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RESEARCH ARTICLE

USE OF CALCIUM CARBONATE AS BRIDGING AND WEIGHTING AGENT IN THE NON DAMAGING DRILLING FLUID FOR SOME OILFIELDS OF UPPER ASSAM BASIN

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ABSTRACT

Traditionally, the Barite (Specific Gravity of about 4.2-4.7) has been using as the weighting agent in conventional drilling fluid. But, the drilling of oil and gas wells from surface to the pay-zone with conventional drilling fluids may damage the producing interval. The formation plugging by drilling fluid's compositional solids, drilled cuttings and polymers' particles;hydration of clay envelop around pay zone particles by filtrate; formation of scales due to chemical reaction between formation fluid and mud filtrate are the most common damage mechanisms attributed to drilling fluid. So,to counter the damage, an ideal mud should not use of non-degradable compositional fine solids; must have minimum drilled fine solids; should reduce the filtration loss; and should generate inhibitive filtrate.Effective field development needs high quality drilling fluid to minimize formation damage and maximize productivity. This paper discusses the development of least damaging drilling fluid basically for development wells in the Upper Assam Basin of India. The idea behind the development of drilling fluid was to avoid fines and polymer plugging by optimizing the Particle Size Distribution (PSD) of fine and medium sized particles of calcium carbonate. The laboratory results have shown the effectiveness of sized particles of $CaCo_3$ in Non Damaging Drilling Fluid (NDDF) to bridge the pore throat on the formation surface to build an external filter cake which is much easier to be removed than an internal filter cake based on the Particle Size Distribution of $CaCo_3$ and Pore-throat diameter study of the sandstone reservoirs of some oilfields of Upper Assam Basin. $CaCo_3$(Specific Gravity of about 2.7-2.8)is also used as the weighting agent in NDDF which is acid soluble and can be removed easily later on. The optimum composition of $CaCo_3$also designed based on the interpretation of the mud properties of laboratory formulated NDDF and required mud properties for successful drilling and completion in the study areas.

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INTRODUCTION

Different fluids are used in the bore-hole for drilling and completing a well. The chemical and physical compatibility of the fluids with the reservoir rock is the most important factor in maximizing production. These fluids may reduce well's productivity by encouraging formation damage in several ways. These fluids are kept at a pressure higher than the formation pressure to stop the invasion of formation fluid into the wellbore. This overbalance pressure is considered as the major cause of inducing formation damage by the invasion of fluid and suspended solid into the formation. These solids (drilling fluid's compositional solids, drilled cuttings and polymers' particles) have a tendency to block the pores to reduce the rock permeability.

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The filtrate will react with the formation minerals to mobilize and subsequently re-deposit them, hydrate the clay envelop around pay zone particles, and may generate scales due to chemical reaction with formation fluid leading to a decrease in formation permeability. Thus, this invasion can cause irreversible formation damage. Therefore, it is always significant to minimize the exchange of fluids between the well and the rock formation and solids invasion in the formation.Due to this, generally we add particulate material in the drilling fluid so as to form a low permeable filter cake on the wellbore walls and thereby minimizing the invasion of filtrate and solids to the formation. The external filter cakes are used to minimize fluid loss and solids invasion to a formation from the wellbore, but subsequently, the cake must be removed to increase the flow area and minimize skin. The acid-soluble solids are usually added in NDDF in order to encourage pore plugging and minimize fluid penetration. Also specific polymers are used that reduce fluid invasion by sealing the walls of the borehole and viscosity effects due to its long chains of monosaccharide. The most commonly used drilling and completion fluids for filtrate loss control in the reservoir are water-based mud comprising polymeric additives and sized calcium carbonate or sized salt.

The NDDF is a clay and barite free polymer mud system mostly used in pay zone section to avoid formation damage and to keep pay zone or reservoir intact. It incorporate long-chain, high molecular weight polymers in the systems either to encapsulate drill solids to prevent dispersion or to coat the shales for inhibition as well as to increase viscosity and reduce fluid loss. An extensive range of particle sizes is used which, on de-hydration, fit together into a strongly compacted very low permeable mud cake on the surface of the rocks to quickly seals off the permeable paths of the pay-zone.

The key elements attributed to formation damage due to solids invasion are: over-balance pressure, formation permeability / pore size distribution, particle size distribution in the fluid, concentration of mud solids, mud circulation rate and rheology (Gaurina- Medimurec *et al*., 1999; Gaurina-Medimurec *et al*., 2002).

One significant aspect in designing drilling mud is the distribution of bridging particle sizes. Suitable particle sizes can reduce fluid loss to the formation and minimize solid invasion into formation pores. Some researchers also discovered that formation damage is a strong function of particle size distribution in the drilling mud and pore size distribution of a formation. For minimizing the formation damage due to drilling and completion fluids, solids used in these fluids must be sized so that they must be large enough to keep them away from entering into formation and must be small enough to be able to form an effective bridging to prevent filtrate, solids, or polymer invasion into the formation (SuriandSharma, 2001; Siddiqui*et al*., 2006). The growing use of open-hole completions in horizontal wells also demands more attention to be paid to the bridging properties of reservoir drilling fluids.

Studies conducted by Bailey *et al*. (1999) also revealed that solids invasion is one of the primary causes of formation damage from drilling fluids. Fine particles penetrate deeply and are not easily removed by back-flushing. Invasion of larger particles is usually localized to near surface. They show an effective correlation between invasion and damage, and that particle bridging reduces spurt loss and damage. Thus, minimizing of internal filter cake and quick formation of low permeable external filter cake is very significant for reducing the invasion of the solids and the filtrate and to control formation damage.

One of the most important factors in designing reservoir fluids to prevent the solids and filtrates invasion into the pay-zone from drilling muds is the proper selection of bridging particle sizes in the system in relation to the formation pore openings to obtain a surface bridge on the formation surface. (Mahajan and Barron, 1980)

According to Abrams (1977), although some solids invasion and formation damage are inherent to all drilling fluids, it is possible to minimize solids invasion and formation impairment by adding bridging material to the muds. This bridging material is chosen by matching its size to the formation-rock pore sizes. His studies revealed that the invasion of solids and filtrate and corresponding formation damage occur with all muds; the depth of invasion and degree of damage is controllable to a certain level by designing the mud incorporating bridging material; The effective bridging is a function of the concentration and particle size of the bridging material and of the pore sizes of the reservoir rock; the impairment is most likely to occur in higher permeability formations since most muds contain sufficient quantities of particles, including cuttings, in the required size range to bridge lower permeability rocks; and where invasion occurs, back flushing does not remove the damage.

Lund (2013) reveals that as the concentration of smaller particles increases, the fluid seemed to perform better in terms of bridging. The bigger particles form some sort of a framework at the fracture mouth, whereas the smaller particles fills the voids between the bigger particles. This indicates that smaller particles are also important in order to achieve good bridging properties.

According to Pang and Sharma (1997), almost every operation in the petroleum reservoir can cause formation damage and thereby decrease of productivity or injectivity of the formation. To avoid this risk and the high cost involved in recovering the damaged formation, it is necessary to minimize it.

Zain and Sharma (2001) have clearly shown that the flow-initiation pressure during flow-back is controlled by solids and filtrate invasion. Flow-initiation pressures show as minimum with increasing rock permeability caused by larger pore sizes; however, more solids invasion increases P_{fi}. Higher overbalance pressures also increase the internal formation damage and flow-initiation pressure.

There are various guidelines used in the industry to choose the particle size of bridging materials that can form an efficient external filter cake and minimize formation damage. Abrams' rule(Abrams, 1977)defines the particle size required to initiate bridging. The ideal packing theory (Smith*et al*., 1996; Dick *et al*., 2000)defines the total particle range required to seal all pores, even those created by bridging agents.Then, all the guidelines have been provedso that bridging material can form an efficient external filter cake and minimize formation damage to the oilfields of Upper Assam Basin (UAB) of India.

In the Upper Assam basin, following producing horizons have been identified (top to bottom): a) Tipam Sand, b) Barail Sand, c) Kopili, d) Sylhet, e) Basal Sandstone, and f) Basement.The geological age of the Barail main sand and Barail coal-shale is Oligocene and that of Tipam is Miocene.

As discussed earlier, the formation damage basically depends upon the type and properties of the mud and formation properties. Table 1 shows that the Median Porosity andPermeability of the producing formations of the oilfields of

Upper Assam Basin are about 20% and 225 mdrespectively which are very much susceptible for filtrate as well as solid invasion. With the conventional Water Base Mud (WBM), the losses during drilling are tremendously high and continuous in this formation. So, the loss cannot be arrested without the use of NDDF.

of some major oilfields of Upper Assam Basin (UAB) have conducted to investigate the clay-mineral contents of the fields to analyse the candidature of the fields for the implementation of NDDF using XRD analyser and Scanning Electron Microscope.

Table 1. Reservoir Properties of Ten (10) Major Oilfields of Upper Assam Basin

Oilfield	Sand	Average Porosity (%)	Permeability (md)	Temperature (°C)
XYZ-G	Gurujan Clay	22	-----------	-----------
	TS	15-22	10-50	70-80
	BCS	15-20	-----------	90-92
	BMS	10-20	5-45	98-105
	KSU	10-15	5-45	100-108
XYZ-R	TS	20-21	-----------	-----------
	BCS	20.1-25	-----------	-----------
	BMS	15-23.8	-----------	-----------
XYZ-L	TS	14.8-32	23-900	74-92.8
XYZ-N	Tipam	18-25	30-900	66-74
	Barail	18-23	33-416	70-93
	LK+TH	12-15	-----------	98-112
XYZ-H	Tipam	16-25	-----------	60-70
	Barail	20-24	300-600	68-75
	LK+TH	16-20	-----------	103-116
XYZ-M	Barail	18-21	7-207	80-99
XYZ-D	LK+TH	18-26	250-2400	103-105
XYZ-J	Tipam	14-25	40-480	65-84
	Barail	19-21	10-380	85-88
XYZ-S	Barail	10-18	12-156	70-90
XYZ- C	Eocene (LK+TH and Langpar)	16-22	500-700	98-106

(OIL and ONGC, unpublished report)

MATERIALS AND METHODS

Materials

The general components used for formulation of NDDF are:

1. Base fluid - fresh water
2. Viscosifier- XCP
3. Fluid loss control agent - Starch e.g. PGS (Pre Gelatinized Starch), PAC (LVG) & PAC (RG)
4. Lubricity- Linseed oil
5. Formation clay/shale inhibitor-Potassium Chloride
6. Weighing and bridging materials: Medium Coarse $CaCo_3$and Micronized $CaCo_3$
7. Other additives- Caustic Soda, Bactericide (Formaldehyde)

To study the effect of XCP, the NDDF is prepared by properly mixing of Fresh Water: 1.5 Litre, XC-Polymer: 0.3%, PGS: 3%, PAC (LVG): 0.5%, PAC (RG): 0.3%, Biocide: 0.1%, NaOH: 0.025%, KCl: 5% and variesthe composition of $CaCo_3$ in gm /100ml basis (Raoand Pandey, 2010) and (Chattopadhyay *et al*., 2010). As discussed earlier, the drilling fluids are designed based upon the formation characteristics. So, to study the detail characteristics of the study area, some data of reservoir rock properties as well as some mud policy & well cards for NDDF of drilled wells, mud chemicals, etc. are collected from different operating companies working in this basin.

Methods

Firstly, the X-Ray Diffractogram (XRD) and the SEM photomicrograph study of the of Core samples of the pay-zones

Secondly, a reaction test was conducted in the laboratory between the 35% pure HCl and Barite;35% pure HCl and Medium Coarse $CaCo_3$;and 35% pure HCl and Micronized $CaCo_3$ to see the effect of acid job after completing the drilling of the wells using these bridging and weighting materials in the mud.

Thirdly, according to proper measuring manual instructions different muds samples are formulated by varying the composition of Medium Coarse $CaCo_3$ and Micronized $CaCo_3$, keeping the other components as constant using the following equipments:

a) Mettler Electronic Precision balance to measure the mass of different chemicals for proper composition.
b) 1000 ml measurable stainless steel cup for measuring the water volume.
c) Hamilton Beach Mixer for proper stirring/mixing water and the mud component for generation of proper mud properties.
d) 15 ml pipette to measure small liquid volume.

Then, the effect of varying composition of Medium Coarse $CaCo_3$ and Micronized $CaCo_3$on mud properties are investigated to select optimum percentage of Medium Coarse $CaCo_3$ and Micronized $CaCo_3$, which gives best parameters to NDDF.

To investigate the effect of varying composition on the various mud properties, the following equipments have used:

a) OFITE 4 scale plastic model Mud Balance to measure the density of formulated mud.
b) OFITE plastic Marsh Funnel Viscometer to measure the Funnel Viscosity of formulated mud.
c) Filter Press for measuring the Fluid Loss and Mud Cake Thickness of formulated mud.
d) pH Meter for measuring the pH of water used for formulating mud and the formulated mud.

Fourthly, the Sieve analysis of the particles of Micronized $CaCo_3$,Medium Coarse $CaCo_3$ and Barite was done using Sieve Shaker to see the Particle Size Distribution of these bridging and weighting materials of drilling fluid. The Mean and Median of the particles of the bridging material (Medium Coarse $CaCo_3$ and Micronized $CaCo_3$) was calculated to examine the bridging material whether it will fulfil the thumb rules for effective bridging or not.

Fifthly, a SEMphotomicrograph study of the Core samples of the pay-zones of some major oilfields of UABhas conducted using Scanning Electron Microscopeto estimate the pore-throat diameters of the fields.The Mean and Median of the pore-throat diameters of the fields was calculated to examine whether bridging material will fulfil the thumb rules for effective bridging or not.

Sixthly, the Mean and Median of the different NDDF parameters of successfully drilled wells in the producing formations of UABwere calculated from the well-cards of the completed wells collected from different operating companies of this basin to design the optimum mud parameters for successful wells in this basin.

Seventhly, again different muds samples were formulated by varying the composition of $CaCo_3$, keeping the other components as constant. Then the effect of varying composition of $CaCo_3$on mud properties are investigated to see the role of $CaCo_3$ in NDDF and to select optimum composition of $CaCo_3$which gives proper / suitable parameters of NDDF for the UAB. The suitable parameters of NDDF for the UABhave been selected from the well cards collected from different operating companies working in this basinand optimum composition of $CaCo_3$was selected by interpreting the parameters with the generated table and graphs.

Finally, a comparison of mud properties among Barite, Medium Coarse $CaCo_3$ and Micronized $CaCo_3$ was done by formulating the different mud samples using these materials.

RESULTS AND DISCUSSION

As discussed earlier, reservoir minerals have a great role in the formation damage mechanism when they come in contact with the filtrate from water base mud (WBM). The minerals of the UAB studied and identified with the help of X-Ray Diffractogram (XRD) and the SEM photomicrograph analysis. The major minerals in most of the rock samples found to present are Smectite, Chlorite, Illite, Kaolinite, Quartz, and Feldspar as shown in XRD Fig.(1-3) and SEM Fig. (4-6). The study reveals that the entire field contains both the swelling (Smectite) and non-swelling (Illite, Kaolinite) clay. Illite and Kaoliniteare known as emigrational fines problem clay. Smectites can swell with changing ionic conditions and eventually disperse and migrate with the flowing fluid.

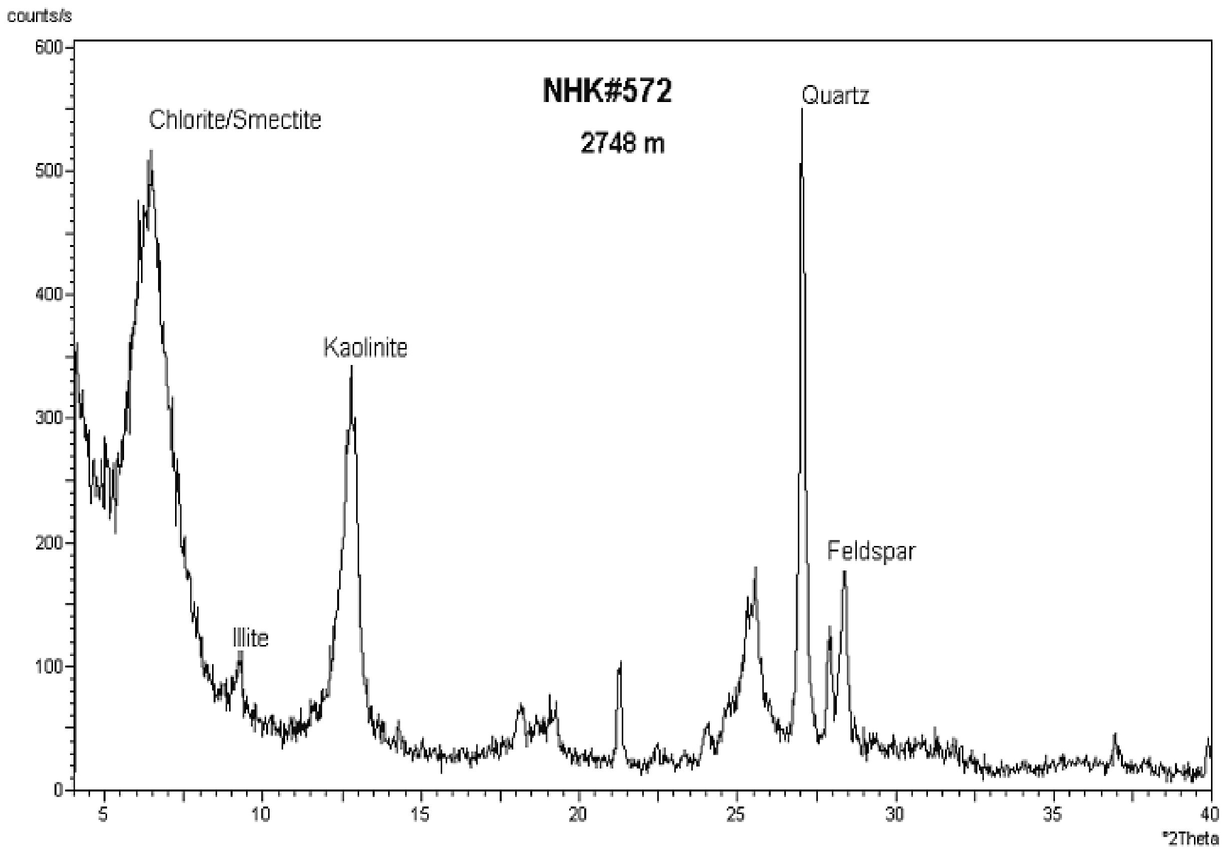

Fig.1. X-Ray Diffractogram (XRD) of Core Sample (Depth: 2748 m) of Naharkotia oilfield showing Smectite/Chlorite, Illite, Kaolinite, Quartz, and Feldspar

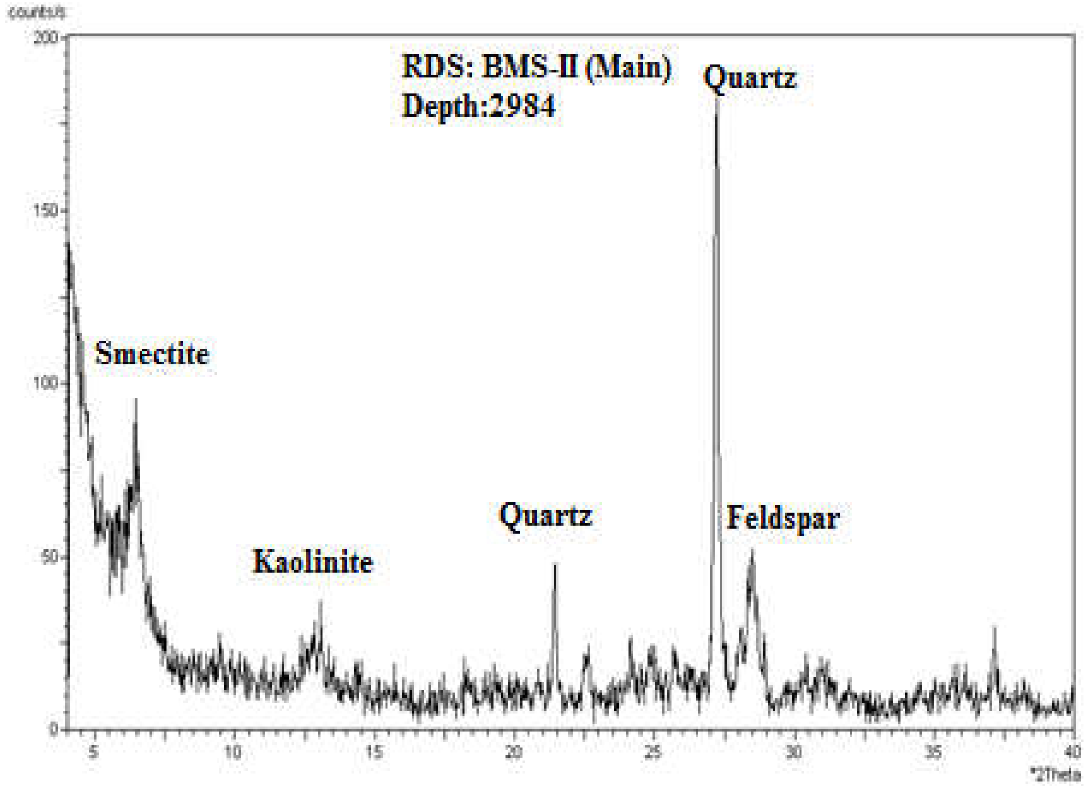

Fig.2. X-Ray Diffractogram (XRD) ofCore Sample (Depth: 2984m) of Rudrasagar oilfield showing Smectite, Kaolinite, Quartz, and Feldspar

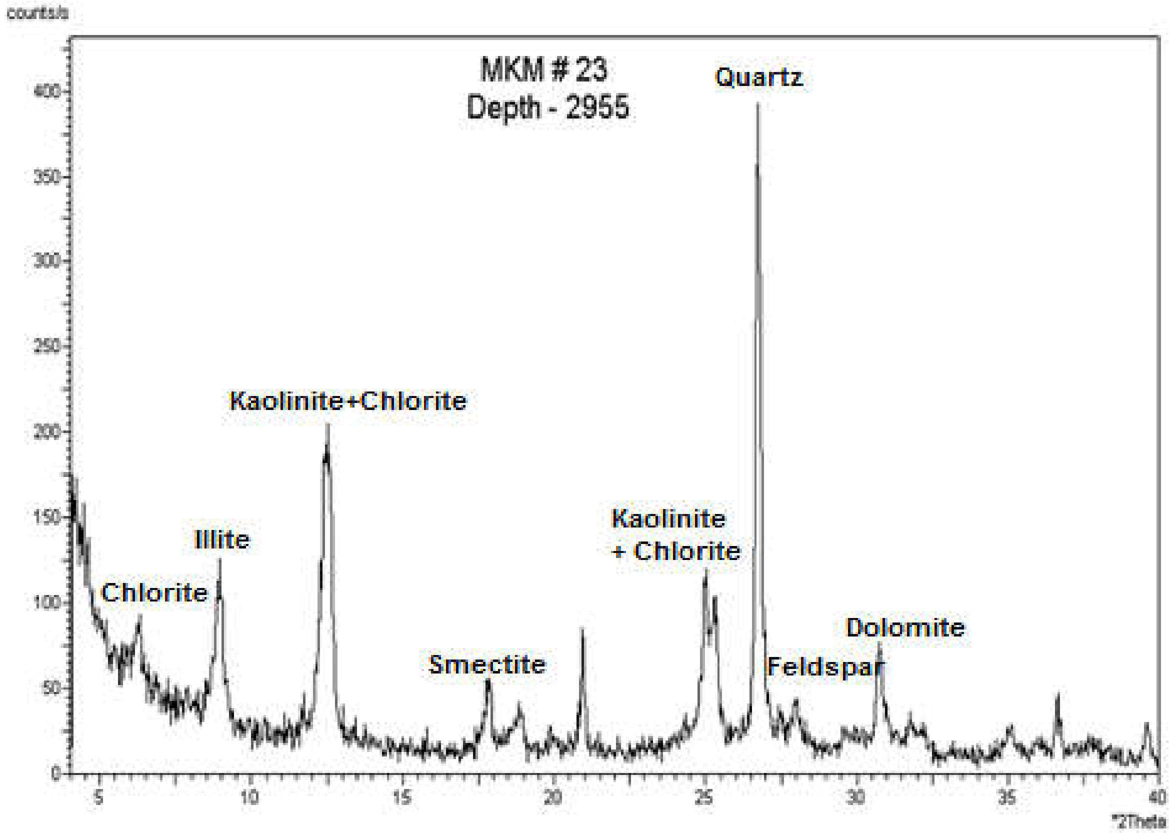

Fig.3. X-Ray Diffractogram (XRD) of Core Sample (Depth: 2955 m) of Makum oilfield showing Chlorite, Illite, Kaolinite, Smectite, Quartz, Feldspar and Dolomite

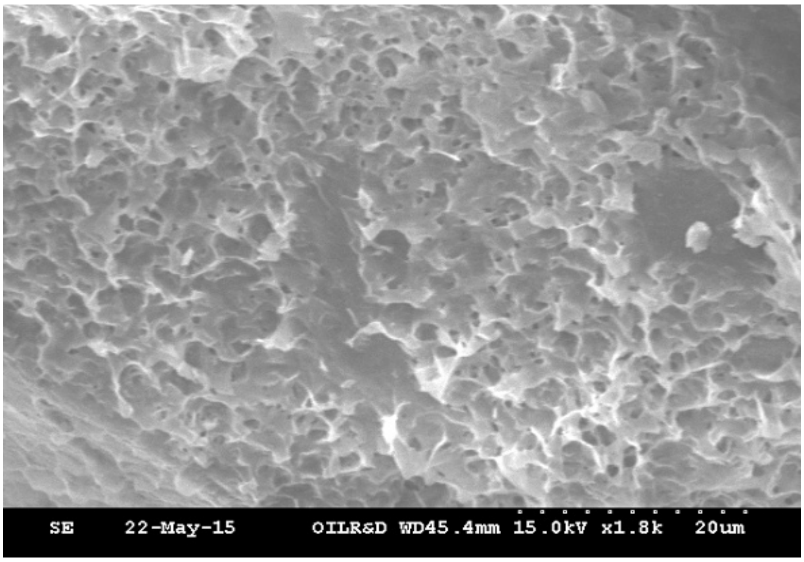

Fig.4. SEM photomicrograph shows Smectite coated on detrital grains in the samples of Lakwa oilfield

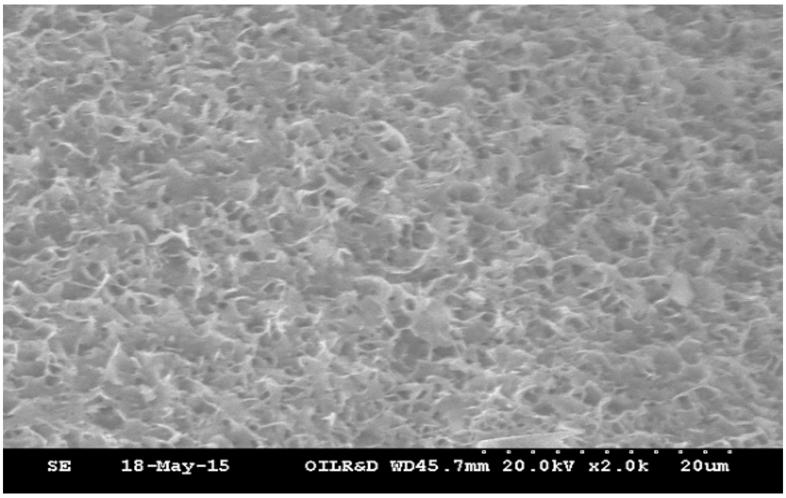

Fig.5. SEM photomicrograph shows Illite and Smectite coated on detrital grains in the samples of Geleki oilfield

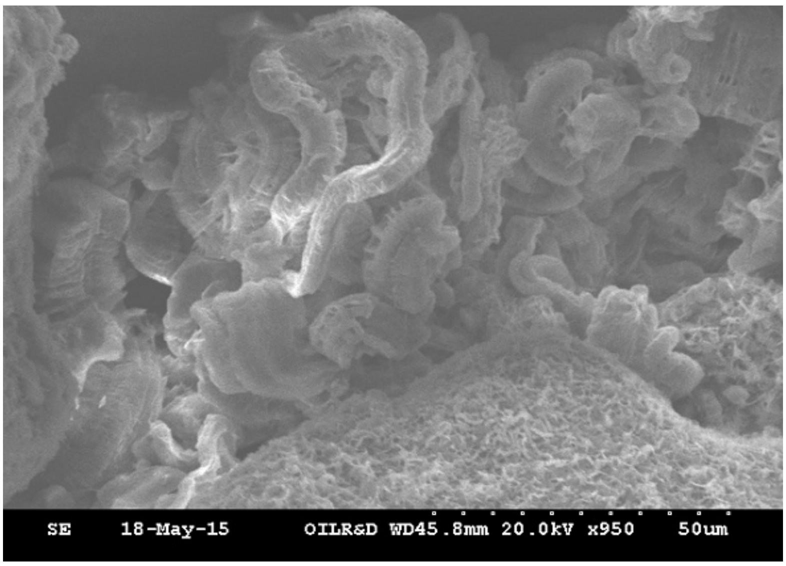

Fig.6. SEM photomicrograph shows pore filling vermiform Kaolinite in the samples of Geleki oilfield

Swelling alone reduces the effective area for flow and causes reduction in permeability. Kaolinite is non-swelling clay,but tends to detach from the rock surface and migrate when the colloidal conditions are conducive for release. The migrating particles can get trapped in pore throats, thus causing a reduction in permeability. High pH (e.g. 10.5) causes the kaolinites to develop sufficiently high potentials to cause them to detach from the surface, migrate and be in the pore constrictions (Mohan, 1993). Thus, the clay contents of UAB are very much prone for the formation damage.The Median Porosity and Permeability of the producing formations of the oilfields of Upper Assam Basin are also very good, which are about 20% and 225 mdrespectively and are very much susceptible for filtrate loss as well as solid invasion. Therefore, the UAB is a very good candidate for the implementation of NDDF.

A reaction test was conducted in the laboratory between the 35% pure HCl and Barite;35% pure HCl and Medium Coarse $CaCo_3$;and 35% pure HCl and Micronized $CaCo_3$. For this, 100 ml of 35% pure HCl was taken in three different container and add 10 gm. each of Barite, Medium Coarse $CaCo_3$ and Micronized $CaCo_3$ in the three different container and allow them to react for 30 minutes. After 30 minutes, the Precipitation of Barite is clearly seen (Fig. 7) at the bottom of the Barite's container and there was no precipitation in the Medium Coarse $CaCo_3$ and Micronized $CaCo_3$'s container. Thus we can conclude that the formation plugging by the NDDF using Medium Coarse $CaCo_3$ and Micronized $CaCo_3$ as the weighting and bridging material can be removed clearly by using acid job after completing the drilling of the wells.

Fig.7. Precipitation of Barite is clearly shown after 30 minutes of reaction with HCl

According to proper measuring manual instructions different muds samples were formulated by taking fresh water volume: 1.5 litre, total composition of $CaCo_3$: 10 gm/100ml out in which varying the composition of Medium Coarse $CaCo_3$ and Micronized $CaCo_3$ keeping the other components as constant. Then the effects of varying composition of Medium Coarse $CaCo_3$ and Micronized $CaCo_3$on mud properties were tabulated (Table 2) and investigated to select optimum percentage of Medium Coarse $CaCo_3$ and Micronized $CaCo_3$, which gives best parameters to NDDF.

In the Table 2, we can see that the Funnel Viscosity, Density and pH are constant for all the mud samples, that means the varying the composition of Medium Coarse $CaCo_3$ and Micronized $CaCo_3$ do not have any effect on these three mud properties.

Table 2. Selection of best composition for the mixture of MCC and MCCC for effective bridging based on the properties of the NDDF

NDDF Volume: 1.5 liter, Total Composition of $CaCo_3$ = 10 gm/100ml							
		Mud Properties					
Amount of Micronized $CaCo_3$ (MCC), gm	Amount of Medium Coarse $CaCo_3$ (MCCC),gm	Funnel Viscosity, Seconds	Density of mud, kg/m^3	pH (Hydrogen Ion Concentration)	Fluid Loss, ml	Mud Cake Thickness, mm	Temperature, °C
100	0	53	1059	9.5	7	0.29	29
90	10	53	1059	9.5	7.1	0.3	29
80	20	53	1059	9.5	7.1	0.29	28
70	30	53	1059	9.5	7	0.29	29
60	40	53	1059	9.5	6.8	0.28	28
50	50	53	1059	9.5	7.1	0.29	28
40	60	53	1059	9.5	7.3	0.3	28
30	70	53	1059	9.5	7.4	0.31	29
20	80	53	1059	9.5	7.6	0.33	29
10	90	53	1059	9.5	7.9	0.35	28
0	100	53	1059	9.5	7.9	0.36	29

But, it is clearly seen that the varying the composition of Medium Coarse $CaCo_3$ and Micronized $CaCo_3$ has a great effect on the Fluid Loss and Mud Cake Thickness. From the table, we can choose 60% Micronized $CaCo_3$and 40 % Medium Coarse $CaCo_3$ in the $CaCo_3$ mixture as the optimum composition for effective bridging and the best mud parameters. For the further experiments, we will take this composition as the best mixture composition of the bridging and weighting material in NDDF.

As discussed above, the effectiveness of a bridging material in minimizing mud solids invasion strongly depends on particle size and concentration of solids used as well as on the pore size distribution of the rock. In order to assess the formation damage induced by solids invasion, a PSD analysis was carried out on $CaCo_3$ and Barite.

In the Table 5, n=50

Therefore, n/2 = 50/2 = 25 → 5thclass is the 'class of median'
So, F=24.18, f_m=5.48, L_m= 53, i= 10.9

Where:
n = the total frequency
F = the cumulative frequency before class median
i = the class width
L_m = the lower boundary of the class median
f_m = the frequency of the class median

Therefore, Median = $L_m + [\{n/2-F\}/f_m]i$
= 53+ {(25-24.18)/5.48}10.9
= 53-8.418613139
= 54.6310219
≈ 54.63Microns

Table 3. Particle size distribution of Micronized Calcium Carbonate, Medium Coarse Calcium Carbonate and Barite using Sieve analysis

Mesh No. / Size in Microns	Range of Particle Size	Average Particle Size	Micronized Calcium Carbonate (50gm)		Medium Coarse Calcium Carbonate (50gm)		Mixture of Calcium Carbonate (50gm) 60 % MCC 40 % MCCC		Barite (50gm)	
			Amount Retained in gm.	% Retained	Amount Retained in gm.	% Retained	Amount Retained in gm.	% Retained	Amount Retained in gm.	% Retained
pan	<25	25	7	14	1.1	2.2	4.64	9.28	11.5	23
500/25	25-36.9	30.95	6.8	13.6	1.8	3.6	4.8	9.6	8.5	17
400/37	37-43.9	40.45	11	22	2.3	4.6	7.52	15.04	5.8	11.6
325/44	44-52.9	48.45	10.1	20.2	2.9	5.8	7.22	14.44	4.5	9
270/53	53-62.9	57.95	3.8	7.6	8	16	5.48	10.96	3.8	7.6
230/63	63-73.9	68.45	2.5	5	7.7	15.4	4.58	9.16	3.3	6.6
200/74	74-87.9	80.95	1.9	3.8	7	14	3.94	7.88	2.8	5.6
170/88	88-104.9	96.45	1.6	3.2	6	12	3.36	6.72	2.3	4.6
140/105	105-148.9	126.95	1.3	2.6	4.5	9	2.58	5.16	1.8	3.6
100/149	149-176.9	162.95	1.1	2.2	3.1	6.2	1.9	3.8	1.5	3
80/177	177-209.9	193.45	1	2	2.2	4.4	1.48	2.96	1.5	3
70/210	210-249.9	229.95	1	2	1.7	3.4	1.28	2.56	1.4	2.8
60/250	>250	250	0.9	1.8	1.7	3.4	1.22	2.44	1.3	2.6

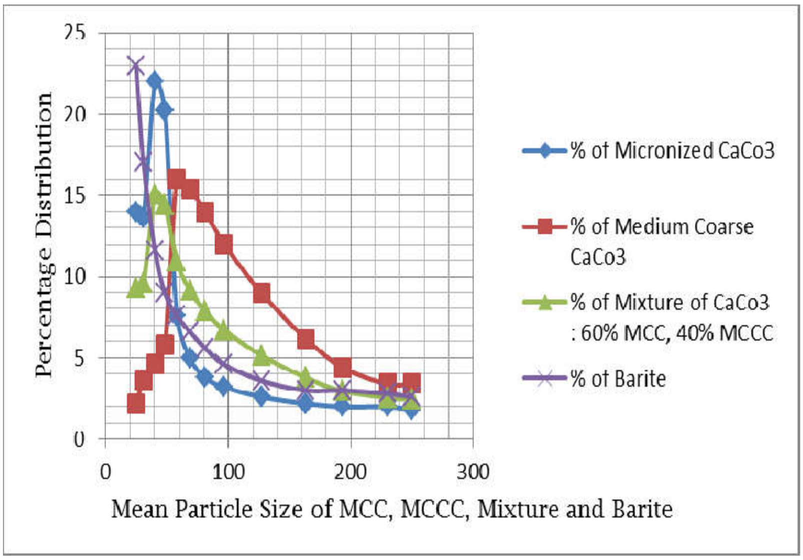

Fig.8. Percentage distribution of Particle Size of MCC, MCCC and Barite

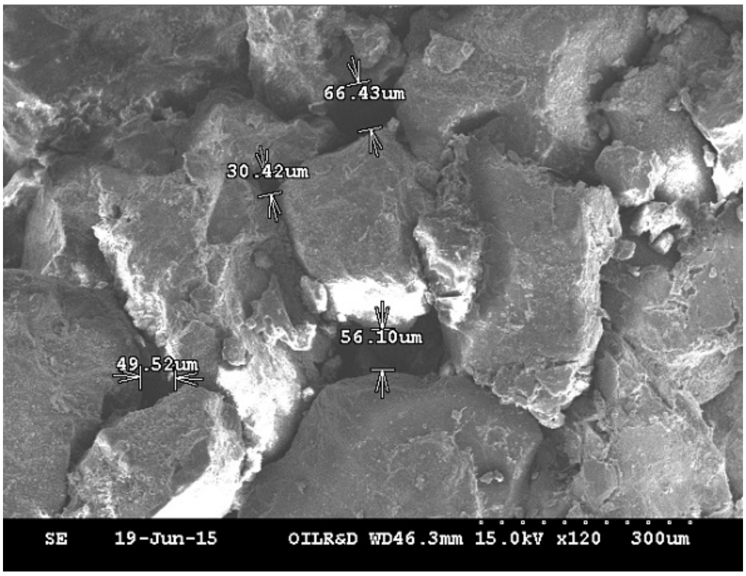

Fig.9. Pore Throat diameter in the samples of Geleki oilfield

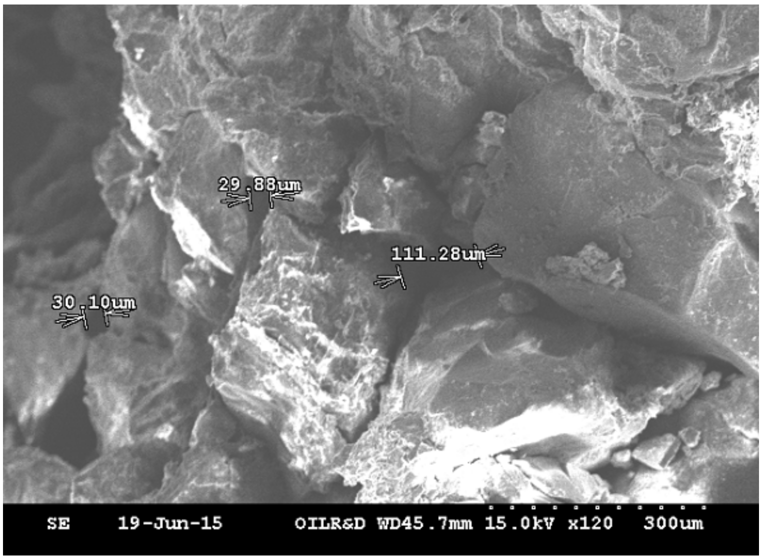

Fig. 10. Pore Throat diameter in the samples of Geleki oilfield

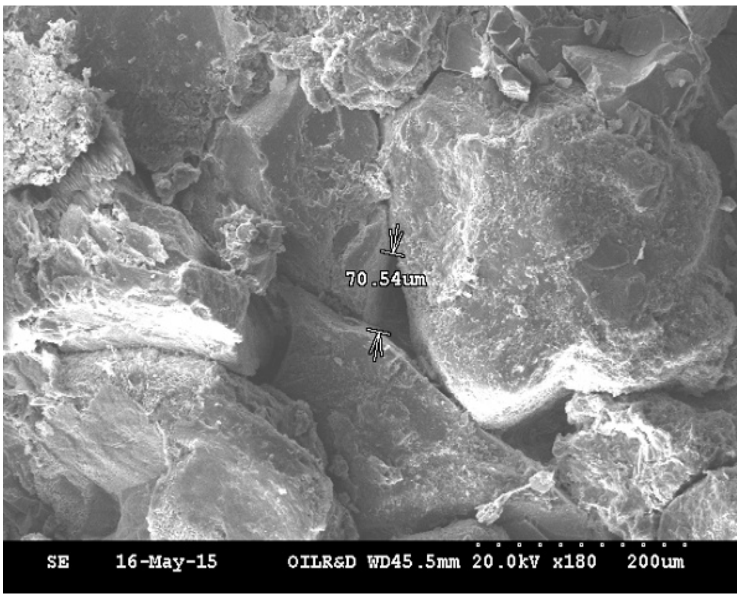

Fig. 11. Pore Throat diameter in the samples of Changmaigaon oilfield

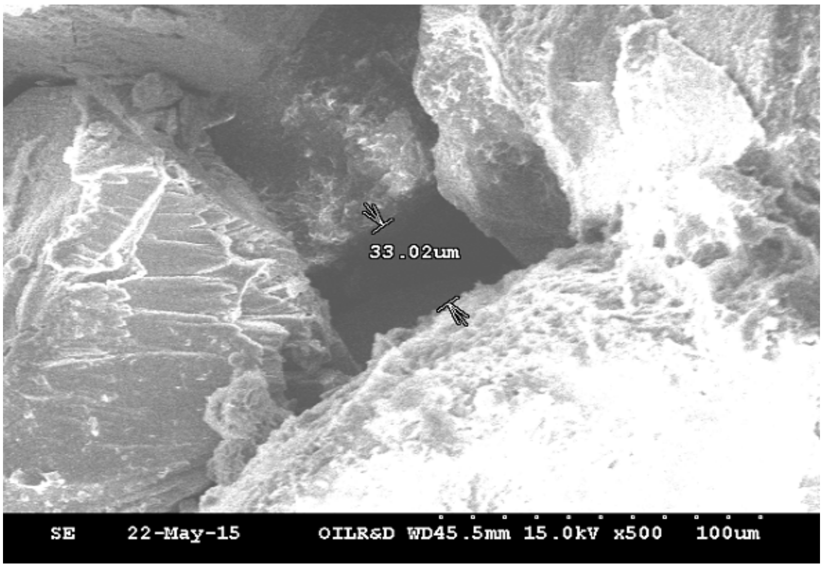

Fig. 12.Pore Throat diameter in the samples of Lakwa oilfield

Table 4. Calculation of Mean particle size of bridging material

Range of Particle Size	Frequency (f)	Weight %	Cumulative Weight	Cumulative Weight %	Mid-Point of Range (X)	√X	fX	Mean, ∑fX/n
<25	4.64	9.28	4.64	9.28	25	5	116	
25-36.9	4.8	9.6	9.44	18.88	30.95	5.563272	148.56	
37-43.9	7.52	15.04	16.96	33.92	40.45	6.360031	304.184	
44-52.9	7.22	14.44	24.18	48.36	48.45	6.960603	349.809	
53-62.9	5.48	10.96	29.66	59.32	57.95	7.61249	317.566	
63-73.9	4.58	9.16	34.24	68.48	68.45	8.273452	313.501	
74-87.9	3.94	7.88	38.18	76.36	80.95	8.997222	318.943	
88-104.9	3.36	6.72	41.54	83.08	96.45	9.820896	324.072	74.3083
105-148.9	2.58	5.16	44.12	88.24	126.95	11.26721	327.531	Microns
149-176.9	1.9	3.8	46.02	92.04	162.95	12.76519	309.605	
177-209.9	1.48	2.96	47.5	95	193.45	13.90863	286.306	
210-249.9	1.28	2.56	48.78	97.56	229.95	15.1641	294.336	
>250	1.22	2.44	50	100	250	15.81139	305	
n=50				∑fX = 3715.41				

Table 5. Calculation of Median of particle sizeof bridging material

Range of Particle Size	Frequency (f)	Cumulative Frequency
<25	4.64	4.64
25-36.9	4.8	9.44
37-43.9	7.52	16.96
44-52.9	7.22	24.18
53-62.9	5.48	29.66
63-73.9	4.58	34.24
74-87.9	3.94	38.18
88-104.9	3.36	41.54
105-148.9	2.58	44.12
149-176.9	1.9	46.02
177-209.9	1.48	47.5
210-249.9	1.28	48.78
>250	1.22	50

The Sieve analysis of the particles of Micronized $CaCo_3$, Medium Coarse $CaCo_3$ and Barite was done using Sieve Shaker to see the Particle Size Distribution (PSD) of these bridging and weighting materials of drilling fluid and tabulated in Table 3. The Mean (Table 4) and Median (Table 5) of the particles of the bridging material (Medium Coarse $CaCo_3$ and Micronized $CaCo_3$) was calculated using proper methods.

A SEMphotomicrograph study of the Core samples of the pay-zones of some major oilfields of UAB has conducted using Scanning Electron Microscope to estimate the pore-throat diameters of the reservoirs of the fields.

The Mean and Median of the pore-throat diameters of the fields was calculated.

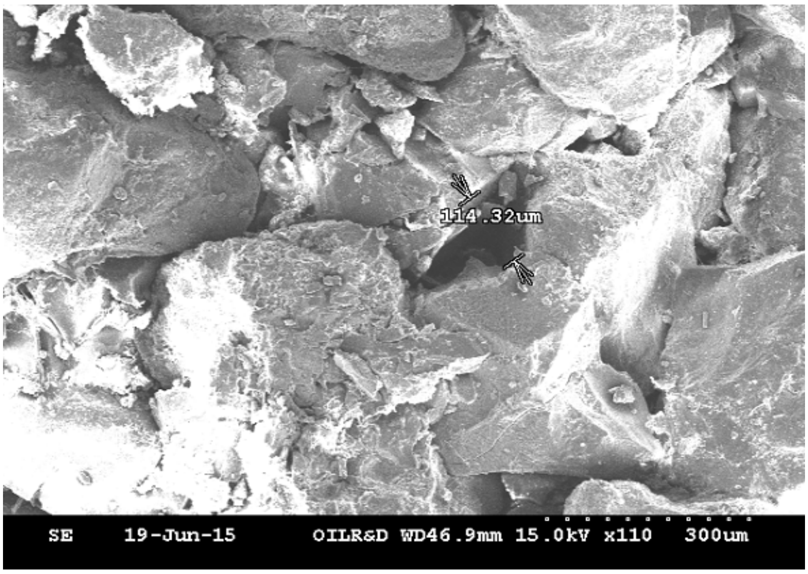

Fig. 13 .Pore Throat diameter in the samples of Changmaigaonoilfield

Table 6. Calculation of Mean and Median of Pore-throats of the rock samples of producing formations of UAB

S.No.	Pore Size, Micron
1	13.9
2	14.38
3	19.62
4	29.88
5	30.1
6	30.42
7	33.02
8	38.09
9	49.52
10	49.89
11	56.1
12	66.43
13	70.54
14	76.43
15	79.91
16	79.96
17	93.89
18	96.34
19	97.45
20	99.11
21	102.32
22	102.66
23	105.78
24	106.86
25	108.18
26	108.62
27	111.28
28	112.4
29	114.32
30	152
Mean	74.98Microns
Median	79.94Microns
1/3rd of Median	26.65Microns

In the Fig. 9-13, somephotomicrographs ofPore Throat diameters measured using Scanning Electron Microscopeof the producing formations of some major oilfields of UAB are shown.

In the Table 6, the calculation of Mean and Median of the Pore-throats of the rock samples of producing formations of some major oilfields of UAB is shown.

Then, the various guidelines used in the industry have been provedwhether bridging material can form an efficient external filter cake and minimize formation damage or not:

- 1/3rd rule: The mean particle size of the bridging material should be greater than one third of the median pore size of the formation. (Smith *et al.*, 1996)

In this case, calculated mean particle size of the bridging material is 74.3083Micron (From Table 4), which is greater than one third of the calculated median pore size (26.65 Micron from Table 6) of the formation. So,effective bridging will be possible using Medium Coarse $CaCo_3$ and Micronized $CaCo_3$as the bridging material.

- A median particle size of the bridging additive equal to or slightly greater than one third of the median pore size of the formation (Abrams, 1977)

In this case, the median particle size of the bridging material is 54.63 Micron, (from Table 5) which is greater than one third of the calculated median pore size(26.65 Micron from Table 6) of the formation. So, effective bridging will be possible using Medium Coarse $CaCo_3$ and Micronized $CaCo_3$as the bridging material.

- The concentration of the bridging agents must be at least 5% by volume of the solids in the final mud mix (Abrams, 1977)

In this case, the concentration of the bridging agents in the laboratory formulated NDDF samples was about 10% by volume of the solids in the final mud mixture. So, according to this rule, effective bridging will be possible using Medium Coarse $CaCo_3$ and Micronized $CaCo_3$as the bridging material.

- The *D90* (90% of the partic1es aresmal1er than size *x)* of the partic1e size distribution ofthe bridging agents should match the largest pore size of formation. Herein the bridging agents will minimize theinflux of fluid and particles into the sandstone network (Hands *et al*., 1998)

In this case, the *D90* (90% of the partic1es aresmaller than size *x)* of the particle size distribution ofthe bridging agents is about 150 Micron (calculated from Table 4). The largest pore size of formations is 152 Micron (from Table 6). Thus, the *D90* of the particle size distribution ofthe bridging agents is approximately matching to the largest pore size offormation and the bridging agents will minimize theinflux of fluid and particles into the sandstone network.

So, according to this rule, effective bridging will be possible using Medium Coarse $CaCo_3$ and Micronized $CaCo_3$as the bridging material.

- *The D50 rule:* The rule means that the value of *D50* (50% of the partic1es are smaller than size *x)* of partic1esof bridging agents should be equal to the mean pore size (in microns) for a given formation. (Wenqiang and Jienian, 2007)

In this case, the *D50* (50% of the partic1es aresmaller than size *x)* of the particle size distribution ofthe bridging agents is about 50 Micron (calculated from Table 4). The mean pore size of formations is 74.98 Micron (from Table 6). Thus, the *D50* of the particle size distribution ofthe bridging agents is approximately matching to the mean pore size (in microns) of the formation and the bridging agents will minimize the influx of fluid and particles into the sandstone network.

So, according to this rule, effective bridging will be possible using Medium Coarse $CaCo_3$ and Micronized $CaCo_3$as the bridging material.

- Ideal packing theory or $D^{1/2}$ 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. (Smith *et al*., 1996; Dick *et al*., 2000)

A graph of Cumulative Weight % of the bridging materials vs. Square-Root of Mean Particle Size was drawn as shown in Fig. 14. Here, we can notice that, up to almost 80% of Cumulative Weight, the cumulative weight % of the bridging materials is directly proportional to the square root of their particle size for all the three curves, but the curves for the mixture of MCC (60%) and MCCC(40%) shows the best results amongst the three. So, we should always use the mixture of MCC (60%) and MCCC (40%) as the bridging material for effective bridging.

- Jamming Ratio: To stop the mud solids at the formation face and to limit the penetration to 1-2 mm, the range for Jamming ratio should be 1 < J.R. < 3,where

$$J.\,R. = \frac{\text{Mean Pore throat diameter}}{\text{Mean mud solids diameter}}$$

In this case, the Mean pore-throat diameter is 74.98 Microns and Mean mud solids diameter is 74.3083Microns. Therefore, the

$$J.\,R. = \frac{74.98}{74.31}$$

$$= 1.009016283$$

$$\approx 1.009, \text{ which comes under the range of } 1 < J.R. < 3$$

Therefore, the bridging can able to stop the mud solids at the formation face and will limit the penetration to 1-2 mm.

- In addition, desired PSD is the bell shaped one (Newhouse, 1991; Dick *et al*., 2000)

The Percentage distribution curves of Particle Size of MCC, MCCC, Mixture of MCC and MCCC and Barite were drawn between Percentage Distribution and Mean Particle Sizes as shown in the Fig. 8 to examine their shapes. Except the Barite, all other samples have shown their PSD as the bell shaped one which is desirable for the bridging material for perfect bridging.So, according to this rule, effective bridging will be possible using Medium Coarse $CaCo_3$ and Micronized $CaCo_3$as the bridging material.

Then, the Mean and Median of the different NDDF parameters of successfully drilled wells using NDDF in the pay-zone sections of the producing formations of UAB were calculated (Table 7) from the well-cards of the completed wells collected from different operating companies of this basin to design the optimum mud parameters for successful wells in this basin.

Again, someNDDF samples were formulated by varying the composition of $CaCo_3$, keeping the other components as constant. Then,the mud properties were start to measure at the day of formulation (Zero-day) after 2-3 hours of proper mixing in the Hamilton Beach mud mixer. The effect of varying composition of $CaCo_3$on mud properties were investigated and tabulated (Table 8) to see the role of

$CaCo_3$ in NDDF and to select optimum composition of $CaCo_3$which gives suitable parameters (i.e. the parameters which will not create any mud related drilling complications and will not damage the pay-zone accomplishing the other mud functions properly) of NDDF for the UAB. Some, graphs of the mud properties vs. changing composition of $CaCo_3$also have drawn for interpretation purpose.

The optimum composition of $CaCo_3$was selected by interpreting the mud parameters of Table 8 with the generated tables and graphs.

For smooth successful drilling without any complications, all the mud parameters must be optimum. Low Viscosity can results in low cutting carrying capacity of mud; high values can results in high pumping pressure which may results in formation fracture, lost circulation, may demands high capacity rig, etc. A low value of Gel strength and Yield Point may results in low capacity to suspend the solids of mud at rest; high values can results in high pumping pressure.

Table 7. NDDF parameters of Sixteen successfully drilled wells in producing formations of Upper Assam Basin

Well Name	Well's Brief Description	NDDF Parameters: Specific Gravity	Funnel Viscosity, Seconds	Fluid Loss, ml	Plastic Viscosity, CP	Yield Point, lb/100ft^2	Gel Strength (Gel_0), lb/100ft^2	Gel Strength (Gel_{10}), lb/100ft^2
A	Development well, Inclined (L) profile, Tipam Pay-zone, 2617 m TVD	1.07-1.08	55-59	5-8	11-16	30-36	8-10	16-18
B	Development well, Inclined (L) profile, Tipam Pay-zone, 2880 m TVD	1.06-1.07	42-55	7-8.5	11-14	16-24	6-8	11-16
C	Development well, Inclined (L) profile, Tipam Pay-zone, 2900 m TVD	1.08-1.11	53-60	5.5-6.2	14-19	25-35	6-7	10-13
D	Development well, Inclined (L) profile, Tipam Pay-zone, 2900 m TVD	1.08-1.12	47-57	4.2-7	10-17	35-38	8-12	15-18
E	Development well, Inclined (L) profile, Tipam Pay-zone, 3051 m MD	1.08-1.12	43-50	3.4-7.6	9-18	22-37	8-12	10-17
F	Development well, Inclined (L) profile, Tipam Pay-zone, 3010 m TVD	1.08-1.12	45-50	4.5-6.5	12-20	23-36	7-12	14-22
G	Development well, Inclined (S) profile, Tipam Pay-zone, 3150 m TVD	1.09-1.11	45-49	5.5-6.0	11-18	20-28	7-11	14-16
H	Development well, Horizontal profile, Tipam Pay-zone, 3258 m TVD	1.04-1.06	54-60	8-10	7-14	26-40	10-15	27-48
I	Development well, Inclined (L) profile, Tipam Pay-zone, 3569 m TVD	1.12-1.18	42-47	5.7-6.5	10-17	19-25	5-7	11-17
J	Development well, Inclined (L) profile, Tipam Pay-zone, 3600 m TVD	1.08-1.09	53-58	6-8	10-12	32-42	10-13	17-20
K	Development well, Inclined (L) profile, Barail Pay-zone, 3850 m TVD	1.14-1.20	50-55	4.6-5.8	14-19	24-43	9-12	15-19
L	Development well, Horizontal profile, Barail Pay-zone, 3085 m TVD	1.05-1.07	45-50	4-6	13-16	23-28	7-9	13-15
M	Development well, S-profile, Tipam and Barail Pay-zone, 3500m TVD	1.06-1.15	45-52	5.5-9	10-16	18-37	8-9	12-18
N	Development well, Horizontal profile, Tipam Pay-zone, 2477 m TVD	1.10-1.14	48-52	5-7	11-18	24-28	9-12	24-30
O	Development well, Inclined (L) profile, Barail Pay-zone, 4250 m TVD	1.08-1.18	44-65	4.6-8.6	12-18	14-39	8-18	15-51
P	Development well, Horizontal profile, Barail Pay-zone, 3073.5 m TVD	1.04-1.06	51-57	8-8.5	13-15	29-36	10-12	16-18
Mean		1.09	51.16	6.43	13.91	29.13	9.53	18.63
Median		1.10	51	6.05	13.75	29.5	9.75	16.75
Designed Value		1.09 ± 0.05	51.1 ± 5	6.3 ± 2	13.8 ± 5	29.3 ± 10	9.6 ± 4	17.5 ± 5

(Prepared from Well-Cards collected from different operating companies of Upper Assam Basin)

Table 8. Properties of the NDDF with the increasing composition of $CaCo_3$(NDDF Volume: 1.5 liter)

Composition of Total $CaCo_3$, gm/100ml	Amount of Total $CaCo_3$, gm	Amount of Micronized $CaCo_3$ (MCC), gm, (60% of total)	Amount of Medium Coarse $CaCo_3$ (MCCC),gm, (40% of total)	Mud Properties: Funnel Viscosity, Seconds	Density of mud, kg/m^3	pH (Hydrogen Ion Concentration)	Fluid Loss, ml	Mud Cake Thickness, mm	Temperature, °C
0	0	0	0	50	1007	9.5	9.8	0.1	29
1.5	22.5	13.5	9	51	1009	9.5	9	0.27	28
3	45	27	18	51	1015	9.5	8.8	0.28	29
4.5	67.5	40.5	27	51	1020	9.5	8.3	0.28	28
6	90	54	36	52	1029	9.5	8	0.29	30
7.5	113	67.5	45	52	1040	9.5	7.6	0.29	29
9	135	81	54	52	1055	9.5	7.2	0.3	29
10.5	157.5	94.5	63	53	1063	9.5	6.9	0.3	30
12	180	108	72	53	1075	9.5	6.7	0.3	28
13.5	202.5	121.5	81	53	1087	9.5	6.6	0.35	29

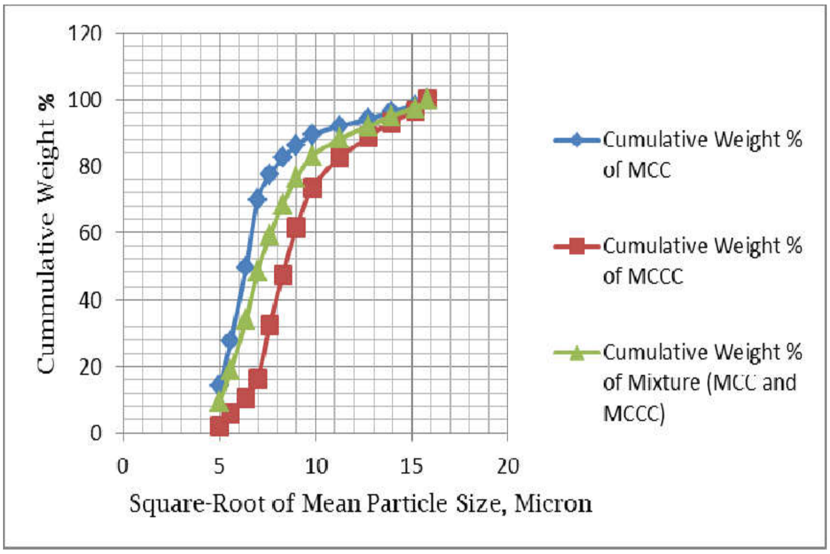

Fig. 14. Cumulative Weight % vs. Square-Root of Particle Size

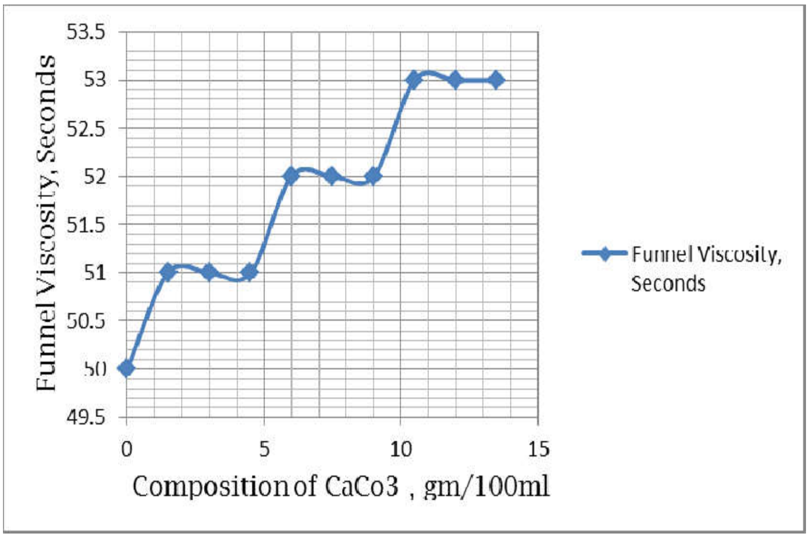

Fig. 15. Funnel Viscosity vs. Composition of $CaCo_3$

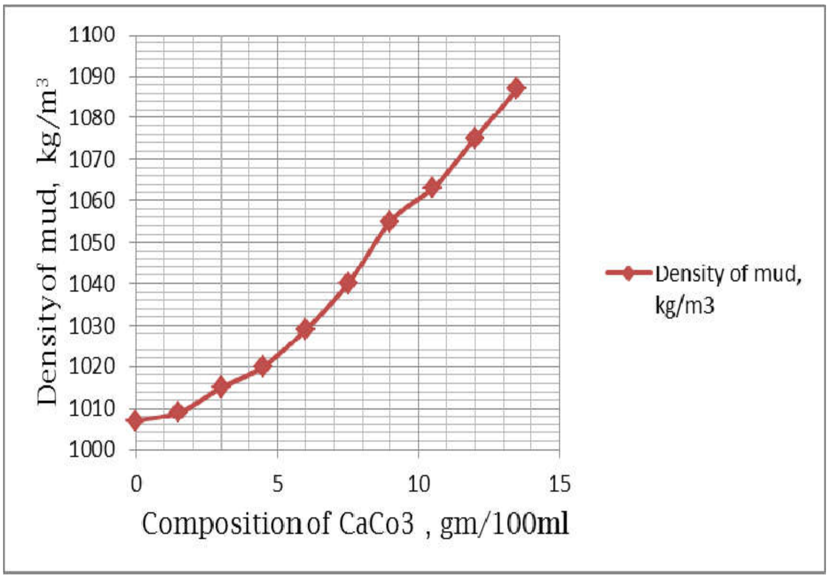

Fig. 16. Density vs. Composition of $CaCo_3$

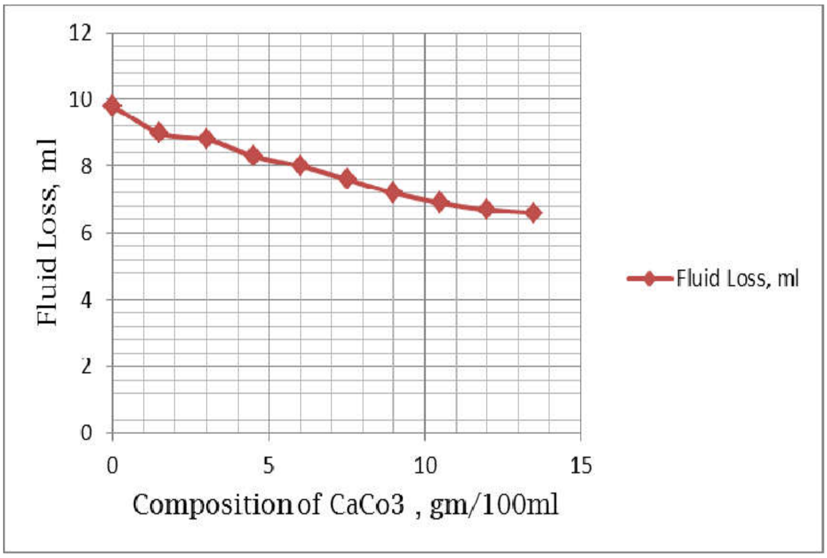

Fig. 17. Fluid Loss vs. Composition of $CaCo_3$

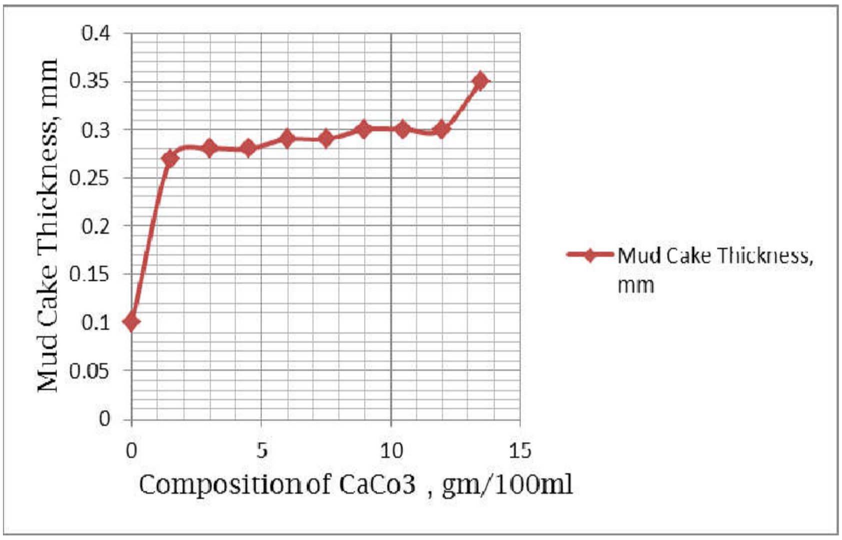

Fig. 18. Mud Cake Thickness vs. Composition of $CaCo_3$

Table 9. A comparison of the Mud properties of Barite, MCCC and MCC at 0 gm/100ml and 13.5 gm/100ml composition

	Mud properties with 0 gm/100ml composition of Barite, MCCC and MCC						Mud properties with 13.5 gm/100ml composition of Barite, MCCC and MCC					
Components	Funnel Viscosity, Seconds	Density of mud, kg/m^3	pH (Hydrogen Ion Concentration)	Fluid Loss, ml	Mud Cake Thickness, mm	Temperature, °C	Funnel Viscosity, Seconds	Density of mud, kg/m^3	pH (Hydrogen Ion Concentration)	Fluid Loss, ml	Mud Cake Thickness, mm	Temperature, °C
Barite	50	1007	9.5	9.8	0.1	29	53	1110	9.5	6.8	0.45	29
$CaCo_3$ mixer (MCC: 60%,MCCC: 40%)	50	1007	9.5	9.8	0.1	29	53	1087	9.5	6.6	0.29	29
Micronized $CaCo_3$	50	1007	9.5	9.8	0.1	29	53	1087	9.5	7.7	0.29	29
Medium Coarse $CaCo_3$	50	1007	9.5	9.8	0.1	29	53	1087	9.5	7.8	0.3	29

Low density can results in well kick and blow out; high density can results in lost circulation and low drilling rate.Both the low and high value of pH is unfavourable for the mud and the surface and subsurface equipments. Low pH results in corrosion and low crude oil recovery related problems; high pH causes the Kaolinite clays to develop sufficiently high potentials to cause them to detach from the surface, migrate and be captured in the pore constrictions, although it has positive role in oil recovery. Low salinity results in decrease in permeability due to clay swelling, increase in the value of pH although it has positive role in oil recovery; high salinity results in corrosion related problem due to decrease in the value of pH.

As we have already discussed that, the composition of $CaCo_3$ does not have an effective role on some mud properties such as Yield Point, Gel Strength, pH, Salinity, etc., but it has great effect on Density, Fluid Loss and Mud Cake Thickness and mild effect on the Viscosity.

For the required Viscosity and other rheological properties, we have used 0.3% XC-Polymer in gm. / 100ml basis which shows effective role for controlling these properties in NDDF. (Talukdar and Gogoi, 2015b)

Basically for the Fluid Loss control and mildly for Mud Cake Thickness control agent,we have used 3% PGS (Pre-Gelatinized Starch in gm. / 100ml basis which shows great role for controlling these properties in NDDF (Talukdar andGogoi, 2015a) and the low viscous grade and regular grade of Poly-Anionic Cellulose (PAC) which are more resistant than PGS for temperature and bio-degradation.

KCl is used as a clay/shale inhibitor to prevent formation damage, which will increase the salinity of the mud. NaOH is used to maintain desired pH of 9-9.5 for maximum hydration.

Here, we are using the $CaCo_3$ basically as the as the bridging and weighting agent. As discussed above, it shows effective role as bridging agent.From the Table 7, the designed values for Funnel Viscosity, Specific Gravity and Fluid Loss required for successful drilling operation in the study areas are 51.1 ± 5 Seconds, 1.09 ± 0.05 and 6.3 ± 2 mlrespectively.

In the Table 8 and Fig. 16, we can see that the designed range of Specific Gravity is starting from the composition of$CaCo_3$ of 7.5%. If we take the composition of $CaCo_3$ of about 7.5 % (112.5 gm. in 1.5 liter sample), out of which 67.5 gm. (4.5 %) MCC and 45 gm. (3%) MCCC, then the build-up mud properties are:

Funnel Viscosity: 52 Seconds
Specific Gravity: 1.04
pH (Hydrogen Ion Concentration): 9.5
Fluid Loss, ml: 7.6 ml
Mud Cake Thickness, mm: 0.29 mm

All of these properties are within the designed range for the study areas.From the Fig. 15-18, we can investigate that the composition of $CaCo_3$has a great effect on Density, Fluid Loss and Mud Cake Thickness; and mild effect on the Viscosity. The Fluid Loss can be decreases further by increasing the composition of $CaCo_3$more than 7.5%, but it may have negative effect on the rate of penetration (ROP)due to the increase in the solid contents in mud and also has the negative effect on Mud Cake Thickness. High ROP is one of the important criteria for NDDF, which will results in low exposed time of the mud to the formation and low degradation of the mud due to low bio-degradation of the polymer used.

Therefore, we can recommend the starting composition of $CaCo_3$ as 7.5%, out of which 4.5% MCC and 3% MCCC and may increase slightly with the requirements during the drilling with proper investigation of the mud parameters.

Finally, a comparison of mud properties among Barite, Medium Coarse $CaCo_3$ and Micronized $CaCo_3$ was done by formulating the different mud samples.In the Table 9, we can see that all five mud properties constant at 0% composition of these materials. At 13.5 % composition, the Funnel viscosity and pH are constant, but the Density, Fluid Loss and Mud Cake Thickness are different. The densities for different grades of $CaCo_3$ are same, but it is very smaller than the density of Barite.Fluid Loss and Mud Cake Thickness, both are the minimum for the mixture of the Micronized $CaCo_3$ and Medium Coarse $CaCo_3$ for the effective bridging that they offer.

Conclusion

From the above discussion, the following conclusions are drawn:

- The major minerals in most of the rock samples collected from the pay-zone sections of some major oilfields of UAB found to present are Smectite, Chlorite, Illite, Kaolinite, Quartz, and Feldspar as shown in XRD Fig. 1-3 and SEM Fig. 4-6. The study reveals that the entire field contains both the swelling (Smectite) and non-swelling (Illite, Kaolinite) clay. Illite and Kaolinite are known as emigrational fines problem clay.And, the Median Porosity and Permeability of the producing formations of the study areas are also very good, which are about 20% and 225 md respectively and are very much susceptible for filtrate loss as well as solid invasion. Therefore, the UAB is a very good candidate for the implementation of NDDF.
- The NDDF using Medium Coarse $CaCo_3$ and Micronized $CaCo_3$ as the weighting and bridging material can be removed clearly by using acid job after completing the drilling of the wells.
- The ratio of 60% Micronized $CaCo_3$ and 40 % Medium Coarse $CaCo_3$ in the total $CaCo_3$ mixture is the optimum ratio for effective bridging and the best mud parameters.
- The mixture of Medium Coarse $CaCo_3$ and Micronized $CaCo_3$ shows very good Particle Size Distribution. It fulfils all the the various guidelines/thumb rules used in the industry for effective bridgingin relation to the formation pore openings of the major producing oilfields of Upper Assam Basinto form a surface bridge/external filter cake on the formation surfaceto minimize formation damage.
- All the reservoirs in the world are heterogeneous. The properties and characteristics are different in different location in the reservoir. Therefore, the composition of any

component or the value of any properties of NDDF to serve any function will not be fixed. In this study, from the laboratory experiments and field experience regarding the composition of $CaCo_3$, We can recommend the starting composition of $CaCo_3$ as 7.5%, out of which 4.5% MCC and 3% MCCC and may increase slightly with the requirements during the drilling with proper investigation of the mud parameters. It should give suitable parameters (i.e. the parameters which will not create any mud related drilling complications and will not damage the pay-zone accomplishing the other mud functions properly) to NDDF for the oilfields of Upper Assam Basin

- The Fluid Loss can be decreases further by increasing the composition of $CaCo_3$ more than 7.5%, but it may have negative effect on the rate of penetration (ROP) and Mud Cake Thickness. High ROP is one of the important criteria for NDDF, which will results in low exposed time of the mud to the formation and low degradation of the mud due to low bio-degradation of the polymers used in NDDF.
- Thus, for low density mud or high ROP required for the reservoir section drilling, $CaCo_3$works excellently as the bridging and the weighting control agent in NDDF.
- Intensive care of the mud and the circulation system is needed during drilling the pay zone section. All the solid control equipments e.g. Shale shaker, De-Sander, De-Silter, Mud Cleaner, etc. should be working properly during the drilling to control the solid particles in mud. Continuous investigation of the properties and functions of the mud, whether they are fulfilling the requirements or not, is necessary and if required we may have to change the composition of the mud during drilling.
- The best wells are often the ones where we expose the formation to the mud system for the least amount of time, no matter what kind of fluid is being used.

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