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Drilling Fluid Technology: Performances and Environmental Considerations

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1. Introduction

Petroleum drilling is the primordial step in the success of oilfield exploration. This success is based, on the one hand, on the important details derived from geological drilled formations and, on the other hand, on the good drill-in reservoir conditions. Thus, the paramount drilling objectives are to reach the target safely in the shortest possible time and at the lowest possible cost, with required additional sampling and evaluation constraints dictated by the particular application. Drilling the wellbore is the first and the most expensive step in the oil and gas industry. Expenditures for drilling represent 25% of the total oilfield exploitation cost and are concentrated mostly in exploration and development of well drilling. In the 90s, drilling operations represented about $10.9 billions, compared with $45.2 billions (API, 1991), the total cost of US petroleum industry exploration and production.

Drilling fluids, which represent till one fifth (15 to 18%) of the total cost of well petroleum drilling, must generally comply with three important requirements: they should be, i) easy to use, ii) not too expensive and iii) environmentally friendly. The complex drilling fluids play several functions simultaneously. They are intended to clean the well, hold the cuttings in suspension, prevent caving, ensure the tightness of the well wall, flood diesel oil or water and form an impermeable cake near the wellbore area. Moreover, they also have to cool and lubricate the tool, transfer the hydraulic power and carry information about the nature of the drilled formation by raising the cuttings from the bottom to the surface. Figure 1 shows a simple diagram of a rotary rig.

Drilling fluids went through major technological evolution, since the first operations performed in the US, using a simple mixture of water and clays, to complex mixtures of various specific organic and inorganic products used nowadays. These products improve fluid rheological properties and filtration capability, allowing to penetrate heterogeneous geological formations under the best conditions.

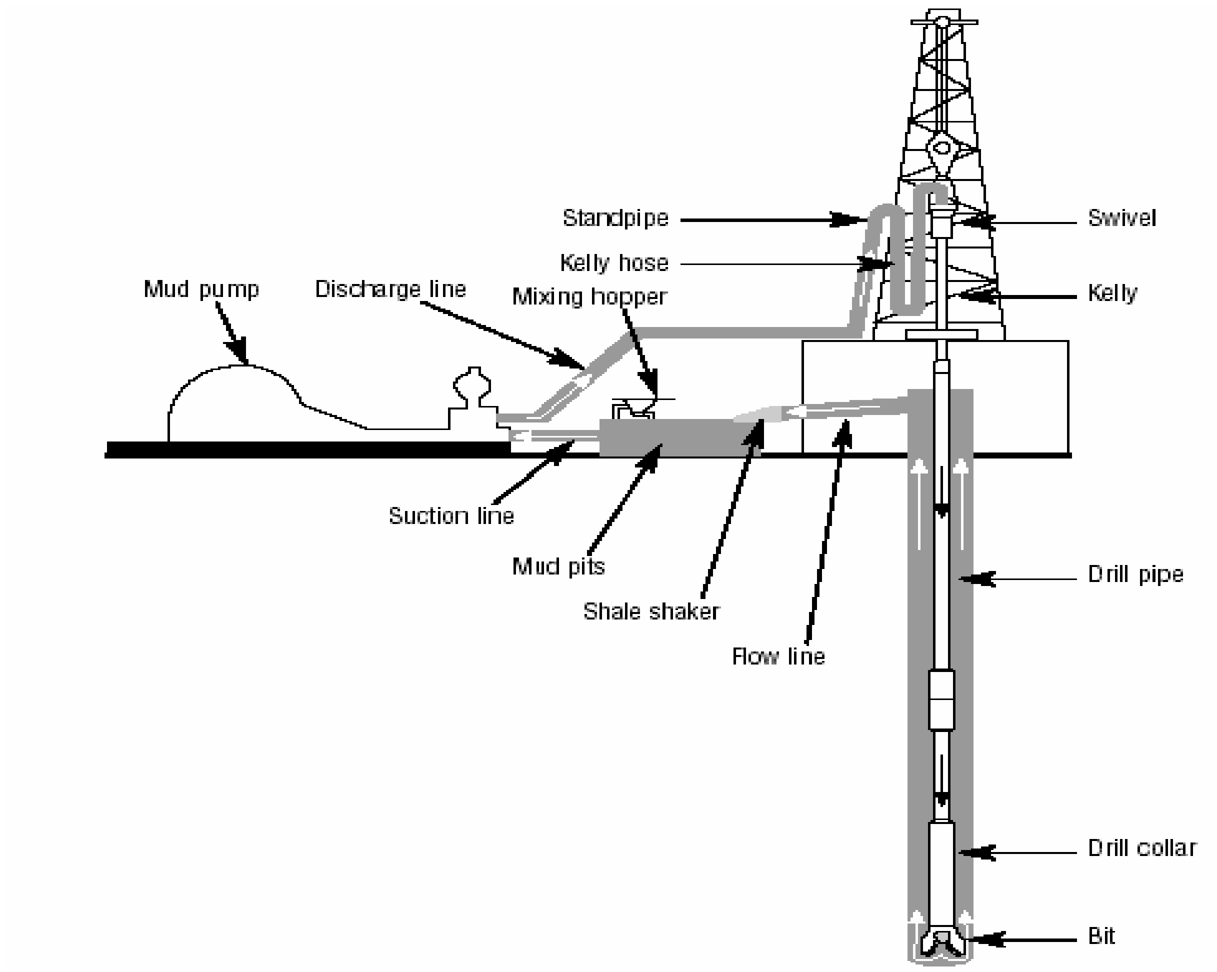

Fig. 1. A simple diagram of a rotary drill rig

In fact, borehole stability remains the main problem during drilling and the selection of drilling fluid type and composition was at the origin of successful drilling. Numerous studies have analyzed shale problems and several methods have been proposed to improve fluid performances for clay swelling inhibition (see §3 and 4) and to evaluate the scattered results already published in the literature. The majority of procedures recommend to compare initial and final sizes (or weights) of cuttings for inhibition estimation after fluid contact.

Then the question is to know which main factor (clay type, clay content or cuttings size) is affecting these disparate results.

In drilling fluid technologies, two main tendencies are currently developed in parallel: i) the search for new additives increasing the performances of water-based muds (WBM) and ii) the development and introduction of new compounds into oil-based muds (OBM). Some pendent questions will be discussed in this chapter, as well as filtration, formation damage and environmental considerations. Finally, some new solutions will be proposed by the authors.

2. History of drilling fluid technology

2.1 Drilling fluid composition

The complexity of the problems met in petroleum drilling has led to emerging techniques for the formulation of appropriate fluids. Generally, drilling muds may be classified in the following three families:

1. The WBM family, in which fresh-, salt-, or sea-water is the continuous phase, is the most used (90-95%). The WBM are mainly composed of aqueous solutions of polymers and clays in water or brines, with different types of additives incorporated to the aqueous solution.
2. The OBM family is less used (5-10%). These drilling fluids have been developed for situations where WBM were found inadequate (Chilingarian and Vorabutr, 1981). The OBM are oil- (usually, gas oil-) based muds. Generally, they are invert emulsions of brine into an oil major, continuous phase stabilized by surfactants. Also, other additives are often added to the organic phase, such as organophilic modifiers of the clay surface. However, although OBM often give better performances, they have major drawbacks such as to be generally more expensive and less ecologically friendly than WBM. Consequently, although OBM give greater shale stability than WBM (Bol et al., 1992), these latter systems have also been developed by many researchers in order to respond to environmental regulations (Simpson et al., 1994; Friedheim et al., 1999; Young and Maas, 2001; Patel et al., 2001; Schlemmer et al., 2002).
3. The third family of drilling fluids comprises gas, aerated muds (classical muds with nitrogen) or aqueous foams (Coussot et al., 2004). These drilling fluids are used when their pressure is lower than that exerted by the petroleum located in the pores of the rock formation. These fluids are called 'underbalanced fluids'. This underbalanced drilling technology is generally adopted for poorly consolidated and/or fractured formations.

Controlled drilling rate tests in various rocks have confirmed that air or gas is a faster drilling fluid than water or oil. Water should be the fastest drilling liquid, however, in this case, drilling tests show that the most commonly used additives have detrimental effects on the drilling rate. Choosing a mud system begins with the selection of a mud family, according to the nature of the rock formation, and should take into account environmental and economic constraints. The choice of the mud formulation will be the second step, where one has to decide on the range of desired properties, leading to use minimum amounts of additives. Figure 2 summarizes the drilling fluid types.

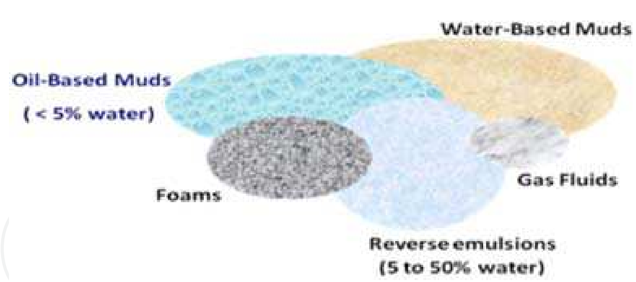

Fig. 2. Drilling Fluid Types

2.2 Biodegradability of drilling fluids

The biodegradability of petroleum products is dependent on the chemical structure of their various components. Compound resistance to biodegradation increases with increasing molecular weight. The oils used in OBM can be classified according to their aromatic hydrocarbon concentration, which contributes to fluid toxicity. However, the relations between hydrocarbon physico-chemical properties and biodegradability have been little studied. Several works (Zhanpeng et al., 2002), dealing with laboratory techniques of biodegradability determination and the influence of experimental conditions, showed the variation of the results according to the used method and considered conditions. In general, the more soluble, lighter petroleum hydrocarbons are more biodegradable than the less soluble, heavier members of the group. Viscosity is also known to have an important impact on biodegradability. Highly viscous hydrocarbons are less biodegraded because of the inherent physical difficulty in establishing contact among contamination and microorganisms, nutrients, and electron acceptors compounds (Cole, 1994). The viscous diesel oil at high amount (>10%) shows low biodegradation rate (4%), but, in the presence of mixed culture (*Enterobacter sp., Citrobacter freundii, Erogenous Pseudomonas, Staphylococcus auricularis, Bacillus thuringiensis, Micrococcus varians,…)* it presents good biodegradation properties (Khodja, 2008). Moreover, the biodegradation behaviour of diesel oil does not obey that of individual compounds. With high amount of aromatics in diesel oil (33%), the difficulty was considerable to relate diesel oil biodegradability to its composition. Numerous works showed good correlation between biodegradability and some physical and chemical parameters. Haus et al. (2003) demonstrated that biodegradability decreased with increasing amounts of aromatic and/or polar compounds. He showed that kinematic viscosity is the significant factor in biodegradability variation with chemical composition and oil physical and chemical properties. Zhanpeng et al. (2002) based their method to calculate biodegradability on three parameters: BOD_5/COD (biological oxygen demand after 5 days/ chemical oxygen demand) ratio, CO_2 production and microorganism activity by ATP (adenosine triphosphate). On the chemical structure scale, some works (Hongwei et al., 2004) showed that biodegradability was a function of total energy and molecular diameter.

2.3 Drilling fluid technology

Drilling fluid technology is in constant evolution due to i) rapidly expanding needs due to more severe conditions, such as high temperature and pressure, tight gas and shale-gas reservoirs…, ii) increasing technical demands, such as increased lubricity requirements in air drilling and iii) growing restrictions on oil-based systems, such as environmental remediation. To comply with the new government regulations restricting the use of some technologies or practices, drilling fluid manufacturers have responded by developing acceptable alternatives. However, these solutions usually have substantial added costs and limitations that are sometimes prohibitive. In summary, drilling fluid development needs to encompass the design of new environmentally acceptable WBM and oil-like systems that will provide alternatives to OBM.

Such new drilling fluids should provide superior filtration control to minimize fluid invasion damaging permeable zones. The properties of the resultant mud cakes should prevent sticking of the drill pipe against the borehole wall due to differential-pressure. Particularly, in horizontal or high-angle wells, these new fluids should also provide adequate hole cleaning capabilities. The study of cuttings transport flow, air foam behavior and fluid viscoelastic behavior will help understanding and improving this process.

In order to attain greater efficiencies and cost savings, the main point in a R&D program is the consideration of all the consequential aspects of drilling technology (Drilling and Excavation Technologies, 1994). Such additional R&D should focus on the 'Development of environmentally-benign drilling fluids', designing non-toxic drilling fluids and foams as alternatives to toxic OBM which are moreover difficult to remove from the drill hole.

2.4 Optimization of drilling fluid performances

Drilling optimization in oilfields is usually formulated by using mathematical models. In these models, some parameters appear to be fundamental.

Fluid density

Density is the first parameter to consider. For desired densities greater or lower than 1, WBM or OBM can be used, respectively. The latter are recommended especially for clay formations where this density should be sufficient for drilling. Generally, for both WBM and OBM, mud weight (density) can be increased by adding various solids or soluble materials. Other undesirable solids issued from geological drilled formations are not easily removed but will be reduced to finer particles, which could have some adverse effects on mud properties. The way to avoid such undesirable phenomena is to use high-speed shale shakers. In additional stages, to remove finer solids down to the 1 µm range, these devices are equipped with 50- to 100-mesh screens, using desanders, desilters, mud cleaners, and centrifuges. Undesirable solids that are less than 1 µm can only be removed chemically using medium- to high-molecular-weight flocculants. In addition, some recommendations specify the effects of size on rheology and fluid performances. Solids less than 1 µm have 12 times more effect on drilling rate than larger particles (Lummus and Azar, 1986). For these solids less than 1 µm, the shearing stress required to start the fluid motion will be greater than for larger particles.

Viscosity

The second parameter to consider is viscosity. It is a general term used to define the internal friction generated by a fluid when a force is applied to cause it to flow. This internal friction is a result of the attraction between the molecules of a liquid and is related to a shear stress. The greater is the resistance to the shear stress, the greater is the viscosity. In fact, standard viscosity measurements do not define flow behavior within shear rate ranges imposed at the bit, annulus, and pits. The viscosity at the bit affects penetration rate, which will be better when viscosity is lower. The viscosity in the annulus affects hole cleaning efficiency and the viscosity in the pits influences the effectiveness of solids separation techniques.

Numerous additives are added to the formulation in order to reach optimized specific purposes which are sometimes contradictory. For example, mud has to be viscous enough in order to be able to lift the cuttings to the surface, but at the same time, viscosity must not be too high in order to minimize friction pressure loss.

Fluid loss

The loss of drilling fluids is the last considered parameter. It is generally defined as the volume of the drilling mud that passes into the formation through the filter cake formed during drilling. It is often minimized or prevented by blending the mud with additives. A number of factors affect the fluid-loss properties of a drilling fluid, including time, temperature, cake compressibility; but also the nature, amount and size of solids present in the drilling fluid.

In high-pressure and high-temperature environments, optimization of the above mentioned three parameters is essential to lighten instability problems when drilling through shale sections. Under these conditions, selection of suitable mud parameters can benefit from analyses that consider significant thermal and chemo–mechanical processes involved in shale–drilling fluid interactions.

Nevertheless, some other factors are not taken into consideration in these mathematical models. For instance, it has been widely experienced that random factors related to soil layers, drill bits, and surface equipment, greatly affect drilling performance. Optimization involves the post-appraisal of offset well records to determine the cost effectiveness of elected variables, which include mud and bit types, weight on bit, and rotary speed. Stochastic models are introduced to describe such random effects. This more practical model provided a better characterization for real oilfield situations as compared with other deterministic models, and has been demonstrated to be more efficient in solving real design problems.

For drilling fluid additive evaluation, five important parameters have been proposed:

1. Main function and chemical nature,
2. Compatibility/salt tolerance with other additives and temperature limitations,
3. Recommended treatment range and cost,
4. History/success of using,
5. Interferences, damage and risk such as geological interpretation effects, formation damage, health safety and environment (HSE) and waste treatment.

2.5 Drilling costs

Remediation costs attributable to drilling are not easily estimated. The difficulty of access, the type of pollutant present, and the nature and time of derived treatment will influence the total cost. In oilfield operations, drilling costs typically account for 50 to 80% of exploration finding costs, and about 30 to 80% of subsequent field development costs (Drilling and Excavation Technologies, 1994). Typical costs for shallow hydrocarbon wells (up to 1,250-ft depth) drilled in the United States are about $27/ft (Anderson et al., 1991).

The boreholes required for environmental remediation will be shallow, so it might be expected that their cost will range between $20 to $30/ft, similar to shallow petroleum wells. However, special circumstances may increase these costs substantially. If the drilled solids contain toxic or radioactive substances, the drilling cost may increase dramatically because of the need to collect, document, and dispose the cuttings and to decontaminate drilling equipment.

3. Shale problems during drilling

The stability of a drilling fluid is generally guaranteed by its homogeneity after a long aging period. For OBM systems, a phase separation and a viscosity decrease are direct indications of drilling fluid degradation. In WBM, phase separation is also an indicator of mud instability. Figure 3 summarizes the evolution of drilling fluid state.

Mud viscosity affects the dispersion and the swelling of shales and decreases the diffusion velocity in porous medium. Muds with high viscosity and a minimum filtrate volume are preferred for inhibition efficiency, according to classical filtration equations. (see §5.1). In terms of its composition and properties, the mud column (i.e., the vertical column of drilling mud in the borehole) is a dynamic system whose characteristics are frequently changing dramatically both in time and space. Mud composition changes as shales migrate into the column and are dispersed into the mud, or by chemical interaction between the mud and the formation.

3.1 Shale instability

Wellbore instability is the largest source of trouble, waste of time and over costs during drilling. This serious problem mainly occurs in shales (principally clays), which represent 75% of all formations drilled by the oil and gas industry. The remaining 25% are composed of other minerals such as sand, salt, etc. The physical properties and behavior of shale exposed to a drilling fluid depend on the type and amount of clay in the shale.

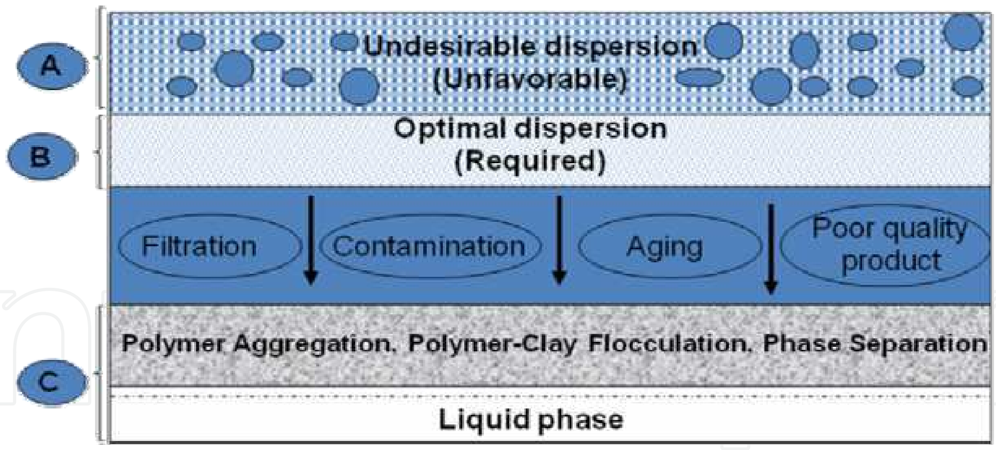

Fig. 3. Representation of drilling fluid destabilization (Khodja et al., 2010)
(Phase separation: low viscosity and high filtrate)
A: Undesirable dispersion with an inhomogeneous additive repartition. Solid-liquid, polymer-solution, dispersed phase-continuous phase are inhomogeneous and unstable.
B: Optimal dispersion with a uniform repartition of additives. The mud system is stable and exhibits good rheological and filtration characteristics.
C: The mud system is unstable for one of the following reasons: dramatic filtration conditions (pressure and temperature), use of incompatible additive (contaminant) or of poor quality products, or considerable aging. Solids, polymers, and salt in WBM, dispersed phase, emulsifiers or others additives in OBM are separated from continuous phase. The system presents a phase separation, involving a degradation of rheological parameters and a high filtrate volume.

Wellbore stability issues were not seriously addressed until the end of the 70s, when a famous published paper (Bradley, 1979) initiated great interest for this topic in the industry. Since that time, wells became more complex and drilling operations were routinely carried out in more difficult environments. In addition to a technical challenge, the occurrence of any wellbore instability-related problems will significantly add to the already high well costs. It is estimated that at least 10% of the well budget is used to perform unplanned operations resulting from wellbore instability. This cost may approach $1 billion/yr. worldwide.
Various aspects of wellbore instability have been presented recently. Shale–fluid interactions can be manipulated to enhance cuttings and wellbore stabilization as well as improving hole-making ability in shale formations (van 0ort, 2003). A membrane transport model was developed for calculating the diffusion potential and the reflection coefficient in shales under different conditions (Rosana et al., 2000). The ionic composition of the fluid saturating the shale appeared to control the magnitude of the membrane potential. This suggests that at least at early time, the type of cations in the drilling fluid is much less important than their concentration since this parameter controls the water activity. Thus, the stability of clay-rich shales is profoundly affected by their complex physical and chemical interactions with drilling fluids.
Most borehole stability and drilling fluid-related problems can be handled with present technology in well-defined environments if stringent quality control actions are maintained. Nevertheless, severe complex drilling situations still present serious challenges to economically viable drilling. Efforts and progress by several Companies have led to new

proprietary, or patented technologies usually available for license, applied in the field but rarely used in laboratories and scarcely published in the accessible literature.

When wellbore walls become unstable, the spilling of cuttings causes a disastrous change in the rheological properties of the mud (Beihoffer et al., 1988). Several studies on shale-fluid interactions confirm that various causes are at the origin of borehole instability: water adsorption, osmotic swelling and cation exchange.

Different approaches to WBM design have been suggested depending on given shale formations (Darley, 1969; Chenevert, 1970; Roehl and Hackett, 1982; Beihoffer et al., 1988; Zamora et al., 1990; Hale and Mody, 1992; Bol et al., 1992; Cook et al. 1993; Mody and Hale, 1993; Bailey et al., 1994; Simpson et al. 1994; Durand et al. 1995; Horsud et al., 1998; Pernot, 1999). Other recent studies focused on shale-fluid interactions (Lomba et al., 2000; Schlemmer et al., 2002; Van Oort, 2003). Consideration is given to maintain borehole stabilization in reactive shales by reducing hydration (swelling) and/or dispersion. This process is generally referred to as 'inhibition'. Clay wettability and inhibition properties were studied by analyzing the behaviour of water-clay-polymer-electrolyte systems. These properties are connected to the rheological and filtration characteristics for both mud and filtrate. Considering the replacement of OBM by WBM, Van Oort (2003) showed that additives, such as polymer and KCl, tend to reduce shale instability. Cuttings characterization is a key parameter to explain how salt, added to WBM, affects shale stabilization.

Although, as in most engineering disciplines, a wide gap appears between R&D studies and field applications, some important research areas could yield significant advances and benefits. In addition to new development, efforts should be made to transfer some of the old existing technologies that could immediately solve problems encountered in borehole stability or formation characterization and validation. The main critical parameters that should be determined are the constitution and strength of the formation, its discontinuities as well as abrasivity, permeability, pore pressure and stress state.

Studying clay stabilization problems, Kelley (1968) met contradictions, showing that some clay formations can be drilled easily meanwhile similar ones are dispersed. Several studies were conducted in order to understand these contradictory data and propose adequate mechanisms and solutions for drilling. Aadnoy (2003) intended to visualize that a good field modeling, based on the understanding of the underlying physics is the key for development of wellbore technologies and practices.

3.2 Clay swelling

Clay swelling is at the origin of well instability during drilling. Low and Anderson (1958) presented osmotic pressure equations for determination of the swelling properties, considering clays like semi-permeable membranes. Chenevert (1969) stating that the main reason of instability during drilling by WBM systems is the swelling of clays, adjusted the water activity of OBM systems, to prevent water adsorption on clays. Steiger (1993) studied clay hydration in a triaxial apparatus by measuring the swelling pressure of clays exposed to different drilling fluids with different water activities. He showed that the addition of potassium salts can reduce the water activity of clay and consequently the swelling pressure. In experiments conducted on site, he observed that the presence of KCl in the drilling fluid improves the stability of clay formations. Mody and Hale (1993) developed a model of stability supporting the interaction between drilling fluids and clay formation. This model identified the optimum drilling fluid parameters, such as density and salinity, for the elimination of instability problems during the use of WBM and OBM. They reported that the chemical potential difference between water in the clays and in the drilling fluid is the most important parameter. Simpson et al. (1994), using an experimental approach, showed that OBM containing an emulsified water phase can prevent moisture and thus the weakening of the clay. According to these authors, the use of a hydrophilic organic compound, namely cyclic with multiple hydroxyl groups (methylglucoside) can also afford other characteristics similar to those of OBM, such as lubrication.

3.3 Laboratory methods for stability evaluation

Hale and Mody (1996) conducted experimental tests to study the direct impact of moisture on the mechanical properties of clay and tried to understand the mechanisms behind the instability of the wells. van Oort et al. (1996a) used the pressure transmission test (PT) (based on the work of Fritz and Marine, 1983) to measure the effectiveness of the clay membranes. They observed that, after increasing the upstream pressure, the outlet pressure increases due to a higher pressure in pore caused by the hydraulic flow. Horsud et al. (1998) have also studied the phenomenon of swelling pressure in clays and concluded that osmosis does not play a role, but that pressure (or suction) is the main parameter that controls the development of the swelling. Pernot (1999) quantified the effect of the swelling pressure of a variety of fluids in contact with several types of clays and concluded that the methylglucoside type 'Gumbo' stops clay swelling. The created barrier blocked the flow of ions and water in clays. Concentrated salt solutions show a low membrane reflection coefficient. Muniz et al. (2004) described the equipment used for the evaluation of clay-fluid interactions. The idea is to combine water and ionic gradients to estimate both the efficiency of the membrane reflectivity and the permeability coefficient and to integrate them into a program for stability evaluation. Zhang et al. (2006) developed the gravimetric swelling test (GST) and showed that water motion is not controlled only by osmosis (water activity) but is also influenced by capillary suction and ionic diffusion. The contact of fluid with clays changes their physico-chemical and mechanical properties.
Drilling fluid additives able to inhibit the swelling and dispersion of clays will be considered in §5.

4. Shale characterization and Inhibition

4.1 Inhibition diagnosis and shale characterization

The mechanism of inhibition is dependent on the choice of the polymer-salt system. It can be identified by the following features:

1. Increase of filtrate viscosity,
2. Reduction of clay permeability,
3. Balancing of the flow of mud filtrate in the clays with pore water by the effect of osmotic pressure ($a_{wdf} < a_{wsh}$), or,
4. Combination of the previous different factors.

Wellbore instability is due to the dispersion of the clay into ultra-fine colloidal particles and this has a direct impact on the drilling fluid properties. Clay characterization is the main parameter allowing understanding borehole stability.
Solid particles are divided into three groups according to size. Colloids from about 0.005 to 1 μm impart the viscous and filtration properties, silt and barite (sometimes called “inert solids”) from 1 to 50 μm provide density, but are otherwise deleterious and sand from 50 to 420 μm, apart from bridging large opening in very porous formations, is objectionable

because of its abrasive property. Clay minerals are considered as particularly active colloids (Bergaya et al. 2006), partly because of their anisotropy due to shape (tiny platelets) and partly because of their molecular structure which presents high negative charges mainly on their basal surfaces, and possible positive charges on their edges. Interaction between these opposite charges strongly influences the viscosity of clay at low velocities, and is responsible for the formation of a reversible gel structure when the mud is at rest.

The main methods developed for shale characterization and fluid inhibition performances deal with composition, reactivity, mechanical and physico-chemical properties of shales (composed in majority of clay). A succinct list of usual methods is presented hereafter:

- **XRD,** X-ray diffraction analysis to determine qualitative mineral content,
- **CEC,** cation exchange capacity to evaluate reactivity of drilled cuttings. The methylene blue test (MBT) method was recommended by API 13I (2003),
- **GST,** a gravimetric swelling test, used to measure water and ion motion during shale/mud interaction (Zhang et al., 2004),
- **CST**, capillary suction time for the determination of filtration properties and salt optimization (Wilcox et al., 1987),
- **ROP**, rate of penetration measured with a penetrometer to estimate the degree and depth of softening (Reid et al., 1993) or with a Bulk Hardness Test designed to give an assessment of the hardness of shale following exposure to a test fluid (Patel et al., 2002),
- **DCM**, dielectric constant measurement to quantify swelling clay content and to determine specific area (Leung and Steig, 1992),
- **Triaxial test** for pore pressure measurements, carried out in downhole simulation cell (DSC) for compressive stress/strain behavior (Salisbury and Deem, 1990),
- **Oedometer test** for pore pressure modification and chemical potential influence (Bol et al., 1992),
- **SDT**, slake durability test, a standard method originally used in geotechnical studies when measuring the weathering and stability of rock slope: ASTM D 4644-97 (ASTM, 2000), reapproved 1992 (Likos et al., 2004),
- **Jar slake testing**, a qualitative method designed to evaluate shale relative durability in contact with a given fluid. Wood and Deo (1975), Lutton (1977) describe details of this method using six indices,
- **DSCA**, differential strain curve analysis for in situ measuring stress orientation and intensity (Fjaer, 1999),
- **Hot-rolling dispersion test** (shale disintegration resistance or cuttings dispersion test), the most widely used technique in optimizing drilling fluid. Appreciated for its simplicity, low cost and duration, it has been recommended by several laboratories and adopted by API 13B-1(2003).
- **Shale pellet inhibition** (pellet dispersion test): pellets and fluid are introduced into a steel bomb and processed as above (hot-rolling dispersion test). For comparison and reference, an OBM system is generally used (Mody and Hale, 1993).
- **Pressure transmission test**, used for confined or unconfined shale (van Oort, 1994). Muniz et al. (2004) described an apparatus designed to evaluate shale-drilling fluid interaction and estimate shale permeability, coefficient of reflectivity (membrane efficiency) as well as ionic diffusion coefficient,

- **Microbit drilling equipment**, requiring core sample availability and costly investment (Lamberti, 1999).

The comparison between all these techniques shows an important contribution of each of them. However, these methods are often criticized regarding feasibility, cost, precision and conditions used.

4.2 A new approach for inhibition evaluation

Swelling measurement is a key test when selecting and developing inhibitive WBM. However new methods are proposed, combining dispersion and pellet tests. The aim is to protect the initial quality of cuttings, to minimize grinding and to avoid moistening, while opting for a preliminary wash to eliminate the contamination of cuttings by the different additives (polymers, surfactants, etc.).

A new approach using a wet-cell X-ray diffraction method is proposed by the authors (Khodja, 2008). The advantage of this method is to evaluate clay swelling after fluid contact and to estimate differences in the rate of solution adsorption between various WBM systems. The principle is to combine in-situ X-ray diffraction in wet-cell with the evaluation of liquid adsorption. This latter method combines filtrate data (volume and rate) with rheological and inhibitive properties. The API fluid loss test (30 min, ΔP=100 psi through N°50 Whatman filter paper, ambient temperature) is the standard static filtration test used in the industry; however, because it uses very fine mesh paper as filter medium, all of the bridging particles are stopped at the surface of the paper and the spurt-loss phase is not simulated properly. A better static filtration test is the permeability plugging test (PPT), which uses a 1/4-inch-thick ceramic disk of known permeability (API 13B1, 2003). But in this test, mineralogy variation is not taken into account. In the new test, experiments were carried out by replacing Whatman 50 filter paper by the pellet in the API filtration cell (Khodja et al., 2008, 2010). The slurry was exposed to a 100 psi pressure for 30 min to obtain filtrate. The compaction force, linked to the deposit mode of the sediments, has a significant influence on the permeability.

With different systems (WBM with PHPA, glycol or silicate; OBM), our results show similar, rather high recovery values for large size (0.8 mm) but low recovery values for small size (0.100 to 0.315 mm) cuttings. When using different inhibitive polymers, almost no difference in recovered weight is noticed between cuttings samples from different geological formations and with different mineralogical compositions.

Our recommendation is then to use, in dispersion tests, preferably small size cuttings, which are in close contact with all additives used in drilling fluid systems. Moreover, when using small size cuttings, clays are fully exposed to the fluid and aggregation effect is eliminated (Khodja, 2008). Xanthan gum (or PAC) added as a viscosifier, acts synergistically with polyalkyleneglycols (PAG) and preserves cuttings integrity. To increase glycol efficiency, an inhibiting ion, preferably potassium, was used. For the silicate system, analyses show high adsorption of silicate ion on shale. The inhibition mechanism also depends on the type of polymer used, controlled by plugging of clay pores, thus reducing the dispersion (PAG), or by surface coating (film formation with PHPA or silicate).

Practically, drilling engineers need to optimize formulations in opposite ways depending on whether they deal with upper geological layers or reservoir formation. In the former case, minimum filtrate, optimal viscosity and high damage are required in fluid formulation selection. In the latter one, low damage is the principal selection parameter.

5. Drilling fluid additive evolution in WBM and OBM

Nearly a century after the birth of the drilling fluid industry, with hundreds of suppliers and thousands of manufactured products, water is still the main compound. Gas oil, initially a major technological breakthrough, has now been often replaced by synthetic low toxical oils (LTO) that lead to many problems and do not resolve critical drilling situations.

Crude starch and cellulose, the first used polymers, were constantly improved for thermal efficiency. Clays, historical bentonite additives, were first used in WBM. Small amounts of surfactants greatly modify drilling fluid performances. Nowadays, after treatment, bentonite is added to OBM under the form of organophilic clay (under the commercial name of Bentone). Clays, as additives, meet restrictions and regulations in accordance with environmental considerations, from the countries involved in oil drilling, or interested in drilling fluid research. This research, occurring at intensive laboratory scale and/or occasionally on site, is mainly based on experiments conducted in the case of drilling new discovered fields or of drilling in unknown geological sites. The less recommended use of OBM has renewed the interest in WBM, which also provide economic benefits. The major problem in the use of WBM is still linked to the instability of the wells, mainly due to the interaction of clays with the formation water, but several acceptable options are put forward. So, now, a large number of fluid systems are offered by specialized companies. In fact, a lot of these products are marketed, despite similar formulations appear under different tradenames.

Hereafter, some examples of WBM additives, which have improved the performance of drilling fluids, are presented.

Bentonite, a worldwide-used drilling fluid additive, is mainly a montmorillonite species. It is added to fresh water i) to increase hole cleaning properties, ii) to reduce water seepage or filtration into permeable formation, iii) to form a thin filter cake of low permeability, iv) to promote hole stability in poorly cemented formations, v) to viscosify the mud and finally vi) to avoid or to overcome loss of circulation. However, a low bentonite content is desired because a high clay content in drilling fluids shows several adverse effects, on the one hand, it greatly reduces the rate of penetration, and, on the other hand, it increases the chances of sticking due to differential pressure and it is the major cause of excessive torque and drag.

PHPA. Partially hydrolysed (30%) polyacrylamide is the most used additive in drilling for borehole stabilization in shale formations. PHPA-clay slurries tend to form a relatively thin filter cake at the borehole wall, characteristic often cited as an advantage (Darley and Gray, 1988).

KCl is a salt commonly used to inhibit the swelling of clays. According to van Oort (2003), the low efficiency of the membrane (1-2%) is probably due to the relative high mobility of KCl in the clays. In addition, conductivity and permeability are not altered and the osmotic pressure generated by KCl is moderate (typically less than 20 MPa). KCl-containing systems have good efficiency for the stabilization of clay cuttings in the presence of PHPA (Clark et al., 1976). Although Na^+ is not as good as K^+ ion, the use of NaCl has additional advantages. NaCl can reduce the invasion of filtrate into the clay. Indeed, close to saturation, NaCl leads to large viscosities and a water activity lower than those observed with concentrated solutions of KCl. In combination with silicates, polyols and methylglucoside, concentrated solutions of NaCl can improve the efficiency of the membrane (cake).

Amines and derived salts. Simple amines are used in several areas for specific applications. Quaternary ammonium salts prevent swelling and dispersion of clays by ion exchange.

Their disadvantages are their high cost, toxicity (Himel and Lee, 1951) and their incompatibility with anionic additives commonly used in fluids.

Anionic and non-ionic polymers. In order to stabilize clay particles and to prevent their swelling/dispersion behavior in the presence of water, some other ingredients are added. A wide variety of anionic (PAC: polyanionic cellulose), non-ionic (polyols, polyglycerols, glycosides, polyvinyl alcohol, hydroxyethylcellulose) or amphoteric polymers were tested. These polymers act by encapsulation, limiting water penetration in clays. However, they are generally less efficient for swelling than some cationic species (Stamatakis et al., 1995). PAC is used as a fluid loss reducer for fresh water and salt-water muds. Due to its anionic nature, adsorption and flocculation occur as a result of hydrogen bonding between solid surfaces and the hydroxyl groups on the polymer. The (poly-)glycerols and (poly-)glycols (Hale et al., 1989 and Perricone et al., 1998), usually simply referred to by 'glycerols' and 'glycols' have been widely used for drilling clays (Chenevert, 1989; Bland, 1991, 1992 and 1994; Downs et al. 1993; Bland et al., 1995). They prevent cuttings from dispersing into the medium (Bailey et al., 1994). Therefore, they increase drilling rates (Reid et al., 1993; Cliffe et al., 1995). Twynam et al. (1994) observed improvements with the use of a high concentration of glycol. Nair (2004) evaluated the performance of two commercial additives (Gilsonite® and Soltex®), respectively natural asphalt and high molecular weight modified hydrocarbon compound (sodium asphalt sulfonate), used as inhibitors in terms of high pressure and temperature (HP/HT), and got a small decrease in permeability without explaining the reasons for this reduction for both products.

Carbohydrates and derivatives. In response to environmental constraints, new families of compounds are proposed such as sugars and their derivatives (saccharides). Sugars increase the viscosity of the filtrate and reduce the flow of water in clays (van Oort, 1994). In addition, they provide a low water activity and generate an osmotic pressure favorable to clay dehydration. The problem with sugars is their susceptibility to biological attack, making them difficult to maintain unspoiled when stored on site. However, methylglucoside (MEG) and generally methylated saccharides are less susceptible to biological attack (Simpson et al., 1994). MEG is a derivative of glucose, supplied as liquid containing 70% solids. Made from corn starch, it is classified as "biodegradable". Saccharides are generally recommended for the stabilization of clays. Added salts to saccharide systems allowed effective dehydration of clays, reduction of "bit-balling" and increasing ROP. These MEG systems have a good filtrate and produce environmentally acceptable cuttings (Chenevert and Pernot, 1998). Soluble in water, MEG has many hydroxyl groups in a ring structure capable of reducing the water activity of the drilling fluid and may be a good additive to WBM.

Silicates and aluminum-based compounds have been introduced in the petroleum industry since the 90s (Ding et al. 1996; van Oort et al., 1996b; Ward and Williamson, 1996). They are strongly recommended for the stabilization of clays. Silicate-containing fluids show good shale swelling inhibition, low depletion rate and high ROP and, additionally, are environmentally friendly (Ward et al., 1997; van Oort et al., 1999; Tare and Mody, 2000). These soluble additives react rapidly with clays (Ca^{2+} and Mg^{2+}) to form insoluble precipitates by gelation which act as a barrier towards clay surface. The mechanism of gelation/precipitation can seal the micro-fractured clays (van Oort et al., 1996b). Compounds containing aluminum, 'Alplex™' (Clark and Saddok, 1993; Saddok et al., 1997), were also developed for this purpose.

The search for inhibitive WBM systems, which would perform like OBM, has been a continuous endeavor in the drilling industry. During the past several decades, many approaches have been taken (Chenevert, 1970; Clark et al., 1976; Retz et al., 1991; Downs et al., 1993; Stamatakis et al., 1995), such as cationic polymer mud systems, glycol-based muds, polymer/salt systems, silicate muds, calcium ion-treated muds and other relatively high-concentration brine systems. However, all these approaches have not been completely successful in inhibiting the hydration of highly reactive systems and have various limitations. For example: i) cationic polymer systems are almost as inhibitive as OBM; however, the cost of running the system, the toxicity of cationic polymers, and their incompatibility with other anionic drilling fluid additives have resulted in limited success in the field; ii) highly-concentrated brine systems have limitations on mud formulations and properties; iii) while silicate muds have good inhibitive properties, they also pose problems related to human health and environmental issues, due to high pH values, logistic problems and mud formulation limitations; iv) some of the anionic and non-ionic polymer systems, e.g., biopolymers and PHPA-based systems, show limited thermal stability and mud formulation limitations.

6. Damage considerations. Petrophysical properties and filtration

6.1 Permeability/Porosity

In reservoirs, the solids found during drilling operation come from two principal sources: reservoir and drilling fluid additives. Generally, the formation damage directly apparent originates in the poor performances of un-weighted (without solid) fluids, giving low return permeability[1] (see §6.3). After fine tuning to achieve optimum particle size distribution (PSD) with a minimum solids, return permeability improved to high values. With bridging material, the invasion of the filtrate through the wellbore (spurt loss), which is a major damage mechanism, can be reduced to a minimum. Abrams (1977) recommended a minimum bridging particle concentration of 5% and a ratio of 1:3 between average pore size and medium particle size. Colloidal and hydrodynamic forces are responsible of fines liberation. Clays and fines are considered as producing one of the major damage of the formation. This damage is located near the wellbore area within a three to four feet radius. Dispersion and fines liberation in the majority of soils is promoted by high pH, high Na^+ saturation and low ionic force (Roy et Dzombak, 1996; Swartz et Gschwend, 1998 and 1999; Saiers et Hornberger, 1999; Grolimund et al., 2001). Kaolinite, in majority, and some illite exist in the formation rocks as pore filling materials. Kaolinite has the tendency to break up from the host grain in large size particles plugging the pore throats. Rahman et al. (1995) showed that the petrophysical properties of reservoirs containing illite depend significantly on the core preparation technique. Illite collapses upon air drying resulting in high porosity, high permeability and low capillary pressure. Illite rebounds, however, on contact with fresh water and projects across the pores, giving rise to low porosity, low permeability and high capillary pressure. Illite has also shown high susceptibility to migration into fresh water; it remains dispersed and is carried with the flowing fluid until the particles are trapped into pore constrictions. It is very difficult to distinguish clay migration damage from clay swelling damage. A steady, usually rapid decrease in permeability with decreasing salinity of the flowing liquids is generally a consequence of clay swelling; however, water sensitivity caused by particle migration will also appear in this case, but

1 Return permeability or damage ratio (D.R.) was determined by comparison of initial (K_{is}) and final permeabilities (K_{fs}) in the stable state (D.R. = $100(K_{is} - K_{fs})/K_{is}$).

sometimes in a more irregular manner. Damage caused by particle plugging was detected by noting a temporary change (usually an increase) in permeability when fluid flow direction was reversed. In summary, porosity and permeability variations are function of several parameters, such as rock mineralogical composition, solids size, pressure, solution type and concentration.

Yan et al. (1996) reported that the optimal effect of bridging occurred when particle diameter is 1/2–2/3 of pore size. Regarding the reservoir heterogeneity with wide mineralogical composition, rock-fluid interaction affects permeability and porosity seriously. Amaefule et al. (1988) pointed out that five primary factors affect the mineralogical sensitivity of sedimentary formations: mineralogy and chemical composition, mineral abundance, mineral size, mineral morphology and mineral location. Mungan (1989) states that clay damage depends on the type and amount of exchangeable cations, such as K^+, Na^+, Ca^{++} and the layered structure existing in the clay minerals. The significance of damage during brine injection was observed to be a strong function of mineralogy and injection rate. The occurrence of a critical velocity, along with other observations, indicated that the primary damage mechanism was fines migration (Shenglai et al. 2008). A low pH may also contribute to less formation damage. At low pH, dissolution of silica and subsequently releasing of fines inside the formation is less.

6.2 Filtration

Filtration refers to the liquid phase of the drilling mud being forced into a permeable formation by differential pressure. During this process, the solid particles are filtered out, forming a filter cake. For filtration to occur, three conditions are required: a liquid or a liquid/solid slurry fluid and a permeable medium must be present and the fluid must undergo a higher pressure than the permeable medium. The knowledge of the filtration properties is very important in the design of drilling fluid formulation. Some works (Loeber, 1992; Li, 1996; Argillier et al., 1997; Benna et al., 1999 and 2001) have shown that the filtration across the cake depends on several parameters such as initial clay content, particle or aggregate association, water retention and permeability, as well as experimental conditions (pH, etc). Ferguson and Klotz (1954) showed that 70% to 90% of the total filtrate volume, flowing through permeable formations, occurred during mud circulation. During this dynamic filtration, the invasion radius reaches a value of 85%. A constant flow rate is reached when filtration forces, leading to the formation of a mud cake, are balanced by hydrodynamic forces, *i.e.* mud circulation that erodes the mud cake.

6.3 Damage mechanisms

The number of horizontally drilled wells has increased dramatically because they offer better contact with reservoir rocks, thus leading to higher production rates. Unfortunately, the larger drainage area contributes to longer exposure time for the drilling fluid. Consequently, fluid invasion cause severe damage, which would then have a considerable influence on productivity (Renard and Dupuy, 1991). Therefore a better understanding of damage mechanisms for various reservoir conditions can minimize the risks of horizontal well drilling and is still an important topic for research. Bishop (1997) summarized the seven mechanisms of formation damage previously reported by Bennion and Thomas (1994) and Civan (2001), as follows:

1. Fluid-fluid incompatibilities,

2. Rock-fluid incompatibilities,
3. Solids invasion,
4. Phase trapping/blocking,
5. Chemical adsorption/wettability alteration,
6. Fines migration,
7. Biological activity.

Some fields present several other formation damages due to salt, scales, or asphaltene deposits and/or clays and fines migration, arising from different sources, such as work-over and snubbing operations, perforations, cement filtrate invasion, reservoir pressure depletion and other pseudo-skin mechanisms, such as turbulence in production, partial penetration, completion problems...

Mineralogy and chemical composition, as well as the mineral by itself (size, morphology, abundance, and location), are considered as the primary factors affecting the mineralogical sensitivity of sedimentary formations (Amaefule et al., 1988). Moreover, Mungan (1989) stated that clay damage depends on the type and amount of their exchangeable cations.

Despite several studies and solutions proposed to reduce damage (Chang and Civan, 1997; Civan, 2000; Fisher et al., 2000; Parn-anurak and Engler, 2005), the problem is still not well understood. The main reason is the complex relationship existing between drilling fluid additives and rock reservoir composition. Both depend on porous medium structure and drilling conditions. Generally, sandstone pores are filled with a single phase or with multiphase fluids. It is widely recognized that experimental conditions i.e. overbalance pressure (Jilani et al. 2002 ; Al-Riyamy and Sharma, 2004), fluid type and composition (Longeron et al. 1995), filtration mode (Dalmazzone et al. 2006 ; van der Zwaag, 2006), solid concentration and pH (Baghdikian et al. 1989) can adversely affect permeability variations and thus cause different formation damage ratios. Some works were carried out to measure the drilling fluid invasion in Berea cores[2] at different overbalance pressures, keeping the other major influencing parameters constant, i.e. core permeability and nature of drilling fluid. Jilani et al. (2002) confirmed that return permeability increases when the overbalance pressure decreases but the invasion intensity starts to increase only after the overbalance pressure reaches a certain low 'critical' value. Overburden pressure can affect the results and parameters estimation seriously.

Due to the complexity of the foreign fluid/formation interaction and several other factors which affect the damage caused by fluid, the return permeability tests undertaken in the laboratory in a filtration cell (Figure 4) are generally the main tests used to explain damage mechanisms and differences noticed in fluid performances.

This test gives macroscopic information by measuring permeability variation, but cannot explain damage mechanisms. Other analyses are performed to study fluid rock interaction, such as additive retention and adsorption, wettability alteration, SEM (Scanning Electronic Microscopy) vizualization,…

[2] For the past 30 years, Berea Sandstone™ core samples have been widely recognized by the petroleum industry as the best stone rock for testing the efficiency of surfactants. It is a sedimentary rock whose grains are predominantly sand-sized and are composed of quartz sand held together by silica. The relatively high porosity and permeability of Berea Sandstone™ makes it a good reservoir rock.

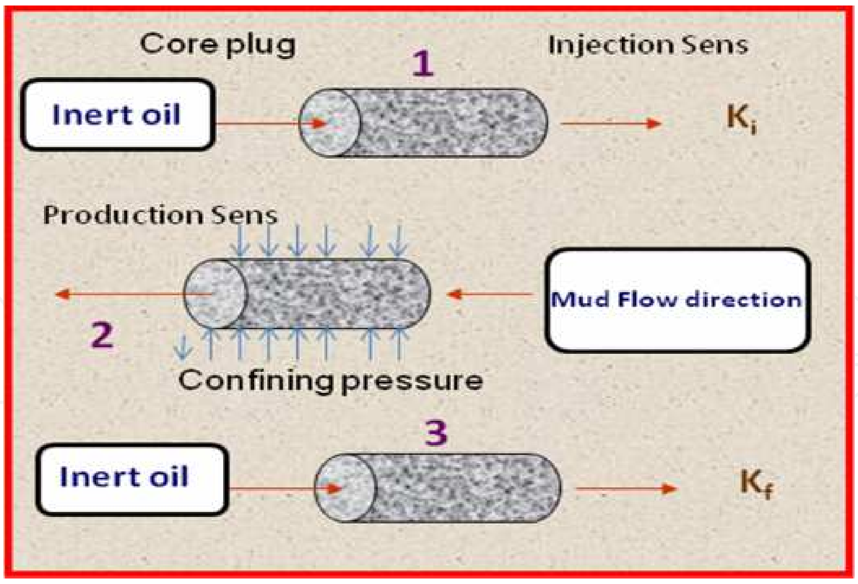

Fig. 4. Filtration cell for return permeability evaluation methodology

Many theoretical and experimental works have focused on the relationships between drilling fluid additive effect and return permeability. This last experimental method evaluates the relative permeability reduction and the effect of additive type and concentration with special scrutiny of solids and clay actions, leading to identify the most probable causes of damage during the selection process of candidate wells for matrix treatments. This also helps engineers to evaluate damage caused by clay swelling in reservoir conditions and to take the decision when to inject water in waterflooding operations.

6.4 Surfactants and wettability change

Drilling fluids contain various surfactants playing the roles of emulsifiers or wetting agents, and other specific additives, as mentioned above. Emulsion stability is often evaluated through rheological and filtration properties of the whole drilling fluid. Unfortunately, information on the nature and composition of emulsifiers is scarce. Acidic products from tall-oil, with an average chain length of 18 carbon atoms, other compounds deriving from tall-oil reactions with polyamines (Skalli et al., 2006), as well as alkanolamides, imidazolines and a variety of fatty acids and amines (Quintero, 2002) can act as emulsifiers. Similar surfactants are often used in traditional reverse emulsion systems (OBM) or in synthetic fluids (SOBM).

These surfactants cause mica and sandstone surfaces to become less water-wet (Skalli et al., 2006) and greatly reduce rock permeability (Yan and Sharma, 1989). Addition of surfactant to crude oil has less effect than sequential exposure of surfaces to crude oil and to surfactant solutions. Morever, the whole drilling muds have less effect on the wettability than their corresponding filtrates because of the presence of filter cakes which effectively prevent infiltration of large quantities of drilling fluid.

Among identified surfactants, which change the wettability of carbonate and sandstone rocks, let us mention i) fluorosilanes: only 1 wt.% concentration and 1 day aging period appear to be sufficient for altering wettability (Adibhatla et al., 2006) and ii) propyleneglycol (PG) (Audibert and Dalmazzone, 2006). The addition of PG to water-based drilling fluids can prevent the formation of in-situ water/oil emulsions and reduce the risk of water blockage. Feng et al. (2009) showed that low-permeability and tight gas reservoirs still produce very strong water-blocking damage in the process of underbalanced drilling, and the lower the initial permeability, the bigger the water-blocking damage. However, the evaluation of water-blocking damage under underbalanced conditions is still in the exploratory stage.

7. Environmental considerations and waste management

Like polluted water and air, polluted soil can affect people health and environment through its action on surface waters (rain-out), underground waters and vegetation (phytotoxicity, bioaccumulation). The contamination may arise either through accidental discharge or uncontrolled industrial wastes. Undeniably, it constitutes one of the main environmental problems linked to the activities of oil and gas companies.

Since the early 90's, regulations do not authorize hydrocarbon losses and the closure of the site after drilling without treatment. Remediation technologies include dewatering, distillation, solvent extraction, cuttings reinjection, fixation, landfarming and (bio)remediation. All affect the economic and environmental acceptability of drilling operations.

To minimize the pollution due to OBM, numerous programs aim at reducing oil content according to regional and/or international standards. Recently, a new trend has gained increased support, namely the holistic approach to solve both drilling and waste problems (Getliff et al., 2000; Paulsen et al., 2001). Some concepts have been introduced to integrate economic and environmental considerations in drilling practices, such as Environmental Performance Indicators (EPI) (Jones et al., 1996) and Total Fluid Management (TFM) (Paulsen et al., 2002). Thus, much effort has been invested in exploring waste minimization opportunities (Greaves et al., 2001). In the 90's, drilling fluid companies devised new types of muds that used non-aqueous fluids (other than petroleum cuts). These fluids included linear paraffins, linear α-olefins, poly α-olefins, internal olefins and esters (Friedheim and Conn, 1996). Synthetic-based muds (SOBM), which have taken over an important niche in offshore drilling, share the desirable drilling properties of OBM but are free of polynuclear aromatic hydrocarbons and have lower toxicity, faster biodegradability and lower bioaccumulation potential. For these reasons, SOBM cuttings are less likely to cause adverse sea floor impacts than traditional oil-based cuttings (Drilling Waste Management Information System, 2004). The development of this new generation of synthetic fluids typically represents a compromise between environmental, economic, and performance considerations. This new approach, aimed at optimizing the design, delivery and management of wellsite fluids and wastes, exploits the natural grouping of all fluid-related products and services (Prutt and Hudson, 1998; Hudson and Nicholson, 1999; Hudson, 1999).

Currently, drilling fluid companies are developing fluid systems that are more amenable to biotreatment of the drilling wastes (Getliff et al., 2000; Growcock et al., 2002). It is likely that companies will continue to develop fluids with suitable drilling properties that contain fewer components or additives that would inhibit subsequent breakdown by earthworms or microbes. In some circumstances, mud components could serve as a soil supplement or horticultural aid.

Nevertheless, the loss of crude oil from producing wells, oil-based drilling fluids and refined petroleum products used in machinery operation and equipment remains the primary source of contamination associated with drilling and production. The waste management assessment is geared towards solving waste problems through a logical developed process and using best practices and knowledge. However, one important question to answer is whether resource management adds any value to the exploration and production (E&P) business.

The philosophy behind the development of such fluids was not to design a system that merely posed a neutral or negligible impact on the environment, but rather one that would prove beneficial. Thus, the goal was to select the individual components of the fluid system, including the base fluid, emulsifiers, internal phase (salt and water), weight material and fluid-loss additives, to allow efficient drilling and generation of drill cuttings that can be used to actively enhance soil quality and subsequently support improved plant growth (Getliff et al., 2000). It is important to consider that the waste disposal method will function with the base fluid used in the continuous phase of the drilling fluid. For example, under the right environmental conditions, bacteria are very efficient at degrading many types of hydrocarbons. However those compounds that bacteria cannot readily degrade can delay the final remediation and close out of the site, thereby increasing the overall cost of the operation (Growcock et al., 2002). Alternatively, if the drilling fluid is optimized for its biodegradability by using a base fluid that does not contain any aromatic, cyclic or branched components, the treatment times can be significantly reduced, since there is no requirement to get rid of or reduce the humptane[3] fraction present in a diesel or mineral oil.

7.1 Waste treatment technologies: an overview

For oil companies, the great problem is to ensure an efficient environmental protection, avoiding over costs that might affect competitiveness. Therefore, the search for effective solutions at lower cost has a promising future. Currently, the treatment of waste from pits includes i) physical and chemical processes (removal of free phase, thermal desorption, excavation and disposal in landfill, deep injection in the wells, dehydration, incineration, neutralization, solidification and stabilization) and ii) biological processes (landfarming, biopiles, composting, phytoremediation and bioreactor).

Thermal techniques contribute significantly to the presence of heavy metals in aerosols. It is thus important to ascertain the quantities and chemical forms of the heavy metals that are emitted because their behavior strongly depends on the thermal and chemical environments.

Solidification/stabilization is currently applied on some mud pits and seems to be very effective. However, the use of solidification consists of a pollution transfer and/or containment without removing or even reducing the concentration of the initial soil pollution. Thus, solidification ensures the confinement of heavy metals and hydrocarbons and leaching, a simulation of rain wash, does not allow pollutant desorption. Losses can be due to a combination of factors including biodegradation, abiotic degradation, volatilization and migration (Khodja et al., 2005).

Biological treatments offer a suitable combination between economical issues and environmental protection. This should help operators to reduce drilling costs, while simultaneously increasing production and enhancing environment-oriented efforts. With a

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[3]In Gas Chromatography, any unresolved components showing a broad "hump" (variously referred to as a "*humptane*" peak) above the baseline.

high potential for destroying environmental pollutants, bioremediation of crude oil-polluted soils (by degradation and detoxification) (Song et al., 1990) is becoming an increasingly important remedial option. The use of inexpensive equipment, the environmentally-friendly nature and simplicity of the process are some of its advantages over remedial alternatives such as physical and chemical treatments.

Numerous methods used for managing drilling wastes have been described in detail in the Drilling Waste Management Information System website (2004). They mainly include:

- **waste minimization**, which reduces volumes or impacts of wastes by minimizing the generation of drilling wastes thanks to special drilling techniques (*e.g.* directional drilling, smaller diameter holes, use of lower amount of fluid) or by using muds and additives with lower environmental impacts (e.g. SOBM or new drilling fluid systems or alternate weighting agents),
- **recycle/reuse**, *e.g.* mud recycle, roadspreading, reuse of cuttings for construction purposes, restoration of wetlands using cuttings or even use of oily cuttings as fuel,
- **other miscellaneous managing drilling waste methods** like disposal through onsite burial (pits, landfills), land application (landfarming, landspreading), bioremediation (composting, bioreactors, vermiculture), discharge to ocean, offsite disposal to commercial facilities, slurry injection, salt caverns or thermal treatments (incineration, thermal desorption). A combination of bioremediation with phytoremediation can afford better results for heavy metals. The selection of the treatment and the remediation technology of contaminated soils in the oil industry are then highly dependent on the drilling fluid composition but also on the environment regulations of the countries, geographic conditions, hydrogeology and climate of the drilled sites. Figure.5 shows drilling fluid waste sources and management methodology.

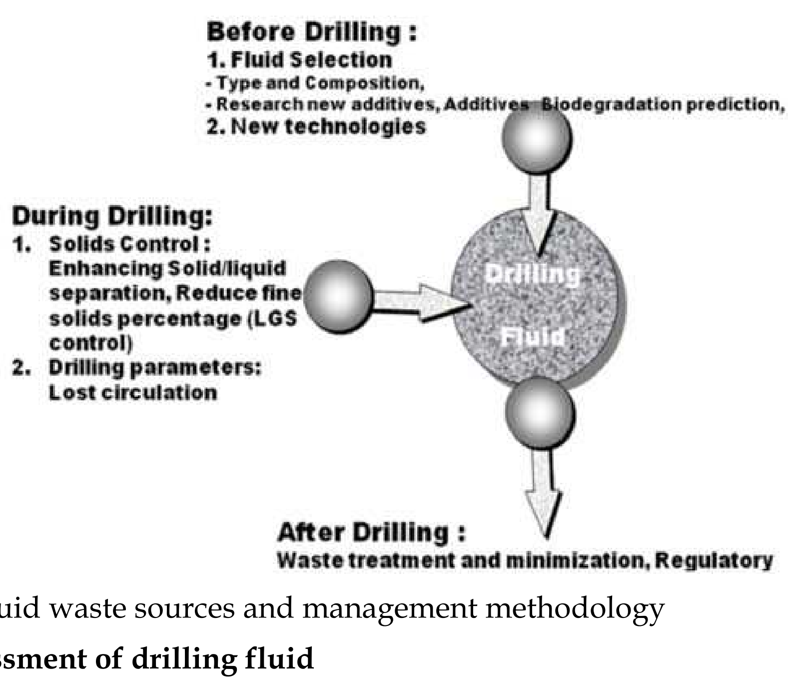

Fig. 5. Drilling fluid waste sources and management methodology

Life Cycle Assessment of drilling fluid

Using Life-Cycle Assessment (LCA) approach, recent work of Ghazi et al., (2008) evaluates the life cycle of all drilling muds, and compares four scenarios of treatment and disposal: thermal desorption, on-line and off-line stabilization/solidification and abandonment of reserve pit (without treatment). The preliminary results obtained show that LCA is a relevant methodology to compare different scenarios of drilling mud treatments and to underline the step of the process which presents the major impact or damage factor.

7.2 Health effects

Some adverse health effects associated with drilling muds are i) irritation of the skin, eyes or alimentary mucosa caused by either low pH mud, surfactant or nuisance dust (de-aromatized hydrocarbons can enhance irritancy), ii) secondary irritation when prolonged and repeated contact (base oils/solvents) with skin will remove natural fats and oils to cause redness, drying and cracking, iii) respiratory irritation primarily from nuisance dusts, iv) inhalation effects such as acute central nervous system (CNS) depression when working with hydrocarbon solvents, especially at elevated temperatures. Solvents used in OBM are of low vapor pressure, and thus should not cause problems of CNS depression, although nausea and headache can occur (McDonald and Portier, 2003), v) possible sensitization to biocides and finally vi) possible carcinogenicity due to polycyclic aromatic hydrocarbons (PAH) and asbestos (Grieve, 1988).

8. Conclusions

Drilling process and drilling fluid formulation involve several parameters, which have to be taken into account, including:

- **Drilling cost in relation with the advanced technology**

The average cost for "conventional wells" (i.e., vertical wells drilled by using standard equipment) was about $75/ft (API, 1991) in the past two decades. This cost is related to the depth, type, and location of wells and also includes the costs of drilling-related services. A comparison with wells with similar depths and locations drilled a few years before indicates a decrease of this drilling cost, partially resulting from advances in technology.

- **Particle size as a source of benefit and damage**

In dispersion tests, our recommendation is to use, preferably, small size cuttings, which are in close contact with all additives used in drilling fluid systems. Moreover, when clays are fully exposed to the fluid, the aggregation effect is eliminated.

However, invasion of fine particles issued from drilling fluids (bentonite, barite, calcite,) also called ‘mud invasion’, or from geological sediments present in the formation, blocks the pores or at least narrows them down. This causes a decrease in the permeability of the formation thereby leading to a decrease in production rate. The economic consequences of this damage justify a thorough study of this problem in order to find ways to minimize its effects.

It has also been shown experimentally that WBM impair the formation permeability more significantly than OBM and polymer-based muds (Yan et al., 1996). The filtrate generated by WBM is more likely to cause physical interactions and chemical reactions with in situ reservoir fluid and rock, inducing severe damage.

Heavier OBM used to drill reservoir sections especially in undeveloped sectors where reservoir pressure is believed to be still high also leads to the main formation damage. This may be due to the particle invasion of the organophilic clays used as viscosifiers.

- **Waste management consideration**

Drilling fluid chemistry is quite complicated, and the effect of discharged mud into the environment is still not completely understood, despite a growing related research. For hydrocarbon decontamination, landfarming, a rapidly growing process, presents satisfactory economic, scientific and environmental issues. In fact, biological techniques, cheaper than physical and chemical ones, prove to be very efficient in different soil types and ecosystems and present indeniable advantages such as no additional pollution, biodegradation either with autochthonous microorganisms or with added fertilizers or microorganism consortium. For heavy metals, a combination of bioremediation with phytoremediation can afford better results.

In conclusion, the authors assume that any technology vision and strategy should have strong anchor set with the business reality and should entirely adhere to industry core values. Worldwide exploration and production (E&P) operators are expecting integrated methods of preventing and minimizing existing waste management problems (i.e., waste generation, control and treatment). For maximum success, emphasis should be placed on assessment and planning rather than individual waste management products and technologies. The applied methodology should be focused on in-process responsive control and treatment methods rather than proposing an after-the-fact cure. The identified key of waste management needs falls into the general categories of engineering tools. Thus, the performance evaluation of all remediation techniques used so far can significantly help manager decision in choosing an appropriate waste treatment for each specific zone.

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