AADE-04-DF-HO-03

Challenging Reservoir Drilling Conditions Overcome by Engineered Water Based Drill-In Fluids.

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This paper was prepared for presentation at the AADE 2004 Drilling Fluids Conference, held at the Radisson Astrodome in Houston, Texas, April 6-7, 2004. This conference was sponsored by the Houston Chapter of the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individuals listed as author/s of this work.

Abstract

The advent of technically advanced oil-based drilling fluids, about thirty years ago, simplified many drilling operations that had previously posed extreme problems. Water sensitive shales, hole stability issues, friction related problems, etc. have ceased to be critical causes for concern. Indeed, the freedom from the constraints of water-based drilling fluid has facilitated the extension of drilling practices into new extremes. Extended reach, long horizontal sections, tortuous trajectories and similar applications involving the risk of high torque and drag are now relatively commonplace.

Huge challenges can arise when the high performance of oil-based fluids is required but use of such fluids is ruled out. This situation arose recently in connection with two operations in Germany. In one case, it was required to drill a reservoir section, 960 metres long at high angle through a severely depleted, layered structure of sandstone and highly unstable, water-sensitive shales. The overbalance was expected to be about 3000 psi and, to mitigate high overbalance, previous drilling campaigns had used an inhibited, low density, foamed drill-in fluid. However, this practice had led to severe washouts and bit-balling, In the second case, the reservoir section was normally pressured but comprised caving shales and the sandstone interval had zones of permeability up to 10 darcies. Previous performance while attempting to drill this section with inhibited water-based fluid had been very poor; with a record of frequently stuck pipe and very high torque levels.

Water-based drilling fluids were tailored for each application, resulting in drilling campaigns that achieved all objectives; hole conditions were excellent and there were no fluid-related problems. Rates of penetration and torque and drag figures were very similar to those commonly achieved with oil-based fluid.

This paper describes the development procedure and aspects of the drilling performance. Also, details are reported of how key aspects of the drilling process were controlled.

Introduction

Generally speaking, oil based mud (OBM) tends to be regarded as a first choice when difficult drilling conditions are expected. Issues of torque and drag, hole stability, shale sensitivity, etc. are well known to be more easily addressed with OBM than when water based mud (WBM) is applied.

Two recent developments in Germany posed very serious difficulties and, for various reasons, the use of OBM mud was ruled out.

The developments were:

- Long horizontal sections of gas storage reservoirs in Breitbrunn in Bavaria [1,2] under very depleted conditions
- Highly deviated Mittelplate wells at Wattenmeer (German Sector of the North Sea) in very permeable sand strata alternating with tectonically stressed and chemically unstable shale layers.

The conditions in each development are described more fully below:

Breitbrunn

The reservoir section in this formation comprises relatively thin sandstone layers (less than 15 m) separated by strata of active shales. The objective was to drill $8^1/_2$ inch diameter sections in the severely depleted, so called Chatt sandstones C and D for use as a gas storage reservoir. The magnitude of the challenge is made clear by the following list of geological and drilling conditions:

- Formation pressure of 30 bar (435 psi) and consequent overbalance up to 195 bar (2830 psi) when using a non-aerated water based drilling mud.
- Heterogeneous reservoir sandstone containing unstable water sensitive shale.
- Length of horizontal sections up to 960 m.
- Inclination of 85-92 degrees.
- Thickness of individual sandstone layers between 3 and 15 m.
- Sand permeability varied from to 5 to 60 md (100 md maximum).

During the first stage of the gas storage construction, in order to address the perceived depletion issue, a foamed inhibitive water based fluid (i.e. 3% potassium acetate) was used as the drilling fluid in the horizontal sections in the target Chatt sand B[1, 2, 3]. During these operations high torque levels, cuttings beds and large washouts were experienced. This behaviour was troublesome during the drilling operations and there were concerns that big hole enlargement in shale sections and in-gauge hole in sand sections would lead to poor cementing quality along the horizontal interval with the consequent risk of gas leakage.

Rock mechanical studies and shale testing predicted that borehole stability in Chatt sands C and D would be enhanced by a higher hydrostatic support pressure in conjunction with inhibition of shale layers. These studies indicated that a higher overbalance would be acceptable, obviating the need for foam. A drilling fluid with excellent inhibitive and lubricating properties and having a lower density than that of a water based fluid could have been formulated as an all-oil based fluid [4], but for ecological reasons, oil based fluids are unacceptable in that part of Germany.

It was therefore imperative to seek to develop a highly inhibitive, non-damaging water based drill-in fluid that would allow safe operations at the highest overbalance when drilling horizontally.

Mittelplate Project

In this case the formation of interest is the Dogger, which shares with Breitbrunn problems involving unstable, caving and reactive shale. The Dogger reservoir is not depleted but one of the challenging aspects is alternating bedding of several water sensitive and tectonically stressed shale layers with sandstone layers of permeability up to 10 darcies.

Geological and drilling details of the Mittelplate injection well H-1 are listed as follows:

- Total depth of 3051 m.
- Length of deviated sections: 549 m.
- Inclination of 60 to 65 degrees.
- Reservoir sandstone interbedded with unstable water sensitive shale layer.
- Permeability of the Dogger Sandstone 2 to 10 darcies.
- Length/thickness of individual sandstone layers between 4 – 30 m [vertical].
- Length/thickness of individual shale layers between 4 – 40 m [vertical].

Historically, drilling on this field with 10% KCl/partially hydrolysed polyacrylamide (PHPA) water-based fluid showed a record of frequently stuck pipe and very high torque levels, for which reason OBM was the fluid of choice. However, for water injection wells an oil-based fluid was not considered acceptable, so the requirement was for a non-damaging water-based fluid of equivalent lubricity and inhibitive properties.

Selection of The Drill-In Fluid.

Although the conditions on Mittelplate and Breitbrunn differed in several respects, the objectives for the drill-in fluids for each application were extremely similar. The requirements for both encompassed:

- Thin, low permeability filter cake for minimal invasion of filtrate into the formation, minimal mud losses and reduced risk of differential sticking.
- Excellent shale inhibition.
- Superior lubricity.
- Good rheology for hole cleaning, particularly in deviated sections.
- Maximum prevention of formation damage.

In both cases, a solids-free formulation was not considered to be appropriate. For example, the high overbalance expected on Breitbrunn and the high permeability of Dogger are both factors that contra-indicate use of solids-free fluids. In each case severe fluid loss would be expected. Furthermore, when a solids free fluid is used there is a tendency for drill solids to be swept into the pore volume and a filtercake of drill solids might be formed. Such solids are not readily soluble in acid or other solvents so any damage caused would not be readily removed.

In order to reduce the potential for formation damage it was considered that the optimum fluid would be able to form a tight filtercake that would be readily soluble if necessary. Sized sodium chloride and sized calcium carbonate were considered, but the minimum density of a sized sodium chloride system (1.26 kg/L) would be too high for either application [4].

The basic system selected was a polymer/calcium carbonate fluid. This comprised:

- Base brine composition selected on the basis of its shale inhibition performance.
- Xanthan gum for rheology: this material disperses easily in low density brines, gives the desired rheological performance and is readily degraded by acid or oxidising agents, which makes the product preferable to some other polymers of microbiological origin.
- Modified cross-linked starch as fluid loss polymer. This polymer is also very easily degraded chemically or by enzymes.
- Ground, sized metamorphic calcium carbonate (marble) as bridging agent. This product is available in a variety of size grades.
- In order to improve the shale inhibition properties of the fluids, supplementary inhibitors were required. This topic is discussed in more detail later in the paper.
- Lubricants also were a requirement. This aspect is also treated in more detail later in the paper.

Optimisation Of The Mud Formulations.

Based on previous world wide experience the basic brine/polymer composition for both applications was [2]:

- Potassium chloride/sodium chloride mixed brine; density as appropriate for each application, e.g. for Breitbrunn as light as possible and for

Mittelplate at higher density.

- Xanthan polymer 2.8 kg/m^3 (1 lb/bbl).
- Modified starch 28 kg/m^3 (10 lb/bbl).

This base fluid was considered most likely to possess the desired rheological and fluid loss properties. This basic formulation served as the starting point for the detailed optimisation.

The process of arriving at the optimum fluid formulations was, to a large extent, agglomerative and reiterative. As each important aspect (e.g. clay inhibition, lubricity, rheology etc) was optimised, the formulation was modified accordingly and if this caused undesirable side effects on other properties (e.g. on rheology) appropriate adjustments were made. The objective was that the final formulation would represent the sum of the individual requirements.

The steps leading to the final formulations are described in the following sections.

Optimising the size distribution of bridging particles

This aspect was regarded as key to preventing formation damage and drilling problems and a great deal of effort went into selecting the most appropriate size and size distribution for the pore throat dimensions in the respective formations. As a guide, use was made of the rule of thumb relating median particle size of the bridging solids and the pore throat size range of the formation. That is, to effectively bridge off the pay zone, 20 to 30% by weight of the bridging material should be equal to one third of the pore size in microns.

Availability of ground marble in very different size ranges (5, 25, 50, 150 and 600 microns) allowed great flexibility in designing the size distribution to achieve the best bridging of porethroats

Sandstone from Breitbrunn wells has permeability of 5 to 100 md and pore throats of 3 to 20 microns. This would be optimally bridged with marble particles with sizes 1 to 10 microns. However, to cater for the possibility of encountering higher permeability or fractures some coarser material was included in the drilling fluid.

High permeability of 2 to 10 darcies with average pore sizes of 50 to 100 microns was expected in the Mittelplate well. Particles of 15 to 50 microns are required to bridge the pore throats. To achieve a good low permeability filter cake, finer sizes of ground marble are also important.

To optimise the particle size distributions for each reservoir, the Particle Plugging Apparatus (PPA) was used. In each case ceramic discs were used that represented the pore throat sizes that existed in the respective formations. Also, the tests were carried out at appropriate temperatures and overbalance pressures. The pore throat sizes, temperatures and overbalance conditions for each sandstone are given in **Table 1** together with the sizes and concentrations of the ground carbonate that were found to be appropriate for optimal bridging.

In summary, the Dogger formation, because of its higher permeability, required a proportion of larger bridging particles and a higher overall concentration of sized solids than was the case for Breitbrunn.

Shale inhibition

Both Chatt sandstone D in Breitbrunn wells and Dogger sandstone in Mittelplate contain problem shale layers that can lead to washouts, sloughing and cavings during drilling. Laboratory tests on cores from both formations demonstrated that uptake of water leads to loss of hardness, disappearance of mechanical strength and a tendency for the cores to disperse completely in the fluid.

Indeed, such behaviour observed in laboratory tests corresponds with drilling experience and it was clear that any attempts to drill these sections with water based mud would need highly inhibitive systems.

The initial step was to establish shale composition, characteristics and properties. Various shale tests were performed by Halliburton and by RWE Dea AG laboratories.

The mineralogical composition of Dogger and Chatt cores as determined by using X-ray diffraction analysis is shown in **Table 2**

Both cores can be classified as clay-rich mudstones containing a water sensitive clay fraction as well as components that are not sensitive to water, such as quartz, calcite, feldspar and dolomite in the Chatt formation. The content and composition of each clay fraction is quite different; Dogger contains more swelling and easily dispersible smectite and illite clay minerals.

In the case of these formations the main cause of the instability is the presence of clay fractions with high swelling and hydration tendency. Different swelling pressures, which result when high or moderate swelling clay is surrounded by a completely non-swelling matrix such as quartz or feldspar, is often a cause of internal stress and hole destabilisation.

Inhibition of Chatt shale (Breitbrunn)

The behaviour of shale was investigated by four different techniques, namely:

- Shale Erosion Test[5].
- Linear Swell Test[5].
- Hardness testing (on linear swell cores) (See Appendix).
- Accretion on steel (See Appendix).

One of the limitations in this work was the desirability of maintaining as low a density as possible, so a high salt concentration was not acceptable. Of the many brine/inhibitors tested the optimum was found to be 6% potassium chloride with 2% of a polyamine clay inhibitor. Potassium ions are well known as stabilisers of smectite shales but the polyamine stabiliser is a relative innovation. The action of this product is believed to be by adsorption on active sites on the clay. The polyamine is a relatively large molecule containing polar sites involving oxygen and nitrogen atoms. The adsorption process is believed to proceed via interaction between the charged or partially charged sites on the clay surfaces and the polar segments in the molecule. Most probably the adsorbed polyamine interferes with the uptake of water by the mineral.

The relative effectiveness of the 6% potassium chloride plus 2% polyamine compared to straight water and a traditional inhibitive mud involving PHPA is given in **Fig 1**. The histograms in the **Fig 1** show that on every test the potassium chloride/polyamine fluid gave by far the best results. Accordingly, potassium chloride/polyamine was accepted as the inhibitive component of the mud for Breitbrunn.

Inhibition of Dogger Shale (Mittelplate)

To indicate the optimum brine type and concentration the Capillary Suction Time (CST) test was used. The test measures dispersing and hydration ability of shale in different solutions. The higher the hydration and dispersion of clay, the higher is CST value. (See Appendix).

More than 20 various solutions of potassium chloride, sodium chloride, calcium chloride and combinations thereof were tested. The results are presented in **Figure 2**. The potassium chloride treatment was clearly most efficient compared to sodium and calcium salt solutions. A concentration of 100 kg/m³ potassium chloride was found to be optimum; further increase of potassium chloride concentration by a factor of two did not lead to sufficient improvement.

The next stage involved tests on the swelling/dispersion of shale in mud based on potassium chloride brine with various inhibiting additives. The tests also included potassium formate, silicate mud and oil based drilling fluid. The results are shown in **Fig 3.**

The clay was very friable and tended to produce high values in the Shale Erosion Test. This friability was demonstrated particularly well in the case of the test in OBM. The weight loss from the test samples was 9.8%, whereas OBM typically yields very low erosion numbers of less than 5%. The results of water based systems should be judged in relation to this number.

It can be seen from **Fig 3** that the water based fluid comprising potassium chloride plus polyamine and polyglycol[6, 7] produced an erosion value that was almost as good as that observed for the OBM and was the best result of all of the water based fluids tested. Inclusion of the cloud point polyglycol and the polyamine with potassium chloride brine reduced the erosion value from 25% by more that a factor of two to 10.8%

The modes of action of polygycol and polyamine are probably similar, but it is believed that the mechanism of their action is very different from that of OBM. In the case of OBM an efficient semi-permeable membrane for the shale is provided by the oil phase and ingress or egress of water into or out of the shale is controlled by osmotic factors. The objective is to ensure that the shale and the OBM are in osmotic equilibrium. Neither polyglycol nor polyamine duplicate the mechanism of OBM. Both types of additive are known to be adsorbed at the surface of the minerals[6, 8] and it has been reported[6] that glycols can penetrate the interior of the clay minerals and increase shale hardness. The main mode of action in both cases is believed to be retardation of uptake of water by the shale; that is, to increase the time before the shale picks up enough water to lead to borehole collapse.

Cuttings Transport; Rheological Considerations with Respect to Formulation.

Cuttings transport is critical when drilling horizontally. To reduce risk of stuck pipe due to cuttings bed build up, an adequate rotation of the pipe, high pump rate, as well as adequate carrying capacity of the drilling fluid, are of high importance.

Fluid carrying capacity was estimated on the basis of hydraulic calculations. The Baroid DFG™ (Drilling Fluid Graphics) software accounts for flow rate, rate of penetration, rotary speed, deviation, fluid rheology, cuttings size, well geometry etc. Applied to the conditions expected for Breitbrunn and Mittelplate the output of the software recommended that the following parameters would provide good cuttings transport at applied pump rates of 1800 to 2500 L/min. That is:

- Plastic viscosity, cps 12 - 20
- Yield Point, lbs/100 sq.ft 25-30
- 6 rpm Fann-reading 8 - 14
- 3 rpm Fann-reading 7 – 11

The most important parameters are the 6 and 3 rpm readings, reflecting the low end rheology at shear rates of 5 sec^{-1} and 10 sec^{-1} which is typical for the mud flow in the annulus. According to the hydraulics software, lower rheological parameters would lead to building of cuttings beds, especially for drilling in sliding mode. Furthermore, higher rheology would not provide further improvement of the cuttings transport, but would increase Equivalent Circulating Density (ECD) by over 1.24 kg/L with attendant risk of differential sticking.

These rheological requirements were achieved by adjusting the polymer (mainly xanthan) in the drill in fluid formulations. The same considerations applied to each of the two applications

The calculations showed that in addition to high pump rates and adequate rheology, rotation of pipe would be necessary. Preferably rotation speed should be higher than 90 to 100 rpm; 2 to 3 bottoms-up circulations would be required after sliding.

Lubricity

Lubricity is often a problem when drilling horizontal and highly deviated well designs using WBM, especially if overbalance is high and/or if the formation permeability is high. Where the well trajectories have significant tortuosity, severe doglegs and hole-angles and/or if there is a tendency to form thick filtercakes or build -up of cuttings beds, then high friction is likely to result from the increased surface contact between the moving drill-string, the surface/intermediate casing and the formations in the open hole. The degree of these frictional increases often results in excessive torque/ drag and pick-up/slack-off weights. One of the most common associated problems is difficulty in achieving weight transfer to the bit while sliding. High friction can also lead to increased risk of mechanical and differential sticking.

The wells planned for both Breitbrunn and Mittelplate all represented cases where excessive friction was likely to be a significant problem.

It has been observed that very often when using water based systems, addition of single liquid lubricants has only limited effect on reduction of torque, drag and pick-up weight. However, using a mixture of selected lubricants can give improved results. This approach has been followed to devise the best "lubricant cocktail" for these applications[9].

A powerful synergistic effect can be achieved by combining different vegetable oil derivatives with different functionality. Modified tall oil fatty acid addresses the cased hole torque and drag issues. The product readily adsorbs to exposed metal surfaces providing a pressure resistant chemical film that is effective in reducing metal-to-metal torque. Soybean oil/alcohol blend focuses on the open-hole torque and drag issues. A vegetable-based ester improves coating properties (on both clays and metal surfaces), and thus improves the ability to slide.

The ester also enhances the overall treatment by minimizing the lubricant side-effects and reducing some of the problems such as balling associated with "sticky clays". The product is an integral part of the lubricant cocktail to provide synergy with the lubricant additives and the mud system Also application of ecological friendly vegetable oils ensured an easy handling of liquid and solids wastes during both projects.

Some results of lubricity testing with an EP-Lubricity Tester[10] are given in **Fig 4**. These results show the effect on lubricity at a steel/steel contact immersed in various type of mud, including oil mud. As can be seen from the figure the lubricant cocktail provided extremely good reduction in friction when using WBM. Remarkably, friction factors were observed that were almost as low as, and some cases lower than , those of OBM. Initially there had been concerns that application of water based systems to these horizontal and extended range wells might be limited due to friction/torque and drag considerations. However, the low friction factor results generated confidence that these earlier concerns would not be an issue.

Mud Formulations

Based on the studies of individual properties final mud formulations were finalised for Breitbrunn and Mittelplate.

The formulations and properties are given in **Table 3** In both cases the rheological properties were as required and the fluid loss properties were excellent over the whole range of expected permeabilities.

In the case of the formulation for Breitbrunn further proving tests were done using sandstone core from the reservoir in question with a particular emphasis on high overbalance. Two samples of drill-in fluid were tested with and without drill solids; the simulated drill solids were actually glass beads with a median size of 50 – 70 microns. The concentration of simulated drill solids was 82 kg/m³.

The drill-in fluids were aged, statically and dynamically, in contact with the core at an overbalance of 175 bar (2538 psi) and a temperature of 55 ^{0}C. The core samples were subsequently examined by scanning electron microscopy (SEM). An example of the micrographs are shown in **Fig 5.** It can be seen that the filtercake was very thin and that invasion was minimal, the mud fines had not penetrated beyond the first line of pore throats..

Results of the SEM analysis are given in **Table 4**

Solids Control; Maintenance Of Desired Particle Size Distribution

Proper design of the drilling fluid allowed selection of optimum sizes of bridging material to minimise fluid loss and filter cake. However, this step is only part of the objective; the size distribution needs to be kept under strict control to maintain fluid properties and density during the drilling operation.

Solids control practices for each location were quite different since drill-in fluids for Breitbrunn and Mittelplate wells have very different bridging requirements .

Breitbrunn Wells

Particle size analysis showed the median particle size of the formation sandstone to be 70 to 75 microns, whereas 25 to 35% of the particles were smaller than 63 microns. Furthermore, particles of less than 20 microns amounted to about 10 to 12% of the total. This meant that the particle size distribution of the drilled fines was substantially different from that of the ground marble (ie a blend of two grades of ground marble with median sizes 5 and 25 microns). That is, at least 50% of the particles were larger than 70 microns and the majority of the sized calcium carbonate was smaller than 70 microns.

This difference facilitated effective removal of drill solids from the mud with the use of all conventional means of solids-control equipment. Three shale shakers, a desilter and two full hydraulically driven centrifuges were used for solids control of the drill-in fluid. 230 to 250 mesh screens with median openings of 59 to 65 microns were used so that it was possible to remove 60 - 70% of drill fines while retaining the smaller bridging solids in the fluid system.

The desilter and centrifuges were used if mud density exceeded 1.1 kg/L. One centrifuge treated the heavy mud/underflow of desilter and another treated the mud from the active system. The rotation speeds of bowl and scroll were adjusted to provide a cut point of 10 microns. By this means removal of further 20 to 25% of drilled sand was achieved, keeping the major fraction of ground marble with median diameter of 5 microns in the system.

To maintain the desired particle size distribution, ground marble with the median diameter of 25 microns was added to the overflow of the centrifuges; this mud was stored in a separate tank for treatment, before being adding to the active system.

The particle size of the mud, as well as of the under- and overflow of the desilter and the centrifuges were controlled using daily on-site measurements with a Laser Particle Size Analyzer.

The Particle Plugging Test was a key tool in controlling the particle size distribution (PSD) and bridging/sealing properties of the fluid. The results obtained had a bearing on the solids control measures implemented.

Mittelplate Well

The fact that the drilled sand was coarser than the sized marble facilitated effective removal of drill solids out of the mud.

The Dogger payzone comprises coarse sand with median particle size of 230 to 270 microns for Dogger gamma and delta sands and up to 800 microns for Dogger epsilon.

The blend of ground, sized marble used included grades with particles up to 100 to 120 microns, so to avoid removal of the bridging material the finest acceptable screens were 125 and 150 mesh (100 to 125 microns). Also, to avoid excessive removal of the marble bridging particles, a mud cleaner and two hydraulically driven centrifuges were not used in this project.

The fluid loss through 60 and 90 micron ceramic discs was used as the indicator for adequate PSD of the mud in this project.

Comments

Similar approaches to removal of drilled solids were used in both the Breitbrunn and Mittelplate projects. The experience of both projects showed that solids control equipment need not necessarily screen out the bridging material, if fluid composition and solids control measures are designed properly.

Since the required sizes of bridging material are normally lower than the diameter of the matrix sand particles in the sandstone, a correct selection of the cut point of the applied equipment will allow optimum removal of the drill solids while simultaneously leaving bridging material in the system.

Drilling Experiences
Breitbrunn

The efficiency of the mud design for both applications was verified during drilling of a total of six horizontal intervals.

- Neither differential nor mechanical sticking, overpulls or other drilling problems were experienced.
- The mud parameters were stable throughout the sections.

The key parameter reflecting the bridging sealing capability of the mud was the particle plugging apparatus (PPA) at bottom hole conditions. Fluid loss through permeable discs (of 5 and 10 micron pore throat diameter) was monitored. The PPA total fluid loss at 175 bar differential pressure and 60°C was maintained in the range of 4 to 8 mL/30 min on all six wells, compared to the value of 15 to 20 mL/30min which would be normally be considered acceptable for other applications. These excellent PPA results demonstrated the high efficiency of the mud and that of the solids control practices.

Optimal utilization of solids control equipment enabled the mud density to be controlled between 1.11 and 1.13 kg/L which corresponds to 2 to 3% of drill solids in the mud. Material balance shows that 85 to 90% of drill solids were removed by the solids control equipment.

Mud treatment with the lubricant cocktail reduced rotational torque by 50-70% (see **Fig 6**) and pick-up weight by 30 to 50%. The downhole torque varied between 800 dN.m at the beginning of the interval and 1400 dN.m at the end of the 8 ½ inch hole section. In the case of foam drilling for which the torque values were in the range 2000 to 2800 dN.m. Thus, the torque values achieved with WBM were almost half the values achieved in previous operations when foam was used in shorter horizontal sections. It is worth noting that the downhole torque values achieved with WBM following addition of the lubricant cocktail were similar to those observed for OBM.

Logging showed an in-gauge hole in all six wells in sand as well as in shale sections. This represented a reduction in washouts, compared with the performance when foam was used, of 90%. For example, during the previous operation involving a foamed mud, although the target hole diameter was 8½ inches, the actual average hole diameter was 17½ inches (**Fig 7**). On the other hand when the new, dense, conventional system was used (**Fig 7**) the average hole diameter was 9 inches. This improvement in performance was due to use of optimal inhibition and mud density.

Cuttings transport was good and there was no evidence of cuttings beds or any hole cleaning problems. Through application of a Logging While Drilling (LWD) geosteering system, the well was mostly drilled in rotating mode, which helped hole cleaning. When sliding was required additional rotation and circulation was applied before the connection. Before pulling out of hole, the hole was circulated clean within 2 to 3 bottoms up. Pumping of cleaning pills was not required.

Mittelplate Injection Well H -1

Drilling results of the highly deviated 539 m long 8½ inch section of the Mittelplate were similar to those achieved on the Breitbrunn project,

No losses and no differentially stuck pipe occurred in highly permeable sand; there were no overpulls, caving or hole instability in shale.

The torque levels of 1000 to 1700 N*m observed throughout the section were similar to those observed for oil mud. To place these results in perspective they should be compared with typical performance of water based mud that has not been treated with the lubricant cocktail. In this application typical downhole torque was 2500 to 3000 N*m. Another advantage achieved through high lubrication was easy sliding and good weight transfer to the bit.

Some washouts in the shale sections did occur, but the incidence was very similar to that commonly observed during drilling with OBM. For example, **Fig 8** shows a comparison between the calliper logs of comparable sections drilled with water based and oil based mud. It can be seen that while drilling with OBM through interlayered claystone and sandstone the hole remained in gauge from 3559m to 3800m and washouts were only seen while drilling in claystone from 3800m to 3860m. Performance with WBM was similar. In this case the hole remained in gauge in claystone and interlayered sections between 2500m to 2650m, 2700 to 2820m and 2870m to 3000m; washouts were evident in two short (30m) claystone sections at 2670 m and 2830m.

Although the observations regarding shale stability are somewhat complicated by differences in stress directions it was very clear that adequate inhibition was provided by 10% potassium chloride polymer mud with additions of polyamine and poly glycol inhibitors.

Another surprising observation was that this well had one of the highest rates of penetration out of the total 9 deviated wells drilled in the field. Thus, it appears that the tailored mud system facilitated high drilling efficiency (**Table 5**).

While drilling the Mittelplate injection well H1, as in the case of the Breitbrunn development, great reliance was placed on the PPA measurements. The fluid loss through 60 and 90 micron ceramic discs (3.6 and 8.1 darcies respectively) was used as a key parameter for the estimation of filtration properties, bridging capacity and adequate PSD of the mud in this project. As had been achieved for Breitbrunn, in the Mittelplatte project the mud was characterised by very low values of the PPA total; for example, fluid loss measured in the range of 4 to 10 mL/30 min. This shows an efficient bridging ability of the drilling fluid designed for permeability up to 10 darcies.

While drilling the interval from 2502 to 3051m, a small increase of the mud density from 1.22 kg/L to 1.23 kg/L was documented. It means that contamination of drill-in fluid with drill solids was about 20 kg/m³, that is, below 1%. Material balance shows, that 91 % of drilled solids were removed on the shakers, which illustrates the very high efficiency of the solids control equipment and practices applied.

Through maintenance of recommended rheological parameters and application of high pumping rate in conjunction string rotation of 90 to 120 rpm, a good hole was achieved.

Conclusions

Seven long highly deviated and horizontal wells from 539 m to 960 m were successfully drilled in difficult drilling conditions.

It was not possible to use oil based mud due to reservoir (water injection well) and ecological reasons. The main challenges were high overbalance of up to 195 bar, unstable shale, high permeabilty and possibility of excessive torque levels due to a requirement to use WBM.

An optimised fluid design, customised for the specific hole conditions, was a key to successful drilling operations.

The main features of the system were:

- Excellent fluid loss properties.
- Lubricious filter cake involving very effective lubricant.
- Customised shale inhibition treatment, preventing swelling and erosion of shale and providing enhanced hole stability.

Important operational features included:

- Selected solids control solutions to maintain optimum PSD as well as stable mud parameters during drilling of long horizontal sections.
- Selection of shaker screen sizes and other mud cleaning equipment to enable removal of drill solids and maintenance of optimum PSD for fluid loss control
- Reliance on particle plugging tests as a means of monitoring important mud parameters

Overall, the water based drill-in mud system showed a drilling efficiency and properties similar to those of oil based system s.

The use of these newly formulated muds is planned for forthcoming RWE Dea AG operations under similar drilling conditions.

Acknowledgments

The authors wish to thank the management of RWE Dea AG and of Halliburton for permission to publish this paper.

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10) Details are given on website: “Combination EP and Lubricity Tester” http://www.fann.com/product_info_main.asp?catid=62

Appendix

Hardness testing on linear swell cores

Hardness is determined by a Shore Durometer, Type ‘A.’ This device consists of a spring lo aded pin that is pressed into the surface of the test material until it is flush with the body of the tester. At this point, the hardness is read from a circular scale that expresses the pressure required as “hardness” in Shore Units.

Accretion on steel Tests:

Hot roll cells were set up containing pre -weighed steel bars (127 x 25 mm). Mud was added level with the top of the bar (± 1 lab barrel volume). 60 g of cuttings were added to each cell and gently mixed. The cells were capped and rolled for 30 minutes at room temperature. The cells were opened and the bars were carefully removed. The bars were allowed to drain for 10 minutes, then w eighed. Accretion was expressed as weight added to bar s.

Capillary Suction Time (CST)

The CST device measures the t ime it takes a given amount of free water from a slurry to travel radially between two electrodes on thick, porous filter paper. The test measures the hydrating and dispersion properties of shales. Highly dispersed particles give low cake permeability and high CST values. Flocculated particles give high cake permeability and low CST values. The CST value depends on solids type and content of the slurry, degree of mixing, pH, salinity, deflocculant or dispersant type, concentration and polymer type an d concentration.

Table 1. Selection of test conditions and ceramic discs, and selected sizes of brid ging material for o ptimizing of the drill-in fluid

Parameter	Chatt Sandstone: Breitbrunn Field	Dogger Sandstone : Mittelplate Field
Formation Paramete rs		
Permeability, md	5-100	2 000 - 10 000
Temperature, °C	55	75
Expected overbalance , bar (psi)	150 to 195 (2175 to 2828)	20 to 40 (290 to 580)
Test Conditions		
Disc Porethroat, micron	5 and 10	35, 60 and 90
Permeability, md	25 and 100	1225, 3,600 an d 8,100
Temperature, °C	55	75
Pressure, bar (psi)	175 (2537)	34.5 (500)
Selected particle sizes and concentrations for optimal bridging		
Ground Marble (Calcium Carbonate), 5 micron m edian diameter, kg/m³	50	28.5
Ground Marble (Calcium Carbonate), 25 micron m edian diameter, kg/m³	30	28.5
Ground Marble (Calcium Carbonate), 50 micron m edian diameter, kg/m³	None	57

Table 2 Mineralogical analysis of shale samples from Breitbrunn and Mittelplate.

	Mineral Content %							
Shale Discription	**Quartz**	**Feldspar**	**Calcite**	**Dolomite**	**Chlorite**	**Kaolinite**	**Illite**	**Smectite and Illite/Smectite mixed layer**
Chatt Shale, Breitbrunn Wells	30	6	16	8	8	-	21	11
Dogger Shale, Mittelplate Wells	29 to 33	1	1 to 2	-	1 to 2	7 to 9	31 to 34	24 to 27

Table 3 Formulations and prop erties

Product Concentration			Drill-in System BREITBRUNN		Drill in System MITTELPLATE		
KCl		g/L	60		100		
NaCl		g/L	-		120		
Xanthan Polymer		g/L	2.8		2.8		
Cross-linked Starch		g/L	28		28		
Magnesium oxide for pH control		g/L	5		5		
Calcium Carbonate 5 µm		g/L	50		28		
Calcium Carbonate 25 µm		g/L	30		28		
Calcium Carbonate 50 µm		g/L	-		56		
Polyamine		g/L	20		20		
Polyglycol		g/L	-		30		
Lubricant Cocktail		%	2.5		2.5		
Biocide		g/L	1		1		
Mud Mixing and Ageing							
Stirred	Min		30		30		
Rolled	Hours		16		16		
Temperature	°C		55		75		
Drilling Fluids Parameters							
Specific Gravity, SG	Kg/L		1.10		1.22		
Rheology @ 50ºC							
600	rpm		58		63		
300	rpm		44		48		
200	rpm		37		41		
100	rpm		28		32		
6	rpm		12		13		
3	rpm		10		11		
Plastic Viscosity	cP		14		15		
Yield Point	Lb/100 ft^2		30		33		
Gels : 10 sec/10 min	Lb/100ft^2		9/11		11/13		
API Fluid Loss	mL		3.2		2.8		
pH			9.6		9.9		
Filtrate through Ceramic Disk (Particle Plugging Test)							
Temperature	°C		55		75		
Diff. Pressure	Bar (PSI)		175 (2530)		35 (500)		
Disc size	micron		5	10	30	60	90
Spurt	mL		1.5	2	1	3	1
30 min filtrate	mL		4.5	2.5	6	5	5
Total mL			10.5	7	13	13	11

Table 4. Results of SEM analysis

	Freshly-mixed drill-in fluid	Drill-in fluid with simulated drill solids
Thickness of the filter cake	30 µm	30-50 µm
Depth of the fluid invasion	100 µm	100 (to 200) µm

Table 5 Mittelplate – Comparison between WBM & and OBM; 8 ½ inch section, clay zones

Well number	Mud type	Inclination	Azimuth	Weight on bit (surface)	Footage [m/h]	SG
H 1	WBM	60°	188°	10 to 16 t	12	1.22 kg/L
A 14	OBM	75°	25°	10 to 20 t	7 to 10	1.22 kg/L
A 16	OBM	75°	7°	6 to 10 t	5 to 9	1.30 kg/L

Figure 1 Effect of KCl and polyamine clay inhibitor on Chatt shale properties (shale recovery %)

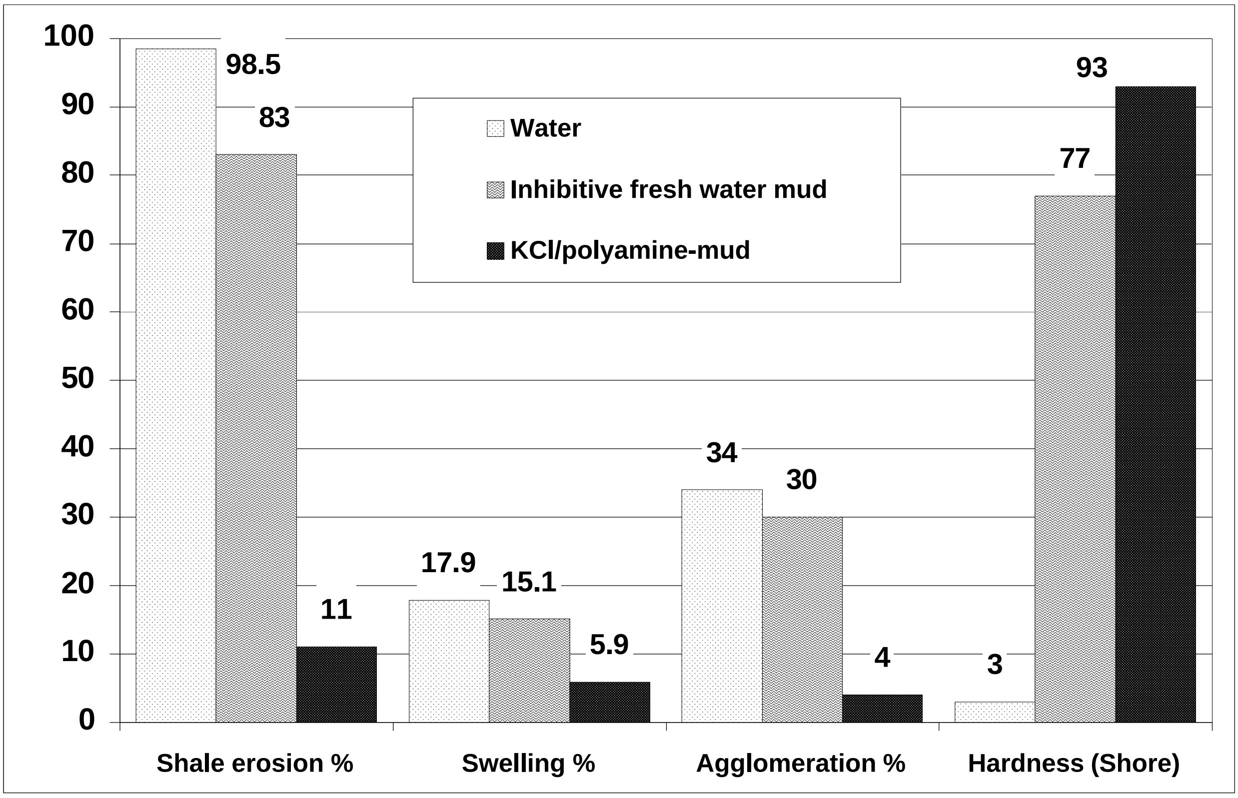

Figure 2 Capillary suction time tests

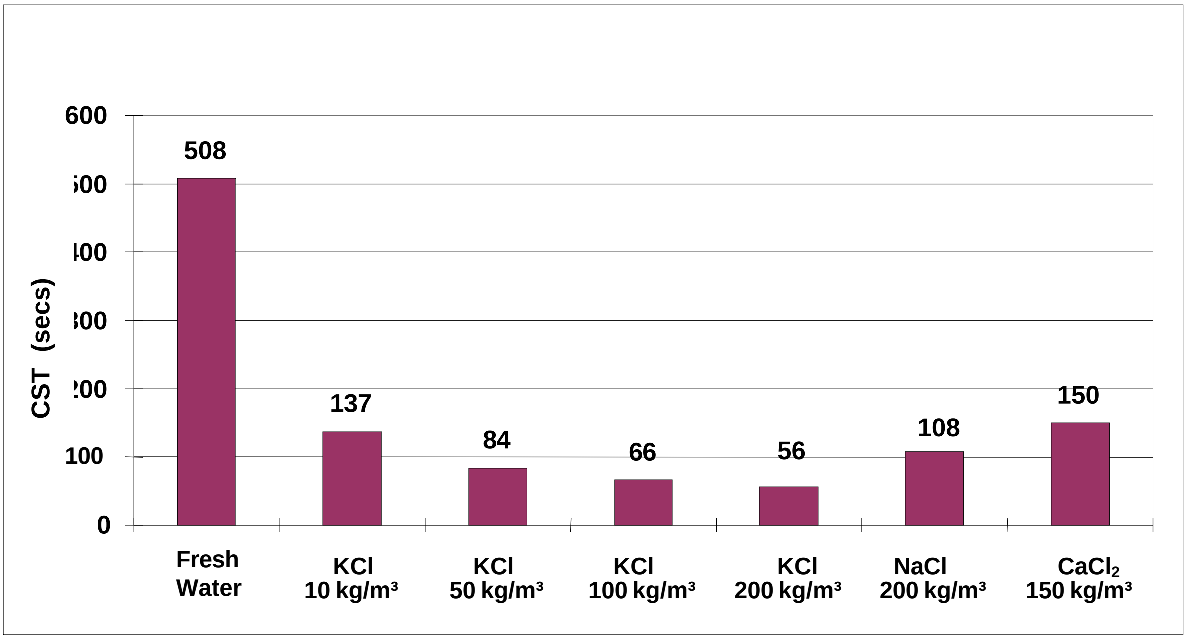

Figure 3. Effect of various inhibitive drilling fluids on erosion and swelling of the Dogger shale

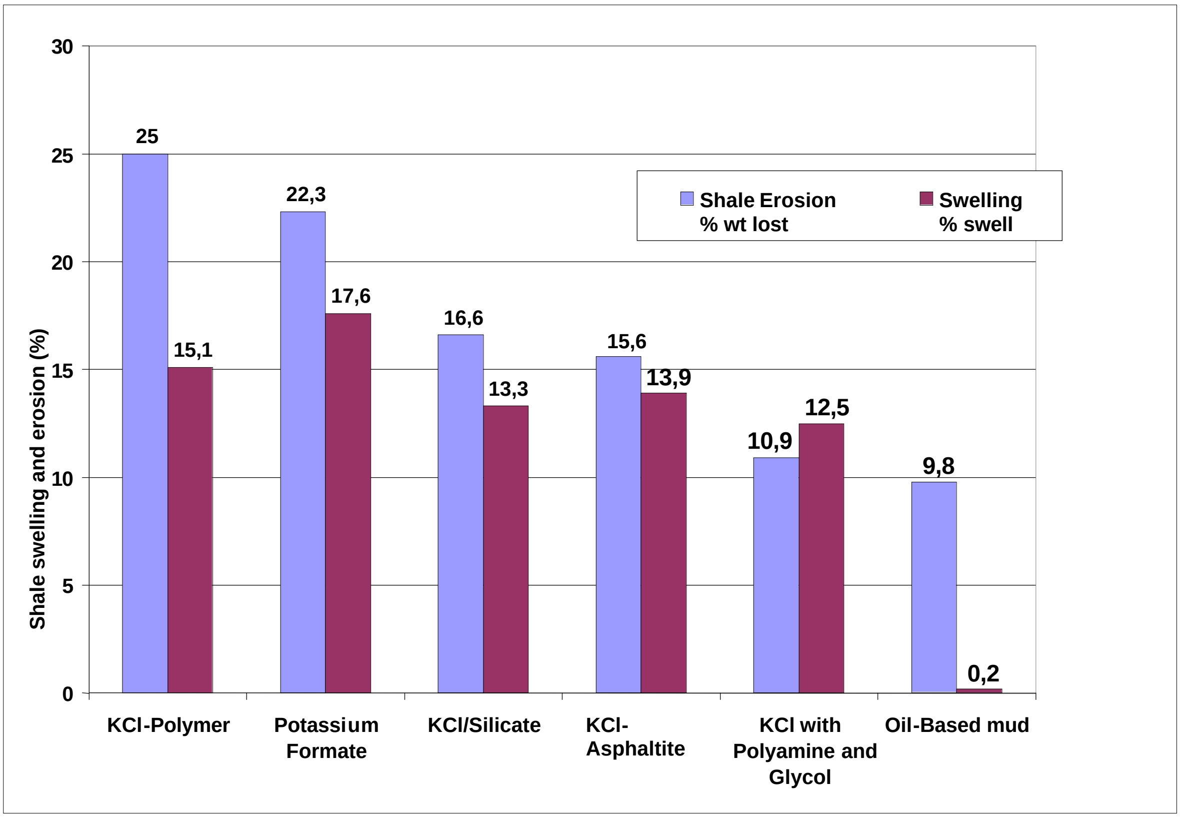

Figure 4 **Steel-to-steel friction reduction due to lubricant cocktail**

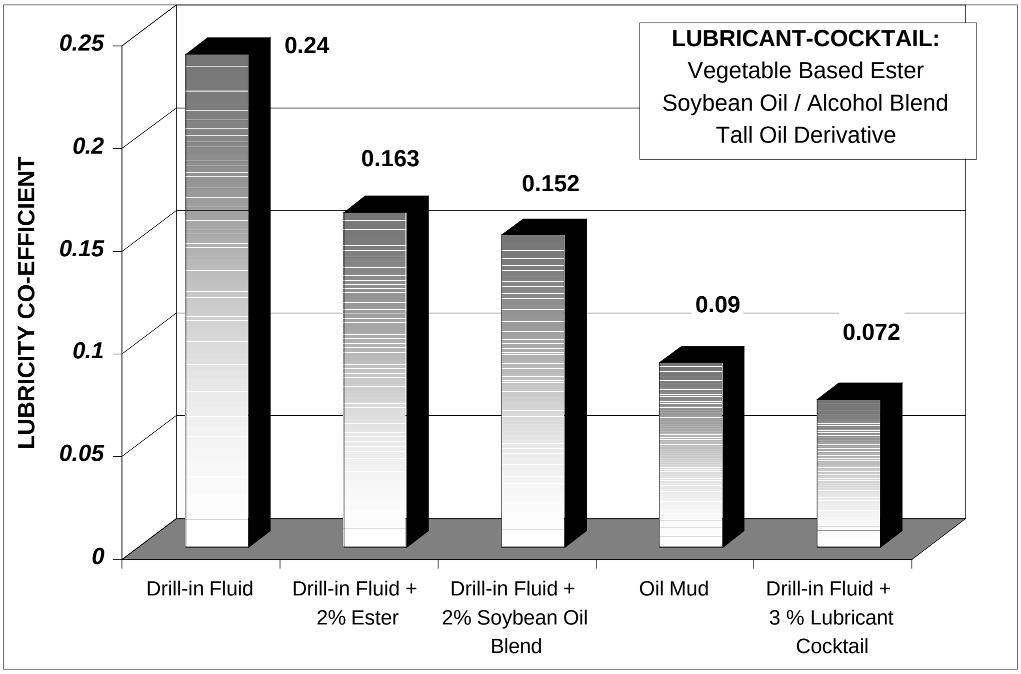

Fig 5 **Scanning electron micrograph s howing filter cake on end of core**

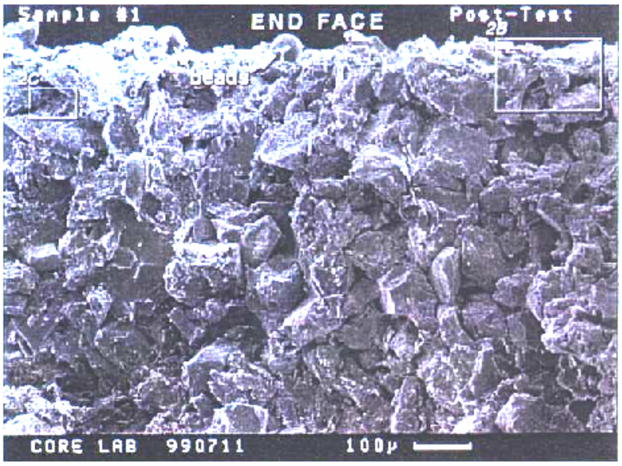

Figure 6 **Torque reduction after addition of the lubricant cocktail.**

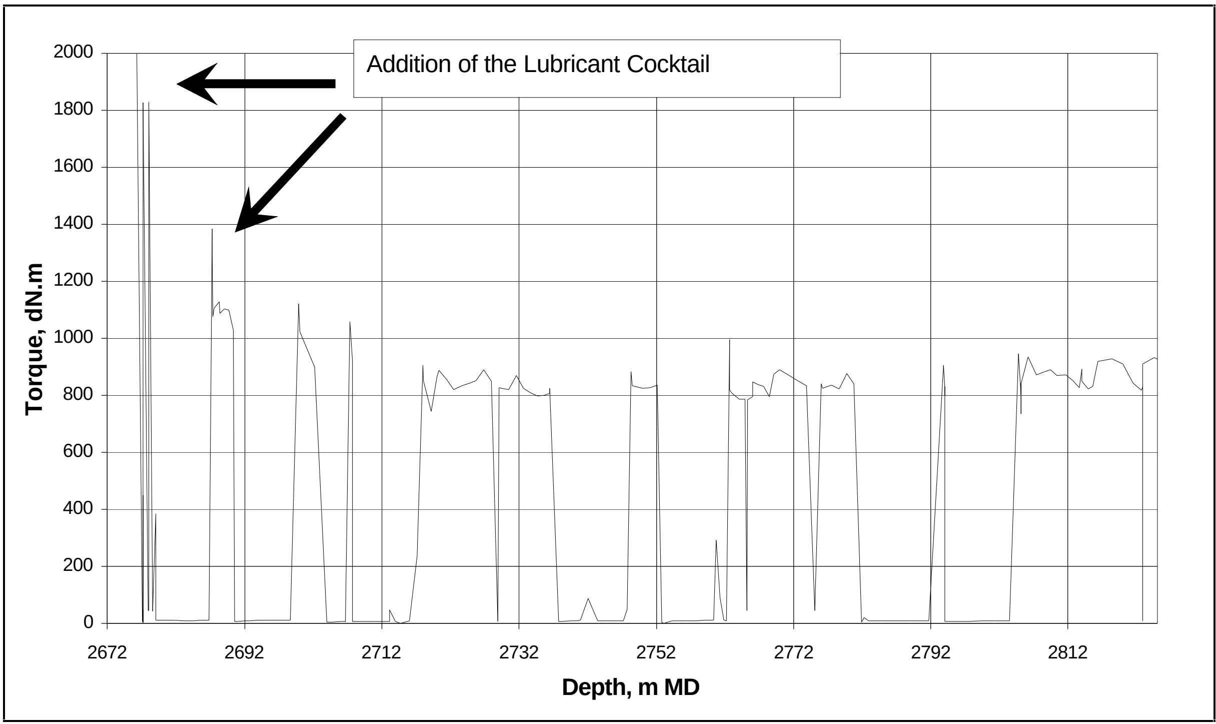

Figure 7 **Borehole diameters with foam and the drill-in fluid (Breitbrunn).**

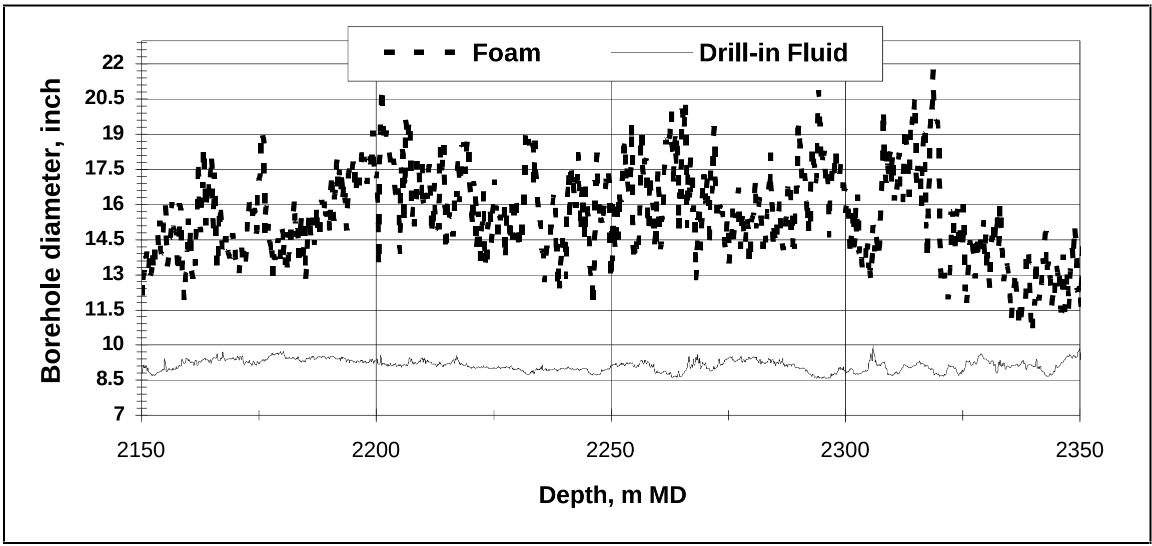

Figure 8 Comparison of calliper logs drilled with water based and oil based fluids