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Fluid Design and Field Application of an Oil-Based Drill-in Fluid Using Copolymer and Flaked Calcium Carbonate in Fractured High-Permeability Depleted Formations

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Abstract

This paper describes the laboratory evaluation and field application of an optimized oil-based drill-in fluid system used to drill productive zones in the Colombian Foothills. Reviewing the existing operational parameters, a reformulated low-density oil-based drill-in fluid, with a copolymer for filtration control, and with the introduction of a unique flaked $CaCO_3$ to further enhance bridging, was studied and field tested.

After careful evaluation, it was determined that gilsonite and asphalt products, in conjunction with improper bridging of both throats and micro fractures in the productive formations, contributed to formation damage.

Final results demonstrate the need for adequate rheological properties for hole cleaning, tight control of the high temperature- high pressure (HT-HP) filtrate, and optimum return permeability for the evaluated conditions, whenever the drill-in fluid is applied.

Introduction

The Cusiana and Cupiagua fields are prolific oil and gas producing fields located in the foothills on the eastern flank of the Colombian Andes mountains. Drilling conditions are challenging due to the more complex geology, characterized by tectonic stresses, steeply dipping beds, numerous faults and alternating sand and shale formations.

The three primary producing zones are the Mirador, Barco and Guadalupe sandstones, which may repeat in the same wellbore, and are typically encountered below 10,000 ft (TVD), ranging from 15,000 to 17,000 ft MD. Bottom-hole temperatures vary from 270^o to 290^o F. The main producing mechanisms are gas cap expansion for the Mirador and solution gas drive and water re-injection for the Barco and Guadalupe formations.

The producing formations are extremely hard, with relatively low porosities of 5-6 PU, but relatively good permeabilities, due to their low clay content. These quartz arenites (quartz sandstones) are very clean and present unusual poro-permeability properties. High permeability at low porosity is the result of large pore size and good interconnectivity. For example, 10% porosity corresponds to 400 mD in normal grain size, and to 800 to 5,000 mD in very coarse grain[1]. Area tectonics produces natural fractures, varying up to 2,000 microns in width.

Due to high production rates during the recent years, the reservoir pressure has progressively depleted to less than 5,500 psi. However, the mud weight being used has not changed, because of the hydrostatic pressure that is required to maintain good control of the interbed shales. As a result, the overbalance between the hydrostatic column and the producing formation is increasing.

During the development of this area, there has been an ongoing concern that the skin factor trend was increasing, and hence productivity of the wells was at risk, especially when considering the depletion factor of the reservoir sections. Frequent meetings have been held to review the historical data, understand the potential damage mechanisms, and to try to quantify the impact of reservoir drilling fluid design on productivity of the wells.

A custom-designed oil-based emulsion (OBM) fluid, with a styrene-butadiene copolymer (SBR) and flaked $CaCO_3$, was systematically evaluated for the reservoir conditions and then used in the field, resulting in a significant improvement over the previous drilling and production results.

Reservoir Drill-in Fluids

Donovan and Jones[2] described the qualities desired in an optimally-formulated drill-in fluid. Their ideal drill-in fluid would:

1. Conform to all acceptable health, safety, and environmental standards

2. Bridge all exposed pore openings with a specially sized bridging material

3. Deposit a non-erosive filter cake that is easily and efficiently removed during the completion phase.

4. Retain desirable drilling fluid properties

In order to properly determine the particle size distribution (PSD) needed to achieve good bridging of *pores*, several approaches have been used in the past, among them we find:

- **Abrams' rule** states that the required median PSD (D50) of the bridging material to initiate bridging should be equal to or slightly greater than 1/3 the median pore size of the formation[3].
- A full range of particle size distribution, combining granular bridging materials with different distributions, based on the known pore throat distribution or formation permeability. This approach tries to address the problem of formation anisotropy by having enough particles to bridge both the small and large pores.
- **The Kaeuffer's D½ relationship** suggests that for ideal bridging, the cumulative weight % of the bridging materials should be directly proportional to the square root of their particle size[4].
- Graphical and statistical determinations to combine sized granular material, to find the appropriate concentration, and match the pore throat distribution[5].

Because of accumulated drilled solids and bridging agents, the potential for breakdown of sized particles creates progressively more potential for formation damage, especially when drilling longer intervals. This is particularly true of thick vertical sections where production sands interbed with clay.

There is a great deal of information[6, 7, 8] available documenting reservoir impairment mechanisms. These range from formation/fluid incompatibility and in-situ fines migration to incompatible stimulation treatments. While each impairment mechanism threatens a well's production ability, one of the most potentially damaging is a difficult-to-remove filter cake.

Many formation damage mechanisms are not applicable in the special case of the quartz-arenite reservoir formations in Cusiana and Cupiagua, due to the absence of reactive clays. Solids invasion into large pores / microfractures can reduce the permeability or plug the interconnected channels. These high permeability zones are, in turn, the main contributors to the production. The main cause of formation damage in the Cusiana and Cupiagua fields has been determined to be the migration of fine solids into the formation while drilling and/or during completion.

Flaked $CaCO_3$ as LCM

Skandia report[9], explains the difference between bridging in porous and permeable zones and bridging in fractures. Permeable zones produce multiple bridges throughout the volume of the porous rock. Consequently, each bridge will be required to withstand only a small fraction of the total pressure drop. Effective sealing of fractures requires that rigid particles (approximately the same size as the fracture) be used as part of the lost circulation material blend.

Flaked LCMs have large planar surfaces and are very thin. They work by forming a "shingle-like" layer against pore openings and are often effective by themselves. They also posses the advantage of relatively low absorbtion of water or oil (in the case of oil or synthetic base fluids) compared to some fibrous materials, and will not cause elevated rheology or emulsion instability. Until recently, flaked LCMs were not used in the reservoir sections because they could not be removed easily or be acidized.

Flaked $CaCO_3$ that is totally soluble in 10-15% HCl acid, has proven in the field to be an excellent additive for drilling fluids that are exposed to the pay zone. This acid soluble feature, help protect the pay zone and facilitate completion of the well after the drilling phase is finished.

Fluid Design Process

Oil-based (OBM) and water-based (WBM) drill-in systems have been used in these fields. Wellbore destabilization and low penetration rates have been experienced while using WBM. Therefore, OBM systems were preferred.

Traditional 90:10 oil-water-ratio (OWR) OBM drilling fluids formulations, with salinities lower than 70,000 mg/L Chlorides, containing different combinations of sized granular $CaCO_3$ were used in the past, to reduce skin damage. The major problem was determination of the amount and size of these bridging materials in the fluid, while drilling, due to the inherent anisotropy, high-permeability and microfractures presented in the reservoir sections.

Proper drill-in fluid characteristics for the specific reservoir conditions were evaluated, in order to produce the desirable protection of the reservoirs, while maintaining drilling fluid performance.

Fluid Loss Control and Rheology

All-oil and invert emulsion drilling fluids are effective for drilling reactive shales due to their natural inhibition, low water activity internal phase, reduced fluid loss to the formation, lubricity and low pore pressure transmission.

The use of these fluids may be limited at high temperatures due to the loss of proper rheology and filtration control, causing low carrying capacity, loss of solids suspension, reduced hole cleaning capabilities and increased fluid loss (increasing formation damage).

Traditional OBM formulations contain emulsifiers and asphalts or gilsonites for filtration control at HT-HP conditions. However, asphalts and gilsonites have been recognized in the industry as a factor contributing to formation damage.

Relatively high concentrations of asphaltene products and/or emulsifiers are needed in OBMs to reduce the HT-HP filtrate, to maintain emulsion stability, and to provide good rheology at higher temperatures. Insoluble asphaltenes particles form part of the internal and external cake formed while bridging, making them tougher and more difficult to remove[10]. Progressive gels are usually experienced with traditional formulations, then induced swab and surge losses may occur.

In 1996-1997 an oil-soluble styrene-butadiene copolymer was developed to help stabilize the HT-HP OBM formulations used in eastern Venezuela. **Table 1** compares the properties of typical OBM formulations and the formulation using the copolymer. The formulation with the SBR copolymer exhibits much better rheological properties and HP-HT filtration when compared to the formulation without the copolymer[11].

The initial application of the SBR copolymer targeted HT-HP applications. Further investigation and field tests expanded its use for low-temperature environments. After several successful field applications[12] in Venezuela and in view of the excellent production of the wells drilled using the SBR copolymer in OBM, a decision was made to run a set of tests to determine the feasibility of its use in the Cusiana – Cupiagua area.

As shown in **Table 2**, a series of tests were designed to evaluate the degree to which the SBR copolymer interacts with the structure formed by the organophilic clay network, balancing the contribution to viscosity, particularly plastic viscosity, and measuring different combinations of SBR copolymer and organophilic clay. It was observed that by increasing the SBR copolymer concentration a lower concentration of organophilic clay was needed to maintain the same rheology, and to achieve <10 mL HT-HP filtrate at 250 ^oF that was the specific target for the first application in the Cusiana – Cupiagua area.

Density and Bridging Properties

Historical data indicates that the highly-fractured interbed shales in Los Cuervos Formation require higher hydrostatic pressure to keep the formation from enlarging to a point where the hole may be troublesome or lost. The initial density required is 8.4 ppg and could as high as 9.5 ppg.

Lessons learned from existing wells demonstrate that salinity (60,000 to 70,000 mg/L Chlorides), mud density (>9.5 ppg), time exposure and hole angle (>20 deg) are factors contributing to hole enlargement.

To improve the accuracy in determining the actual particle size distribution of the solids in the system, particle size analyzers have been used since 1996, but their resultant particle size distributions are smaller than distributions obtained from sieve analysis of mud samples in the field. Larger particle concentrations were usually neglected, due to the size limitations of the particle size analyzer equipment and internal statistical calculations that convert all solid particles to their equivalent spherical shape.

Solids attrition and solids control equipment constantly reduced the amount of larger particles needed for effective bridging, resulting in mud losses and solids invasion into the formations. The reduction of large $CaCO_3$ particles, required for bridging the large pores, together with the typical high overbalance with OBM allowed the continuation of the existing problem of partial mud losses and seepage in the reservoir.

The productive formations are heterogeneous and microfractured presenting a wide range of permeabilities in each well. Although the bridging theories are based on proven geometrical and laboratory tests, the pore throat opening distribution (which is the base of all the theories) is difficult to obtain, due to unusual poro-permeability properties of the quartz-arenite formations with natural microfractures and high permeability (2,000 to 5,000 mD) sections.

These phenomena rendered kill pills and drill-in fluids bridging particles ineffective for control of partial and seepage losses in the reservoir sections, despite the promising lab results and a progressive improvement in reducing skin damage in the wells. Even more noticeable, was the fact that, every time the mud weight was increased to control the interbed shales, the mud losses appeared to increase, necessitating extra granular $CaCO_3$ pills to reduce the losses to a point where the operations could continue.

To obtain the optimum combination of bridging materials, a non-conventional approach was tried by introducing flaked $CaCO_3$. Successful case histories, from Venezuela and in the U.S., using both WBM and OBM systems, showed that partial and seepage losses were controlled by the use of this novel additive.

Flaked $CaCO_3$ is available in four grades (super fine, fine, medium and coarse), that cover a D-50 size from 75 to 3,200 microns (see **Figure 1 and 2**).

To demonstrate the bridging capabilities of the fluids formulated with the flaked $CaCO_3$, a permeability plugging apparatus (PPA) was used as the primary screening device for the design and implementation of these fluids. A detailed explanation of the equipment and the procedure has been reported previously[2].

A 150-micron disk was used to emulate large pores and microfractures because the D50 range of pore throats found in the rock formations are from 60 microns to 110 microns. In some instances, the D95 pore throat is as high as 500 microns, not taking into consideration the microfracture openings that go up to 2,000 microns in width. **Table 3** shows the results of the laboratory evaluation of the OBM with SBR copolymer and combinations of two sizes of flake $CaCO_3$ on a 150-micron disk. The results demonstrate that the coarse or medium particle sizes reduce the spurt loss and filtration volume compared to the base formulation. However, the best results were obtained with a combination of medium and coarse size particles that generate lower spurt loss and filtration volumes.

Return Permeability

To evaluate the effect of the SBR copolymer on the permeability, a series of return permeability tests were performed using Berea sandstone cores with permeability between 300 and 540 mD.

The tests were conducted at temperatures between 180 and 300°F, with overbalance of 500 psi. The results shown in **Table 4** indicate a complete return of the initial permeability on Berea sandstone cores which indicates minimum formation damage to the reservoir.

Sand Pack return permeability tests were evaluated using 140/270 gravel and kerosene (test oil). A description of the Sand Pack Apparatus and its procedure has been previously described.[2] As shown in **Table 5**, three mud formulations were evaluated using different concentrations of the SBR copolymer and flaked $CaCO_3$. The results of Sand Pack tests show more than 90% return permeability and break out pressures lower than 13 psi, demonstrating no formation damage when using the proposed compositions.

Return permeability tests were also performed by an independent laboratory (ICP-Ecopetrol), using a Hassler-permeameter. Their results show even higher percentage of return permeability, when compared with the results obtained in the Sand Pack equipment.

Field Applications

The first field application of the SBR copolymer to replace asphaltic materials in traditional OBM formulations was performed in the 6” lateral section at 16,770 ft MD through the Barco formation, using an OBM formulation with 6.0 ppb organophilic clay and 3.0 ppb of SBR copolymer. This mud formulation improved the drilling operations compare with the previous well that was drilled with OBM without SBR copolymer.

However, indications of some $CaCO_3$ settling while running the completion liner led to a task force study of the low shear rate viscosity of the fluid using the RJF Viscometer[13]. The results of the study concluded that that the formulation has a low risk of solids settling, because the application was within the acceptable defined window to avoid sedimentation of solids (see **Figure 3**).

Flaked $CaCO_3$ additions to the system were made whenever losses occurred. The first field application and the effect of the addition of Flaked $CaCO_3$ is described in **Table 6**.

The next wells were drilled with a modified formulation (see **Table 7**). The 90/10 low-toxicity mineral oil/water system contains between 5.0 and 11.0 ppb of organophilic clay, flaked $CaCO_3$ and required only 1.40 to 1.60 ppb of copolymer to control the filtrate and maintain rheology at the desired values. No further $CaCO_3$ setting was reported.

This modified formulation was then used for drilling the Mirador, Barco and Guadalupe reservoirs. The sections drilled were 8 1/2” and 6” that extend to 17,900 ft in some of the wells. Mud losses were successfully controlled following the decision tree in **Figure 4**. In these wells, there were no problems while drilling and the seepage and partial losses were controlled.

Table 8 shows the productivity data comparison from the field. The drilling results with the new fluid formulation using SBR copolymers and a combination of coarse and medium flaked $CaCO_3$ include reduction of drilling fluid losses, good cuttings transport, hole cleaning and increased productivity of the wells.

The present mud program for the area required the use of 2 ppb of flaked $CaCO_3$ in the drilling fluid, with 4 to 5 50 lb-sacks/hour additions, when drilling of the target reservoir section begins.

Conclusions

- Oil soluble copolymers effectively replace the use of asphalts/gilsonites used in traditional OBM and provide additional rheology for these systems.
- Flaked $CaCO_3$ improves bridging capabilities of drill-in fluid in high-permeability fractured formations present in these fields.
- Seepage losses in the reservoir sections have been reduced to a minimum or eliminated.
- Flaked $CaCO_3$ is now used in intermediate and reservoir sections in the area to control seepage and partial losses.
- Overall, well productivity improvement was achieved whenever the system was applied.
- The new drill-in fluid design provides adequate rheological properties for hole cleaning, excellent control of the HT-HP filtrate and optimum return permeability under the evaluated conditions.

Nomenclature

OBM = Oil based muds
WBM = Water based muds
SBR = Styrene-butadiene rubber copolymer
PSD = Particle size distribution
OWR = Oil water ratio
MW = Mud weight
PPA = Permeability plugging apparatus
PV = Plastic viscosity
YP = Yield Point
HT-H P= High Temperature – High Pressure
10-sec gel = API 10 second gel strength
10-min gel = API 10 minute gel strength
^{o}F = Temperature, degrees Fahrenheit
LCM = Lost Circulation Material
sx=sacks
MD= Measure depth
ppb=pounds per barrel

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Table 1- Properties comparison between typical OBM formulations and styrene-butadiene copolymer

Additives	OBM without SBR copolymer		OBM with SBR copolymer	
Oil base, bbl	0.72		0.72	
Organophilic clay, lb/bbl	6		6	
Emulsifier, lb/bbl	6		6	
Lime, lb/bbl	4		4	
SBR copolymer, lb/bbl	-		3	
Densifier, lb/bbl	365		364	
Properties	**Initial**	**HR@350 °F**	**Initial**	**HR@350 °F**
PV, cP at 120 °F	15	15	35	37
YP, lb/100 sq ft	5	1	18	17
6-rpm reading	3	1	8	9
10-sec gel, lb/100 sq ft	4	1	8	10
10-min gel, lb/100 sq ft	7	2	8	10
HPHT Filtrate, mL/30 min	-	21	-	5

Table 2- Required concentration of soluble copolymer to replace Asphaltenes products in Mirador, Barco and Guadalupe formations

Additives	Mud 1	Mud 2	Mud 3	Mud 4	Mud 5	Mud 6
OWR	90/10	90/10	90/10	90/10	90/10	90/10
Organophilic clay, lb/bbl	10	10	10	8	8	6
Emulsifier, lb/bbl	1.5	1.5	3	3	4	4
SBR copolymer, lb/bbl	-	1	1	1.5	3	3
$CaCO_3$ M-200,lb/bbl	40	40	65	65	65	65
$CaCO_3$ Special,lb/bbl	35	35	10	10	10	10
Gilsonite, lb/bbl	4	-	-	-	-	-
Asphalt, lb/bbl	3	-	-	-	-	-
Properties @ 150°F						
MW, lb/gal	8.3	8.4	8.4	8.3	8.4	8.3
PV, cP	16	20	25	11	18	17
YP, lb/100 sq ft	10	32	30	13	25	22
10-sec Gel, lb/100 sq ft	15	16	19	10	16	15
10-min Gel, lb/100 sq ft	21	32	31	15	29	25
HPHT @ 250°F, mL/30 min	16	10	8	7	5	7

Table 3- Effect of the Flaked $CaCO_3$ on PPA analysis (250 F & *150-micron disk*)

Additives	Base Mud	Mud 1	Mud 2	Mud 3
OWR	90/10	90/10	90/10	90/10
Organophilic clay, lb/bbl	5	5	5	5
Emulsifier, lb/bbl	1.5	1.5	1.5	1.5
SBR copolymer, lb/bbl	6	6	6	6
$CaCO_3$ M-200, lb/bbl	40	40	40	40
$CaCO_3$ Special, lb/bbl	35	35	35	35
Flaked $CaCO_3$ Coarse, lb/bbl	-	2	-	1
Flaked $CaCO_3$ medum, lb/bbl	-	-	2	2
Properties @ 150°F (after hot-rolled at 250°F)				
MW, lb/gal	8.4	8.4	8.4	8.4
PV, cP	9	10	9	10
YP, lb/100 sq ft	16	17	18	15
PPA at 250°F (150 Microns Disk @ 1000 psi)				
Spurt Loss, mL	10	9	8	6
Total Filtrate, mL/30 min	14	11	12	10

Table 4- Return of permeability tests performed with Berea sandtone core

Fluid density (lb/gal)	Temperature (°F)	Overbalance pressure (psi)	Permeability, mD		
			Initial	Final	Return permeability, %
8.0	180	500	303	341	112
10.5	280	500	274	295	108
12.0	300	500	536	577	108

Table 5- Sand Pack return permeabilities using SBR copolymer and Flaked $CaCO_3$

Additives	Mud 1	Mud 2	Mud 3	Mud 4	Mud 5	Mud 6	Mud 7	Mud 8
Organophilic clay, ppb	10	8	8	6	5	5	6	11
Emulsifier, lb/bbl	3	3	4	4	1.5	1.5	2	2
SBR Copolymer, lb/bbl	1.5	1.5	3	3	6.0	6.0	1.2	1.5
$CaCO_3$ M-200,lb/bbl	50	50	40	40	40	40	33	33
$CaCO_3$ Special,lb/bbl	25	25	35	35	35	35	22	22
Lime, lb/bbl	8	8	8	8			6	6
Flake $CaCO_3$ Medium, lb/bbl	-	-	-	-	1.0	2.0	-	-
Flake $CaCO_3$ Coarse, lb/bbl	-	-	-	-	2.0	-	-	-
Fluid density, lb/gal	8.4	8.4	8.4	8.4	8.4	8.4	7.8	7.8
Sand Pack Results								
Sand Pack Gravel	140/270	140/270	140/270	140/270	140/270	140/270	140/270	140/270
Initial Pressure, psi	17.8	14.2	18.2	18.7	17.6	16.7	14.4	13.9
Final Pressure, psi	12.9	9.9	14.2	13.2	11.6	12.4	9.9	7.8
Temperature, °F	76	74.8	76	75.8	76	75.8	75.8	76.2
Filtrate, mL/30 min	10.5	5.5	12.5	6.4	2	2.4	5	4.5
Return Permeability, %	97	95	97	94	92	93.4	94	93

Table 6- Summary of losses during the first field application

Sequence of Treatment	Additives				Downhole losses, bbl/hr
	Graded Fiber	SOLU-FLAKE (Flaked $CaCO_3$)	$CaCO_3$ Special	Organophilic clay	
1 - 15 lb/bbl Check Loss & 60 lb/bbl $CaCO_3$ Special (coarse). 50 bbl pill	-	-	-	-	from 450 to 60
2- 25 lb/bbl Check Loss & 60 lb/bbl $CaCO_3$ Special (coarse). 50 bbls pill	-	-	-	-	
3- 50 lb/bbl Check Loss & 60 lb/bbl $CaCO_3$ Special (coarse). 50 bbls pill	-	-	-	-	
4- 50 lb/bbl Check Loss & 60 lb/bbl $CaCO_3$ Special (coarse). 50 bbls pill	-	-	-	-	
5- Continuous addition to the system Final concentration	8 sx/hr 5.9 lb/bbl	-	5 sx/hr 27.7lb/bbl	-	from 60 to 40
6- Two -25 lb/bbl Check Loss & 60 lb/bbl $CaCO_3$ Special (coarse). 50 bbl pill	-	-	-	-	from 40 to 30
7- Continuous addition to the system Final concentration	5 sx/hr 4.9 lb/bbl	-	5 sx/hr 25.43 lb/bbl	5 sx/hr 5.7 lb/bbl	from 30 to 20
8- Continuous addition to the system Final concentration	4.53 lb/bbl	6 sx/hr @ 2.2 lb/bbl @ 3.8 lb/bbl	5 sx/hr 27.5 lb/bbl	5.24 lb/bbl	from 20 to 3 from 3 to 0

Table 7- OBM formulation used in the drilling operations

Additives	Field Formulation
Organophilic clay, lb/bbl	5.0 – 11.0
Emulsifier, lb/bbl	1.5 – 3.0
Lime, lb/bbl	6.0 – 8.0
SBR copolymer, lb/bbl	1.4 – 1.6
$CaCO_3$ M-200, lb/bbl	50 - 60
$CaCO_3$ special, lb/bbl	25 - 15
Flaked $CaCO_3$, lb/bbl	4 to 5 sx/hr up 8 lb/bbl theoretical concentration
Properties after hot-rolled at 240 °F	
Mud weight, lb/gal	8.4
Oil/water ratio	90/10
PV, cP at 120 °F	11-17
YP, lb/100 sq ft	18-20
10-min gel, lb/100 sq ft	14
HPHT Filtrate, mL/30 min	6.2

Table 8- Well Productivity (Mirador Formation)

	Drilling Applications / Conditions	Density, lb/gal	Production, bbl/day
Well 1	High Overbalance, SBR Copolymer & Flaked $CaCO_3$	8.4 – 9.3	15,000
Well 2	Low Overbalance – At balance	7.2 – 7.5	6,000
Well 3	Underbalance	6.9 – 7.2	1,050
Well 4	High Overbalance, SBR Copolymer & Flaked $CaCO_3$	8.4 – 9.4	13,500

Figure 1 - SEM Photograph of flaked $CaCO_3$

50 X

Figure 2 - Photograph of flaked $CaCO_3$ on API 200 mesh screen

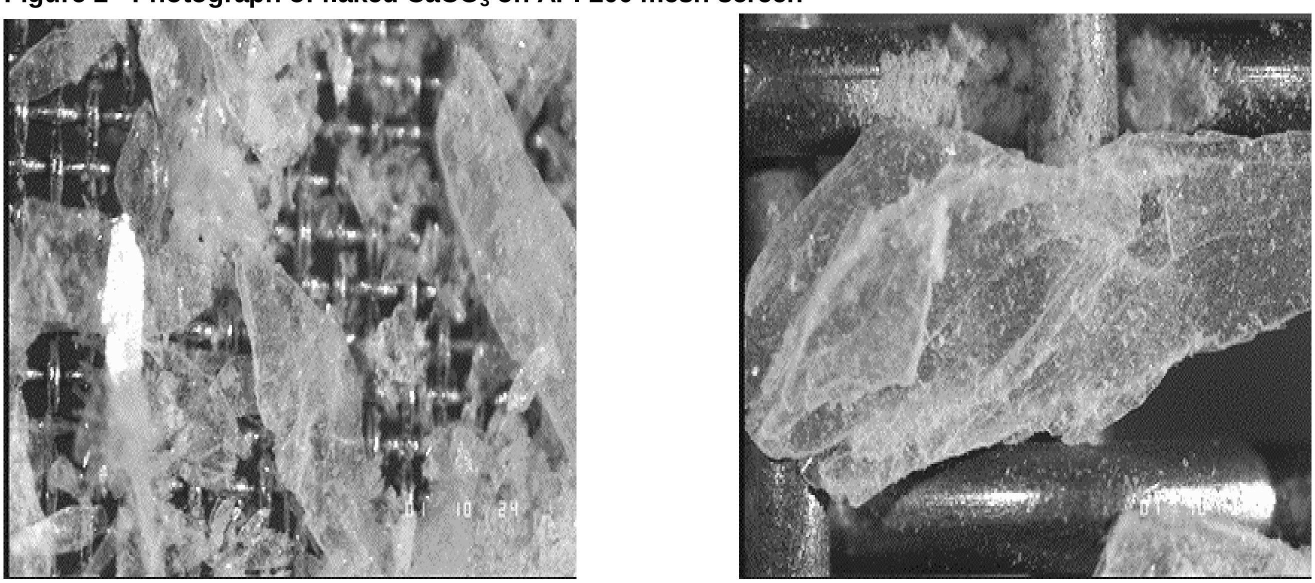

Figure 3 - $CaCO_3$ saging study using the RJF Viscometer

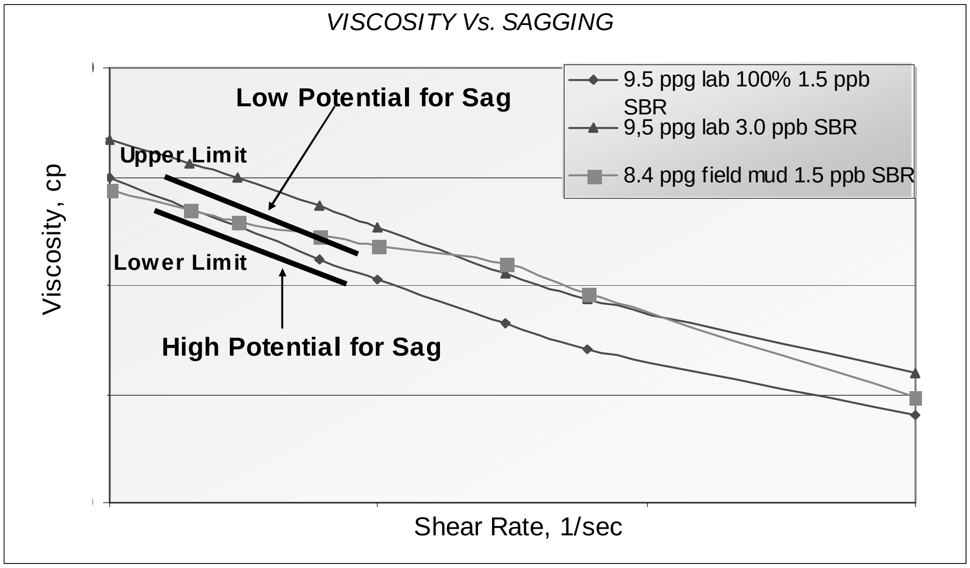

Figure 4 - Lost circulation strategy for reservoir sections in Cusiana - Cupiagua Wells.