Stabilizing boreholes while drilling reactive shale formations with silicate-base drilling fluids

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SILICATE-BASED DRILLING fluids have been used to drill successfully[1,2] through a wide range of troublesome shales in various parts of the world. With the advent of stringent environmental regulations and foreseen phasing out of oil-based and synthetic-based drilling fluids, current petroleum industry efforts are focused towards finding alternate environmentally acceptable water-based drilling fluids.

With this in view, silicate-based systems are being used extensively in the oil and gas well drilling industry. Silicate-based fluids are therefore replacing oil-based/synthetic-based muds (OBM/SBM) in a wide range of applications where troublesome clay-bearing formations such as shales and claystones are to be drilled. The mechanisms by which OBM/SBM inhibit the hydration of shales have been reviewed here, as is the failure of common water-based muds (WBM) to duplicate the success of OBM/SBM in drilling these troublesome formations.

BACKGROUND

Shale is term applied in geology to all argillaceous strata that exhibit a laminated structure, and consequently split up more or less perfectly in the direction of their bedding. Clay, for example, is massive or plastic and void of structure; marl is friable or crumbly; shale always exhibits some degree of lamination. In the drilling industry and for the purpose of this discussion; however, shale will be termed as an ill-defined heterogeneous argillaceous material ranging from the relatively weak clay-rich gumbo to highly cemented shaly siltstone, with the common characteristic being a matrix of extremely low permeability that contains clay minerals to some degree.

Borehole instability in shales in most cases arises from insufficient hydrostatic support on the borehole wall, resulting from either inadequate mud pressure gradient or a time-dependent increase in near-wellbore pore pressure. An increase in water content in the near-wellbore region will result in lowered shale strengths[3,4]. The movement of water in and out of a shale is governed by a number of mechanisms[3,4,5] but the most influential[6] are hydraulic pressure difference (DP) between the wellbore pressure and the shale pore pressure, and the chemical potential differences (Du) between the drilling fluid (filtrate) and the shale pore fluid. Van Oort[7] determined that, supposing the shale was drilled in the presence of a fluid of correct density, such that shear failure (too low mud weight) or tensile fracturing (too high mud weight) does not occur, then there are 3 mechanisms by which time dependent instability may occur as a function of drilling fluid exposure:

• Elevation of near-wellbore pore pressure due to mud pressure invasion, leading to an effective reduction in mud pressure support;

• Elevation of swelling pressures (e.g. due to inappropriate cation selection leading to unfavourable cation exchange at clay sites) reducing effective stresses;

• Chemical alteration and weakening of cementation bonds.

Membrane efficiency: The pore-pressure transmission measurement apparatus above is used to gauge "membrane efficiency" of various fluids. Membrane efficiency is a measure of the mobility of solutes through a shale pore network. The Na silicate solution influences this mobility by reducing the effective radius of the shale pore, thus increasing the exclusivity of the membrane. For example, the membrane efficiency of 35% CaCl2 in only 5%. For 72% KCOOH, it measures 7.9%. But the membrane efficiency of a 21% NaCl/7.5% Na silicate mud has been measured at 61%.

OIL-BASED MUDS

The effectiveness of OBM in stabilising shales has been well-documented. The osmotic transport of water from the shale to the OBM through a semi-permeable membrane provided by the OBM emulsifiers has long been regarded as the fundamental driving mechanism. Laboratory data presented by Mody, et al[3,4], based upon the two fundamental driving forces (DP and Du), and hydraulic and osmotic transport mechanisms, are used to explain why an OBM is effective in stabilising shales:

The presence of threshold capillary entry pressures between the OBM and low permeability shales. These capillary entry pressures are translated to a net compressive radial stress on the borehole wall, which promotes hole stability.

Laboratory experiments confirm the belief that the OBM emulsifier surrounding discrete water droplets provides the characteristics of a semi-permeable membrane, which allows the osmotic transport of water to or from the shale. The OBM water phase activity (molar free energy) is manipulated to ensure water is transported from the shale. This may also lead to an increase in shale strength in the near-wellbore region.

WATER-BASED MUD

Early researchers focused on chemical means to stabilise shales in the presence of WBM. Thus came the introduction of salt muds, lime muds and potassium muds. Later, the application of D'Arcy's Law to the problem of shale hydration led researchers to find ways of manipulating the viscosity of mud filtrate (e.g., using xanthan gum, PHPA), the pressure difference DP (low mud density fluids), and the shale permeability (blocking agents such as asphaltenes and gilsonite).

Later research to identify the driving mechanisms of shale hydration[3,4,5,6] led to a recognition that a WBM/shale system was more complex than a OBM/shale system, since the hydraulic pressure difference is in communication. The net compressive radial stress dissipates with time until there is pressure equalisation between the wellbore and the shale (DP=0). At this point, there is no effective mud pressure support against the shale, and the shale will fail. This occurs to varying degrees depending on a number of factors, least of which are shale permeability and the magnitude of DP.

Since shale mineralogy varies infinitely across the whole spectrum of argillaceous materials, it would seem almost impossible to design a WBM which would be capable of eliminating changes in swelling pressures and cementation integrity. For example, potassium ion (K+) may be useful in inhibiting swelling of montmorillonite clays, has little or no effect on illites, and may increase swelling pressures in kaolinite.

It was recognised by researchers[4] that the low-permeability, clay-rich matrices of intact shales exposed to WBM's may act as a non-ideal membrane, since the mobility of solutes through the pore network varied with solute type and was a function primarily of the solute hydrated radius. "Membrane efficiency" measurements have been taken[7] and draw distinctions between various base fluids (35% $CaCl_2$—membrane efficiency, 5%; 72% KCOOH—membrane efficiency, 7.9%) using Pierre Shale. The membrane efficiency of a 21% NaCl/7.5% Na silicate mud has been measured at 61% based on recent tests utilising the pore pressure transmission test.

SILICATE MUDS

It has been stated that membrane efficiency is a measure of the mobility of solutes through a shale pore network. The Na silicate solution influences this mobility by reducing the effective radius of the shale pore, thus increasing the exclusivity of the membrane. 2 mechanisms by which silicate solutions seal or partially block shale pore throats have been described[1].

Filtrate containing silicate oligomers small enough to enter the pore throats by diffusion or hydraulic flow comes into contact with shale pore fluid. Pore fluid of near neutral pH will cause a fall in filtrate pH, allowing the growth and development of silica gels. Calcium ions associated with shale pore fluid will react instantaneously with silicate oligomers to form insoluble Ca silicate precipitates. However, such a "dual action" may not in fact occur.

The effect of a minor dilution of silicate filtrate with near-neutral shale pore water is unlikely to lead to a sufficient drop in filtrate pH such that polymerisation and gelation of the silicate oligomers occurs, especially since the pore fluid is presumed to be displaced by filtrate in its passage into the pore network. Shale pore water pH varies considerably; however, and some shale pore waters may be analogous of weak acids in their reaction with sodium silicate solutions. The consistency of a silica gel is dependent on the water content, temperature, pressure, etc[8]. The initially nearly liquid, mobile hydrogels formed by the decomposition of soluble Na silicates by dilute acid are continually changed by a systematic dehydration to a hornlike or brittle substance. A great part of the water in the initially jelly-like gels may be "squeezed out" of the solid inner framework of the colloid either spontaneously (syneresis), or by external pressure, temperature, etc.

It should be noted also that Ca silicate precipitates formed by the reaction of soluble Na silicates with free Ca^{2+} either in the shale pore water or associated with clay basal surfaces, are not crystalline in nature, but are amorphous precipitates which sequester other ions such as OH^-[9]. The Ca silicate will also sequester other silicate oligomers, and a 3-dimensional gel structure will rapidly grow around the Ca^{2+} ion. Thus only a very small amount of Ca^{2+} is required to form a substantial gel structure with Ca^{2+} ion at its centre. This gel structure is unlike that formed by the silicate polymerisation process alone, in that it is considerably stronger and more durable.

At this stage, it is unclear which mode described above is predominant. The research is being currently done to determine the precise nature of the reactions taking place within the shale pore network, by measuring the extent of pressure sealing a variety of shale types in the pore pressure transmission tests.

A recent joint study by **BP** and **Baroid**[10] has shown that fractured shales of relatively high permeability (up to 25uD) may be effectively sealed by a fresh water silicate mud, so long as sufficient SiO_2 is present in the filtrate. It was determined that a concentration of 45 g/l SiO_2 was required to seal the shales tested. Other WBM's tested were not able to seal these fractured shales.

MUD DENSITY REQUIREMENTS

It has been noted that the correct mud density is required to ensure that stable hole conditions are maintained. If the mud density is too low, then immediate compressive shear failure may occur. If the mud density is too high, then tensile fracturing may occur. This is especially important when drilling highly deviated wellbores, and even more so when drilling highly deviated wellbores using a silicate-based fluid as a replacement for OBM/SBM used previously in a particular area. With OBM/SBM, there are 3 factors contributing to shale stability:

- Mud pressure support from the mud column;
- Increased radial stresses due to high threshold capillary entry pressures;
- Increased near-wellbore shale strength due to osmotic dehydration of the shale.

Detailed analyses of offset wells should be carried out to determine the required mud pressure before using a silicate-based fluid to replace OBM/SBM in high angle sections through shales that are known to be troublesome.

FIELD OBSERVATIONS

The field applications of Na silicate muds have been by and large successful. Field data support laboratory observations[8] that Na silicate muds will either completely seal shale pore throats or else may increase membrane efficiency such that shale stability may be effected by manipulating the activity of the mud with respect to that of the shale. Some field observations suggest that shale pore throat size may be a design factor which mud technologists should use when determining the concentration of Na silicate and the mud activity (concentration of soluble salts) appropriate to any particular shale.

CASE 1

A NaCl/Na silicate mud was used to drill the upper "gumbo" sections of a well in the Gulf of Mexico. These shales are characterised by high water content, high degree of plasticity and relatively shallow depth of deposition. A 12% NaCl/4.5% Na silicate solution was used as the initial base fluid. During drilling, it was seen that cuttings produced were quite firm on their surface, but when broken were seen to be soft inside. Some drags were noted, and cuttings accretion to the BHA was seen on a trip out of the hole. The NaCl concentration was increased to 18% and an immediate improvement was seen. Cuttings were firm to hard, and there were no more drags or cuttings accretion.

This suggests that the pore throats were not being blocked completely by the Na silicate fluid, but that membrane efficiency had improved such that a lower mud activity promoted the osmotic flow of water out of the shale. Conversely, it suggests that in this type of shale, underestimating the salt content required in the Na silicate mud to balance or overbalance the shale salinity could promote borehole instability.

CASE 2

A 35% NaCl/Na silicate mud was used to drill the U Cretaceous Chalk, the Cromer Knoll, and the Triassic claystone/halite sequence and into the Bunter Sands on a well in the Southern North Sea. The Cromer Knoll shale may be characterised as competent shale having high reactivity. Chalk, shale and salt were drilled without difficulty and hole conditions were excellent. Unfortunately, the drillstring became differentially stuck in the underlying Bunter Sand. In an attempt to free the stuck pipe, the mud was displaced from the hole with seawater, and stayed filled with seawater under static conditions for the next 72 hours. When the string was finally pulled, the hole was observed to be still in excellent condition and had not deteriorated at all.

The strong suggestion is that in this instance, the Ca2+ silica hydrogel formed a permanent and complete seal in the pore throats, and allowed the hole to remain stable under conditions, which would normally be expected to lead to catastrophic borehole failure.

CONCLUSIONS

Borehole stability and hydration mechanisms were reviewed for both OBM and WBM.

Shales display the characteristics of a "leaky" membrane when exposed to WBM.

Silica gels may not completely seal shale pore throats. Where they do not, membrane efficiency will be increased by a reduction in pore throat size and thus in membrane selectivity.

The membrane efficiency of current Na silicate muds may depend primarily on the shale pore throat size, which can vary considerably and is a function primarily of age and depth of deposition of the shale. In controlled pore pressure transmission tests, membrane efficiencies in the range of 55-61% have been recorded.

The precise chemical reactions which take place within a shale pore exposed to Na silicate filtrate are not known.

Mud density requirements for silicate-based fluid will be higher than OBM/SBM on similar offset wells. The density requirement can be determined by analysis of radial stress and near-wellbore strength contribution to the overall OBM/shale model.

Field observations continue to support the contention that silicate-based fluids are considerably more efficient than other WBM in protecting shales.

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