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A STATE-OF-THE-ART STUDY OF DRILLING PROBLEMS IN
SELECTED SHALES*

by

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ABSTRACT

The Stanley formation of southeastern Oklahoma is believed to contain large quantities of natural gas. Due to the high cost of drilling this formation and due to the low gas production rate from the sands, it is not economical to produce from this formation at the present time. One possible approach to reducing drilling costs is to drill with air and take advantage of the higher penetration rate obtainable. However, this approach tends to create additional problems associated with borehole stability and hole cleaning.

This paper will summarize the results of a state-of-the-art study which was directed toward shale drilling problems, air drilling problems, and their reported solutions. Also, future plans for investigating the effects of various drilling fluids on selected samples of shale will be presented.

INTRODUCTION

Since fossil fuel producing formations are frequently overlain by numerous layers of sedimentary deposits, the driller trying to reach these production zones has to penetrate these layers and cope with the drilling conditions presented by each layer. One type of sedimentary deposit that has frequently presented some of the most difficult drilling problems is shale. Shales are quite varied in composition and characteristics. Some are penetrated with little or no trouble, while other types are fraught with drilling problems to the point where the hole is frequently abandoned. It is the purpose of this study to examine the drilling problems and potential solutions, as reported in the literature, and to investigate the possibility of applying some of these techniques to the Stanley shales of southeastern Oklahoma.

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The Stanley shales are of particular interest because it is believed that the sands in these formations contain large reserves of natural gas that could be made productive if an economical drilling technique can be found. Fortunately, the formations have been tilted such that the older, deeply buried deposits outcrop at the surface allowing access to rock samples which can be used for laboratory drilling tests.

GEOLOGY OF THE STANLEY FORMATION

In order to understand the nature of the Stanley formation, it is worthwhile to review the geology of the region. The significant geological development started late in the Paleozoic era when the present Ouachita mountain region was in a deep water area with very little sedimentation occurring. In the late Mississippian period, strong ocean currents and turbidity deposited large quantities of sand and silt which gradually filled the deep troughs. This continued intermittently until late in the Pennsylvanian period when an uplift started to raise the region. The map of Figure 1 shows the uplift as it is believed to have appeared in the middle Permian period, about 50 million years after the deposits were laid down. The uplift was caused by the tectonic plate movement of Africa and South America pushing against the eastern and Gulf Coast region of North America. This uplift formed the Ouachita and Marathon mountains which now form a ridge from southern Arkansas through Oklahoma to the Marathon region of west Texas and on down into Mexico. It is interesting to note that either during or prior to this uplift, the equator was believed to be north of this region running across North America from 37° on the west to 50° on the east, (1) thus making these deposits of the marine equatorial type. The faulting and folding created by this uplift produced a structural complexity along the southern edge of the stable cratonic region that lies just to the north of the uplift. The folding of the sedimentary deposits created many traps for oil and gas and are today some of the richest deposits in the country.

Figures 2A, B, C, and D shows the orogeny of the Ouachita mountain region starting from mid Mississippian period through the end of the Pennsylvanian period. Early in this period, a series of elongated domes of basement rock started to form in the deep water regions leaving troughs for sedimentation to accumulate. This thrust from the south, due to tectonic plate movement, gradually caused deepening of the troughs and raising of the ridges. These troughs were ideal settling places for the erosion from the protruding islands to gather. It was this process that generated the Stanley shale deposits, sometimes to a thickness of 10,000 feet. Above the Stanley deposits the Jackfork sandstone attained

a thickness of 6,000 ft. These formations were deposited relatively rapidly in a deeply subsiding trough. The last of the Pennsylvania to be deposited was the Atoka shale which now outcrops north of the Ouachita mountains and is frequently encountered throughout Oklahoma.

With the ensuing overthrusting and uplifting, the various sedimentary deposits became exposed at the surface with a generally northeast to southwest strike and dip of up to 70°F. Figure 3 shows a cross section of the deposits as they are today. This view is along the strike, in the vicinity of Medicine Springs about ten miles east of Antlers, Oklahoma.

The fact that each of the strata that must be penetrated to reach deeper fossil fuel traps is exposed on the surface, makes it possible to select surface cores that can be used in drilling experiments.

SHALE DRILLING PROBLEMS

Shale is defined as a fissile rock that is formed by consolidation of clay, mud, or silt; has a finely stratified or laminated structure; and is composed of minerals essentially unaltered since deposition. This is a dictionary definition; however, since the shale is the sedimentation derived from millions of years of ocean bottom accumulations, many variations in shale characteristics occur. The composition of the clay, silt and mud will be a function of geological and marine variations that have occurred during that time period. In addition to these deposition variations, the shales are buried at different depths and are therefore subjected to a wide range of temperatures and pressures for varying periods of time.

The deeply buried shale undergoes a dewatering and compaction process that is a function of the time, temperature and pressure to which it has been subjected. This produces a shale that is harder and more dense than the younger surface shales. Water is contained in the formation as bound water, interlayer water, and as interstitial water. Bound water is the water that is chemically bonded to the clay. Interlayer water is the water that has penetrated the unit layers of the clay molecule and is part of the structure of the clay. It can be thought of as the water of hydration. Interstitial water is the excess water that is between the clay particles.

During early burial, the formation is subjected to a relatively light overburden pressure and the interstitial water is expelled. As the pressure increases with deeper burial, the excess interlayer water and some of the bound water are expelled. If the expelled water is allowed to freely leave the formation, the shale will

compact fairly uniformly and the weight of the overburden will be supported by the mineral matrix.⁽²⁾ If, however, the water cannot readily escape due to being confined by impermeable layers, the contained water will support the weight of the overburden and create an abnormally pressured zone. The pressure being determined by the weight of the overburden. When these zones are drilled, the abnormal pressure causes the borehole wall to slough into the well. This type of problem is one of the familiar "sloughing shale" problems frequently encountered. Another type of problem that falls in the "sloughing" category occurs in shale bodies where there may be little hydratable clay in the bulk of the formation, but the formation has numerous minute fracture lines that contain hydratable clay that acts as a binding agent for the whole structure. Water invasion of these small fissures weakens the clay bond and the borehole wall can slough.⁽²⁾ The corrective action for the first type of sloughing is to weight the mud to counteract the pressure. For the second type, a chemical additive for fluid loss control is necessary.

A characteristic of shale that contributes greatly to drilling problems is its sensitivity to water. The softer dispersible shales near the surface hydrate readily in the presence of water (Ref 3). The hydration causes the shale to swell, and as it swells it softens to a plastic state. This results initially in a shrinking of the hole diameter. If the clay softens sufficiently, it can disperse into the mud leaving a cavity or enlarged hole. When this cavity becomes large enough to undercut the overlaying layer, the layer collapses into the borehole. This phenomenon is generally termed "heaving shale" and is controlled by chemical additives in the mud that decrease hydration. Usually salts of potassium and calcium are used.

The more dense, less dispersible, deeply buried shales absorb water by a surface hydration mechanism, causing an expansion of the surface material. The resulting volume increase causes the shale to crack and cave-in in hard fragments. This is referred to as "caving." These are common problems when drilling shale with water based muds. The most common solution to these problems is to add special chemical additives to the mud that inhibit the hydration and dispersion, or use an oil based mud.

The above problems are the major problems associated with drilling shale when mud is used as the drilling fluid. Table I summarizes these problems and remedies.

AIR DRILLING

The production formations of the Stanley sands are reported to have a permeability range of .1 to 1.7 md, with porosity of about 12% and connate water of 25%. With this low permeability and the high costs of drilling these wells, gas production is not economically feasible at the present time.

One of the best ways to reduce drilling costs is to increase the penetration rate. This is frequently done by using air or aerated mud in place of the drilling mud. The curve shown in Figure 4 shows cost per foot as a function of penetration rate. This curve is based on an equation that considers bit cost, rig cost, trip time, and total penetration per bit. This cost per foot calculation cannot be used to calculate total well cost because it does not consider the many other factors such as logging time, casing, fishing, mud cost, etc. However, it does show how sensitive cost is to penetration rate.

It has been stated that air drilling can increase penetration rate by a factor of eight over mud drilling. Applying that factor to this curve, it can be seen that the cost can be reduced from approximately \$100 per foot to around \$12 per foot by converting to air drilling. The dashed line on Figure 4 shows the affect of increasing the bit life from 50 hours to 200 hours.

It is generally believed that the increase in penetration rate of air drilling over mud drilling is due to the much lower pressure of the air against the formation compared with the much higher hydrostatic pressure of the mud.⁽⁴⁾ The well known curve of penetration rate as a function of differential pressure, Figure 5, shows how rapidly penetration rate is changing as zero differential pressure is approached. For air drilling, this curve would have to be extended far to the left of the ordinate to a negative differential pressure. The negative pressure will be determined by the difference between the air pressure in the annulus and the overburden pressure which is a function of the depth of the hole. When the rock face is subjected to a crushing force from the bit in the presence of this pressure difference, the rock is fractured, allowing pieces of rock to be expelled from the rock face. They are then swept up the annulus to the surface. On the way to the surface the rock particles are subjected to collisions with each other, the borehole wall and the drill pipe. This action reduces the particle size such that it appears at the surface as a dust or sand.⁽⁴⁾

In addition to high penetration rate, other benefits have been reported. Most notable of these are: 1) Longer bit life,

probably due to better bearing cooling and less contamination. 2) Better evaluation of the formation being drilled, since the low pressure in the annulus allows formation products to enter the well where they are quickly brought to surface. 3) Reduced damage to liquid sensitive pay formations. 4) Reduced lost circulation in porous zones.

There are also disadvantages associated with air drilling. By far the greatest problem occurs when water invades the borehole. Because of the low annulus pressure, the water can flow unrestricted into the hole. This water wets the cuttings causing them to become sticky and to ball up. The balls accumulate and form a muddy mass around the drill string and on the borehole wall. This accumulation creates a restriction to the air flow and a decrease in the ability of the air to remove cuttings from the hole. If allowed to continue, complete loss of returns and stuck pipe can result.

The first indication of water invasion will be an increase in air pressure at the rig floor and possibly a decrease in drill string weight. The corrective action is to inject soap and use mist drilling. Mist drilling is reported to be capable of removing up to 200 bbl per hour of influx water.⁽⁴⁾ A further increase in water influx results in an increased restriction and an accompanying pressure increase until either the restriction is blown out or the limit of the compressor is reached. The case where the restriction builds up and is repeatedly blown out is sometimes referred to as slug drilling. Because of its instability, it is an undesirable mode of drilling; but does remove additional water.

When the influx of formation water cannot be handled by mist drilling, aerated fluid drilling can be used.⁽⁴⁾ This method consists of injecting air into drilling mud in the standpipe. This technique serves the purpose of increasing the carrying capacity in the annulus; however, its use is accompanied by a decrease in penetration rate.

Downhole water invasion is the most troublesome problem associated with air drilling; however, there are other serious problems that can occur. Most important of these are downhole fires and explosions, sloughing, and crumbling or weak formation walls.

Downhole fires can also be a problem in air drilling. When gas is encountered while drilling with air, the presence of a spark or very hot surface can cause ignition of the air-gas mixture. Depending on the volume and the oxygen to gas ratio, either an explosion or fire can result. There are three conditions that can cause ignition of the gas-oxygen mixture. The most prevalent is an obstruction build-up in the annulus such that the pressure

builds up and ignition occurs from the temperature rise, similar to ignition in a diesel engine. Once ignition has occurred and air and gas are continuously supplied, the eventual result is a burned off drill string. Experience has indicated that most burn-offs occur in the drill collar section string at the top of the gas entry zone. In most cases, at the time of burn-off, the pipe has been stuck, indicating a build up of mud in the annulus. (4)

Another method of ignition can occur when dust drilling in very dry formations. When the hard steel drill string or bit inserts strike hard rock surfaces, sparks are produced. If the air gas mixture is right, ignition will occur. The third source of ignition is related to small pinholes in the drill string. The heat generated by the friction of the air passing thru the hole can produce a hot spot sufficient to ignite the air gas mixture.

Cooper, Hook, and Payne state "There may be no absolute method to prevent a downhole fire while drilling with air: - - - Constant supervision is an absolute necessity." Reference 4 gives a detailed description of alarm systems and procedures for preventing a burn-off.

DRILLING FLUID DEVELOPMENT

In order to develop an economical air drilling technique for "troublesome shale," the combination of shale drilling problems and air drilling problems must be considered. It appears that the use of a drilling fluid system that can be aerated throughout a wide range of densities is the best approach. This variable density characteristic will allow adjustment of the hydrostatic pressure to the optimum pressure to control sloughing and still maintain the best penetration rate. Some of the water invasion problems may also be controlled by pressure.

The fluid phase of the system must contain chemical constituents that will inhibit clay hydration. It should also have a foaming characteristic to provide the capability of lifting the cuttings and invasion water to the surface. This foam should break down when it reaches the surface to release the air and cuttings prior to being reinjected.

When this system is used in the very low density, mist drilling phase, it would be desirable to have the capability of providing some mechanical stability to the borehole walls. This would be helpful in those cases where a small amount of sloughing and backfilling is occurring when air pressure is shut off to make connections.

A cooperative arrangement with private industry to develop such a fluid is being sought. A fluid system that can be initially laboratory tested using cores taken from the outcroppings of Stanley shale will be developed. If the results of this phase prove encouraging, arrangements will be made to evaluate the technique in the field.

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Figure 1

UPLIFTS DUE TO TECTONIC PLATE
FORCE ON SOUTH AND
EASTERN UNITED STATES (1)

Figure 2

OROGENY OF OUACHITA MTS.
MID-MISSISSIPPIAN THRU
PENNSYLVANIAN PERIOD

Figure 3

SUBSURFACE GEOLOGY IN THE VICINITY
OF MEDICINE SPRINGS OKLAHOMA

Table 1. Shale drilling problems, causes and remedies

Problem	Cause	Remedy
Sloughing	1) Hydratable bond weakens structure 2) Abnormal pressure zone	Control fluid loss into bonds Weight up mud
Heaving	Undercutting overlaying layer until it collapses	Chemical treatment to prevent hydration
Tight Hole	Swelling of wall causing plastic condition, hole is undergauge	Chemical treatment to prevent hydration
Hole enlargement	Hydration followed by dispersion of shale into mud	Chemical treatment to prevent hydration
Caving	Applies to deep shale where water is adsorbed by surface hydration, causes cracking	Chemical treatment to prevent hydration plus weighting

Figure 4

COST PER FOOT AS A
FUNCTION OF PENETRATION RATE

Figure 5

RELATION OF PENETRATION RATE
TO DIFFERENTIAL PRESSURE