue due to the characteristics of the materials associated. Fault rocks have complicated structural characteristics that make the borehole drilling a technically difficult task.

Through the different analysis made in the present study, some of the proposed hypothetical causes of the failure have been discarded and others have been reached as the hypothesis that, with more probability, produced the pipe sticking in the boreholes FAM-1 and FAMSISIGN.

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 weakness planes and schistosity, being this characteristic an essential feature in the development of this final conclusion.

<u>Thus, the conclusions reached are the following</u>:

- Differential sticking was discarded as a possible cause of the failure due to the low permeability of the materials and the non-presence of fluids within the formations.

- Swelling clays test showed a negative result, forcing the hypothesis of a reactive formation hole reduction and sticking to be removed, X-ray diffraction showed presence of small amounts of swelling phyllosilicates, but the null expansion in the oedometer determined the inability of the formations to expand and close the borehole.

- Caliper logging results showed the presence of breakouts along the borehole, mainly in the last meters of “Fault Gouge”, but the reason of this enlargement of the diameter was justified by the eccentricity of the drilling bit while drilling. The presence of unconsolidated formations that could have produced a hole pack off by flowing sand was refused.

- The observation of the dipping angles of the formations in comparison with the vertical axis of the borehole, lead us to think about the instability of the formations, the “Fault Gouge” and blue-phyllites formations had inclinations of more than 45º along the borehole and in the transitional zone between both materials. Above this inclination of the weak planes with respect the vertical axis of the borehole, the materials have high probabilities to become unstable and produce a collapse in the borehole wall. This fact, in combination with the low recovery percentages, helped us to conclude that one of the causes of the failure was related with the dipping angles, and the more instability material present in the transitional zone.

- A plasticity study of the materials through the Atterberg limits test was developed to observe if the materials could flow plastically inwards the borehole, sticking the strings. A plastic index of 4.6% determined that the formations only can behave this way in a small range of humidity, thus, the possibility of a sticking pipe caused by plastic materials flowing was not taken into account.

- The optimal polymer concentrations requirements for drilling this formations demand from 0.75-1 kg/1000liters of fresh water, the concentrations used did not reach this value, being above the minimum requirements but below the recommendations for this type of formations. Thus the muds took relevant importance in the failure having lower density and viscosity as required to remove all the cuttings.

- The last chapter discussed had the purpose of evaluating the borehole deviation to determine a failure by key seating or “dog leg”. At least until 139 meters depth, the borehole did not reached any sudden deviation, the maximum reached the 3º of tilt, and was progressively produced. Therefore, the failure was not produced by borehole deviation.

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 (above 45º with respect to the vertical axis), 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

With the purpose of helping in future borehole drilling in the same or similar areas, would be important to take into account the studies made in the present work. The future planning should take into account the potential risks that drilling a fault zone, directly in the fault plane, brings. If an accurate evaluation of the parameters that probably produced the failure in boreholes FAM-1 and FAMSISIGN had been made, the pipe sticking in the transitional materials between the formations would be avoided.

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

-<u>Dipping angles of the weakness planes of the formations</u>:

Once the inclination of the formations is known, the angles respect of the axis of the boreholes will be determinant, being angles equal and above 45º very 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 (Aminui Islam, 2009).

-<u>Drilling muds characteristics</u>:

While drilling formations that potentially can cause instabilities in the borehole wall, it is important to generate a drilling mud with enough density and viscosity to remove the cuttings correctly. 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. For example, polymer AMC-50 (as the used in the boreholes of this work) allows concentrations from 0.5 to 1 kg/1000L of fresh water, in the case of future drillings in this area, would be advisable using concentrations above 0.75 kg/1000L water.

Selecting different mud types, with more density and viscosity would work as well, for example the use of bentonite would be advisable in this area, stabilizing the borehole walls and removing the cuttings correctly.

<u>Mud additives</u>:

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.

<u>Casing plan</u>:

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.

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9 ANNEXES

ANNEX – A

Table A-01 *Rock Quality Designation (RQD) Index for the altered Schists/Phillytes.*

	DEPTH		Segments >10	Length	RQD (%)	Rock quality
Run	**Bottom**	**Top**				
3	2,20	3,60	10	140	**7,14**	Very Poor
4	3,60	5,00	11,15,14,25		**46,43**	Poor
5	5,00	6,25	10	125	**8,00**	Very Poor
6	6,25	7,10	13	85	**15,29**	Very Poor
9	7,70	9,20	10,14,16	150	**26,67**	Very Poor
11	9,60	11,20	14,4	160	**34,00**	Poor
12	11,20	12,50	11,14,13,16	130	**41,15**	Poor
17	15,70	16,90	12,16	120	**23,33**	Very Poor

*If there is no continuity in the runs, means no presence of fragments>10cm in the missed runs.

Table A-02, *JRC test result for the altered schists*

DEPTH		**JRC**
Bottom	Top	
0	11,2	**II**
11,2	14,2	**III**
14,2	15,7	**II**
15,7	16,9	**III**
16.9	20.5	**II**

Table A-03, *Rock Quality Designation (RQD) Index for the altered Schists/Phillytes.*

	DEPTH		Segments >10	Length	RQD (%)	Rock quality
Run	**Bottom**	**Top**				
27	24	25,5	20,25,12,13	150	53,00	**Fair**
28	25,5	26,75	12,1	125	18,00	**Very Poor**
29	26,75	27,4	12,13	65	38,00	**Poor**

30	27,4	28,6	10	120	36,00	**Poor**
32	28,6	30,2	12,32,10,15,20	160	56,00	**Fair**
33	30,2	31,8	25,18,20,10,23,24	160	75,00	**Good**
35	33,4	35	10,18,10,10,13,24,14,22	160	76,00	**Good**
36	35	36,6	17,10,43,21,17,10	160	74,00	**Fair**
37	36,6	38,1	11,30,34,18,25,11	150	86,00	**Good**
38	38,1	39,6	55,27,40	150	55,00	**Fair**
39	36,6	38,1	80,11,11,16	150	79,00	**Good**
41	41,7	43,1	11,19	140	21,00	**Very Poor**
43	45	45,8	23,1	80	41	**Poor**
45	46,1	47,2	27,17	110	40,00	**Poor**
47	47,2	48,6	35,2	140	39,00	**Poor**
51	53,1	54,1	20,15,23,10	100	68,00	**Fair**
52	54,1	55,25	11	115	10,00	**Very Poor**
60	58,9	60,1	12	120	10,00	**Very Poor**
61	60,1	61,7	14,13,13	160	25,00	**Poor**
62	61,7	62,9	10	120	32	**Poor**
63	62,9	63,6	10	70	32	**Poor**
65	65	65,65	10	65	35	**Poor**
66	65,65	66,9	11	125	8,8	**Very Poor**
67	66,9	68,6	11	170	42.9	**Poor**

*If there is no continuity in the runs, means no presence of fragments>10cm in the missed runs.

Table A-04, JR*C test results for the quartz-schists*

DEPTH		**JRC**
Bottom	Top	
16,9	30,2	**II**
30,2	36,6	**V**
36,6	45,8	**II**
45,8	47,2	**III**
47,2	52,7	**II**
52,7	68,6	**V**

Table A-05, *RQD variations with depth in FAM-1*

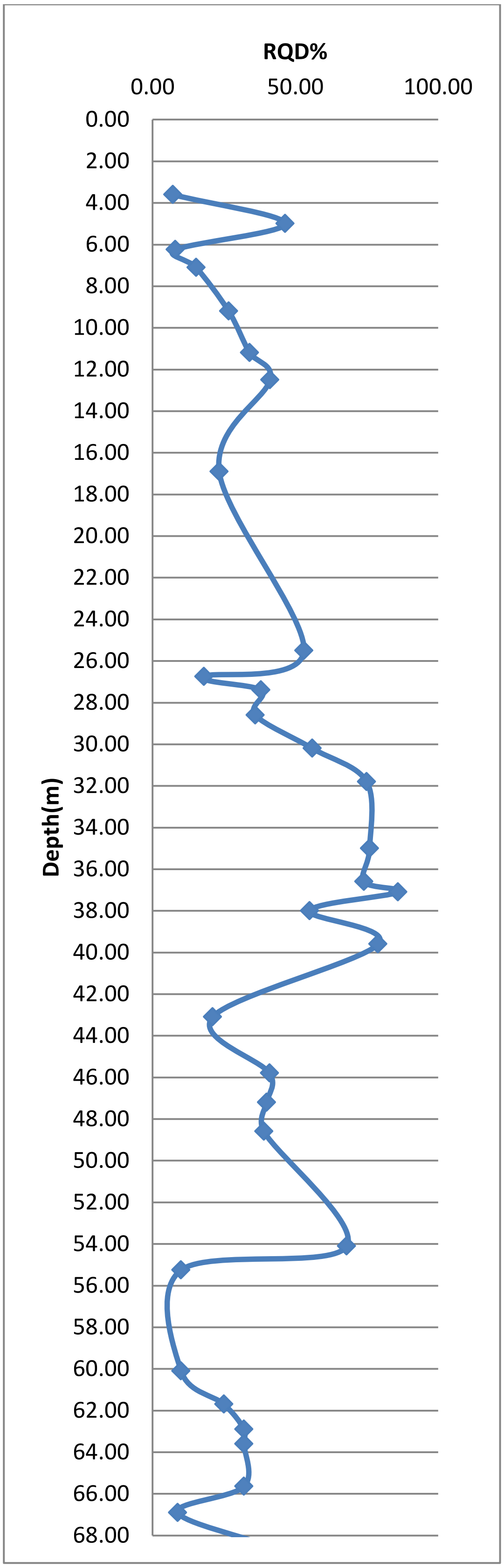


Table A-06, *Rock quality designation index, definition*

DEERE AND DEERE ON ROCK QUALITY DESIGNATION INDEX

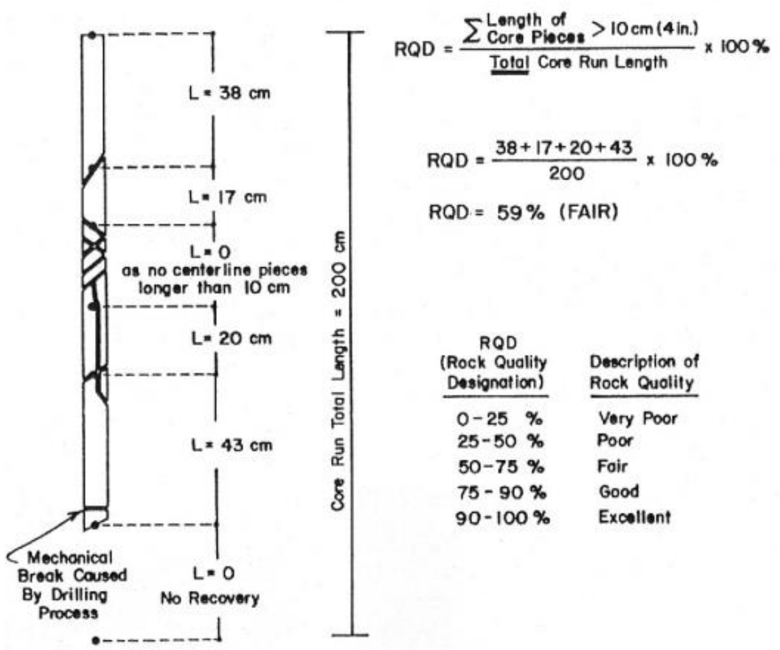
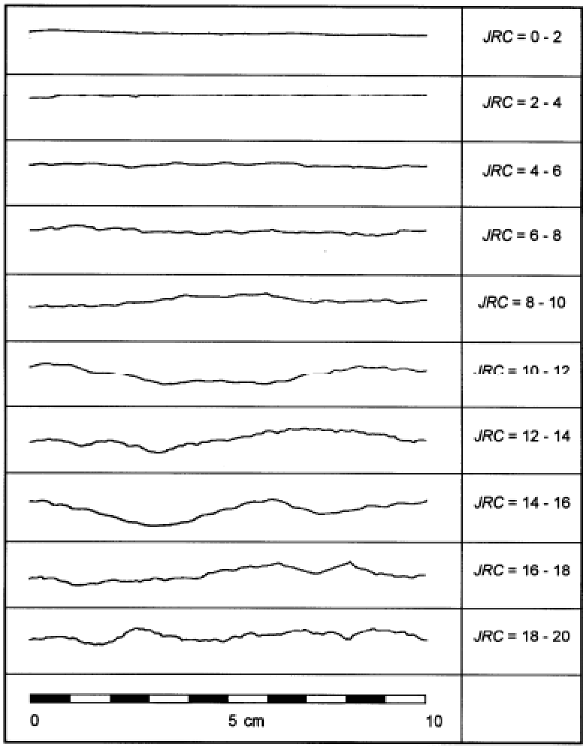
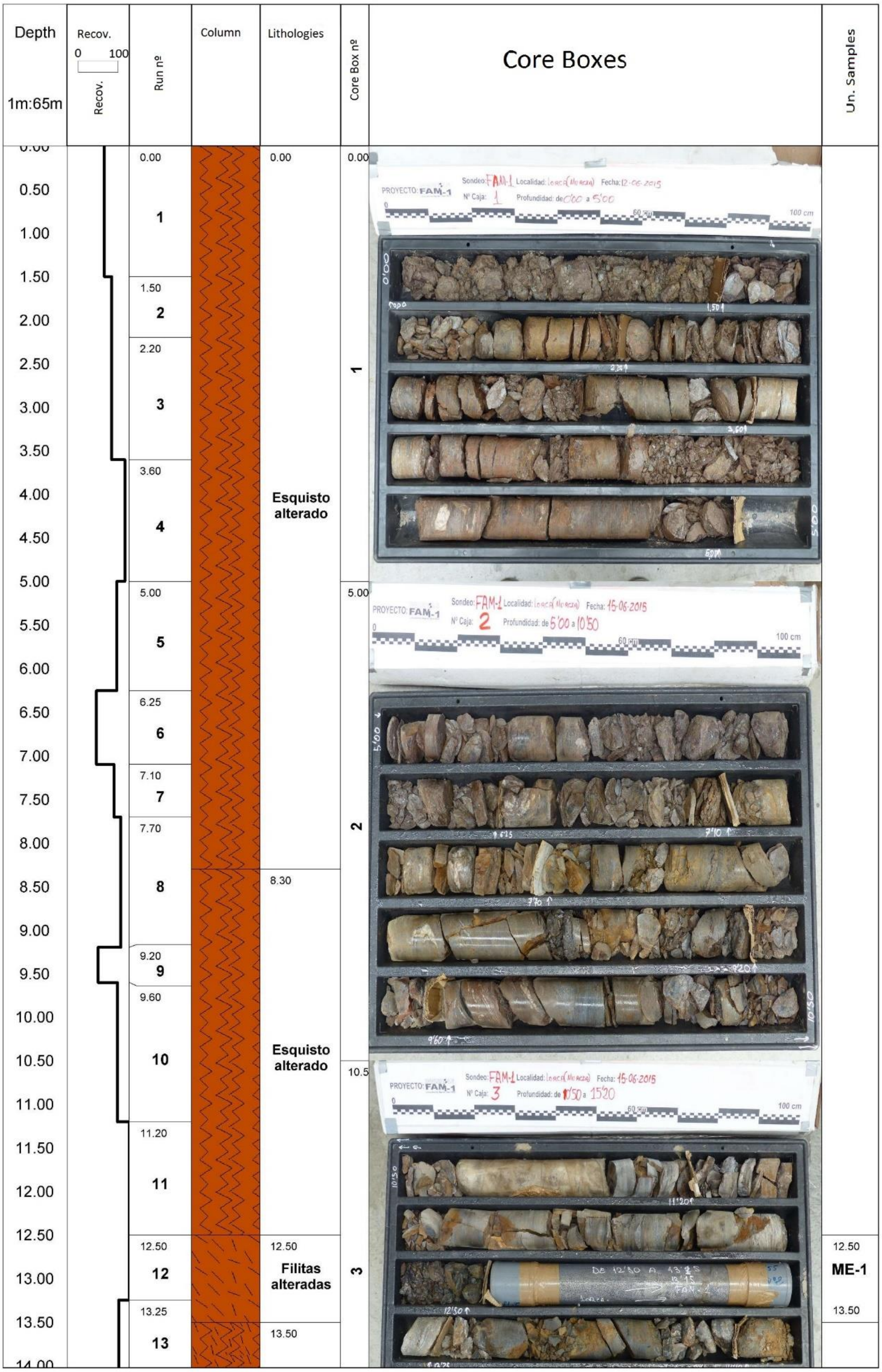


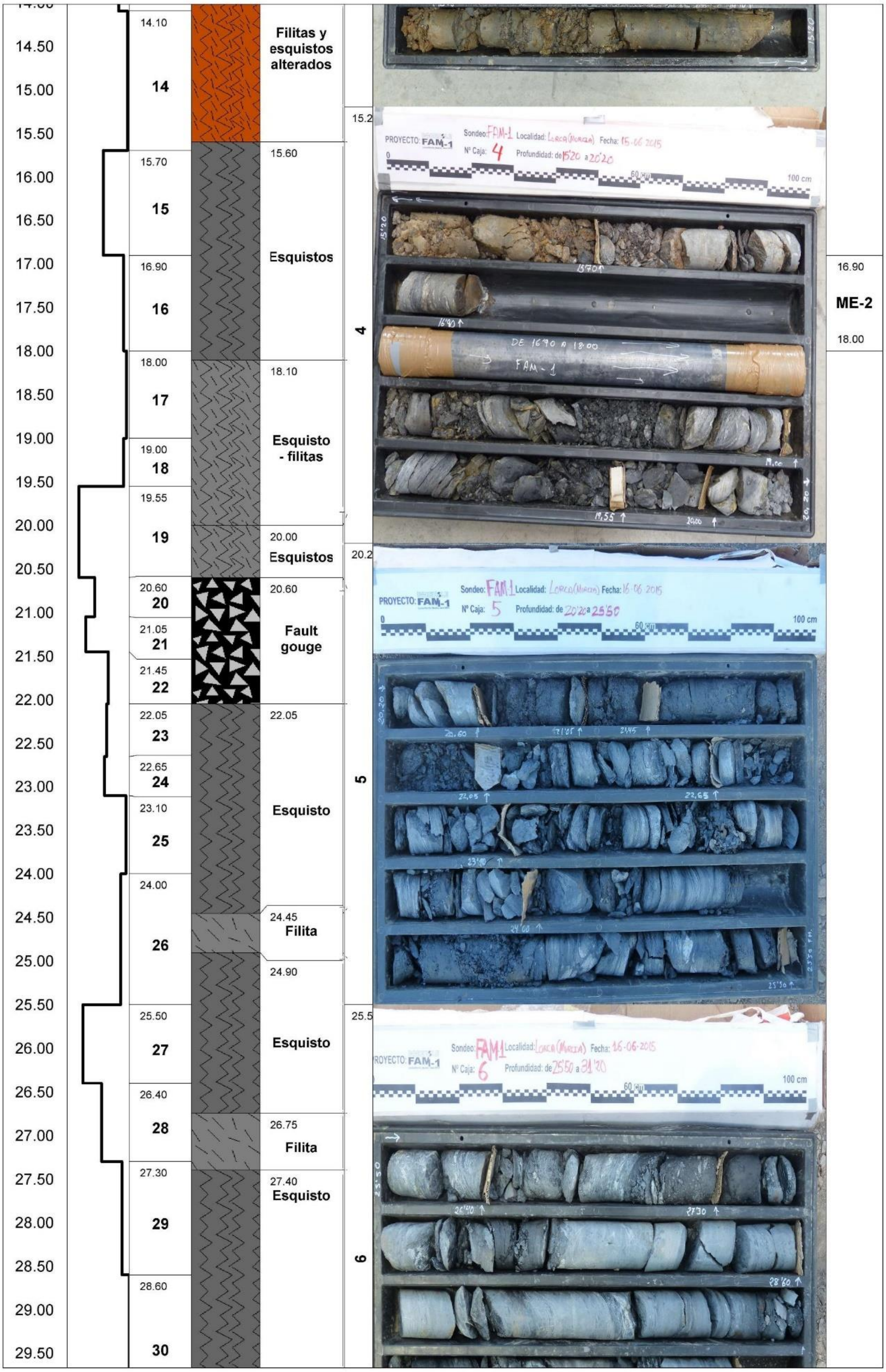
FIG. 1—*Procedure for measurement and calculation of RQD.*

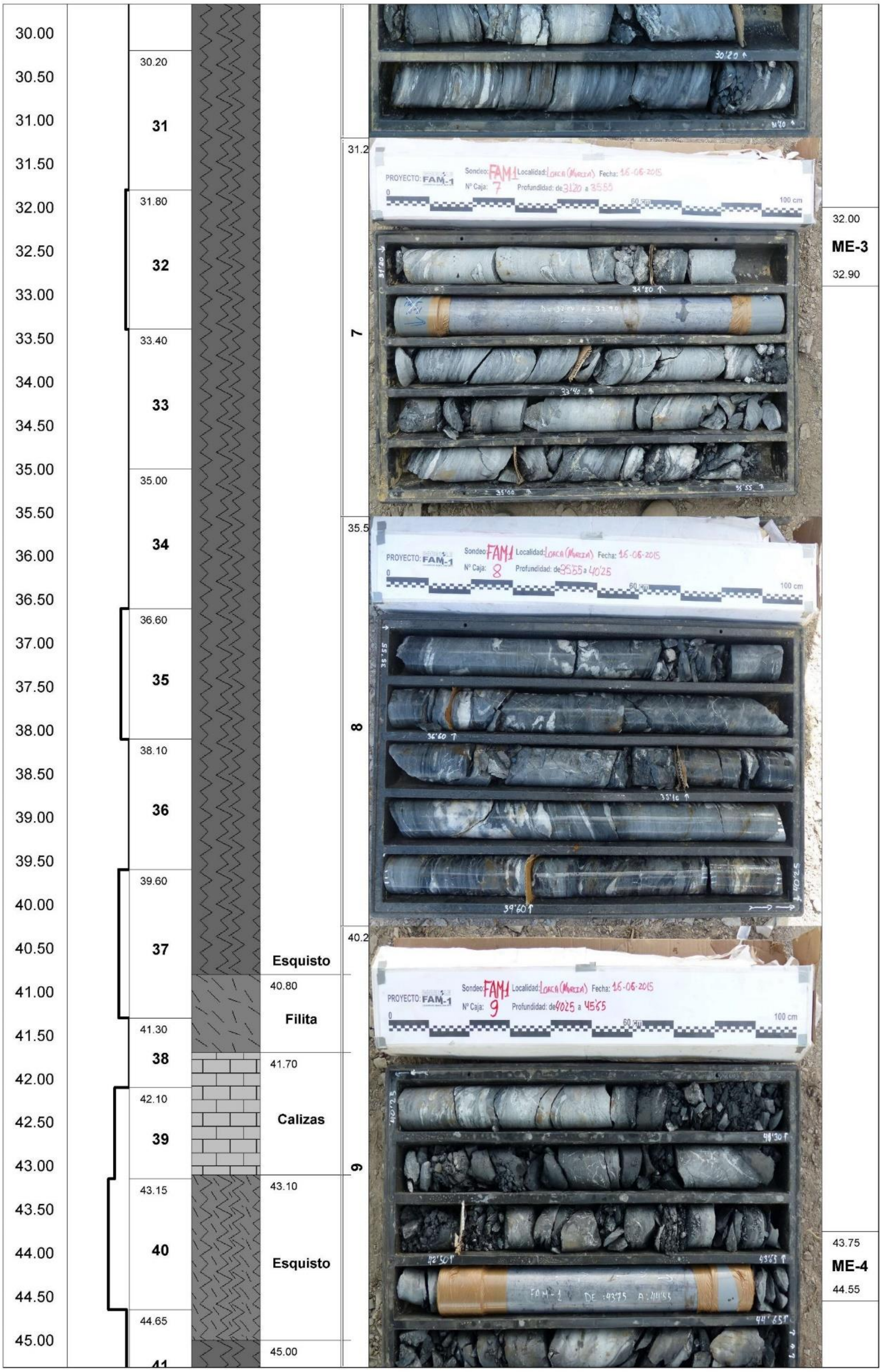
Table A-07, *JRC designation index, comparative table*



8.2 ANNEX-B: DEVIATION, LITHOLOGIES AND BOXES




14.50
15.00
15.50
16.00
16.50
17.00
17.50
18.00
18.50
19.00
19.50
20.00
20.50
21.00
21.50
22.00
22.50
23.00
23.50
24.00
24.50
25.00
25.50
26.00
26.50
27.00
27.50
28.00
28.50
29.00
29.50
14.10
14
15.70
15
16.90
16
18.00
17
19.00
18
19.55
19
20.60
20
21.05
21
21.45
22
22.05
23
22.65
24
23.10
25
24.00
26
25.50
27
26.40
28
27.30
29
28.60
30
Filitas y esquistos alterados
15.60
Esquistos
18.10
Esquisto - filitas
20.00
Esquistos
20.60
Fault gouge
22.05
Esquisto
24.45
Filita
24.90
Esquisto
26.75
Filita
27.40
Esquisto
15.2
4
20.2
5
25.5
6
16.90
ME-2
18.00


30.00
30.50
31.00
31.50
32.00
32.50
33.00
33.50
34.00
34.50
35.00
35.50
36.00
36.50
37.00
37.50
38.00
38.50
39.00
39.50
40.00
40.50
41.00
41.50
42.00
42.50
43.00
43.50
44.00
44.50
45.00
30.20
31
31.80
32
33.40
33
35.00
34
36.60
35
38.10
36
39.60
37
41.30
38
42.10
39
43.15
40
44.65
41
Esquisto
40.80
Filita
41.70
Calizas
43.10
Esquisto
45.00
31.2
7
35.5
8
40.2
9
PROYECTO: FAM-1
Sondeo: FAM1
Localidad: LORCA (MURCIA)
Fecha: 16-06-2015
Nº Caja: 7
Profundidad: de 31'20 a 35'55
Nº Caja: 8
Profundidad: de 35'55 a 40'25
Nº Caja: 9
Profundidad: de 40'25 a 45'55
100 cm
32.00
ME-3
32.90
43.75
ME-4
44.55

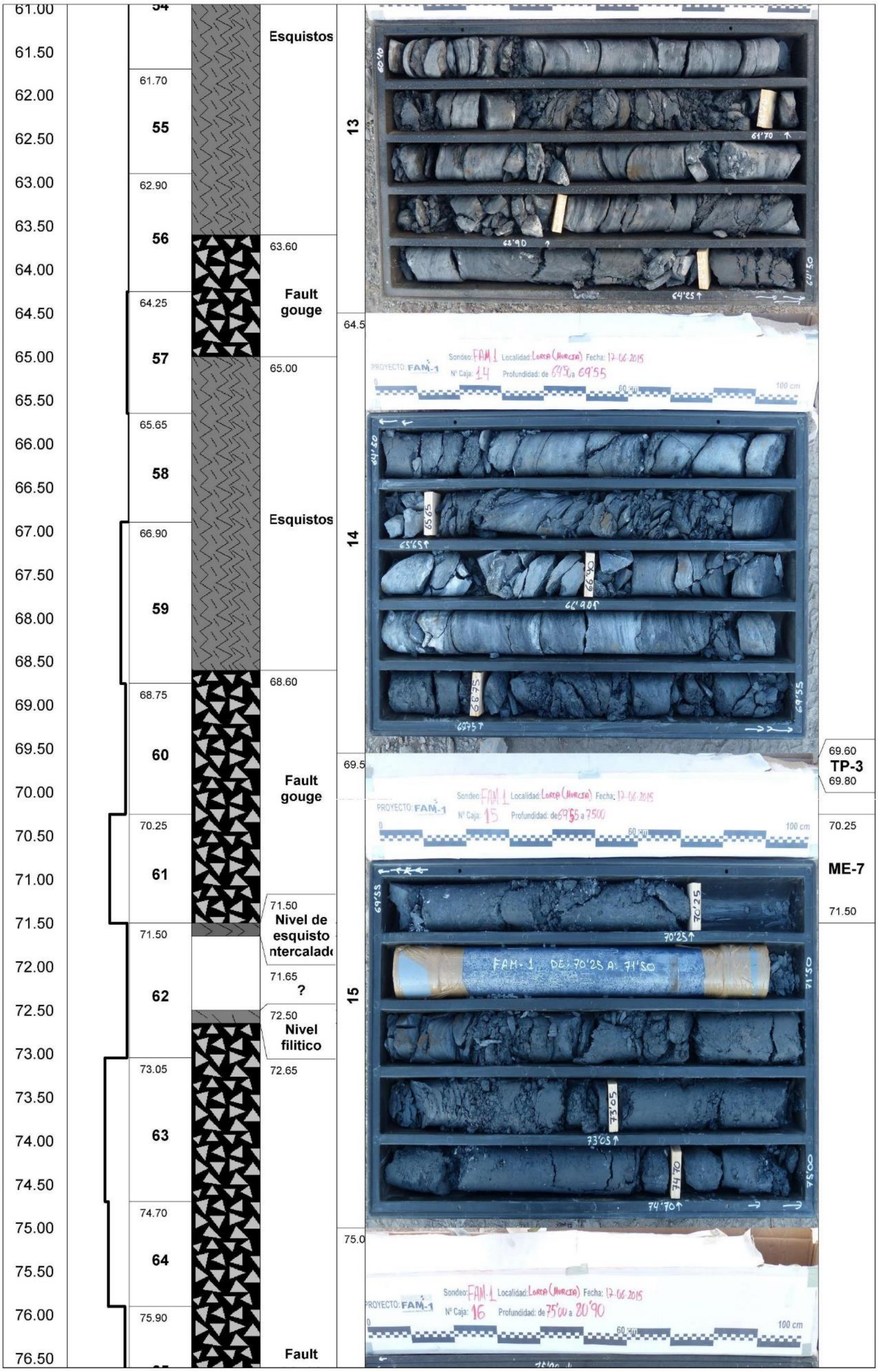
Profundidad
45.50
46.00
46.50
47.00
47.50
48.00
48.50
49.00
49.50
50.00
50.50
51.00
51.50
52.00
52.50
53.00
53.50
54.00
54.50
55.00
55.50
56.00
56.50
57.00
57.50
58.00
58.50
59.00
59.50
60.00
60.50

Desde	Tramo
45.80	42
47.45	43
49.00	44
50.10	45
51.20	46
52.35	47
53.00	48
54.10	49
55.25	50
56.25	51
57.75	52
58.90	53
60.10	54

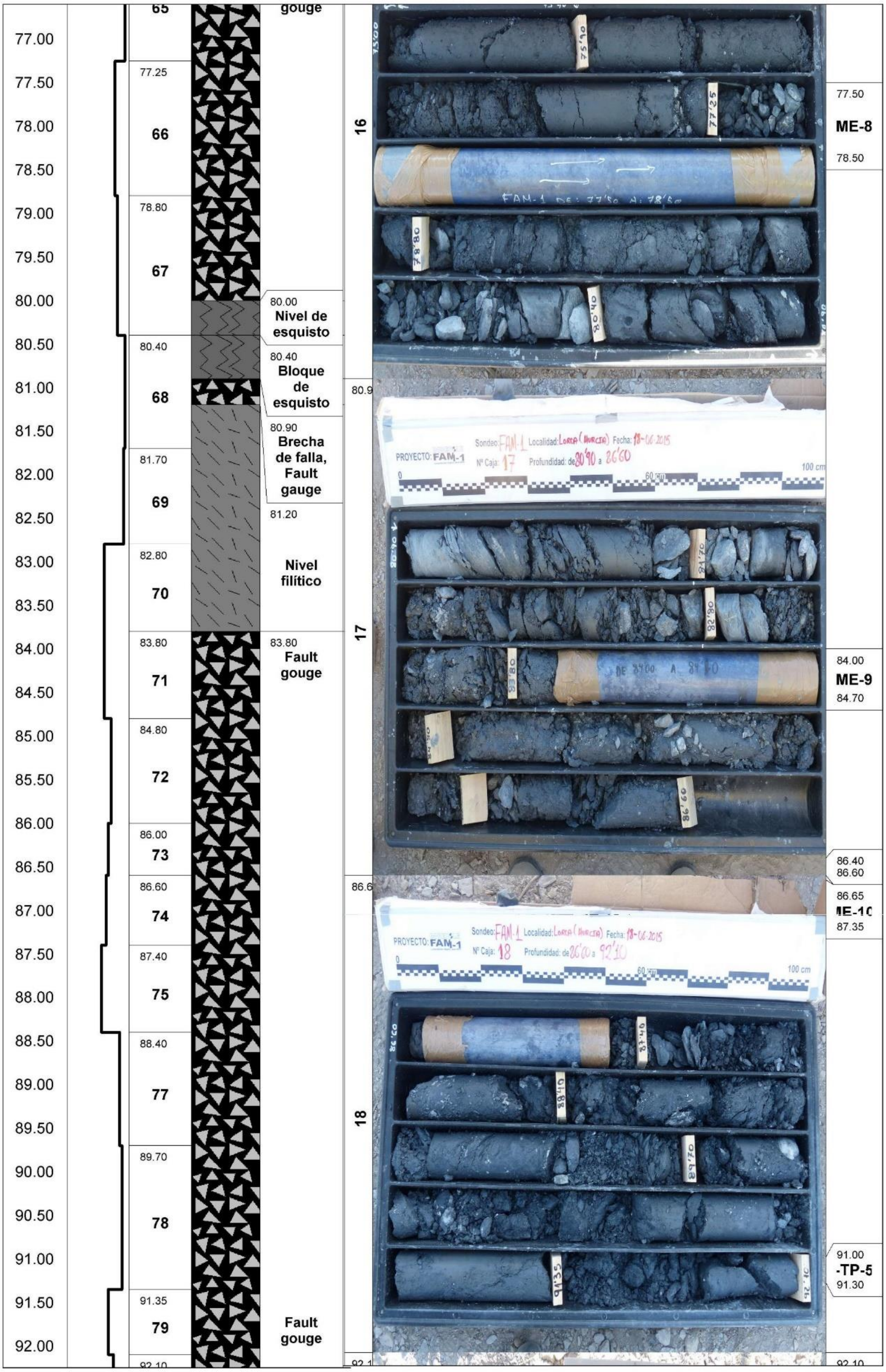
Desde	Litología
	Esquisto
45.80	Filitas
46.10	Esquistos
47.20	Esquistos
48.00	Esquistos filitas
50.10	Esquistos
51.20	Esquistos - filitas
52.70	Esquistos
55.25	Esquistos
56.90	Filitas
58.90	

Caja	Desde
10	45.6
11	50.8
12	55.2
	60.1

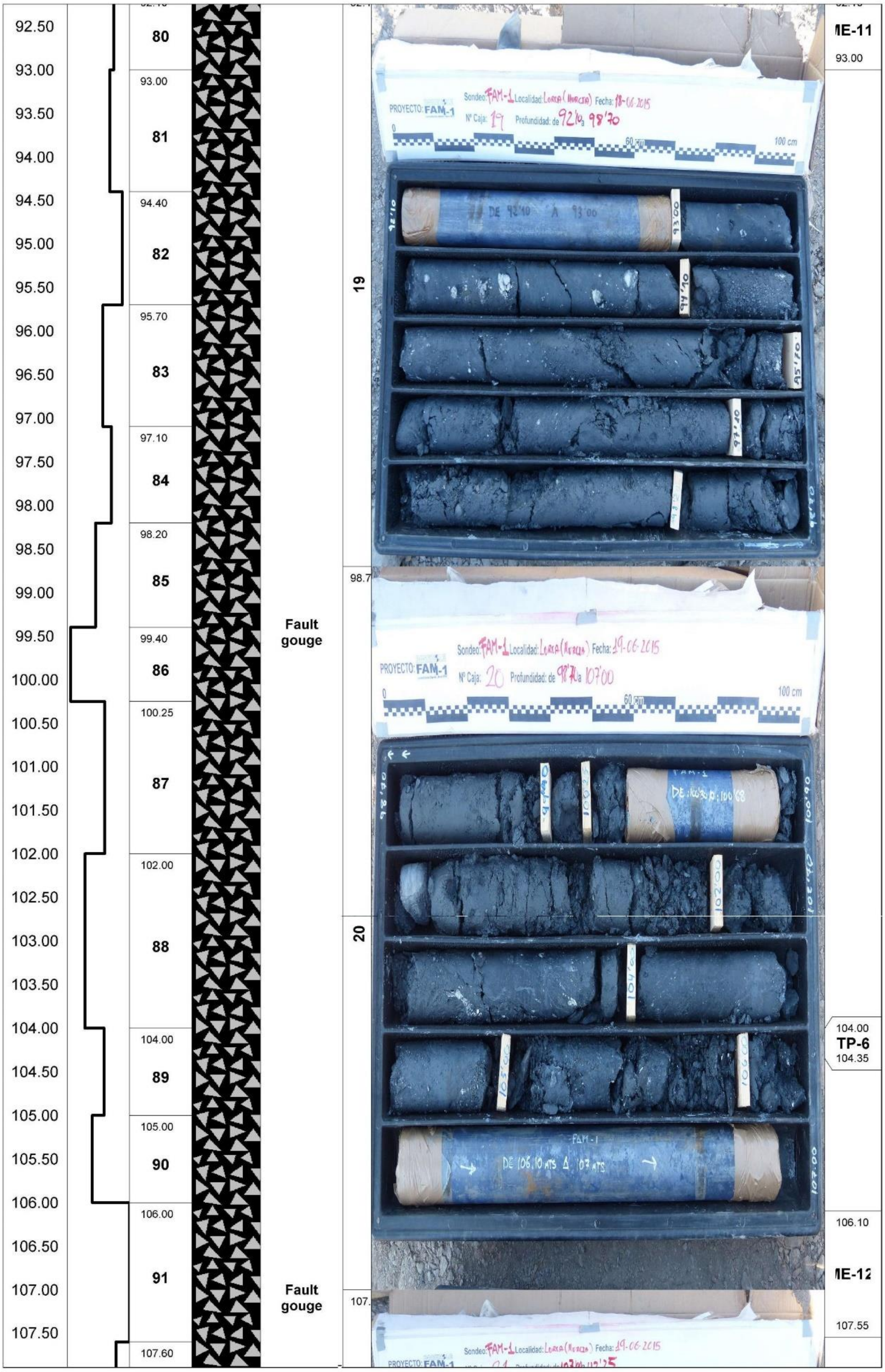
Muestra	Desde	Hasta
TP-2	47.00	47.20
ME-5	59.05	60.00

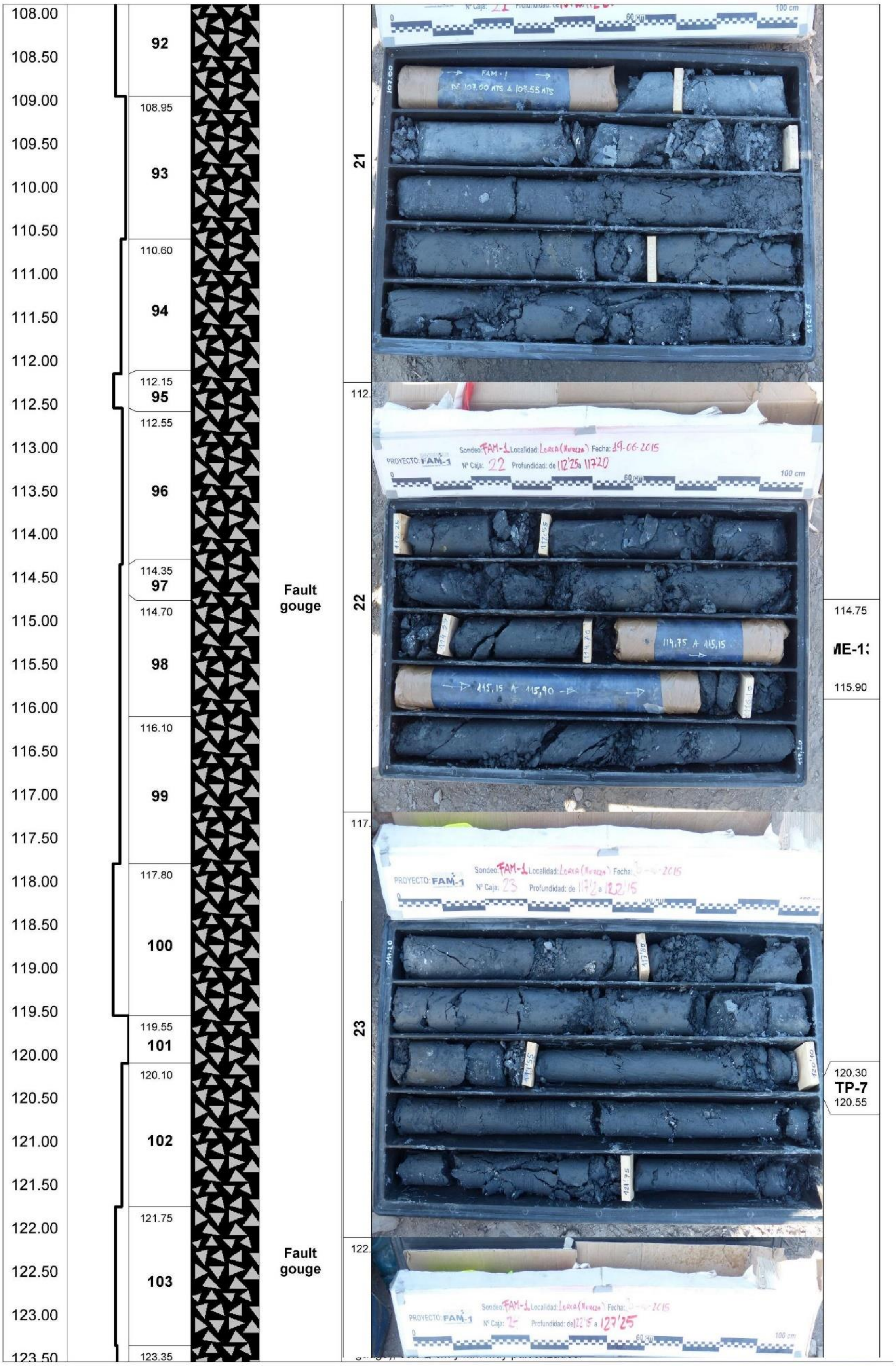


61.00
61.50
62.00
62.50
63.00
63.50
64.00
64.50
65.00
65.50
66.00
66.50
67.00
67.50
68.00
68.50
69.00
69.50
70.00
70.50
71.00
71.50
72.00
72.50
73.00
73.50
74.00
74.50
75.00
75.50
76.00
76.50
54
61.70
55
62.90
56
64.25
57
65.65
58
66.90
59
68.75
60
70.25
61
71.50
62
73.05
63
74.70
64
75.90
Esquistos
63.60
Fault gouge
65.00
Esquistos
68.60
Fault gouge
71.50
Nivel de esquisto intercalado
71.65
?
72.50
Nivel filitico
72.65
Fault
13
64.5
14
69.5
15
75.0
69.60
TP-3
69.80
70.25
ME-7
71.50
PROYECTO: FAM-1
Sondeo: FAM 1 Localidad: Lorca (Murcia) Fecha: 17-06-2015
Nº Caja: 14 Profundidad: de 64'50 a 69'55
Nº Caja: 15 Profundidad: de 69'55 a 75'00
Nº Caja: 16 Profundidad: de 75'00 a 80'90
100 cm
FAM-1 DE: 70'25 A: 71'50

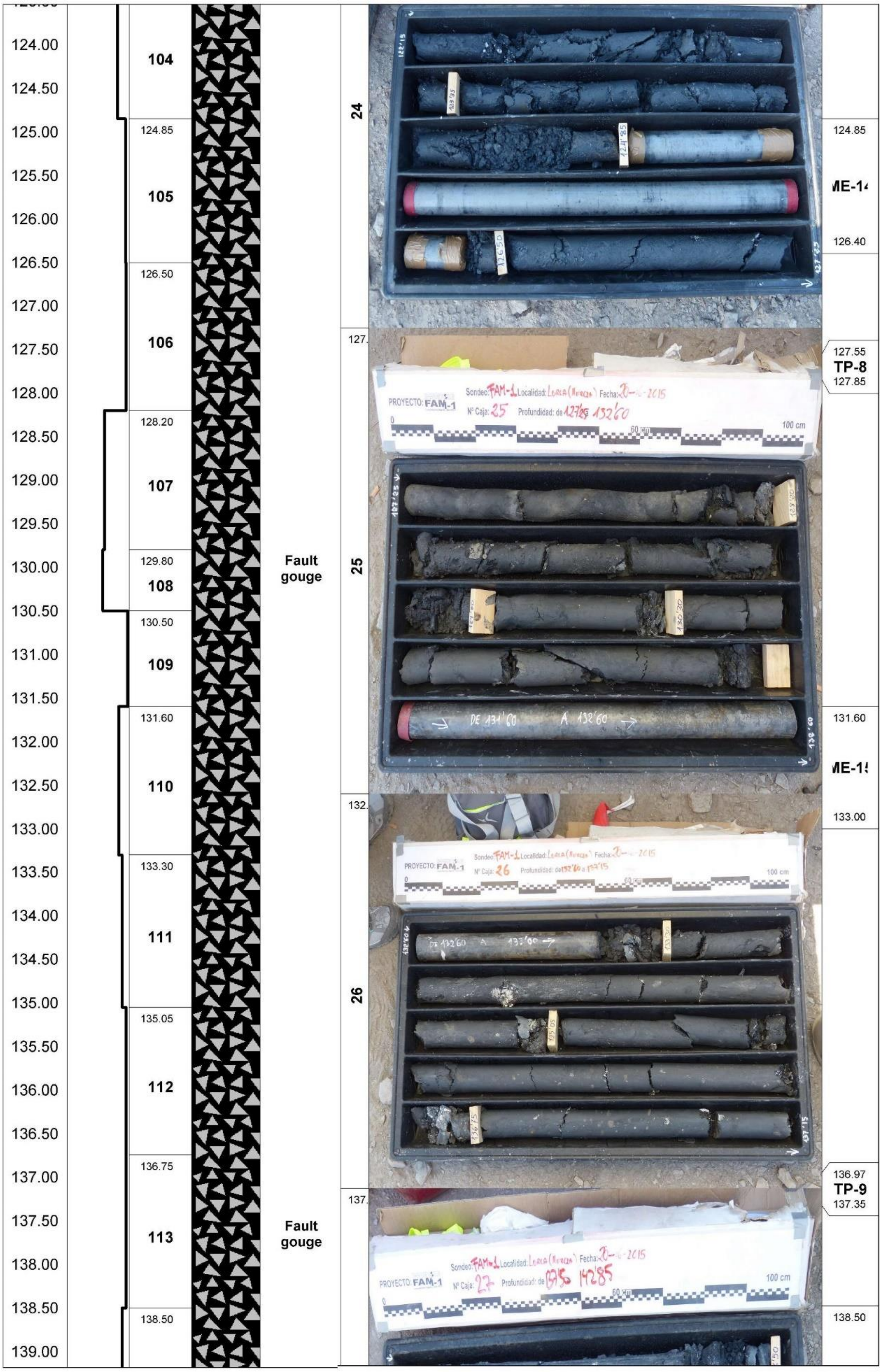


77.00
77.50
78.00
78.50
79.00
79.50
80.00
80.50
81.00
81.50
82.00
82.50
83.00
83.50
84.00
84.50
85.00
85.50
86.00
86.50
87.00
87.50
88.00
88.50
89.00
89.50
90.00
90.50
91.00
91.50
92.00
65
77.25
66
78.80
67
80.40
68
81.70
69
82.80
70
83.80
71
84.80
72
86.00
73
86.60
74
87.40
75
88.40
77
89.70
78
91.35
79
92.10
gouge
80.00
Nivel de esquisto
80.40
Bloque de esquisto
80.90
Brecha de falla, Fault gauge
81.20
Nivel filítico
83.80
Fault gouge
Fault gouge
16
17
18
80.9
86.6
92.1
PROYECTO: FAM-1
Sondeo: FAM-1 Localidad: Lorca (Murcia) Fecha: 18-06-2015
Nº Caja: 17 Profundidad: de 80'90 a 86'60
Nº Caja: 18 Profundidad: de 86'60 a 92'10
100 cm
60 cm
77.50
ME-8
78.50
84.00
ME-9
84.70
86.40
86.60
86.65
ME-10
87.35
91.00
-TP-5
91.30
92.10


92.50
93.00
93.50
94.00
94.50
95.00
95.50
96.00
96.50
97.00
97.50
98.00
98.50
99.00
99.50
100.00
100.50
101.00
101.50
102.00
102.50
103.00
103.50
104.00
104.50
105.00
105.50
106.00
106.50
107.00
107.50
80
93.00
81
94.40
82
95.70
83
97.10
84
98.20
85
99.40
86
100.25
87
102.00
88
104.00
89
105.00
90
106.00
91
107.60
Fault gouge
Fault gouge
19
98.7
20
107.
ME-11
93.00
104.00
TP-6
104.35
106.10
ME-12
107.55



108.00
108.50
109.00
109.50
110.00
110.50
111.00
111.50
112.00
112.50
113.00
113.50
114.00
114.50
115.00
115.50
116.00
116.50
117.00
117.50
118.00
118.50
119.00
119.50
120.00
120.50
121.00
121.50
122.00
122.50
123.00
123.50
92
108.95
93
110.60
94
112.15
95
112.55
96
114.35
97
114.70
98
116.10
99
117.80
100
119.55
101
120.10
102
121.75
103
123.35
Fault gouge
Fault gouge
21
22
23
112.
117.
122.
114.75
ME-1
115.90
120.30
TP-7
120.55


124.00
124.50
125.00
125.50
126.00
126.50
127.00
127.50
128.00
128.50
129.00
129.50
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130.50
131.00
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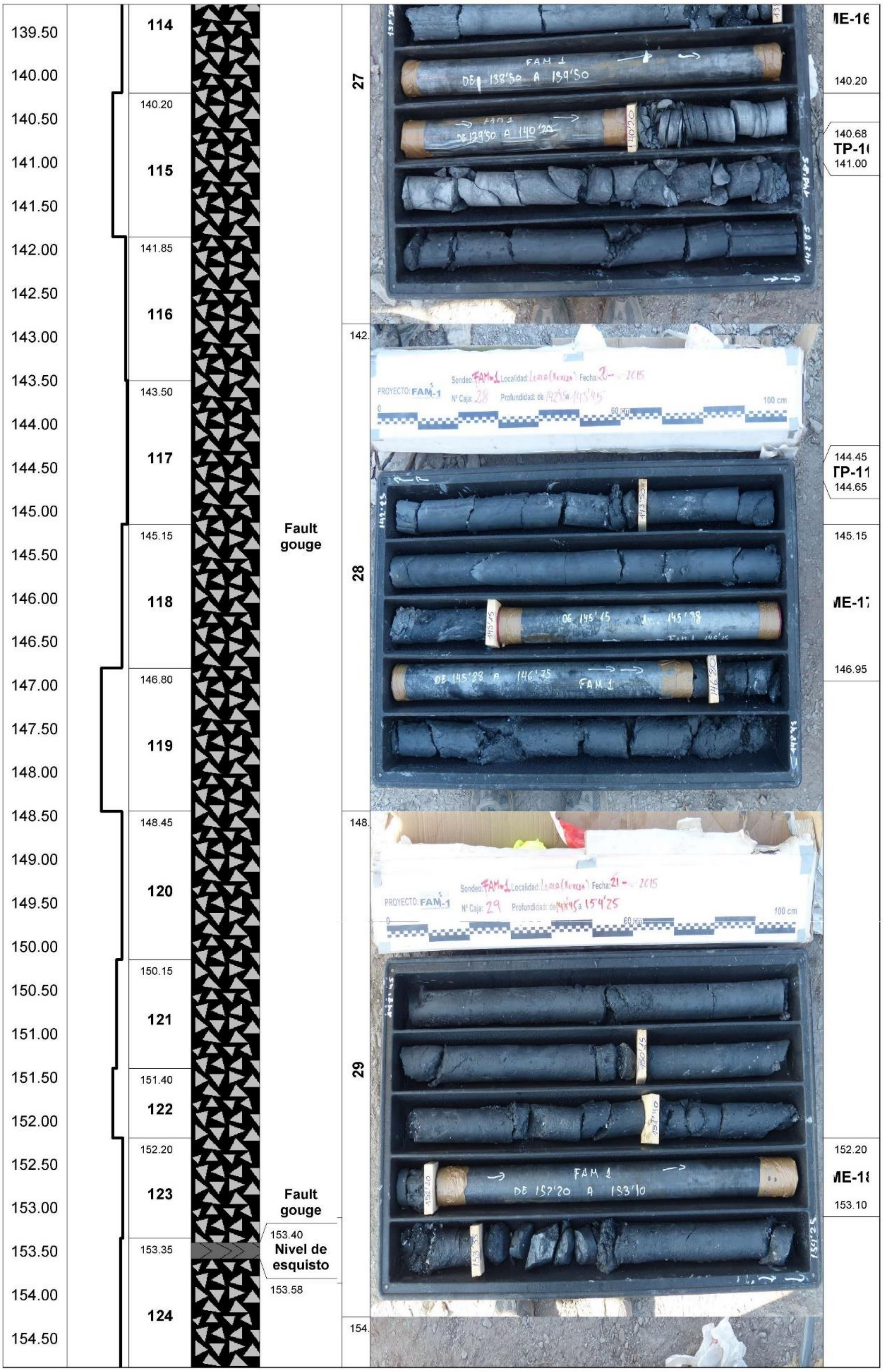
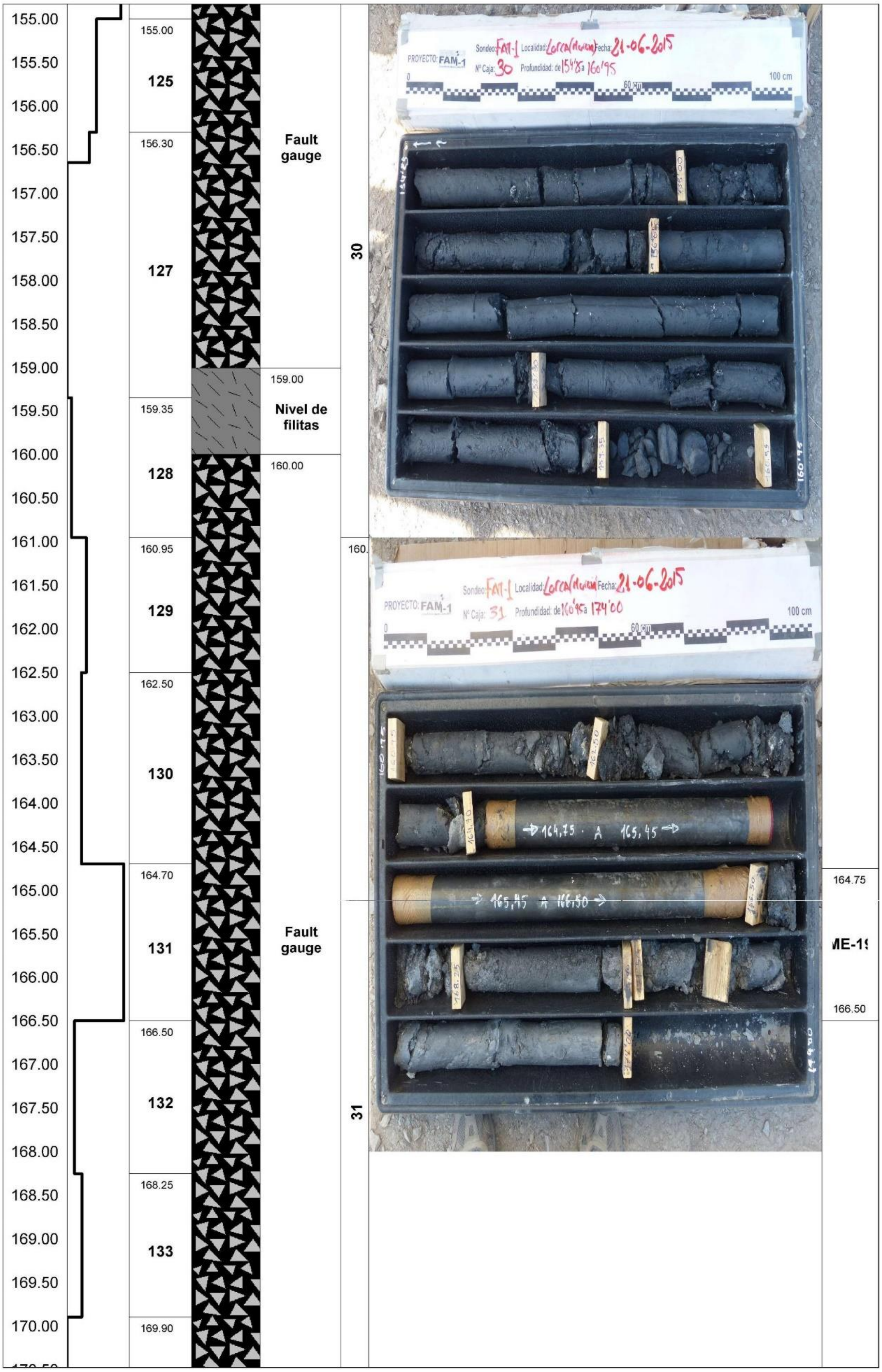
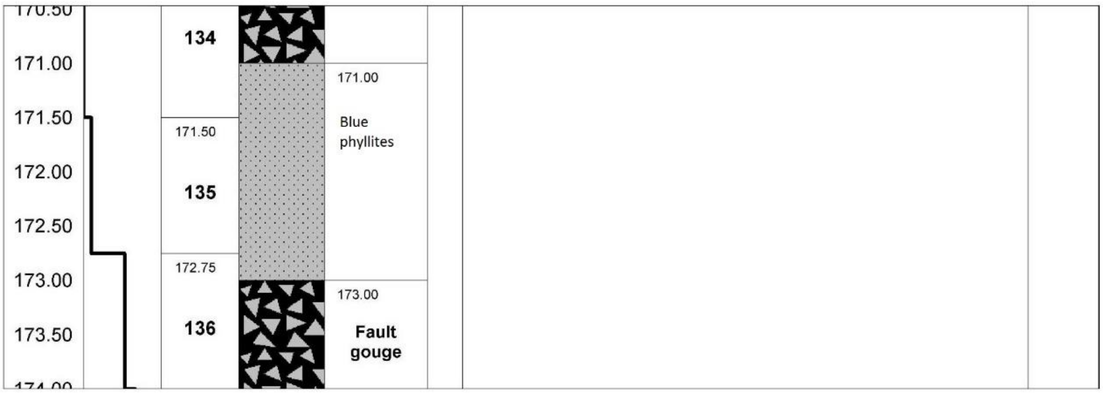
132.00
132.50
133.00
133.50
134.00
134.50
135.00
135.50
136.00
136.50
137.00
137.50
138.00
138.50
139.00
104
124.85
105
126.50
106
128.20
107
129.80
108
130.50
109
131.60
110
133.30
111
135.05
112
136.75
113
138.50
Fault gouge
Fault gouge
24
25
26
124.85
126.40
127.55
TP-8
127.85
131.60
133.00
136.97
TP-9
137.35
138.50


139.50
140.00
140.50
141.00
141.50
142.00
142.50
143.00
143.50
144.00
144.50
145.00
145.50
146.00
146.50
147.00
147.50
148.00
148.50
149.00
149.50
150.00
150.50
151.00
151.50
152.00
152.50
153.00
153.50
154.00
154.50
114
140.20
115
141.85
116
143.50
117
145.15
118
146.80
119
148.45
120
150.15
121
151.40
122
152.20
123
153.35
124
Fault gouge
Fault gouge
153.40
Nivel de esquisto
153.58
27
28
29
142.
148.
154.
FAM 1
DE 138'50 A 139'50
DE 139'50 A 140'20
140'20
Sondeo: FAM-1 Localidad: Loma (Revilla) Fecha: 2015
PROYECTO: FAM-1
Nº Caja: 28 Profundidad: de 142'55 a 148'45
100 cm
60 cm
DE 145'15 A 145'98
DE 145'88 A 146'75
FAM 1
146'80
Sondeo: FAM-1 Localidad: Loma (Revilla) Fecha: 21 2015
PROYECTO: FAM-1
Nº Caja: 29 Profundidad: de 148'45 a 154'25
100 cm
60 cm
FAM 1
DE 152'20 A 153'10
152'20
ME-16
140.20
140.68
TP-10
141.00
144.45
TP-11
144.65
145.15
ME-17
146.95
152.20
ME-18
153.10


155.00
155.50
156.00
156.50
157.00
157.50
158.00
158.50
159.00
159.50
160.00
160.50
161.00
161.50
162.00
162.50
163.00
163.50
164.00
164.50
165.00
165.50
166.00
166.50
167.00
167.50
168.00
168.50
169.00
169.50
170.00
155.00
125
156.30
127
159.35
128
160.95
129
162.50
130
164.70
131
166.50
132
168.25
133
169.90
Fault gauge
159.00
Nivel de filitas
160.00
Fault gauge
30
160.
31
164.75
ME-1
166.50
PROYECTO: FAM-1
Sondeo: FAM-1
Fecha: 21-06-2015
Nº Caja: 30
100 cm
60 cm
PROYECTO: FAM-1
Sondeo: FAM-1
Fecha: 21-06-2015
Nº Caja: 31
100 cm
60 cm


170.50
171.00
171.50
172.00
172.50
173.00
173.50
174.00
134
171.50
135
172.75
136
171.00
Blue
phyllites
173.00
Fault
gouge

8.3 ANNEX-C: BOREHOLE DEVIATION, DIPPING ANGLES OF THE FORMATIONS and CALIPER results.

Figure C-01: Borehole deviation with casing placed (right) and at open hole (left).

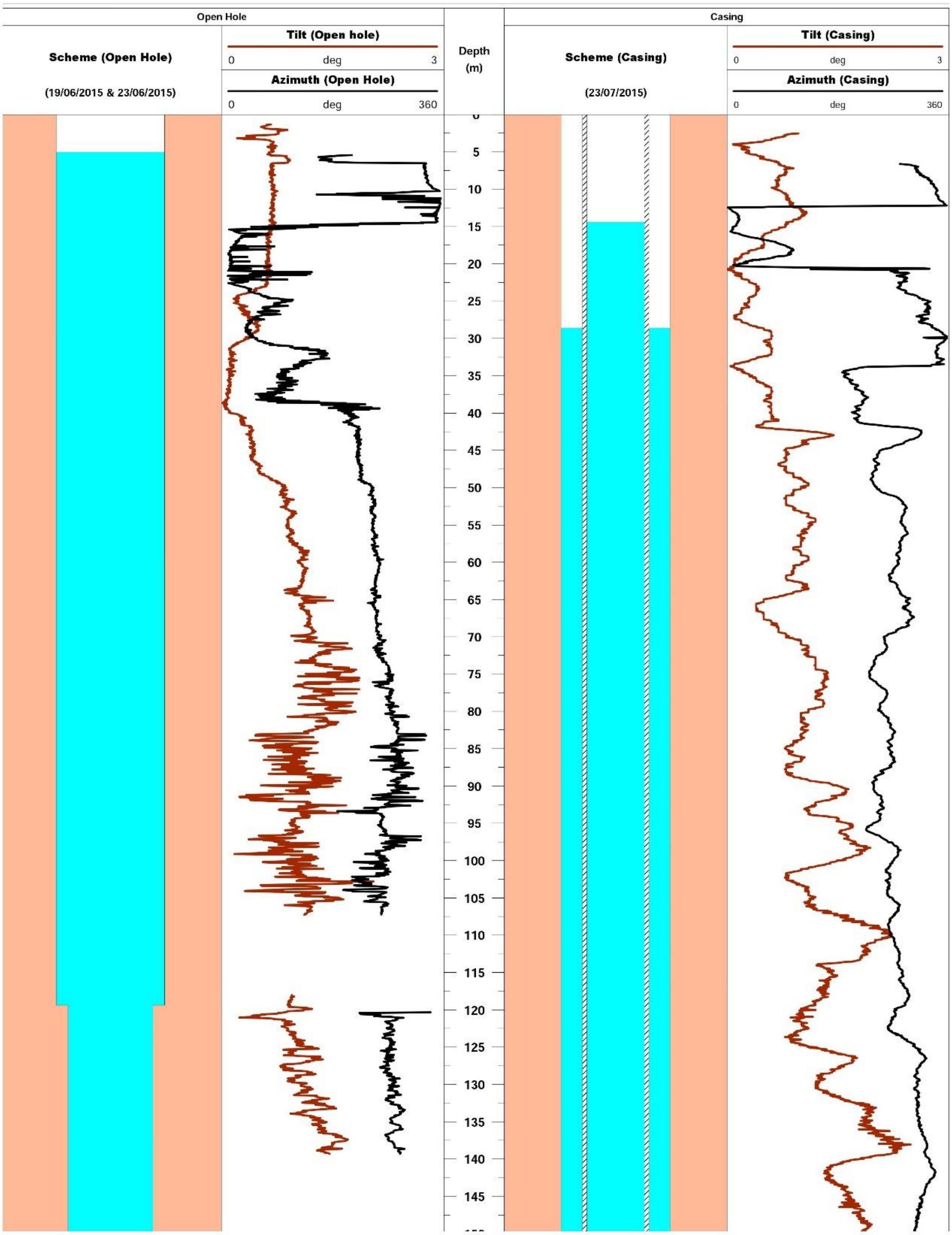


Figure C-02: *Geophysical logging results for calliper.*

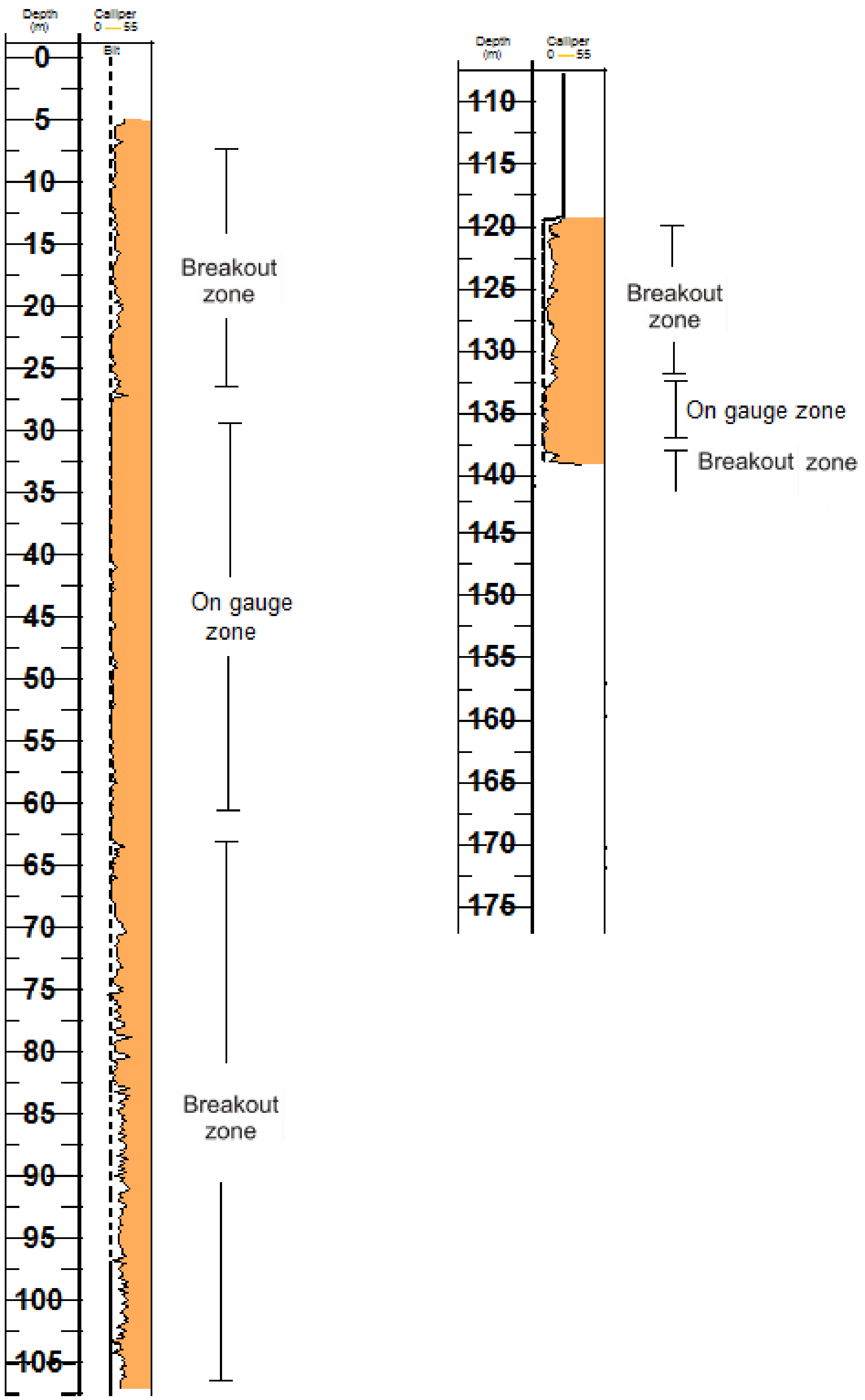
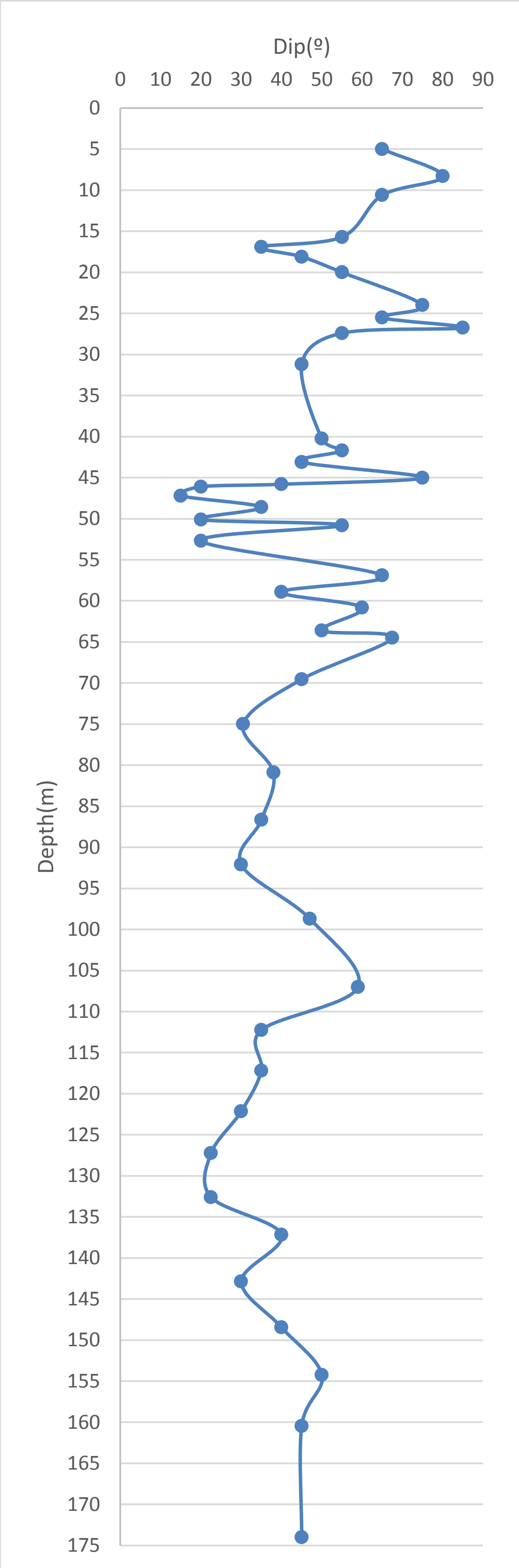


Figure C-03: *Dipping angles variations of the formations in boreholes FAM-1 and FAMSISIGN*



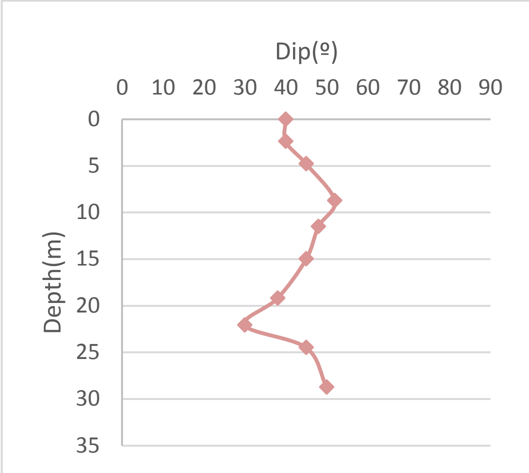


Figure C-04: *Percentage of particles that are included in the mud due to low recovering in borehole FAM-1.*