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Shale problems and water-based drilling fluid optimisation in the Hassi Messaoud Algerian oil field

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A B S T R A C T

Drilling fluid formulation and properties play a fundamental role in drilling operations. Clay minerals behave initially as a beneficial rheological adjuvant in drilling muds. Nevertheless, the contamination of oil reservoirs by clay minerals present in the drilled geological formation (shales) may generate major problems during drilling as plug formation. In this context, our study deals with the optimisation of drilling conditions in the Hassi Messaoud Algerian field. The mineralogical heterogeneity of this field is first discussed. The rheological and filtration characteristics of water-based muds with different polymer and electrolyte concentrations are investigated. The physical and chemical changes of both drilled formation and drilling fluid during the drilling process are studied. Therefore, depending on the clay present in the geological formation, an optimised drilling fluid system using a new filtration procedure is proposed. A good correlation is found between filtration/rheological properties and inhibition.

1. Introduction

The complex drilling fluids represent 15 to 18% of the total cost (about \$1 million) of petroleum well drilling. Their formulation and characterisation need various techniques. The classical water-based muds (WBM), at least spud muds, contained only water and clay but their performances, directly evaluated by the stability of the system and the rheological and filtration properties, were generally poor. Current tendencies are to increase the WBM performances or to use biodegradable additives in oil-based muds (OBM).

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 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 (Charlez and Heugas, 1991).

The physical properties and behaviour of shale exposed to a drilling fluid depend on the type and amount of clay in the shale. Generally, OBM provide excellent wellbore stability and afford good

lubricity and temperature stability. However, their use becomes restricted by environmental regulations, so that there is a great need for environmentally-friendly WBM able to provide the same acceptable requirements (borehole stability) as OBM.

The drilling performances of 100 Algerian wells located in the Hassi Messaoud (HMD) field were compared. Results show that major problems occur in the 12^m^{1/4} (actually 16^m) interphase and are observed at 700–950 m depth as a consequence of variable rate of penetration (ROP), varying from 8 to 24 m/h. Several problems are mentioned such as lost circulation, specially in Turonian and Salt Senonian formations, shale instabilities, hole cleaning problems due to a reduction of annular velocities in enlarged hole sections, well caving and collapse.

Dispersion tests were carried out on Algerian cuttings samples and the results are discussed and compared with field experiments. Cuttings samples containing clay with different characteristics (type, size, content, cation exchange capacity) were chosen from various wells and at different depths. Numerous tests were performed in different experimental conditions:

1. conventional dispersion tests with original cuttings samples,
2. observation tests of confined shale pellets of different sizes in contact with muds,
3. filtration tests through shale compacted in API cell within different pressure ranges,

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4. filtration tests through shale and/or core samples compacted in Hassler cell under actual field conditions (pressure and temperature).

For all these experiments, the influence of parameters, such as fluid type, cuttings mineralogy, pressure and temperature was studied.

1.1. Shale instability

When the 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 are suggested (Bol et al., 1992; Cook et al., 1993; Mody and Hale, 1993; Van Oort, 2003).

Many works also focused on the selection of drilling fluids for given shale formations (Darley, 1969; Chenevert, 1970; Roehl and Hackett, 1982; Beihoffer et al., 1988; Zamora et al., 1990; Hale and Mody, 1992; Bailey et al., 1994; Simpson et al., 1994; Durand et al., 1995; Horsud et al., 1998; Pernot, 1999). More recent studies on shale–fluid interactions suggest a new approach to WBM design (Lomba et al., 2000; Schlemmer et al., 2002; Van Oort, 2003). Consideration is given to maintain borehole stabilisation in reactive shales by reducing hydration (swelling) and/or dispersion. This process is generally referred as “inhibition”.

Scarce research and few field tests have been conducted on Algerian fields to investigate WBM effects on drilling operations. Van Oort (2003) considered the replacement of OBM, currently used in some Algerian fields, by WBM. This author shows that the presence of additives in WBM, such as polymer and KCl, aims to reduce shale instability. Clay wetability and inhibition properties were studied by analysing the behaviour of water–clay–polymer–electrolyte systems. These properties are connected to the rheological and filtration characteristics for both mud and filtrate.

Cuttings characterisation is a key parameter to explain how salt added to WBM, affects shale stabilisation. Recovered cuttings, generally contaminated by drilling fluid, are washed. Specialised laboratories recommend cuttings solvent washing (Gupta and Santos, 2002; M.I. Corporation, 2002). The washing could lead to positive effects such as plugging which reduces permeability and filtration, or negative effects in inhibitive tests such as contamination of shale samples which affects polymer evaluation seriously. The development of a prototype device to collect and preserve a washed, continuous stratigraphic sequence of drill cuttings is worth mentioning.

1.2. Role and composition of drilling fluids

Drilling the wellbore is the first and the most expensive step in oil and gas industry. Although OBM give greater shale stability than WBM (Bol et al., 1992), several WBM systems have been developed to replace OBM in order to respond to environmental regulations (Simpson et al., 1994; Friedheim et al., 1999; Patel et al., 2001; Young and Maas, 2001; Schlemmer et al., 2002).

For laboratory tests, a typical mud contains several additives at concentrations commonly used, including a viscosifier (xanthan gum with or without bentonite), a fluid loss reducer (polyanionic cellulose: PAC), and different polymeric swelling inhibitors such as partially hydrolysed polyacrylamide (PHPA), sodium silicate and polyalkylene glycols (PAG or “glycol”) to improve shale stability.

Bentonite, a worldwide-used drilling fluid additive, is added to fresh water to increase hole cleaning properties and to form a thin filter cake of low permeability. Its main functions are to viscosify the mud and to reduce the loss of fluids in the formation. In order to stabilise clay particles and to prevent their swelling/dispersion behaviour in the presence of water, other additives, such as polymers

cited above, are added. Clay–polymer interactions are thus important in drilling fluids (Bailey et al., 1994). The challenge is then to find which type of polymer-based drilling fluid should be used.

PHPA is a water-soluble anionic synthetic polymer, which is commercially available in dry (granular powder) or emulsified form. The most commonly used in drilling for borehole stabilisation in shale formations is the partially hydrolysed (30%) polyacrylamide. PHPA–clay slurries tend to form a relatively thin filter cake at the borehole wall, a characteristic often cited as an advantage (Darley and Gray, 1988). Moreover, silicate-containing fluids show good shale swelling inhibition, low depletion rate and high rate of penetration (ROP) and additionally they are environmentally friendly (Ward et al., 1997; Van Oort et al., 1999; Tare and Mody, 2000).

In WBM, poly-(glycerols) and poly-(glycols) (abbreviated in the following as glycerols and glycols) have been widely applied in shale-drilling fluids (Chenevert, 1989; Bland, 1991; Bland et al., 1995; Downs et al., 1993; Cliffe et al., 1995; Reid et al., 1993; Twynam et al., 1994). 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).

Moreover, potassium salts have been used for a long time as swelling inhibitors in WBM. The inhibition is explained by the possible penetration of small non-hydrated ions into the porosity of the shale (Simpson et al., 1994), thus forming an effective semi-permeable membrane. Organic (xanthan gum, PAC, PHPA and PAG) or mineral (sodium silicate) polymers are probably too large to enter shale pores. Some theoretical models (Van Oort et al., 1994, 1995, 1999) explain the reduction of the filtrate flow into shale by both mechanisms, an increase of the viscosity leading to a reduction of shale permeability and a flow of mud filtrate into the shale driven by osmotic pressure.

1.3. Filtration and inhibition

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 Benna et al., 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, experimental conditions, etc. Ferguson and Klotz (1954), show that 70% to 90% of the total filtrate volume, flowing through permeable formations, occurs 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.

1.4. Shale characterisation and inhibition techniques

The main methods developed for shale characterisation and fluid inhibition performances deal with composition, reactivity, mechanical and physico-chemical properties of shales (or clay):

- X-ray diffraction (XRD) analysis to determine qualitative mineral content,
- Cation exchange capacity (CEC) and methylene blue test (MBT) to evaluate reactivity and shale factor of drilled cuttings. The MBT method was recommended by API 13I, Section 11 (2003),
- A gravimetric swelling test (GST), used to measure water and ion motion during shale/mud interaction (Zhang et al., 2004),
- Capillary suction time (CST) for determination of filtration properties and salt concentration optimisation (Wilcox et al., 1987),
- Penetrometer to estimate the degree and the depth of softening (Reid et al., 1993) or “Bulk Hardness Test” designed to give an assessment of the hardness of shale following exposure to a test fluid (Patel et al., 2002),

- Dielectric constant measurement (DCM) to quantify swelling clay content and determine specific area (Leug and Steig, 1992),
- Triaxial test for pore pressure measurements, carried out in downhole simulation cell (DSC) for compressive stress/strain behaviour (Salisbury and Deem, 1990),
- Oedometer test for pore pressure modification and chemical potential influence (Bol et al., 1992),
- Slake durability test (SDT), 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,
- Differential strain curve analysis (DSCA) 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 optimising drilling fluid. Appreciated for its simplicity, low cost and duration, it has been recommended by several laboratories and adopted by API (1997). It consists of adding a known amount of shale cuttings to a standard volume of test fluid contained in a steel bomb. The bomb is rolled for a fixed time, usually 16 h, at a given temperature; the shale is then recovered on a sieve. The amount of recovered shale is expressed as a percentage of original weight. High percent recoveries and low moisture contents are indicative of inhibitive fluids. Clearly with a poorly inhibitive fluid, cuttings will disperse into the fluid and zero recovery (and therefore no moisture content determination) will result. If two fluids give the same recovery ratio, the fluid which gives the lower moisture content is regarded as being slightly more inhibitive. Indeed, a lower water uptake by the cuttings reduces the risk of dispersion or swelling in the wellbore. A comparative measurement of inhibition can be obtained by considering the relative cuttings weights retained on each screen size,
- Shale pellet inhibition (pellet dispersion test): shale cuttings are dried and ground to less than 80 mesh, then mixed into homogeneous paste with 10 wt.% water. Pellets are made by pressing approximately 20 g of this paste in a carver using a hydraulic press under 7000 psi for 2 min (Mody and Hale, 1993). Pellets and fluid are introduced in a steel bomb and processed as above (hot-rolling dispersion test). For comparison and reference, an OBM system is generally used,
- 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).

2. Materials and methods

Algerian bentonite was used in WBM formulation. The other additives provided by MISwaco Algeria are i) xanthan gum as viscosifier: this water-soluble polymer, slightly anionic and highly branched is a very effective stabiliser for aqueous colloidal systems, ii) polyanionic cellulose (PAC) as fluid loss reducer: this water-soluble polymer also acts as viscosity modifier and is available in two types (high- or low-viscosity grade), both of which impart the same degree of fluid loss control but different degrees of viscosity, and iii) sodium silicate as a mineral inhibitor, used to improve lubricity and shale stability, and also two polymers as inhibitors: a partially hydrolyzed polyacrylamide (PHPA) and polyalkyleneglycol (PAG provided from BASF-Baroid, Algeria).

Some shale cuttings and core samples from Hassi Messaoud Algerian wells have been analysed as follows:

- Cuttings were air-dried at room temperature and powdered in a porcelain mortar.
- The moisture content of each shale was measured by drying at 105 °C until a constant weight was obtained.
- According to some earlier results regarding organic contamination (Benayada et al., 2003; Khodja, 2006; Khodja, 2008), all cuttings samples used were washed with n-hexane and dried at 105 °C. The absence of organic carbon after washing was noted.
- The mineral composition was determined by XRD analysis, with a Philips PW1710 diffractometer.
- The cation exchange capacity (CEC) was determined by using the cobalthexammine trichloride method (Chauveteau et al., 1988).
- Different fluid systems were prepared using API equipments (API RP 13B-1, 2003).
- Densities, pH and rheological parameters were determined. The rheological measurements were conducted at variable speed (3 to 600 rpm) using a Fann 35 A viscometer giving values in cP or in mPa.s and with using the following formulas from API recommended practice for field testing drilling fluids. The numerical value of the plastic viscosity (PV in cP) is given by: (600 rpm dial reading – 300 rpm dial reading), apparent viscosity (AV in cP) is given by: [(600 rpm dial reading)/2], and Yield Point (YP in Pa) by: $2(AV - PV)$. Other rheological measurements on polymer solutions were carried out with AR 2000 equipment (Texas Instruments).
- API filtrate, and gel 0/10 (3 rpm dial reading after mixing and after 10 min) are determined with using API recommendations (API RP 13B-1, 2003).
- Cuttings samples of different sizes (36 to 800 μm) were prepared for filtration operations, within the 20–150 kPa pressure range.
- Fluid displacement test was determined with Corelab filtration system equipment (Argillier and Audibert, 1999; Muniz et al., 2005). Core samples were saturated with synthetic formation brine solution during 24 h, placed in a Hassler cell under 14 kgf/cm² of overbalance pressure under 80 °C. Soltrol 130 was used for filtration tests in a Hassler cell to evaluate initial and final (after fluid injection) permeabilities. Return permeability or percentage of damage (D) is determined from comparison of initial and final Soltrol permeabilities in the stable state.
- New filtration test:
In drilling fluid, “inhibition” covers all the mechanisms that can reduce or/and eliminate swelling, dispersion, and clay–water interactions in order to enhance shale wellbore stability during drilling. Inhibition percentage is the difference between initial and final cuttings weight recovery after fluid contact. API (1997) give some recommendations about those inhibition methods:
 - a. Test is only a relative measure and should be included as a part of a comprehensive testing program, and as a comparison of various whole mud compositions,
 - b. It is strongly recommended that the shale is maintained as near as possible its in-situ moisture content and must not to be air- or oven-dried before testing.
 - c. The drilling fluid rheology parameter has proven to be difficult to control from test to test. Modest changes in the rheology from one fluid to another can strongly influence shale dispersion final results.

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

In this paper, we propose a new method combining dispersion and pellet tests. By using this method we aim to protect the initial quality of got back cuttings, minimise grinding and avoid moistening, while opting for a preliminary wash to eliminate the contamination of cuttings by the additives (polymers, surfactants, etc.) in the drilling fluids.

Table 1
Mineralogical composition of cuttings, cores samples and Algerian bentonite.

	% Clay	% Non clay	Kaolinite	Illite	Chlorite	I-Mont. ^a	Montmorillonite	Quartz	Calcite	Dolomite	Anhydrite	Barite	Halite
Turonian top	0	101	–	–	–	–	0	3	1	7	87	3	–
Turonian medium	0	100	–	–	–	–	0	3	38	19	36	4	–
Turonian bottom	0	98	–	–	–	–	0	5	52	7	24	6	4
Cenomanian medium	0	83	–	–	–	–	0	6	45	5	20	3	4
Medium 16" interval ^b	13	87	5	70	5	20	0	19	6	8	13	11	30
Reservoir core 1	6	94	50	5	45	–	0	94	–	–	–	tr ^c	tr
Reservoir core 2	8	92	95	5	–	–	0	92	–	–	–	tr	–
Berea sample	19	81	75	15	5	5	0	80	tr	1	tr	–	–
Algerian bentonite ^d	83	17	–	5	–	–	95	13	4	–	–	–	–

^a Interstratified illite–montmorillonite.

^b Sample obtained with mixing cuttings issued from several depth in 16" phase in Hassi Messaoud well.

^c Traces.

^d Reference.

Our new proposed method combines filtrate data (volume and rate) with rheological and inhibitive properties.

3. Results

3.1. Mineralogical composition and CEC

Mineralogical compositions of cuttings, cores samples and Algerian bentonites are reported in Table 1. All Turonian shale compositions are similar. Top sample shows anhydrite predominance (87%). The amount of this mineral decreases with depth, as calcite content increases till 52% in the bottom sample. The sample noted b in Table 1 is representative of an average composition frequently present in Hassi Messaoud shales (Fig. 1). The presence of salt in shales was confirmed by XRD and Scanning Electron Microscopy (Fig. 2). Contamination by salt is probably related to the drilling formulation used (OBM with NaCl-saturated water). Indeed, salt is added to the water phase in order to enhance emulsion stability (electrical effect and water activity) and to increase both density and viscosity.

For reservoir cores and Berea sandstone sample, high quartz content and kaolinite predominate. It is noticed that quartz is present in all samples. The CEC of all samples are low, from 3.4 to 6.3 meq/100 g clay except for Algerian bentonite whose CEC is 60 meq/100 g.

In field conditions, problems occurring during drilling are not systematically related to the presence of clay because the samples tested in Turonian and Cenomanian do not contain clays (Table 1). For example, borehole stability problems at the Turonian and Cenomanian levels are solved by HCl injection for the dissolution of carbonates, especially abundant in those formations (Table 1).

3.2. Drilling fluid performances

The stability of drilling fluids is generally indicated by its visual homogeneity after a long period of ageing. For OBM systems, a phase separation and a decrease of viscosity are direct signs of degradation. In WBM, phase separation is also an indication of mud instability. Fig. 3 summarises the behaviour of drilling fluid state evolution. The viscosity of mud 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.

In the first part, the rheological behaviour of polymers used in conventional drilling formulations is studied. Fig. 4a and b show shear stress versus shear rate for xanthan polymer solution (0.005 to 0.2 wt.%) and PAC (0.05 to 1 wt.%), respectively. As expected, at low shear rate, xanthan solutions show shear-thinning behaviour, but above 500 s⁻¹, fluids behave as quasi-Newtonian (0.2 wt.%) or slightly shear-thickening (lower concentrations). The latter observation may be an artifact due to turbulence induced by high shear rates on the low-viscosity fluid.

At the same concentration, the viscosity of PAC solution is much higher than for xanthan solutions. Addition of KCl to a mixture of xanthan (0.2%) and PAC (1%) seems predominantly to decrease the viscosity in comparison with the viscosity of the equivalent PAC (1%) solution, even if a slight increase is observed as the KCl concentration (Fig. 4c). Indeed, it is known that anionic polymer PAC is particularly sensitive to monovalent and divalent cations (K⁺, Ca²⁺, Mg²⁺) and may induce polymer dehydration leading to a viscosity loss of the polymer solution.

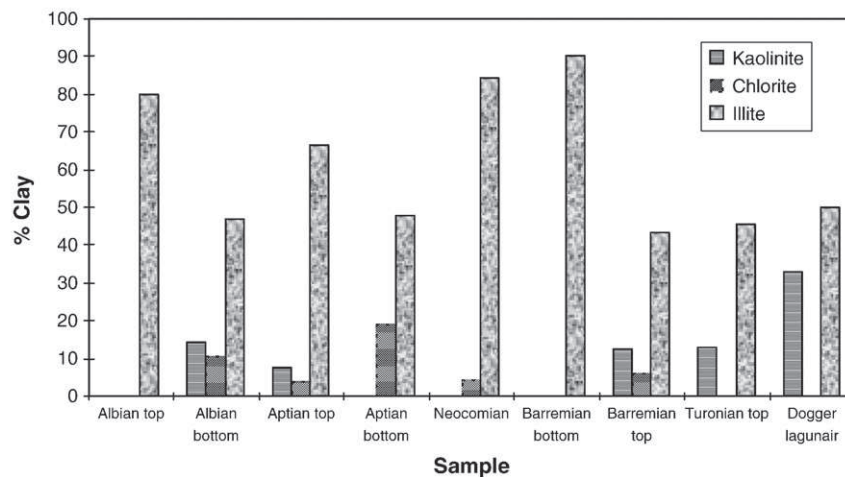


Fig. 1. Hassi Messaoud Algerian shale analysis.

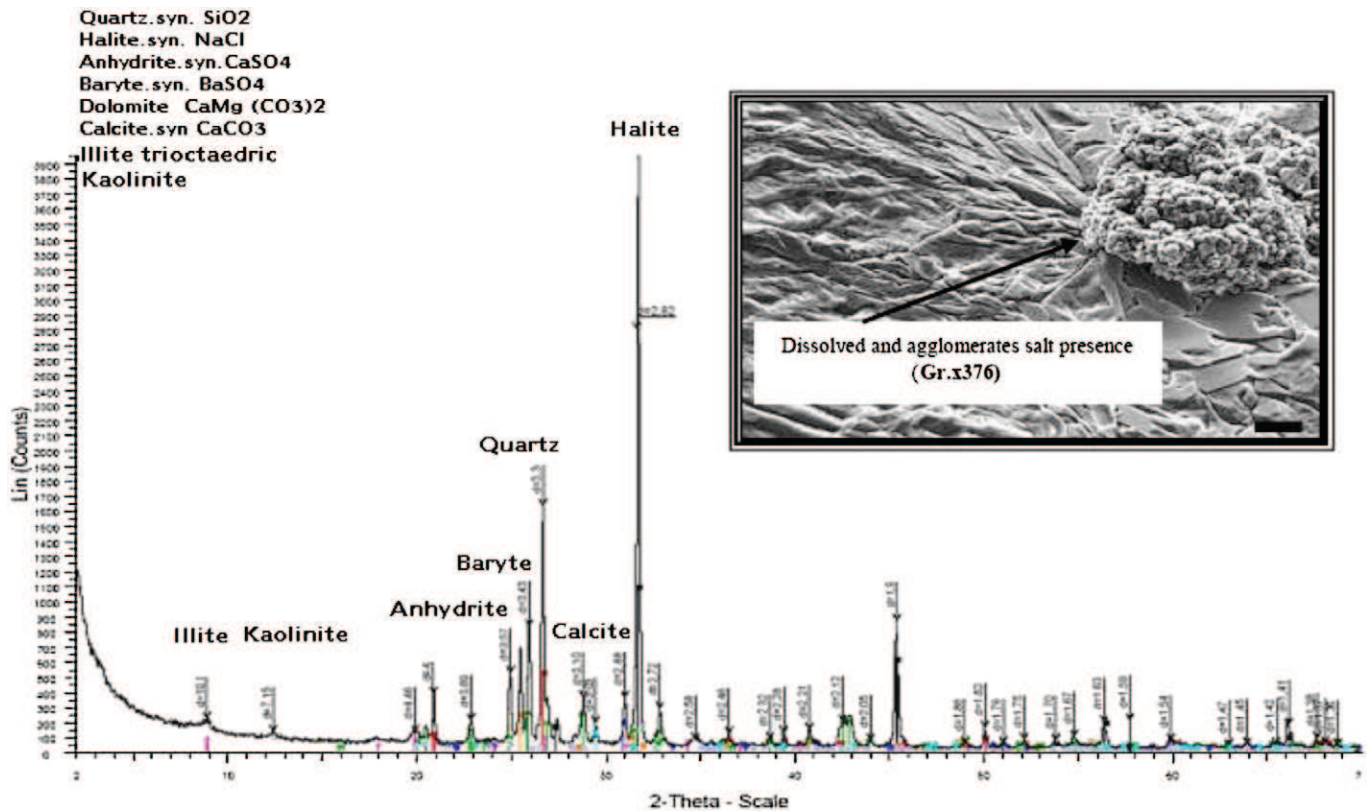


Fig. 2. XRD and scanning electron micrograph of shale (16" Hassi Messaoud sample) and salt contamination cuttings.

In the second part, the rheological behaviour of four mud systems (PHPA, PAG, silicate, and spud mud) whose compositions are reported in Table 2 is studied. Power law models were often proposed to define the behaviour of KCl/polymer type drilling fluids (Kök and Alikaya, 2004) but most drilling fluids do not conform exactly to any of the proposed models. Herschel–Bulkley and Ostwald–de Waele rheological models were retained for those systems (muds and filtrates). The estimation of the three rheological parameters for Herschel–Bulkley and the two parameters for Ostwald–de Waele equations are shown in Table 3.

The PAG and PHPA systems present similar properties, whereas the silicate system exhibits the best results (viscosity, filtrate and

gels). As regards the PHPA system, the mud and the filtrate seem to follow different models (Table 3).

The selected PHPA formulation and spud mud with PHPA polymer possess acceptable rheological and filtration characteristics (Table 4) according to HMD drilling fluid required properties (density: 1.20 to 1.25, PV < 30 cP, Gel: 7 to 15 lb/100 ft² and API Filtrate < 10 mL. PHPA is present in the same range of concentrations in the mud and in the filtrate but does not show the best inhibitive role (Table 3 and Figs. 6 and 9) whereas for the two other systems, silicate and glycol, the formed cake is less permeable and thus the filtrate is less concentrated. In fact, preliminary drilling operations in HMD, using silicate have shown good results with both tendencies to resolve shale instability and to respond to environmental regulations.

The flow behaviour of some mud systems is illustrated in Fig. 5. A similar trend is observed for all the studied solutions at increasing shear rate. The filtrate volumes obtained from PHPA, silicate or glycol systems are compared in Fig. 6. With the same polymer concentration (Table 2), the silicate system presents a higher viscosity than the PAG one (Table 4 and Fig. 5). Filtrate volumes (Fig. 6) increase in the order: silicate < PAG < PHPA. PAG and PHPA show identical filtrate volumes, but not the same filtration velocity. This behaviour can be related to polymer molecular weight and shale–polymer interaction type. With the same fixed polymer concentrations (xanthan, PAC, PHPA and silicate), the PHPA system gives a lower interfacial tension than the silicate one, probably due to a lower viscosity. Low viscosity promotes wettability and encapsulation that widely governs inhibitive mechanisms (Khodja, 2008).

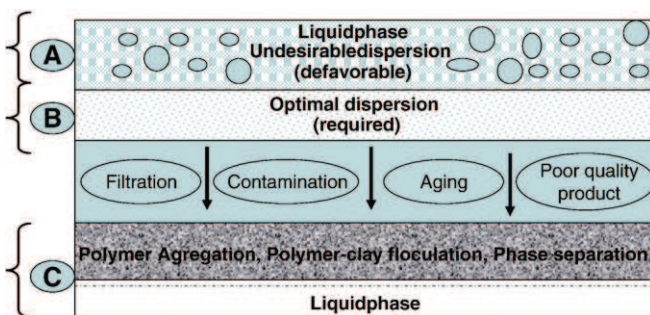


Fig. 3. Representation of drilling fluid destabilisation (phase separation: low viscosity and high filtrate). A: Undesirable dispersion with an inhomogeneous additive repartition. Solid–liquid, polymer–solution, dispersed phase–continuous phase are inhomogeneous and unstable. B: Optimal dispersion with a uniform additive repartition. 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 an incompatible additive (contaminant) or of poor quality products, or considerable aging. Solids, polymers, and salt in WBM, dispersed phase, emulsifiers or other additives in OBM are separated from the continuous phase. The system presents a phase separation, involving a degradation of rheological parameters and a high filtrate volume.

3.3. Shale inhibition and filtration tests

Shale testing helps to develop inhibitive WBM systems. In our study, among all the techniques mentioned before, two methods were used: hot-rolling dispersion test and pellet test. Moreover, a new procedure for filtration across pellet in an API cell was used to

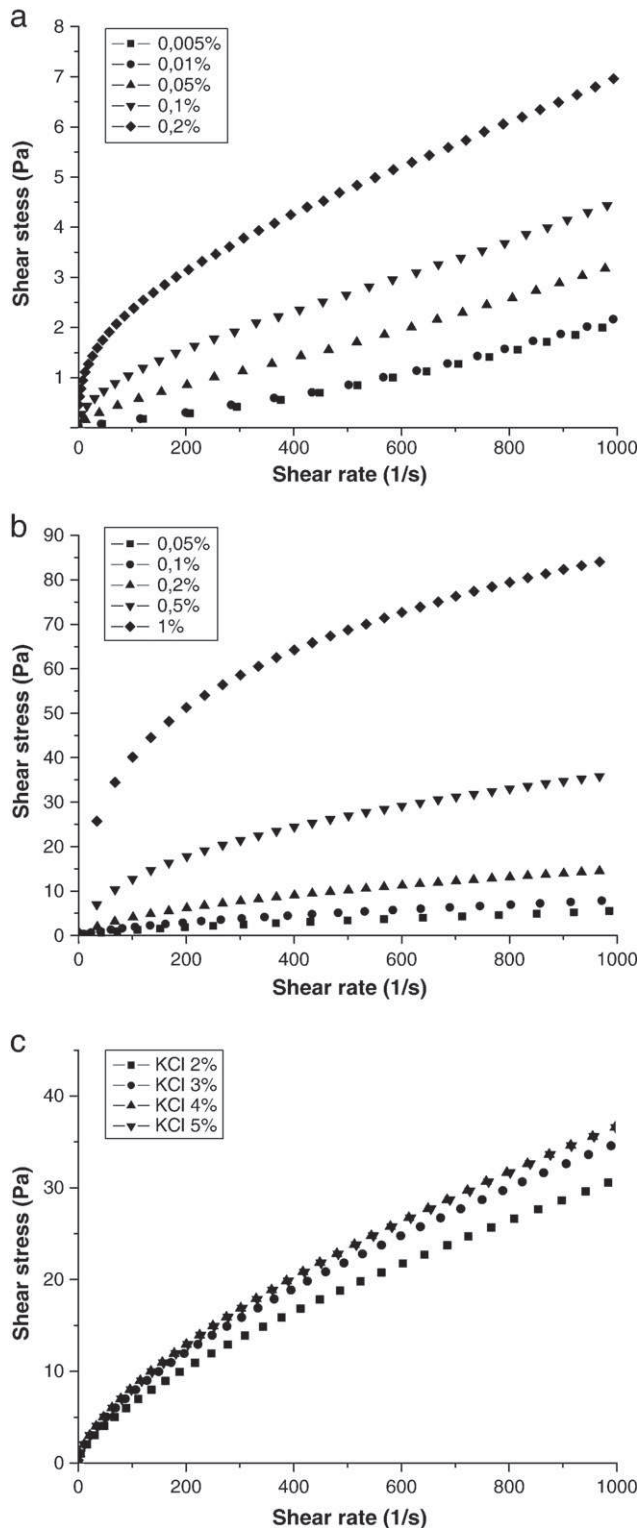


Fig. 4. a: Shear stress vs. shear rate for xanthan polymer solutions. b: Shear stress vs. shear rate for PAC polymer solutions. c: Shear stress vs. shear rate for xanthan polymer solutions (0.2%) + PAC (1%) at different KCl concentrations (2 to 5% w/w).

evaluate shale inhibition with mud systems, using different inhibitor polymers (PAG, silicate and PHPA).

3.3.1. Hot-rolling dispersion test

The hot-rolling dispersion test recommended by API and adopted by several laboratories, is widely appreciated for its simplicity and its

Table 2
Water-based mud formulations.

Additive	Bentonite ^a (g)	KCl (g)	Xanthan (g)	PHPA ^b or PAG ^c or Silicate (g)	PAC ^d (g)
Concentration	20	30	1	5	5

^a Bentonite prehydrated in water during 24 h; other additives introduced into 1 L of bentonite slurry.

^b Partially hydrolysed polyacrylamide.

^c Polyalkyleneglycol.

^d Polyanionic cellulose.

Table 3
Herschel–Bulkley and Ostwald–de Waele parameters.

System	Herschel–Bulkley ^a $\tau = \tau_0 k \cdot \gamma^n$	Ostwald–de Waele $\tau = k \cdot \gamma^n$
PHPA ^b mud		
τ_0	0.686	
k	2.654	
n	0.538	
PHPA filtrate		
k		3.418
n		0.519
PAG ^c mud		
τ_0	2.013	
k	0.626	
n	0.643	
PAG filtrate		
τ_0	1.459	
k	0.220	
n	0.702	
Silicate mud		
k		10.86
n		0.317
Silicate filtrate		
k		0.080
n		0.712

^a τ : shear stress (Pa); τ_0 : shear stress at the threshold (Pa); k : consistency index of the medium; γ : shear rate (s^{-1}); n : flow behaviour index (adimensional, $0 < n < 1$).

^b Partially hydrolysed polyacrylamide.

^c Polyalkyleneglycol.

low cost. Some laboratories recommend using a core sample for inhibition evaluation but cuttings are generally used because of core unavailability. Several cuttings samples from various Hassi Messaoud geological formations are used for laboratory dispersion tests on silicate- or PAG-containing WBM and OBM systems (Table 4). These tests show that the inhibition percentages obtained with silicate-WBM (96–98%) are similar to those of OBM, but higher than those of a PAG-WBM system (78%). Numerous integrity tests performed on field samples with PAG and silicate systems, lead to select silicate formulations which are optimised and proposed for pilot test on the Hassi Messaoud field (Khodja, 2003). Hot-rolling dispersion test clearly shows a similar behaviour for all samples with silicate and PHPA (Fig. 7).

Several procedures recommend comparing initial and final sizes (or weights) for estimating inhibition after fluid contact. The question

Table 4
Properties of the PHPA^a formulation.

d^b (g/cm^3)	PV ^c (cP)	AV ^d (cP)	YP ^e (lb/100 ft ²)	Gel_0^f (lb/100 ft ²)	Gel_{10}^f (lb/100 ft ²)	Filtrate volume (mL)
1.03	22	42.5	41	7	8	8.5

^a Partially hydrolysed polyacrylamide.

^b Density.

^c Plastic viscosity.

^d Apparent viscosity.

^e Yield point.

^f ω_3 after mixing and after 10 min.

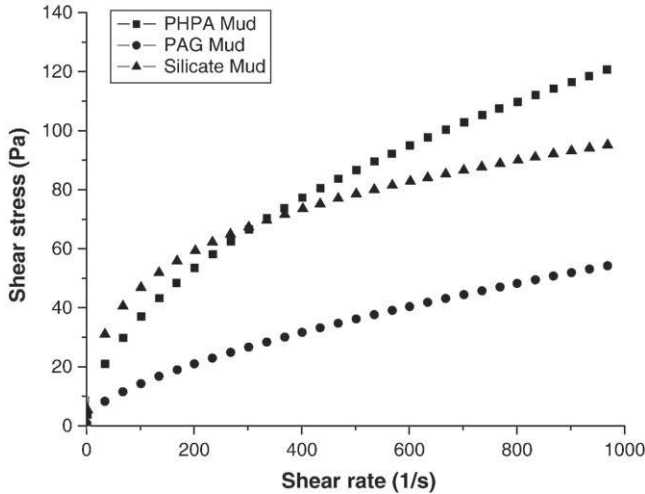


Fig. 5. Shear stress vs. shear rate of whole mud systems.

is: which is the main factor (clay type, clay content or cuttings size) affecting the dispersion results?

With all systems, our results show similar, rather high recovery values for large size (0.8 mm) (Fig. 7a) but low recovery values for small size (0.100 to 0.315 mm) cuttings (Fig. 7b). 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.

Xanthan gum or PAC added as a viscosifier, acts synergistically with 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).

3.3.2. Pellet dispersion test

A homogeneous paste is formed by mixing a dried, ground shale (< 80 mesh) with 10% (wt./wt.) water. Pellets are obtained by pressing approximately 20 g of this paste in the carver hydraulic press at 7000 psi for 2 min (Fig. 8). The results obtained with this test and hot-rolling dispersion test are similar for samples from different

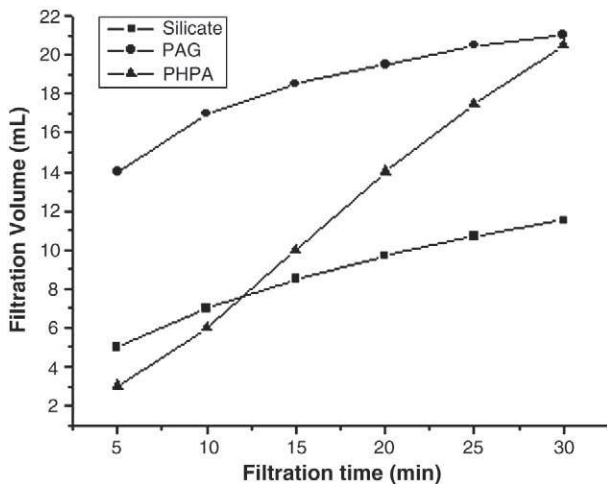


Fig. 6. Mud systems API filtrate vs. time.

HMD geological formations and using PAG-WBM or OBM systems (Tables 5 and 6).

3.3.3. New filtration test

The new API water loss (or fluid loss) test was carried out by replacing Whatman 50 filter paper by the pellet in the API filtration cell (Fig. 8). The slurry was exposed to a 100 psi pressure for 30 min to obtain filtrate. Fig. 9 shows that for all systems, the filtrate volume is proportional to compaction force. Whatever the compaction force, silicate and PAG systems present the lowest filtrate volumes. PHPA formulation under different compaction forces (from 60 to 150 kN) clearly shows large filtrate volume. Even below 60 kN, the whole fluid was filtered. The compaction force, linked to the deposit mode of the sediments, has a significant influence on the permeability.

It is necessary to underline that the difference of compaction is one of the difficulties met during these experiments. The compaction force, the initial water content of the powder and the grain size are taken into account since these parameters have an influence on the mechanical behaviour of the compacted material.

Fig. 10 presents a Hassler cell operating under reservoir conditions (temperature and pressure) for the filtration of pellets compacted under 10 kN. Permeability (k) was calculated using Darcy's law equation.

$$dV / dt = k \Delta P / \eta e A \quad (1)$$

ΔP : pressure; A : Area (cm^2); η : viscosity (cP); V : filtrate volume after t (cm^3); e : cake thickness after t (cm); t : time (s); and k : cake permeability ($1 \text{ darcy} = 1 \mu\text{m}^2$).

Damage (D) is determined by comparing initial (k_i) and final (k_f) permeabilities in the stable state.

$$D = 100(k_i - k_f) / k_i \quad (2)$$

Hassler cell results with Turonian cuttings pellets show clearly that PAG exhibits low damage values (D) (Table 7). Higher values are obtained with PAC, xanthan and PHPA solutions. Analysing D and V values, mechanisms for xanthan and PAG solutions can be proposed. These two polymers do not reduce the filtrate sufficiently; however xanthan exhibits a high viscosity and PAG high water absorption. Higher damage value with xanthan (67%) is due to its helical molecular structure, high molecular weight (MW) and anionic charge compared with the low molecular weight of electrically neutral PAG. Xanthan and PAG prevent flocculation thanks to steric and Coulombic effects.

On the contrary, silicate, PAC and PHPA yield low filtrate volumes but relatively high damage values. The relatively thin filter cake formed using PHPA is not sufficient to prevent excessive fluid losses.

The following step concerns the influence of polymers on the drilling fluid flow through natural porous media: reservoir cores and Berea sandstone samples (Table 8). Inhibitive polymers: PHPA, PAG or silicate, are added selectively to xanthan- and PAC-containing fluids. The results reveal the following points:

1. for similar porosity, \emptyset , and air permeability, k_{air} , the addition of KCl to PHPA reduces damage (D) and filtrate volume (V),
2. for similar rock and air permeabilities, the silicate system exhibits high damage compared with the PHPA system,
3. The PHPA system gives similar filtration properties in the new filtration test in API cell (pellet) and in Hassler cell (core reservoir) (Fig. 9 and Table 8). Damage values are 65% (Table 7) and 38% (Table 8), respectively, for PHPA with pellet and PHPA with core reservoir. In terms of damage ratio on Berea sandstone, Table 8 shows that final Soltrol permeability (k_f) for PHPA without salt is the highest, due to easier desorption. Paradoxically, PHPA gives the lowest filtrate volume (0.7 mL) with minimum damage (35%)

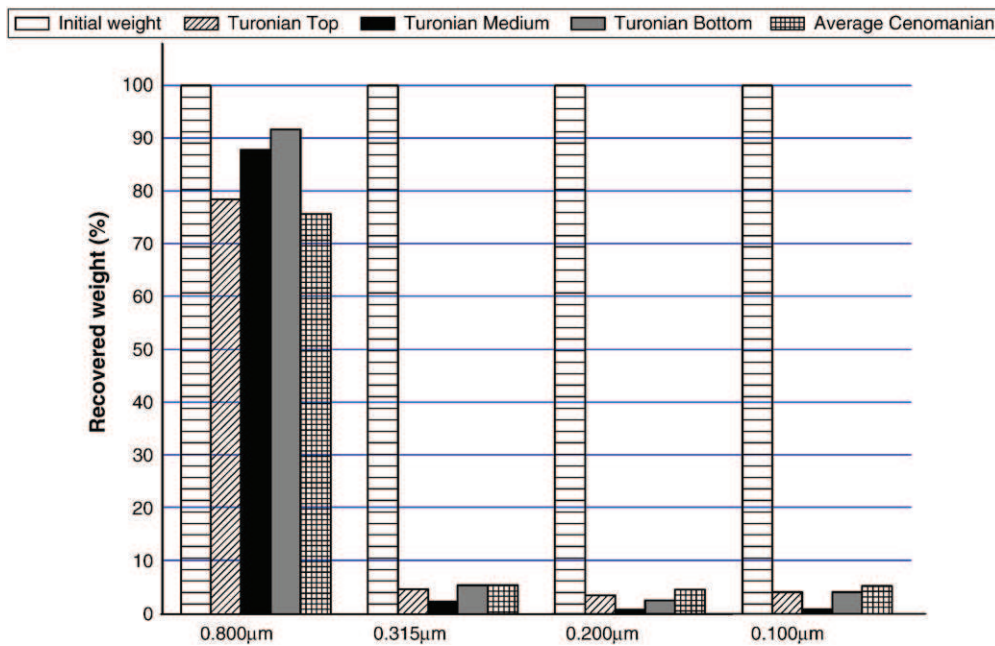
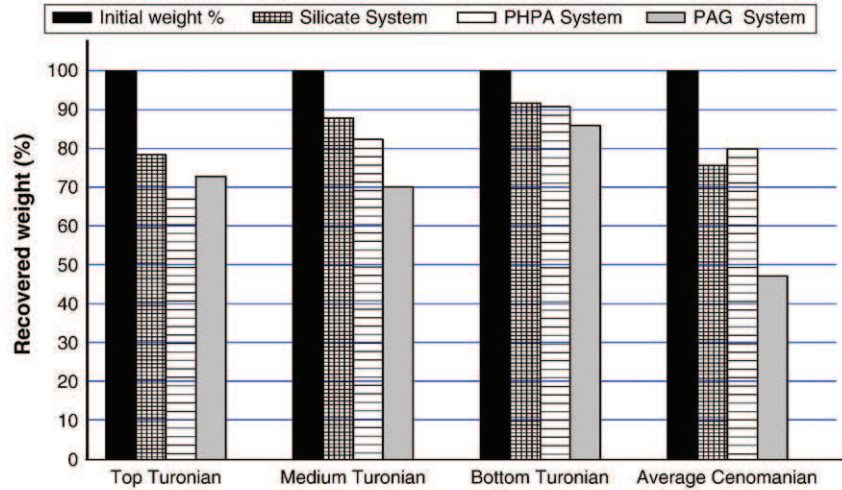
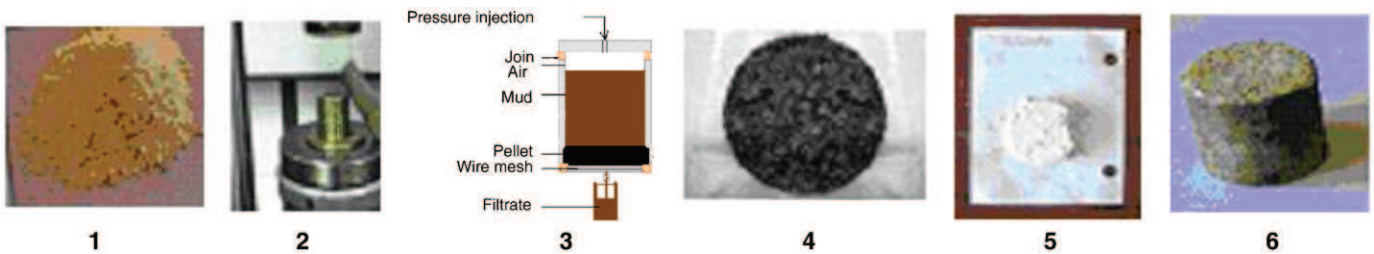


Fig. 7. a: Hot Rolling dispersion test with the same cutting size (800 µm) and different mud systems. b: Hot Rolling dispersion test with a silicate system.



1. original cuttings used for conventional hot-rolling dispersion test,
2. hydraulic press used for pellet preparation,
3. procedure for compacted pellet used in API cell filtration (API filter replacement),
4. cake with pellet obtained in API cell filtration after fluid contact (PHPA system, $F = 100 \text{ kN}$, diameter = 140 mm, $e = 2 \text{ mm}$),
5. turonian pellet compacted at 10 kN and used in Hassler cell with silicate system after 48 hrs in ambient air
6. reservoir core used for filtration test under high temperature (80°C) and differential pressure (196 N) in Hassler cell.

Fig. 8. Cuttings, cores samples, and procedure used in filtration methods.

Table 5
Hot-rolling dispersion test with water-based muds (WBM) and oil-based muds (OBM) systems.

Sample	Polymer-free-WBM	Inhibition PAG-WBM	Ratio (%) silicate-WBM	OBM
Albian top	52	79	98	98
Barremian bottom	51	77	98	98
Turonian top	53	76	98	99

Table 6
Pellet dispersion test with polyalkyleneglycol-water-based muds (PAG-WBM) and oil-based muds (OBM) systems.

Sample	% Cuttings PAG test 1	% Cuttings PAG test 2	% Cuttings PAG test 3	% Cuttings average (PAG)	% Cuttings OBM
Albian top	60	62	63	62	99
Barremian bottom	61	63	65	63	98
Turonian top	61	63	62	62	98

(Table 8). This result is probably related to a surface accumulation of PHPA, reducing the flow through more compact porous Berea sandstone. By using a pellet and in the new filtration test, a filtrate volume provokes the maximum damage (Table 8 and Fig. 9) due to swelling (clay-water interaction), solid disintegration and plugging phenomena through porous media. The comparison of damage for both silicate and PAG systems, shows that the PAG system gives maximum filtrate and minimum damage by using a pellet and Berea

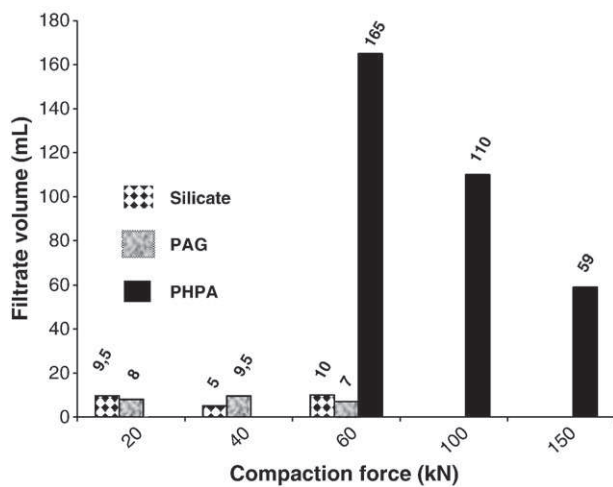


Fig. 9. Mud system filtrate volume vs. compaction force.

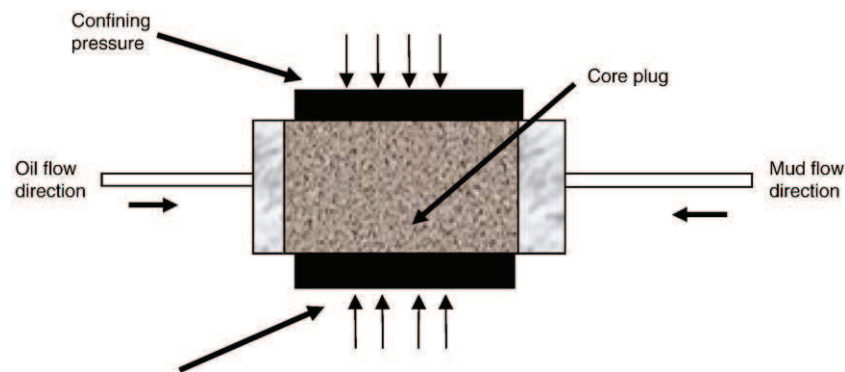


Fig. 10. Filtration cell for formation damage evaluation.

(Tab. 7 and 8), but the silicate system gives minimum filtrate and maximum damage (Tables 7 and 8).

4. With a small molecular size, the environmentally-friendly silicate system presents high viscosity, low filtrate volume and high damage. It is then recommended to use it in upper layers but not in reservoir.

Practically, drilling engineers need to optimise 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. Generally, a silicate system is not used in reservoir. Silicate reacts readily with Ca^{++} and Mg^{++} ions. High concentrations of divalent ions will deplete the effective silicate concentration and decrease its inhibitive performance. However, the in-situ gelation of silicates has been employed to reduce aqueous fluid flow in oil- and gas-bearing formations.

Evaluation made on the cuttings samples of HMD, based on laboratory tests, showed a high percentage of inhibition with the silicate system in comparison with glycol and PHPA systems. The study of the mechanisms of inhibition of polymers shows that PHPA inhibits clay dispersion by encapsulation and acts by steric effect but, for glycol and silicate, electrokinetic effect governs inhibition mechanisms.

The field tests realised on four wells in the Hassi Messaoud field with a silicate system show a rate enhancement and a reduction of loss phenomena and shale problems (Khodja, 2008). In this formation, characterised by its average reactive and rich fracturing, it is desirable to formulate a silicate drilling fluid with a perfect inhibitive capacity, ideal rheological properties and good filtration control. After laboratory and field tests, and collaborative work with oil and drilling fluid service companies, an optimal formulation of a sodium silicate/KCl/specific polymer drilling fluid system was developed.

The drilling rate (ROP) is practically identical for all cases with this silicate drilling fluid (7.23–7.49 m/h). One of the key factors to maintain acceptable rheological properties and filtration control character is the proper proportion of each additive: KCl and silicate. This choice of silicate and KCl concentrations is a function of some parameters which cannot be optimised on the laboratory scale, such as reactivity and size of shale, drilling parameters (WOB: weight on bit, ROP, mud pressure, bit type...). In four drilled wells, the proportion of silicate ranges from 40 to 74 kg/m^3 , and KCl concentration decreases from 14% in the first well to 4.5% in the third one. According to McDonald et al. (2002), this system presents high inhibition, offering Health, Security and Environment benefits over traditional OBM. Moreover, based on the review of various drilling fluid candidates, it was determined that a silicate-based system was the best choice.

Table 7

Results of flow tests with polymer solutions through Turonian cuttings pellets in Hassler cell.

Polymer solution	k_i (mD)	k_f (mD)	D (%)	V (ml)
PAC (0.5 %)	0.6	0.17	71.7	2
Xanthan (0.1 %)	0.49	0.16	67.3	21
PHPA (0.5 %)	0.54	0.19	64.8	5
PAG (0.5 %)	0.39	0.22	43.6	30
Silicate (0.5 %)	0.66	0.27	59.1	2

k_i : initial permeability, k_f : final permeability (both in milliDarcy), V : filtrate volume, D (damage) = $[(k_i - k_f)/k_i] \cdot 100$.

4. Conclusion

The aim of this study was to find which WBM formulations are efficient on shales contained in HMD field.

As the samples tested in Turonian and Cenomanian do not contain clays, problems occurring during drilling are not systematically related to the presence of clay.

In HMD field conditions, the shale is characterised by its average dispersive fracturing. It is recommended to pay high attention to drilling parameters contributing to borehole stability. The importance of pre-treatment and conservation of cuttings is highlighted. Differences in filtration and inhibition properties are widely related to shale (clay content and size) and to drilling fluids (type and concentration of additives, structure and charge of polymer).

The rheological behaviour of polymers used in conventional drilling formulations was studied. Herschel-Bulkley and Ostwald-de Waele rheological models were retained for those systems (muds and filtrates). The addition of increasing salt concentrations to a combination of anionic polymers (PAC and xanthan) increases the viscosity of the solutions. The viscosity range is higher for KCl-polymer solutions, at all shear rates, than for polymer only. The PHPA is mainly used as a swelling inhibitor; however, it also plays the roles of a viscosifier and a loss reducer agent. The action of PHPA, which adsorbs onto multiple sites on clay surfaces, may thereby avoid disintegration of shale material. Low viscosity promotes wettability and encapsulation that widely governs inhibitive mechanisms of PHPA system.

All the field tests enabled us to increase the inhibition efficiency and to optimise the formulation. This inhibition evaluation method considers several factors such as the shale samples and allows simulating the solid-liquid interactions in drilling operations. The proposed new filtration method constitutes a useful tool to formulate drilling fluids. This new filtration method as well as the classical dispersion tests reveals that silicate-containing muds give the best results. Among the PAG, PHPA and silicate formulations used in drilling operations, a silicate system has been selected in HMD field. This approach also allows quantifying drilling fluid/shale interactions. The ionic effect of silicate, PAC, xanthan and the steric effect of PHPA confer favourable rheological, filtration, and inhibitory properties to drilling fluids.

Table 8

Damage results with polymer drilling fluids through Reservoir and Berea cores in Hassler Cell.

Fluid	Sample	\emptyset (%)	k_{air} (mD)	k_i (mD)	k_f (mD)	D (%)	V (ml)
PHPA with KCl	Reservoir core 1	8	12	1.4	0.87	38	25
PHPA without KCl	Reservoir core 2	10	13	1.6	0.6	62	30
PHPA	Berea	17	1280	209	135	35	0.7
Silicate	Berea	16	1001	293	42	86	5
PAG	Berea	8	1131	167	39	76	12

\emptyset : porosity, k_{air} : air permeability, k_i : initial Soltrol permeability, k_f : final Soltrol permeability, V : filtrate volume, D (damage) = $[(k_i - k_f)/k_i] \cdot 100$.

Due to the non-availability of core samples for inhibition tests, the use of various sizes of cuttings is suggested. In our inhibition method, the use of the finest homogeneous samples is recommended because shales are then directly in contact with all additives. By using a fine powder sample, the higher surface area availability increases the adsorption rate.

Polymers used in drilling fluids improve the stability with a synergetic effect, and seem to be a future solution from environmental and economic aspects. With a small molecular size, the environmentally-friendly silicate system presents high viscosity, low filtrate volume and high damage. It is then recommended to be used in the upper layers but not in the reservoir.

Nomenclature

A	area (cm ²)
API	American Petroleum Institute
AV	apparent viscosity (cP = mPa.s)
D	damage (%)
d	fluid density
e	cake thickness (mm)
F	compaction force (kN)
$G_{0/10}$	Gel after 0 and 10 min (lb/100 ft ²)
HMD	Hassi Messaoud field (Algeria)
k	cake permeability (1 darcy = 1 μ m ²)
k_{air}	air permeability (millidarcy)
k_i	initial Soltrol permeability (millidarcy)
k_f	final Soltrol permeability (millidarcy)
MW	molecular weight
OBM	oil-based mud
PAC	polyanionic cellulose
PAG	polyalkyleneglycol
PHPA	partially hydrolysed polyacrylamide
PV	plastic viscosity (cP)
ROP	rate of penetration (m/h)
SEM	scanning electron microscopy
t	time (s)
V	filtrate volume after time t (cm ³)
WBM	water-based mud
WOB	weight on bit (T)
YP	yield point (Pa = lb/100ft ²).
ΔP	pressure (Pa)
\emptyset	porosity (%)
η	viscosity (cP or Pa.s)
τ	shear stress (Pa)
τ_0	shear stress at the threshold or yield value (Pa)
γ	shear rate (s ⁻¹)

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References

- API, 1997. Laboratory Testing of Drilling Fluids Seventh Edition. ISO 10416: 2002 API 131 Supplement 2 - 01-Jun.
- API RP 13B-1, 2003. Recommended Practice Stand. Proced. for Field Testing Water-Based Drilling Fluids.
- Argillier, J.-F., Audibert, A., Janssen, M., Demoulin, A., 1997. Performance of a new bio-degradable ester-based lubricant for improving drilling operations with water based muds. Proceedings - International Symposium on Oilfield Chemistry, pp. 539-549. Houston (TX), Feb. 18-21.
- Argillier, J.-F., Audibert, A., Longeron, 1999. Performance Evaluation and Formation Damage Potential of New Water-based Drilling Fluids. SPE European Formation Damage, La Haye. 31 May-1 June.
- ASTM, 2000. Standard test method for slake durability of shales and similar weak rocks. ASTM D4644-87, Annual Book of ASTM Standards, D18.

- Bailey, L., Keall, M., Audibert, A., Lecourtier, J., 1994. Effect of clay/ polymer interactions on shale stabilization during drilling. *Langmuir* 10, 1544–1549.
- Beihoffer, T.W., Dorrrough, D.S., Schmidt, D.D., 1988. The separation of electrolyte from rheological effects in studies of inhibition of shales with native moisture contents. SPE Paper 18032. IADC/SPE Drilling Conference, Houston, TX, 2–5 October.
- Benayada, B., Habchi, K.N., Khodja, M., 2003. Stabilisation of clay walls during drilling in Southern Algeria. *Appl. Energy* 75, 51–60.
- Benna, M., Kbir-Arighuib, N., Magnin, A., Bergaya, F., 1999. Effect of pH on rheological properties of purified sodium bentonite. *J. Colloid Interface Sci.* 218, 442–455.
- Benna, M., Kbir-Arighuib, N., Clinard, C., Bergaya, F., 2001. Static filtration of purified sodium bentonite clay suspensions. Effect of clay content. *Appl. Clay Sci.* 19, 103–120.
- Bland, R.G., 1991. Development of new water-based mud formulations. Chemicals in the oil industry: developments and applications. Spec. Publ.-R. Soc. Chem. 97, 83–98 Springer-Verlag.
- Bland, R.G., Smith, G.L., Eagark, P., van Oort, E., 1995. Low salinity polyglycol water-based drilling fluids as alternatives to oil-based muds. Paper SPE/IADC 29378. IADC/SPE Drilling Conference, Amsterdam, February 28–March 2.
- Bol, G.M., Wong, S.W., Davidson, C.J., Woodland, D.C., 1992. Borehole stability in shales. Paper SPE 24975. SPE European Petroleum Conference, Cannes, Nov. 16–18.
- Charlez, P., Heugas, O., 1991. Evaluation of optimal mud weight in soft shale levels. Proceedings of the 32nd US. Symposium Rock Mechanics as a Multidisciplinary Science. Balkema N.A.A., Rotterdam, Netherlands, pp. 1005–1014.
- Chauveteau, G., Lecourtier, J., Lee, L.T., 1988. Méthode de détermination de la capacité d'échange cationique des argiles. *Rev. Inst. Fr. Pétr.* 4, 533–543.
- Chenevert, M.E., 1970. Shale alteration by water absorption. *J. Petr. Technol.* 22, 1141–1148.
- Chenevert, M.E., 1989. Glycerol mud additive provides shale stability. *Oil Gas J.* 60–64 July 17.
- Cliffe, S., Dolan, B., Reid, P.J., 1995. Mechanism of shale inhibition by polyols in water-based drilling fluids. SPE Paper 28960, SPE International Symposium on Oilfield Chemistry. San Antonio, TX, 14–17 February.
- Cook, J.M., Goldsmith, G., Geehan, T.M., Audibert, A.M., Bieber, M.T., Lecourtier, J., 1993. Mud/shale interaction: model wellbore studies using X-ray tomography. Drilling Conference, paper SPE/IADC 25729. Amsterdam, February 23–25.
- Darley, H.C.H., 1969. A laboratory investigation of borehole stability. *J. Petrol. Technol.* 883–892 July.
- Darley, H.C.H., Gray, G.R., 1988. Composition and Properties of Drilling and Completion Fluids, 5th Edition. Gulf Professional Publishing, Houston (TX).
- Downs, J.D., van Oort, E., Redman, D., Ripley, D., Rothmann, B., 1993. TAME—a new concept in water-based drilling fluids. SPE paper 26699. Offshore Europe Conference, Aberdeen, September 7–10.
- Durand, C., Forsans, T., Ruffet, C., Onaisi, A., Audibert, A., 1995. Influence of clays on borehole stability: a literature survey. *Rev. Inst. Fr. Pétr.* 50 (2), 187–218.
- Fjaer, E., 1999. Static and dynamic moduli of weak sandstones. Proceedings of the 17th US Rock Mechanics Symposium. Vail, Colorado, 6–9 June.
- Ferguson, C.K., Klotz, J.A., 1954. Filtration from mud during drilling. *Trans. AIME* 201, 29–42.
- Friedheim, J., Touts, B., van Oort, E., 1999. Drilling Faster with Water-Based Mud. AADE Houston – Annual Forum – Improvements in Drilling Fluid Technology. Houston (TX), March 30–31.
- Gupta, A., Santos, H., 2002. A novel procedure for screening drilling fluid compatibility. *J. Can. Petr. Technol.* 41 (5), 39–43.
- Hale, A.H., Mody, F.K., 1992. Experimental investigation of the influence of chemical potential on wellbore stability. IADC/SPE Paper 23885. New Orleans (LA), February 18–21.
- Horsud, P., Bostrom, B., Sonstebo, E.F., Holt, R.M., 1998. Interaction between shale and water-based drilling fluids: laboratory exposure tests give new insight into mechanisms and field consequences of KCl contents. SPE Annual Technical Conference and Exhibition, New Orleans (LA), September 27–30.
- Khodja, M., 2003. Silicate drilling fluid results on Hassi Messaoud Algerian wells. Internal report N°25. Sonatrach/CRD, Boumerdès, Algeria. March.
- Khodja, M., 2006. Solid-Liquid Interactions and Filtration Properties, Master Geosciences, Environment and Risk. Louis Pasteur University, Strasbourg, France. 42 pp.
- Khodja M., 2008. Drilling fluid: performance study and environmental considerations, Ph.D. Thesis, Institut National Polytechnique, Toulouse, France.
- Kök, M.V., Alikaya, T., 2004. Determination of rheological models for drilling fluids, a statistical approach. *Energy Sources* 2, 153–165.
- Lamberti, C.M.C., 1999. Polymers and Performance Chemicals, Laboratory Test – PAC Used in Drilling Fluid Formulation. Albizzate, Italy.
- Leug, P.K., Steig, R.P., 1992. Dielectric Constant Measurements: A New, Rapid Method to Characterize Shale at the Wellsite. IADC/SPE Drilling conference, New Orleans (LA), February 18–21.
- Li Y., 1996. Static and dynamic filtration of different clay, electrolyte, polymer systems. Ph.D. Thesis, University of Orléans, France.
- Likos, W.J.L., Loehr, J.E., Kiranmayee, A., 2004. Engineering evaluation of polymer-based drilling fluids for applications in Missouri shale. Research, Development and Technology. Missouri Department of Transportation Research, July.
- Loeber L. 1992. Study of clay mud cake structure formed during drilling. Thesis, University of Orléans, France.
- Lomba, R., Chenevert, M.E., Sharma, M.M., 2000. The ion-selective membrane behavior of native shales. *J. Petr. Sci. Eng.* 25, 9–23.
- Lutton, R.J., 1977. Slaking indexes for design (Report FHWA-RD-77-1). Design and Construction of Compacted Shale Embankments, US Department of Transportation, vol. 3. Federal Highway Administration, Washington DC. 88 pp.
- McDonald, M., Reifsnnyder, R., Sidorkiewicz, V., LaPlant, D., 2002. Silicate-based drilling fluids: a highly inhibitive mud system offering HS&E benefits over traditional oil-based muds. Drilling & completion fluids and waste management. Houston (TX), April 2–3.
- M.I. Corporation, 2002. M.I. Drilling Fluids Engineering Manual, Revision No. A-1. Houston, (TX).
- Mody, F.K., Hale, A.H., 1993. A borehole stability model to couple the mechanics and chemistry of drilling fluid shale interaction. SPE/IADC Paper 25728. SPE/IADC Drilling Conference, Amsterdam, Netherlands. February 23–25.
- Muniz, E.S., Fontoura, S.A.B., Lomba, R.F.T., 2004. Development of equipment and testing methodology to evaluate rock-drilling fluid interaction. Paper 599, GulfRock04. 6th North America Rock Mechanics Symposium (NARMS), Houston (TX).
- Muniz, E.S., da Fontoura, S.A.B., Duarte, R.G., Lomba, R.F.T., 2005. Evaluation of the Shale-Drilling Fluid Interaction for Studies of Wellbore Stability. The 40th U.S. Symposium on Rock Mechanics (USRMS), Alaska Rocks. June 25–29, Anchorage (AK).
- Patel, A., Stamatakis, E., Friedheim, J.E., Davis, E., 2001. Highly inhibitive water-based fluid system provides superior chemical stabilization of reactive shale formations. Drilling Technology, American Association of Drilling Engineers, AADE National Drilling Technical Conference, AADE 01-NC-HO-55. Houston, TX, March 27–29.
- Patel, A., Stamatakis, E., Young, S., Stiff, C., 2002. Designing for the future – a review of the design, development and inhibitive water-based drilling fluid. Drilling and Completion Fluids and Waste Management. Houston (TX), April 2–3.
- Pernot V.F., 1999. Troublesome Shale Control Using Inhibitive WBM. Ph.D., Univ. of Texas, Austin, May.
- Reid, P.I., Elliott, G.P., Minton, R.C., Chambers, B.D., Burt, D.A., 1993. Reduced environmental impact and improved drilling performance with water-based muds containing glycols. Paper SPE 25989. SPE/EPA Exploration and Production Environmental Conference, San Antonio (TX), March 7–10.
- Roehl, E.A., Hackett, J.L., 1982. A laboratory technique for screening shale swelling inhibitors. SPE paper 11117, 57th Annual Fall Meeting. Society of Petroleum Engineers, New Orleans (LA), 26 September.
- Salisbury, D.P., Deem, C.K., 1990. Tests show how oil muds increase shale stability. *World Oil* 211 (4), 57–65 October.
- Schlemmer, R., Friedheim, J.E., Growcock, F.B., Headley, J.A., Polnaszek, S.C., Bloys, J.B., 2002. Membrane Efficiency in Shale – An Empirical Evaluation of Drilling Fluid Chemistries and Implications for Fluid Design. SPE 74557. IADC/SPE Drilling Conference, Dallas (TX), 26–28 February.
- Simpson, J.P., Walker, T.O., Jiang, G.Z., 1994. Environmentally acceptable water-based mud can prevent shale hydration and maintain borehole stability. Paper IADC/SPE 27496. IADC/SPE Drilling Conference, Dallas (TX), 15–18 February.
- Tare, U.A., Mody, F.K., 2000. Stabilizing boreholes while drilling reactive shales with silicate-based drilling fluids. *Drilling Contractor*, May/June, 42–44.
- Twynam, A.J., Caldwell, P.A., Meads, K., 1994. Glycol-enhanced water-based muds: case history to demonstrate improved drilling efficiency in tectonically stressed shales. Paper IADC/SPE 27451. IADC/SPE Drilling Conference, Dallas (TX), February 15–18.
- van Oort, E., 1994. A novel technique for the investigation of drilling fluid induced borehole instability in shales. Paper SPE/ ISRM 28064. SPE/ISRM Conference on Rock Mechanics in Petroleum Engineering, Delft. August 29–31.
- van Oort, E., Hale, A.H., Mody, F.K., 1994. Critical parameters in modeling the chemical aspects of borehole stability in shales and in designing improved water-based shale drilling fluids. SPE Paper 28309. SPE Annual Technical Conference and Exhibition, New Orleans (LA), September 25–28.
- van Oort, E., Hale, A.H., Mody, F.K., 1995. Manipulation of coupled osmotic flows for stabilization of shales exposed to water-based drilling fluids. SPE Paper 30499. SPE Annual Conference and Exhibition, Dallas (TX), October 22–25.
- van Oort, E., Ripley, D., Ward, I., Chapman, J.W., Williamson, R., Aston, M., 1999. Silicate-based drilling fluids: competent, cost-effective and benign solutions to wellbore stability problems. SPE paper 35059. SPE/IADC Drilling Conference, New Orleans (LA), March 12–15.
- van Oort, E., 2003. On the physical and chemical stability of shales. *J. Petr. Sci. Eng.* 38, 213–235.
- Ward, I., Chapman, J.W., Williamson, R., 1997. Silicate-based muds: chemical optimization based on field experience. SPE paper 55054, SPE International Symposium on Oilfield Chemistry, pp. 551–560. Houston (TX), Feb. 18–21.
- Wilcox, R.D., Fisk Jr., J.V., Corbett, G.E., 1987. Filtration method characterizes dispersive properties of shales. SPE Paper 13162, 59th Annual Technical Conference and Exhibition, Houston (TX), SPE Drilling, Eng. J. 2, 149–158 June.
- Wood, L.E., Deo, P., 1975. A suggested system for classifying shale materials for embankments. *Bull. Assoc. Eng. Geol.* 12, 39–55.
- Young, S.Y., Maas, T., 2001. Novel polymer chemistry increases shale stability. Drilling Technology, American Association of Drilling Engineers, AADE National Drilling Technical Conference, AADE 01-NC-HO-41. Houston (TX), March 27–29.
- Zamora, M., Lai, D.T., Dzialowski, A.K., 1990. Innovative devices for testing drilling muds, SPE drilling, Eng. J. 5, 11–18 March.
- Zhang, J., Chenevert, M.M., Talal, A., Sharma, M.M., 2004. A new gravimetric-swelling test for evaluating water and ion uptake of shales. SPE 89831. SPE Annual Technical Conference and Exhibition, Houston (TX), September 26–29.