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Drilling and Early Testing of a Sidetrack to the Slant-Hole Completion Test Well: A Case Study of Gas Recovery Research in Colorado's Piceance Basin

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ABSTRACT

During the summer of 1990, a slant hole test well, funded by the U.S. Department of Energy, was drilled to 9,466 ft to evaluate the effectiveness of directional drilling in the tight, naturally fractured gas sands and coals of the Mesaverde Group. Mechanical problems following cementing of a production liner resulted in loss of the completion interval, and operations were suspended.

In early 1991, DOE decided to sidetrack the hole to permit production testing of the lost interval. The sidetrack was designed to parallel the original wellbore, but to be drilled 1,000 ft to the east to minimize the chances of encountering formation damage from the original hole. The sidetrack, like the original hole, was to intersect the paludal lenticular sands and coals at 60° and to penetrate the underlying Cozzette sand horizontally. This paper discusses the directional drilling operations and problems and the subsequent production testing of the horizontal portion of the sidetracked well.

Sidetrack drilling was initiated at 4,162 ft in the original hole. All subsequent depths are given as measured depth. An 8-3/4-in. hole was drilled at 11 to 16° inclination, on a complex azimuth starting at S 71°E at the first KOP at 6,550 ft, and ending at N 13°E at the end of the first build at 7,309 ft. Drilling proceeded satisfactorily with 6-3/4-in. motors, until a bit and stabilizer were lost at 6,708 ft. Fishing operations created a 15°/100 ft dogleg, and subsequent efforts to ream out the hole resulted in sidetracking the sidetrack. The hole was plugged back to 6,450 ft and was then successfully redrilled with motors to the top of a long tangent section at a 57° inclination on an azimuth of N 14.6°E. A 1,230 ft tangent section was rotary drilled at 60° through the paludal Mesaverde, the Rollins sand, and the Mancos Tongue shale at 8,588 ft. The tangent was logged using drillpipe conveyed tools; the well was cased to 8,588 ft and cemented to isolate the tight target sands and preserve caving coals. A 3-1/2-in. drillpipe was picked up to drill a 6-in. hole to final depth. The second build to near-horizontal was drilled using 4-1/2-in. motors to 9,051 ft, at an angle of 86.5° and an azimuth of N 10°E. The Cozzette lateral was then rotaried to 9,308 ft, using an underbalanced mud weight of 14 ppg to prevent formation damage to natural fractures. A brief but quickly controlled blowout, resulting from inadvertently swabbing the well in during a trip, then forced the use of 16+ ppg mud over the rest of the hole. Significant mud losses during the last footage in the Cozzette lateral resulted in drilling being terminated at a total depth of 9,407 ft. A permanent packer with a landing nipple was set at 8,453 ft, just above the 7-in. casing shoe. The well was flowed through the drillpipe to remove as much mud as possible from the Cozzette fractures. It then was briefly tested at very high, but unmeasured, gas volumes from the Cozzette open hole before being shut in to await the formal testing program.

After re-entering the well in late 1991, early production testing of the Cozzette showed that the 300 ft of in-pay horizontal hole can produce at rate 5 to 10 times higher than vertical wells in the same area. Well testing and results will be presented in the paper.

References and figures at end of paper.

INTRODUCTION

Improved technology is needed to enhance natural gas production from extensive low-permeability sandstones and interbedded coal seams found in many U.S. geologic basins. From 1981 to 1988, the U.S. Department of Energy sponsored a focused tight gas field research program in the Piceance Basin of western Colorado.

Three closely-spaced wells were drilled through the Mesaverde tight gas section, and a number of individual marine and fluvial tight sands were extensively tested to characterize reservoir geology, gas production potential, and stimulation effectiveness. The synergism of geology, physics, and reservoir and production engineering, working together at the field test site, resulted in development of insights into the Mesaverde reservoirs and in characterizing production-oriented technology. Test results focused on depositional environments, the importance of natural fracturing to well productivity, the effects of parameters such as in situ geologic stress on hydraulic fracturing behavior, and the development of fracturing treatment design and evaluation techniques[1]. State-of-the-art hydraulic fracturing and well tests showed that the fractures paralleled the prevailing natural fracture network and were not very effective in stimulating gas production from the tight sands.

The Late Cretaceous-age Mesaverde Group in the Piceance Basin is a thick section of low permeability fluvial gas sands, interbedded coals, and marine blanket sands. Figure 1 shows a Mesaverde geologic column representative of the slant hole test site and the two completion intervals targeted by the slant hole. Gas production from the micro-darcy reservoirs rocks is primarily a function of natural fracture presence, spacing and orientation. Reservoir over-pressuring[2], found in much of the Mesaverde section, also plays a role in production and reserve potential. At the test site, over-pressuring begins in production and reserve potential. At the test site, over-pressuring begins at a depth of about 5,500 ft and increases to a reservoir pressure gradient of 0.80 psi/ft in the marine interval at the bottom of the Mesaverde, based on 6,300 psi in the Cozzette sand at a depth of 7,850 ft.

In 1990, DOE drilled a slant hole at the Multiwell Site[3] to evaluate directional drilling as an alternative completion technique to hydraulic fracturing. The test well was drilled on a northerly azimuth to maximize intersection of the east-west trending natural fractures, and with a complex inclination path so that two hole configurations, high angle and horizontal, could be evaluated. A thick section of interbedded tight fluvial sands and coal seams was intersected with a long 60° tangent, and then the well was turned to near-horizontal in the underlying Cozzette sand. The slant hole was extensively cored in both sections, showing that most natural fractures formed open slots in situ. Heavy gas shows were encountered throughout the tight reservoir section. The slant hole was drilled to total depth, and a liner was run into the horizontal section. After cementing the liner, gas migration into the cement-filled wellbore resulted in the loss of the hole, when still setting cement was circulated to the surface while attempting to drill out the top of the liner. Intensive fishing operations succeeded in recovering 5,335 ft of cemented drillpipe before progress stopped, leaving the completion intervals plugged and unavailable for production testing.

PLANNING THE SIDETRACK HOLE

During the winter of 1990 to 1991, the Department of Energy evaluated several options to completing the originally-planned slant hole production tests. A decision was made to sidetrack the original hole and to redrill the 60 and 90° sections. A complex well path was designed to parallel the optimum northerly azimuth and the high angle-horizontal inclination program, but to directionally drill the lower wellbore 1,000 ft to the east of the old hole. The hole displacement was planned to avoid formation damage from over 1,500 barrels of drilling mud lost in the first well. The new well was designed to depart the old hole at about 5,300 ft. The planned sidetrack point was based on the well being cleaned out to 5,330 ft, and the assumption that the 7-in. casing could be cut off and pulled to the same depth. (The bond log indicated that the 7-in. casing cement top was below 6,000 ft.) A service rig was to be used to pull as much as possible of the casing prior to moving in the drilling rig, thus providing a large open-hole section for the sidetrack.

The new well was to be drilled solely to production test the two completion targets, since the original slant hole had already supplied the coring and logging objectives. A low solids non-dispersed mud with closely controlled weights, and gas detection and removal equipment including a high capacity gas buster (mud/gas separator), were designed to avoid formation damage and loss of circulation while safely controlling gas influx. It was planned to drill the reservoir interval at or slightly below formation pressure balance.

The directional program called for the well to be kicked off at 5,250 ft, and then drilled away from the old hole at a constant 12° inclination and a S60°E heading to a measured depth of 6,500 ft. MWD equipment was to be used throughout for steering, and mud motors were to be used for all build sections and correction runs. At that point, the hole was to be turned gradually to a N20°E azimuth while building the hole inclination to 60° at a measured depth of 7,100 ft. A constant 60° tangent was to be drilled through the lenticular sands/coal seams completion target and the underlying lost circulation zone in the Rollins sand to the top of the second build at 8,900 ft MD. When the Rollins was reached, a set of wireline correlation logs were to be run across the target reservoirs to correlate the sidetrack with the original slant hole. The second build was to take the well to 87° on a north heading and to the planned casing point in the top of the Cozzette target, which was expected at around 9,250 ft. Seven-inch casing was to be run and cemented in two stages, to seal off the Rollins lost circulation interval and to isolate the sands and coal seam reservoirs in the upper completion interval for the planned stimulation test.

At that point, the rig was to be converted to operate with 3-1/2-in. drillpipe and smaller MWD and motors; this was done to drill through the Cozzette sand pay at a near-horizontal inclination of 87° and a north heading. It was planned to drill underbalanced 500 ft of 6-in. hole, while slowly dropping through the Cozzette pay zone. The projected TD was to be 9,750 ft MD, and the Cozzette was to be completed as open hole. On reaching TD, a production packer with a sealbore and an 'R' nipple assembly were to be set in the 7-in. casing just above the shoe joint. Prior to releasing the drilling rig, the 3-1/2-in. drillpipe was to be stung into the packer to backflow drilling mud from the open hole. A retrievable 'R' plug

was then to be set in the 'R' nipple to shut off the Cozzette open hole in preparation for the production testing program which was to start later that year.

The follow-on production testing was planned in two phases. On re-entering the well, the Cozzette lateral was to be tested open hole. No stimulation was planned in view of the production potential exhibited by the original hole. Well deliverability was to be established, followed with a continuous flow test into pipeline.

At that point, the Cozzette interval is to be temporarily blocked off to evaluate the upper completion target in the 60° lenticular sands and coal seams interval. A stimulation treatment and an extensive pre- and post-frac well testing program are planned for this completion zone. A final commingled flow test of both completion targets is planned to complete the slant hole completion test program.

SIDETRACKING PREPARATIONS

Opening a Window

As mentioned earlier, the sidetracking plan called for pulling of about 5,300 ft of the 7-in. casing from the old well, so that the lower hole could be redrilled with 8-3/4-in. bits. Pipe recovery operations were initiated on April 26, 1991, using a well service unit and casing jacks; operations came to a halt 10 days later at 4,100 ft when no more joints came free. A stuck pipe log was run at this time which indicated that the 7-in. casing was tight from 4,180 to 4,215 ft. It became evident that approximately 140 ft of tightly held 7-in. casing would have to be washed over to provide a 100-ft open-hole window below the 9-5/8-in. intermediate casing shoe.

The well directional plan was adjusted to the shallower than expected kickoff point from which to sidetrack the hole. It was believed that washover operations could be performed more efficiently with the drilling rig. Consequently, the service unit was moved off and the drilling rig was moved on the hole on May 12, 1991. A pilot mill was run, and 2 ft of the casing stub was milled to 4,102 ft to smooth the top of the cut. An 8-5/8-in. washover shoe and five joints of 8-5/8-in. wash pipe were then used to over core the 7-in. casing stub from 4,100 to 4,239 ft. The casing was chemically cut at 4,237 ft; 136 ft of casing was recovered from the well. A Class G cement plug was set in the 7-in. casing stub from the cut-off at 4,237 ft to 5,087 ft to seal off the lower portion of the old hole. An additional Class G plug containing 2 percent $CaCl_2$ was set from 4,237 to 4,019 ft to serve as the actual kickoff plug.

Sidetrack Kickoff Operations

The kickoff plug was dressed off to 4,160 ft. A bottomhole assembly, consisting of an 8-3/4-in. IADC Code D8X5 sidetrack bit, a steerable mud motor with a 2° bent sub, and eleven 6-1/4-in. drill collars were used to kick off the sidetrack. At 4,254 ft, the kickoff BHA was pulled after drilling a distance of 92 ft. The hole inclination had been built to 6°, while the hole azimuth was S88°E. The sidetrack bit was replaced with an 8-3/4-in. IADC Code 537 insert bit, and a 1.5° bent sub was run with the steerable motor. Drilling continued to 4,504 ft at which time the motor and the sidetrack drilling assembly were laid down. At 4,504 ft MD, 4,499 ft TVD, the hole inclination was 12° and the azimuth was S78°E.

DRILLING EQUIPMENT

Drilling Rig

The drilling rig chosen to drill the sidetrack had a depth capacity of 15,000 ft with 5-in. drillpipe. This diesel electric rig was equipped with a 142-ft mast having a 960,000 lb hook load capacity with 10 lines. The rig was equipped with a 30-ft substructure rated at 1,200,000 lbs capacity sufficient to rack 7,600 ft of 5-in., 19.50 lb/ft drillpipe and 2,100 ft of 5-in., 50 lb/ft heavy weight drillpipe.

Mud Pumps

The rig was equipped with two PZ-9 triplex 1,000 HP mud pumps. The circulation rate required by the mud motors to drill an 8-3/4-in. hole through the first and second build and through the tangent interval required 400 gpm at 3,000 psi. One of the pumps, with 5-1/2-in. liners at 150 spm, could supply the expected required circulating rate. Drilling the 6-in. diameter hole below the 7-in. casing set at 8,588 ft required a circulating rate of 165 gpm at 3,000 psi.

Mud System

A low solids non-dispersed (LSND) mud system was chosen to drill the sidetrack hole. This system was chosen over an oil-base mud based on the excellent results with that mud while drilling the original slant hole. This highly-shear thinning system contained a minimum of solids for improved penetration rate along with minimum viscosity at the bit, resulting in maximum annular velocity for hole cleaning. The mud system had the following properties: (1) Ph at 9.0 to 9.5; (2) 30 minute filtrates at 5 cc to 6 cc; (3) mud weights maintained with barite to 16.4 ppg; and (4) 8 percent diesel and a non-hydrocarbon lubricant to increase lubricity. The rig was equipped with a fine screened shale shaker, desander, desilter, mud cleaner, vacuum degasser, and a high capacity mud/gas separator (gas buster).

Drill String

Five-inch, 19.50 lb/ft, Grade 'E' drillpipe with 4-1/2-in. IF tool joints were chosen as the lightest pipe that could be used in the long 60° tangent, without buckling under the expected 30,000 to 40,000 lb weight on bit. Five-inch, 50 lb/ft, heavy weight drillpipe was selected for handling the reverse bending stresses induced by rotating the pipe through the build intervals. The 5-in. drillstring was later changed out to 3-1/2-in., 15.50 lb/ft, S135 drillpipe and 3-1/2-in., 25.3 lb/ft, heavy weight drillpipe, after the 7-in. casing had been run and cemented at 8,588 ft. The

physical properties of the 3-1/2-in. S135 drillpipe and 3-1/2-in. IF tool joint were sufficient to handle the buckling and reverse bending stresses imposed during rotary drilling operations in the build intervals, and in the Cozzette horizontal hole.

BHA Design

Angle-building in the 8-3/4-in. section of the hole was typically done with 8-3/4-in. IADC Code 537 insert bits, 6-3/4-in. steerable, adjustable motors designed to build 8.5°/100 ft, float subs, 8-1/2-in. OD string and IBS stabilizers, non-mag drill collars, 6-3/4-in. MWD tools, and a joint of compressive service non-mag drillpipe. A section of 180 ft (6 jts) of 5-in. heavy weight drillpipe, drilling jars, and another 1,950 ft (65 jts) of heavy weight drillpipe provided weight on bit and buckling and wear resistance in the build intervals. The amount of heavy weight drillpipe and its relative position within the drill string sections were periodically adjusted according to the well's then current directional profile.

Tangent sections were drilled with surface rotation. The rotary BHA typically consisted of 8-3/4-in. insert bits, 8-3/4-in. near bit stabilizer, 6-3/4-in. MWD tool, 30 ft non-mag drill collar, 8-3/4-in. non-mag string stabilizer, 10-ft non-mag drill collar, and a 30-ft drill collar. The BHA was topped by 180 ft (6 jts) of 5-in. heavy weight drillpipe, drilling jars, and 2,050 ft (68 jts) of 5-in. heavy weight drillpipe.

The BHA used to rotary drill the Cozzette lateral consisted of a 6-in. IADC Code D2R2 natural diamond bit, a 6-in. 3 pt roller reamer, 13-ft non-mag drill collar, 4-11/16 bottomhole orientation sub, 29-ft non-mag drill collar, circulating sub, a 6-in. string stabilizer, and a joint of compressive service non-mag drillpipe. Weight on bit and strength while being rotated in the two main build sections were supplied by 798 ft (26 jts) of 4-3/4-in. heavy weight drillpipe, drilling jars, 61 ft (2 jts) of 4-3/4-in. heavy weight drillpipe, 662 ft of 3-1/2-in. drillpipe, and 1,261 ft (41 jts) of heavy weight drillpipe.

Figure 2 presents the profile and plan views of the sidetrack wellbore.

DRILLING THE SIDETRACK

First Build and Paludal Tangent

Getting Thero

The upper part of the new hole was rotary drilled using conventional surface rotation, single shot surveys for position control, and an 8-3/4-in. IADC Code 517 insert bit on a packed hole assembly. The well was drilled away from the old hole on a more or less straight tangent, at an inclination of 12 to 15 degrees and a southeasterly azimuth. Over this section, from 4,504 ft to the first kickoff point at 6,550 ft MD, the average penetration rate was 6.81 ft/hr, while rotary drilling 2,046 ft of hole.

Making the Turn (and Associated Problems)

The kickoff point was reached at 6,550 ft at a hole inclination of 15.8°, on an azimuth of S67.7°E. Drilling of the first build proceeded satisfactorily, completing the compound turn at 7,309 ft and a hole inclination of 56° on an azimuth of N13.3°E. A 10.4 ppg mud weight was carried throughout the first build to 7,309 ft.

At this depth, a packed hole rotary assembly was run in the hole to begin drilling the tangent section. The assembly became stuck at 6,708 ft in a portion of the build having a 15°/100 ft dogleg. On jarring loose, the bit and a near-bit stabilizer were left in the hole, but were subsequently recovered. Efforts to ream out a second 15°/100 ft dogleg between 6,803 ft and 6,833 ft in a coaly section ultimately resulted in the hole being sidetracked at 6,833 ft. It was then decided to plug back to 6,450 ft and attempt a second kickoff. The first cement plug failed to set and was circulated from the hole. The second plug was satisfactory and a second kickoff was undertaken at 6,475 ft.

Redrilling of the first build proceeded slowly to 7,358 ft. The mud weight ultimately was raised to 12.5 ppg to stabilize sloughing shales and coal stringers. Extreme care was taken to hold dogleg severity below 8°/100 ft while drilling through the fractured interval where the 15°/100 ft doglegs occurred in the original hole. At the end of the build at 7,358 ft, the wellbore inclination was 57.1° and the hole azimuth was N14.6°E. The average penetration rate while drilling the 823 ft of the first build was 6.11 ft/hr.

Drilling The Tangent to 8,588 Ft

The first 208 ft of the tangent to 7,566 ft were drilled with both motor and surface rotation. An 8-3/4-in. insert bit was utilized with the steerable and rotatable motor to hold the hole inclination at 57.3° while turning the azimuth to N9.7°E. The remainder of the 1,230 ft tangent section to 8,588 ft was rotary drilled using an insert rock bit beefed up with heel buttons and stabilizer lugs. At 8,588 ft MD, the hole inclination was 60.4° and the hole azimuth was N9.7°E. While drilling the tangent section, it was necessary to steadily increase the mud weight to 14.3 ppg at 8,588 ft in the Mancos Shale to maintain wellbore stability. The lost circulation zone in the Rollins sand, where over 1,000 bbl of mud had been lost in the original slant hole, was drilled without incident. The mudlogger's background gas peaked at about 1,000 units while drilling through two paludal sand lenses. The coal (pressure-cored in the original slant hole[3]) above the upper sand peaked at 950 units, while the coal (conventionally cored in the slant hole[3]) below the lower sand peaked at about 900 units. Figure No. 3 presents a plot of mud weight versus true vertical depth for the sidetrack ('1991') and for the original slant hole ('1990').

Tangent Drilling Problems

Two separate fishing operations had to be conducted while drilling the tangent section. The first problem began while

tripping out for a bit change after drilling to 8,422 ft, when the pipe got stuck part way out of the hole. Circulation with full returns was maintained even though the drillpipe could not be rotated or reciprocated. Apparently, hole caving occurred at a major coal encountered at 7,280 ft. The drillpipe was backed off at 7,283 ft and pulled, and a fishing assembly consisting of a cut lip screw-in sub and bumper and oil jars was run to the top of the fish. After screwing into the fish, it came free following several minutes of down-jarring. The fish was then washed and reamed through the caving rough hole area around 7,280 ft and pulled from the hole.

After drilling to 8,588 ft, the second fishing operation also occurred on a trip out of the hole. The top IBS in the drilling assembly became key seated at 7,645 ft in a shale above a coalseam. The drillpipe was backed off at 7,602 ft, and the hole was circulated clean. The previous fishing assembly was run in the well to the top of the fish and screwed in. The fish was jarred up the hole just 10 ft when it stuck again. A second backoff was performed at 7,622 ft. The fishing assembly was rerun and screwed into the fish, which was finally jarred free and pulled from the well.

With the increased frequency of hole instability, particularly caving in the paludal coals, it was decided to run drillpipe-conveyed logs across the paludal Mesaverde completion target, and then to run and cement the 7-in. casing at the present TD of 8,588 ft to stabilize the wellbore.

Drillpipe Conveyed Logging

The log suite for the paludal Mesaverde interval consisted of phasor induction spherically focused log, lithodensity, compensated neutron, gamma ray, and caliper tools. The logs were recorded in two runs from 8,230 to 6,582 ft, using drillpipe to convey the tools. This operation required careful coordination between the rig and logging crews, since logging was performed while tripping drillpipe into and out of the hole. The entire pipe-conveyed logging operation took approximately 18 hours; the operation went smoothly and log quality was good.

MWD survey information was input to generate logs on true vertical depth for correlation purposes with offset wells; logs were also printed in measured depth format.

Casing Operations

Two-hundred-one joints of 7-in., 29 lb/ft N80 LT&C casing were run in the hole to 8,579 ft, 459 ft below the Rollins, and into the Mancos Shale. Fifty-one centralizers were placed with one centralizer above every collar through the tangent and build sections of the hole to the stage tool at 6,364 ft. Ten additional centralizers were placed above every second collar above that point. Some difficulty was experienced running the casing below 8,083 ft, but it was worked and washed down to bottom at 8,588 ft MD, 7,780 ft TVD. Full returns were experienced throughout the washdown operation. The string weight was 165,000 lb, and the casing was landed in tension with 205,000 lbs setting on the slips.

The casing was cemented in two stages. The first stage consisted of 385 sx Class G cement containing silica flour and additives to control cement weight and water loss. The well was circulated through the stage collar for ten hours prior to cementing the second stage. The second stage consisted of 285 sx Class G cement containing additives to control weight and water loss. Full returns were experienced while cementing both stages.

Second Build

The second kickoff point was determined as the well was being drilled, using detailed structural mapping of the Cozzette sand target in conjunction with well-to-well correlation of geologic markers. These markers include the major paludal coals, Rollins Sandstone, Mancos Tongue, a thin geologic marker in the Mancos Tongue characterized by high gamma ray and neutron porosity signatures, and the top of the Upper Cozzette Sandstone. A gamma ray log was run through drillpipe to fine tune the geologic correlation points and to accurately select the second kickoff point.

A 6-in. diameter hole was drilled out from under the 7-in. casing shoe at 8,588 ft to the second kickoff point at 8,660 ft, using surface rotation and an angle building BHA with an insert bit.

The first part of the second build interval, from 8,660 to 8,812 ft, was drilled with 5°/100 ft steerable motors and two insert bits. The average penetration rate was poor at 3.61 ft/hr. Three different fixed angle-build assemblies were run over this 152 ft interval attempting to build angle. These BHAs seriously underperformed, and only built 7° of hole angle over the distance. The remainder of the second build, from 8,812 to 9,020 ft, was drilled with an 11.6°/100 ft fixed angle-build motor and three insert bits. The average penetration rate was 4.17 ft/hr, and the build rate improved. The overall build rate through the second build interval averaged 6.9°/100 ft. At this point, the wellbore inclination was 85.9°, and the Cozzette was reached.

Cozzette Horizontal Section

The First 300 Ft

The top of the upper Cozzette target interval was encountered at a depth of approximately 9,006 ft MD, 7,928 ft TVD, where the hole azimuth was N10.9°E. Detailed structural mapping indicated that the Cozzette dips to the north at about 1.7°. The intent was to gradually drop through the 60-ft thick Cozzette sand over a planned course length of 500 ft. Consequently, the required average angle of penetration of the Cozzette was 87.6°.

The Cozzette lateral from 9,006 to 9,289 ft was drilled using an IADC Code D2R2 natural diamond bit on a rotary angle hold assembly. Surveys from 9,050 to 9,112 ft indicated that the hole inclination was locked on 87.7°; unexpectedly, the bit tended to remain parallel to bedding, and the borehole was not cutting across the sand's thickness as planned. This problem did not occur in the

original slant hole; in fact there the hole dropped out of the sand a little ahead of schedule. An attempt was made with a steerable motor to increase the drop angle, but with marginal results. The diamond bit run averaged a penetration rate of 4.04 ft/hr. The lateral to 9,308 ft was rotary drilled ahead with an insert bit at an average penetration rate of 2.5 ft/hr.

The mud weight was held at 14 ppg to drill the naturally fractured Cozzette pay. By design, this weight underbalanced reservoir pressure to minimize the loss of drilling fluid to the fracture system, as experienced in the original slant hole, as well as to minimize suppression of gas shows. The mud log indicated at least ten major gas shows with chromatograph readings ranging from 190 units to 800 units between 9,138 ft and 9,308 ft. The produced gas was successfully handled through the rig's gas buster. Figure 4 illustrates the location of natural fractures as indicated by gas increases on the mud log.

Fire at 9,308 ft

While tripping out of the hole for a bit change and with the bit at 5,200 ft, a very heavy gas kick threatened to blow out the well. The BOP was closed with 2,100 psi on the kelly, and an attempt was made to check the annular pressure. At that point, the 4-in. return line from the BOP stack ruptured just upstream of the choke manifold house. The released gas pressure pulled loose some electrical wiring and ignited. The resulting flash fire was quickly extinguished by closing the lower pipe rams on the BOP stack. Two rig site employees were injured. Only minor damage was done to the choke manifold house, but the 4-in. line to the choke manifold house had to be replaced.

As a result of the gas kick, the retrievable MWD tool was blown up the inside of the drillpipe approximately 1,000 ft, before it wedged in a tool joint and plugged the drillstring. Since it was not possible to circulate during subsequent well control efforts, a hole volume (250 bbl) of 16 ppg mud was bull headed down the drillpipe-casing annulus to kill the well. After a short quiet period, the well resumed flowing gas. Finally, 250 bbls of 18.7 ppg mud were pumped down the annulus to control the well. The pipe trip out was completed, and the MWD tool was located and recovered. A cleanout trip was made to 9,234 ft to circulate out the 18.7 ppg kill mud and replace it with 16.3 ppg mud prior to drilling the remainder of the Cozzette lateral.

Drilling on to 9,407 ft TMD

An IADC Code D2R2 natural diamond bit was selected to drill the remainder of the hole to TMD, projected at 9,500 ft, using an angle drop BHA and surface rotation. Seventy-five barrels of mud were lost while drilling from 9,308 to 9,358 ft. The presence of natural fractures was indicated by calcite and quartz crystals in cuttings samples. The mud weight was sufficiently overbalanced to suppress most of the gas shows. An additional 60 barrels of mud were lost as more fractured intervals were intersected between 9,376 ft and 9,407 ft. Three hundred feet of horizontal, highly-fractured Cozzette pay had been cut. At that point, it was decided to stop drilling operations at 9,407 ft TMD, 7,948 ft TVD, to minimize further mud loss to the fracture system. Approximately 400 bbls of drilling mud were lost into the Cozzette natural fracture system as a result of drilling and the post-fire well control operations. Figure 5 presents a diagram of the slant hole sidetrack wellbore at the end of drilling.

Flow Back Testing at 9,407 ft

The Cozzette bottomhole completion assembly is illustrated on Figure 6. A permanent production packer with one 6-ft joint of 2-7/8-in. tubing and an 'R' nipple was run on drillpipe and set at 8,453 ft. The mud in the drillpipe was displaced with 2 percent KCl water, and the seal assembly was stung into the packer. The Cozzette was allowed to flow back to the burn pit through a choke manifold. Gas began arriving at the flare after 40 minutes while KCl load water slowly flowed from the well. Gas, water, mud and clouds of steam continued to flow at rapidly increasing rates, until approximately 200 bbls of water and drilling mud were recovered. After recovery of liquids stopped, up to 15.8 MMCFD of gas production were tested over a 3-hour period.

Following the brief flow test, a plug was set in the packer's 'R' nipple to isolate the Cozzette open hole, a retrievable bridge plug was set in at 8,372 ft as a safety precaution, and the hole was displaced with 2 percent KCl water. The drilling rig was released on August 24, 1991.

EARLY TESTING AND CLEANUP OF COZZETTE

Reentry Problems

Operations to prepare the well for testing and production were initiated on December 10, 1991. A cement bond log run with 1,500 psi on the casing indicated 60 to 80 percent cement bond between 7,200 ft and 8,210 ft. It should be remembered that the casing was subjected to very high internal pressures during well control operations after the flash fire, which may have degraded the cement to casing bond. The retrievable bridge plug was successfully recovered, and the hole was cleaned out to the production packer at 8,453 ft. A 2-in. flush joint stinger assembly was picked up and run on 2-7/8-in. tubing to circulate mud from the pup joint and 'R' plug below the packer. Following recovery of several barrels of drilling mud, the tubing was pulled from the well minus the stinger. Following three days fishing, the stinger was recovered.

The seal assembly was run in the well on 2-7/8-in. tubing and stung into the packer, the wellhead was installed, and the well was prepared for flowback to the flare pit. Following an unsuccessful attempt to wireline retrieve the 'R' plug, a coiled tubing unit was used to circulate 160°F water to clean out the remaining mud above the 'R' plug. The plug's equalizing pin was retrieved, using wireline conveyed tools, without incident. This allowed gas to flow through two 3/16-in. ports in the 'R' plug. Further attempts to recover the 'R' plug with wireline tools were unsuccessful. An attempt to recover the 'R' plug using coiled tubing was aborted when pieces of the 'R' plug

were found inside the choke housing during routine inspection.

It was decided to run a modified isochronal flow test to determine the extent of flow restriction caused by the 'R' plug. The results of this testing were inconclusive. A decision was made to cut off the 'R' plug to eliminate any conjecture about downhole restriction and the validity of future well test information.

The attempt to cut off the 'R' nipple using a jet cutter resulted in leaving the jet cutter body and 33 ft of sinker bars in the hole, when the wireline pulled out of the rope socket following cutting off the 'R' plug. On the way out of the hole, the wireline became hung up in the grease injector, jammed and parted. This left 3,000 ft of braided line hanging from the top of the lubricator, through the master valves, and into the well. The wireline BOPs would not hold pressure sufficiently to allow removing the lubricator to replace the grease head so that the line could be pulled from the well. A wellhead freeze (using a bentonite plug and dry ice) was used to isolate the wellbore at the upper master valve. The lubricator and wireline BOP were then removed and repaired, the wireline was restrung, and the lubricator was reinstalled. The wellhead was thawed, and the wireline was recovered without incident.

Initial Flow Testing

The slant hole completion test was turned into the pipeline on January 16, 1992, at a rate of 3,048 MSCFD, 0 BWPD at 4,700 psi FTP. The well is currently being tested into the pipeline at various rates to determine the effect of pressure draw down on gas and liquid production rates. The current projection of absolute open flow potential for the Cozzette horizontal hole is in excess of 11 MMCFD.

CONCLUSIONS

Several findings concerning the production potential of the tight sands and coals were made during the drilling and preliminary testing of the slant hole sidetrack wellbore.

- Building hole angle smoothly in fractured, interbedded shale and coal intervals is difficult, and care must be taken to avoid dog legs that can lead to other problems.

- Holding mud weight below the point where the Rollins lost circulation interval breaks down results in caving of the coals and general hole instability. This mud weight balance problem could be solved with an extra casing string, but would also greatly increase well costs.

- Underbalanced drilling of the naturally fractured Cozzette sand can be a safe practice that prevents mud damage to the fractures and permits recording of gas shows by the mudlogger. However, extreme care must be taken during pipe trips to keep the hole full, and to avoid swabbing effects that can lead to loss of well control.

- While drilling underbalanced, multiple mudlog gas shows indicated the number and location of specific open natural fractures as they were intersected by the horizontal Cozzette wellbore.

- Even after sustaining heavy mud loss to the natural fracture system, three hundred feet of horizontal hole in the Cozzette pay has a production potential of at least 5 to 10 times that of vertical wells in the area of the slant hole test.

- Intersection of the natural fracture system, even in microdarcy rocks, can produce excellent production rates from the tight Mesaverde tight gas reservoirs.

ACKNOWLEDGEMENTS

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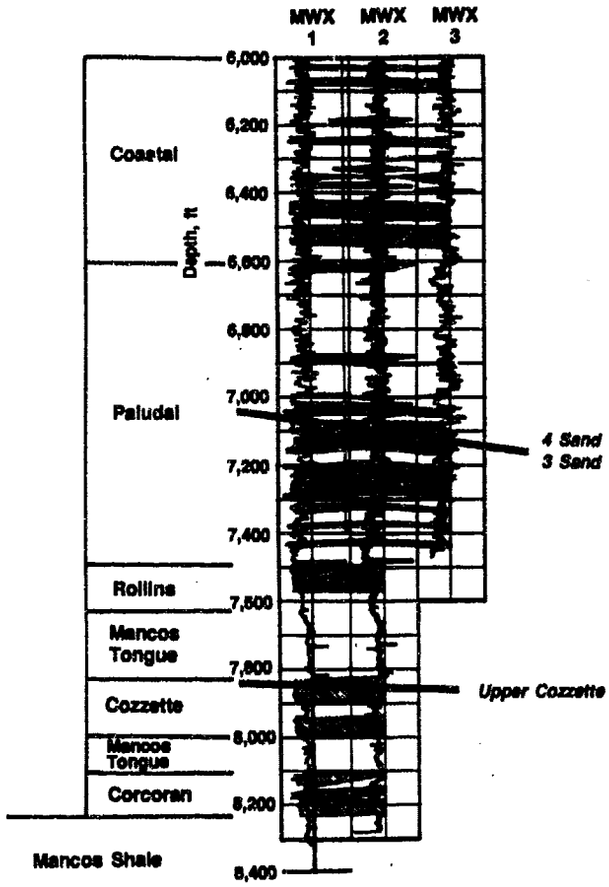

Figure 1 Mesaverde Geologic Column Near the Slant Hole Test Site

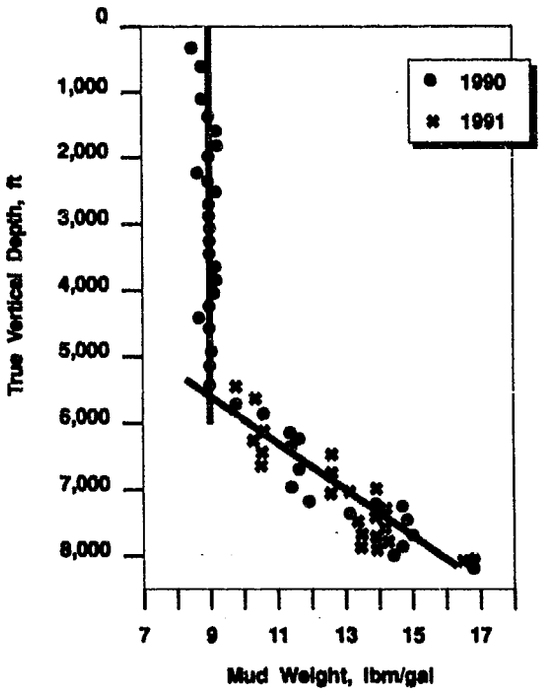

Figure 2 Slant Hole Wellbore Profile and Plan Views

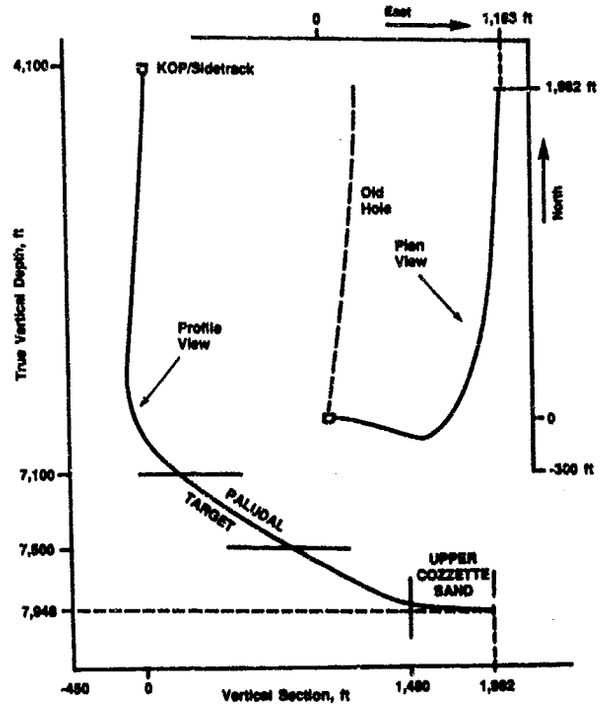

Figure 3 Mud Weight Vs. True Vertical Depth

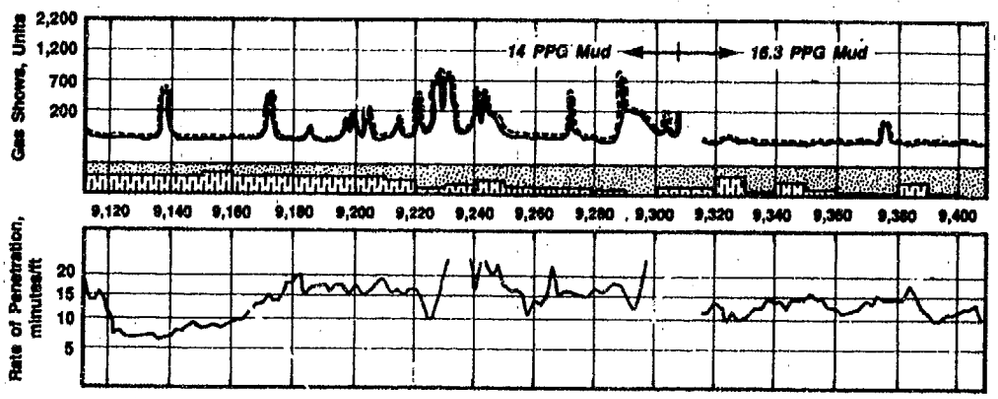

Figure 4 Mud Log Gas Shows In Cozzette Horizontal Hole

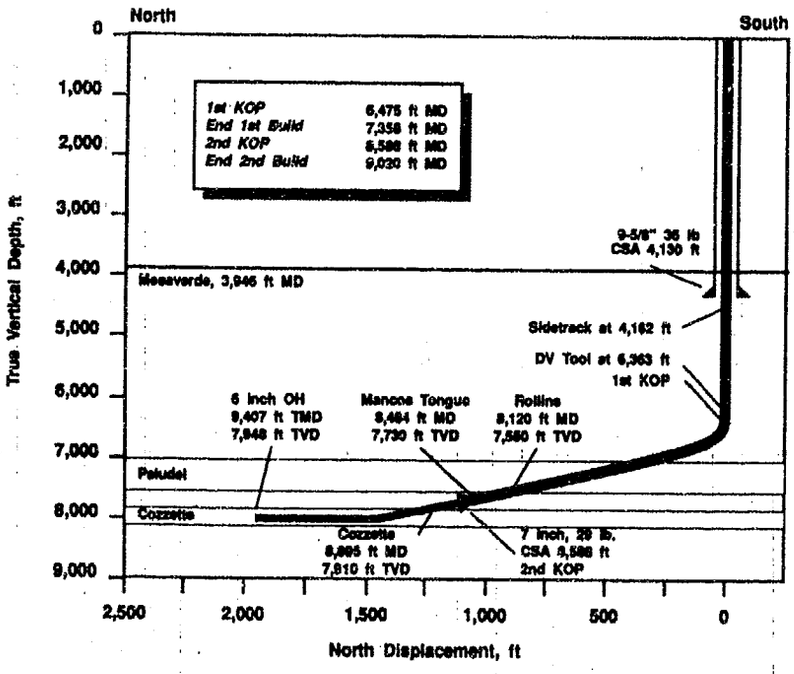

Figure 5 Slant Hole Sidetrack Wellbore Diagram

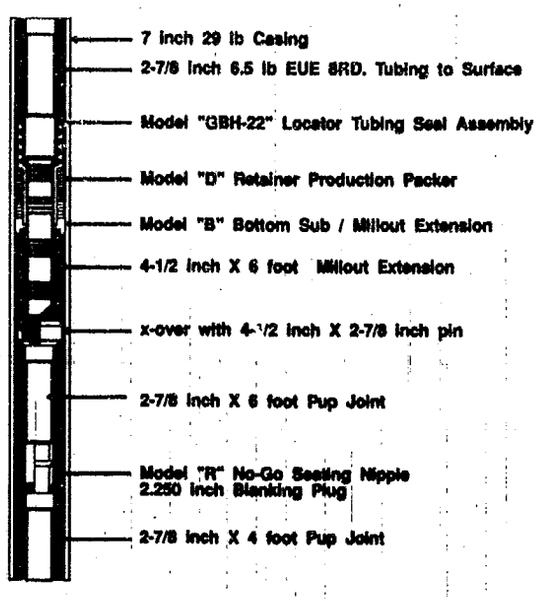

Figure 6 Cozzette Completion Assembly