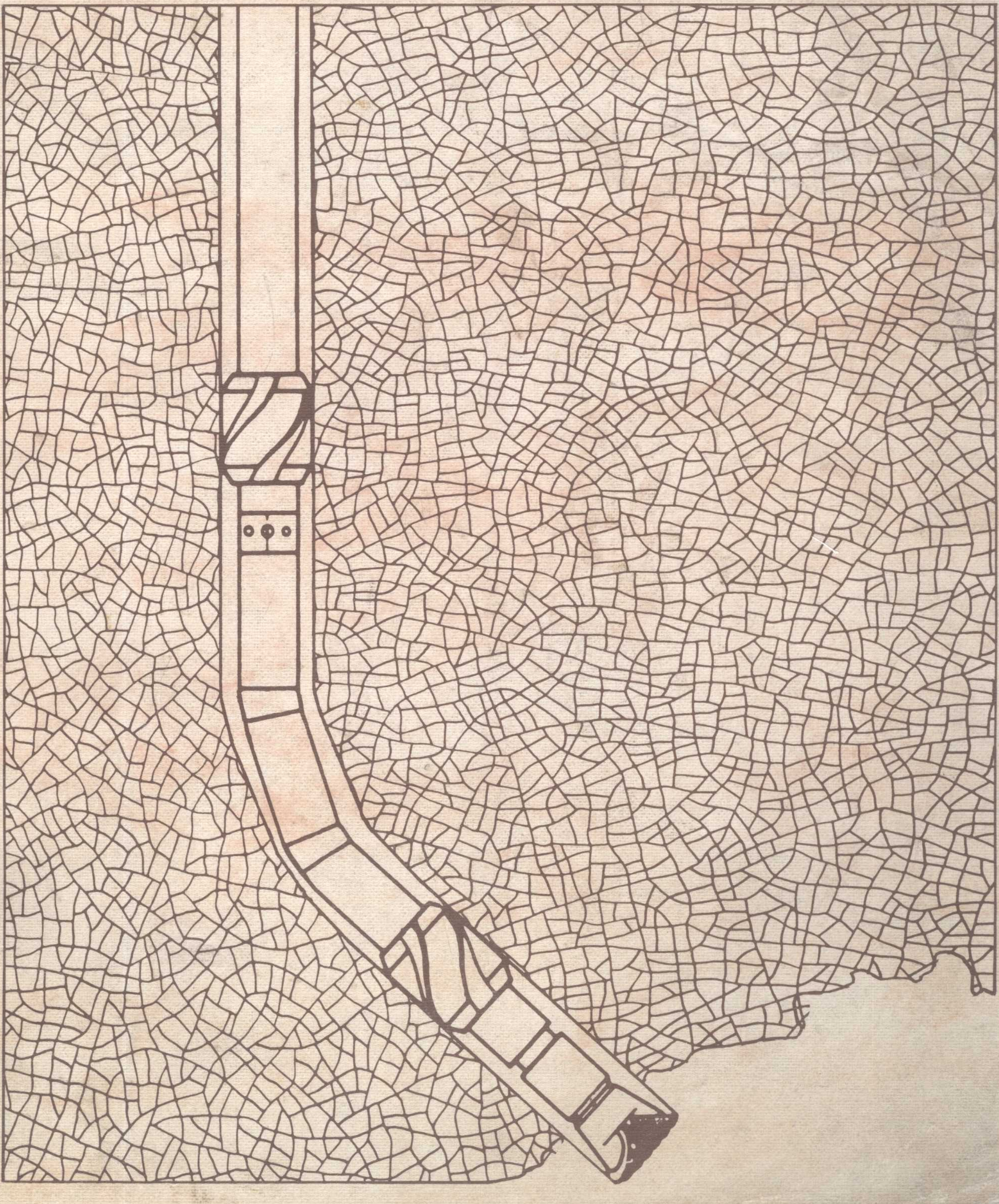
SPE REPRINT SERIES

NO. 33 HORIZONTAL DRILLING



Published by the Society of Petroleum Engineers

SPE REPRINT SERIES NO. 33

HORIZONTAL DRILLING

1991 Edition

Published by the
Society of Petroleum Engineers
Richardson, TX

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ISBN 1-55563-037-5

Preface

This Reprint Series book encompasses three primary areas of horizontal-well technology: drilling, completions, and reservoir engineering. While this important technology is rapidly advancing, the concept is not new. The earliest publication on horizontal wells found during our literature search was "The First Horizontal Oil Well" by Leo Ranney, published in *The Petroleum Engineer* in June 1939. Ranney's perception of the need for technological advancement is as true today as when he made the following comments in his publication: "In the oil industry, the man who has learned nothing new in the last 10 years may as well retire—if losses have not already retired him. The panorama of oil production changes constantly—the eternal search for new methods of producing oil at a smaller cost per barrel, and of recovering a larger percentage of the oil in the ground. That is true conservation. The production engineer is forever groping for a better way to produce oil. Whenever he stops to think that today he is leaving more than half the oil in the ground—then he seeks almost a revolutionary way. So, an entirely new method of attack, simple in plan, easy to install, having worthwhile possibilities, especially if it has been successfully tried, at least merits investigation and trial."

The application of horizontal wells to oil and gas reserves recovery is definitely a significant technological advancement in our industry, one that merits investigation and trial. Even though this technology is not new, the interest generated and technological advances made in the last few years have resulted in a substantial number of new technical publications available to the industry. The Special Reprint Committee compiling this volume discovered some 900 technical papers, news clips, and articles related to horizontal-well activity. We made every attempt to select publications for reprinting that are important to the practicing engineer and others interested in a more in-depth understanding of this technology. Because of space limitations, we were unable to include all the publications that we felt were of interest. These other publications are referenced in the Annotated Bibliography or the Bibliography. With this compendium on horizontal-well drilling, completion, and reservoir engineering, one can enrich his understanding of these important areas of horizontal wells from both a theoretical and practical standpoint.

I want to express my thanks to the Special Reprint Committee members for their efforts and expertise in putting this book together. Assisting the committee was Vicki Phelps, Oryx Energy Co., who provided literature-search/data-base support. The committee is greatly indebted to her. And finally, the support of the Society's professional staff including Holly Hargadine, is greatly appreciated.

Gerald R. Coulter, Chairman

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Part 1—Drilling

In this section, we endeavored to provide a collection of the basic technology on horizontal drilling and to include papers on applications that we hope anticipate future trends.

The first paper, a case history by Brannin *et al.*, describes methods implemented to achieve the objectives for the first horizontal well in the Tyra field offshore Denmark. In the next paper, Stewart and Williams discuss the redevelopment of the Helder field, offshore The Netherlands, with the drilling and completion of eight horizontal wells. Barrett and Lyon then describe use of the navigational drilling system to overcome problems with conventional drilling assemblies in horizontal wells, and Schuh explores several methods for designing the build curve to hit a small horizontal target when a single bottomhole assembly is used for the angle-building portions of the hole. The paper by Markle discusses unique engineering problems encountered with shallow, long-displacement horizontal wells, and Dawson and Paslay present information on drillpipe buckling in inclined holes. The final paper, by Wilkirson *et al.*, is a case history of a horizontal drilling project in Prudhoe Bay, AK.

Most successes to date in horizontal wells have involved simple well designs and techniques. The future growth of horizontal drilling will require smaller vertical targets and more complex techniques. We also anticipate continued efforts to increase the length of horizontal wells. These efforts will increase the importance of drillstring design, especially torque, drag, and buckling considerations.

We hope that the papers in this section expand the readers' understanding of the interesting choices faced in horizontal-well design and provide currently available tools to evaluate alternative choices.

IADC/SPE 19985

Drilling a Record Horizontal Well: A Case History

C.S. Brannin, Texaco Denmark; L. Velser, Maersk Oil & Gas A/S; and M.P. Williams, Eastman Christensen

SPE Members

This paper was prepared for presentation at the 1990 IADC/SPE Drilling Conference held in Houston, Texas, February 27–March 2, 1990.

ABSTRACT

During early 1989, Maersk Oil & Gas A/S, as operator for Danish Underground Consortium, drilled the first horizontal well in the Tyra field, offshore Denmark. Prior experience acquired during horizontal drilling operations in the Dan field enabled Maersk to establish ambitious objectives for well TEB-1, including:

- displacement at total depth of 10,000 ft [3050 m],
- horizontal section of 3,000 ft [910 m], with maintenance of a 20 ft [6,1 m] vertical tolerance throughout,
- cementation, with rotation, of a 6 5/8-in [168,3-mm] production liner across the horizontal completion interval.

To achieve these objectives economically, Maersk implemented a well profile with both long- and medium-radius characteristics; steerable medium-radius angle-build drilling motors; thermally-stable synthetic diamond drill bits; and the most recent advances in liner hanger technology.

The unqualified success of drilling operations on well TEB-1 has confirmed the viability of precisely placed, high displacement, horizontal completion intervals as an economical alternative to more conventional field development strategies.

INTRODUCTION

The Tyra field was discovered by Danish Underground Consortium (DUC) in 1968. Located in Danish North Sea waters, approximately 134 miles [215 km] west of Esbjerg (Fig.1), the Tyra structure is a rather flat, east-west trending anticline with dips of 1.5 to 3.5 deg [0,026 to 0,061 rad] and minor faulting. The Tertiary Danian and Cretaceous Maastrichtian chalk intervals are principally gas-bearing, with the majority of Tyra gas reserves contained within the former.

By mid-1987, Tyra field development consisted of 36 wells drilled from two platforms, with coverage confined to the western and central portions of the structure (Fig.2); the eastern flank had not yet been drilled.

RESERVOIR DESCRIPTION

The Tyra reservoir unit targeted as a completion objective for an eastern flank appraisal well was the gas-bearing Danian D1, which is uniformly comprised of a beige, moderately-hard chalk with extensive sub-vertical hairline fracture networks and a modicum of chert.

In the crestal area of the Tyra field, Danian D1 porosity and permeability generally falls within the range of 40 to 50% and 1 to 10 md respectively; reservoir characteristics deteriorate somewhat in the flank regions of the structure.

Gas column thickness in the developed central and western portions of the field ranges from 220 to 90 ft [67 to 27 m], while that in the eastern flank ranges from 90 ft [27 m] downward to zero. Detailed information on the distribution of gas column thickness in the eastern flank was not available due to the absence of positive geologic control.

FLANK WELL OBJECTIVES

The principal objective of the Tyra eastern-flank appraisal well was to establish geologic and economic justification for a flank development

Reference and illustrations at end of paper.

scheme. A successful appraisal effort would provide:

- longterm production data to facilitate an assessment of flank development contribution to total gas recovery,
- improved definition of flank structure and reservoir quality,
- calibration data for the Tyra field seismic model.

Reservoir evaluation requirements included a comprehensive wireline logging program, coring of the Danian D1 and D2 units to the gas/oil contact (GOC), and RFT sampling of select chalk intervals.

WELL PROGNOSIS FORMULATION

With flank appraisal objectives clearly defined, additional study of ongoing geophysical interpretations confirmed a location approximately 10,000 ft [3050 m] to the south-east from Tyra East "B" (TEB) platform as the best candidate for flank appraisal.

Consideration of appraisal well objectives, in view of reservoir information inferred from geophysical and general field data, suggested that a horizontal completion interval in the Danian D1 unit would mitigate the potential for substantial water influx, thereby facilitating the accumulation of long-term production data. Furthermore, an extension of the horizontal wellbore beyond the prognosed completion interval would afford an excellent opportunity to investigate the GOC/GWC at the south-east flank periphery.

An appraisal well prognosis requiring a horizontal interval of 3,000 ft [910 m] at a departure of 10,000 ft [3050 m] appeared viable based on previous drilling experience in nearby Dan field[1], where three wells had been successfully completed with horizontal sections and total departures averaging approximately 2,060 ft [628 m] and 6,440 ft [1963 m] respectively.

DRILLING PROGRAM DEVELOPMENT

Tyra field development drilling operations had established sound guidelines for casing and drilling fluids programs, and field drilling practice in general. The more challenging prognosis for well TEB-1, while beyond the scope of nominal Tyra drilling operations, was well founded in the experience gained during several horizontal drilling projects in the nearby Dan field. Therefore, drilling program development for well TEB-1 drew on proven practice from Tyra field development drilling operations as well as specialized practice successfully tested in the Dan field.

Casing Program

The casing program for earlier Tyra field development wells was considered adequate for well TEB-1 (all depths RKB):

- 24-in [609,6-mm] pipe driven to 400 ft [122 m] TVD, giving approximately 140 ft [43 m] seabed penetration;
- 18 5/8-in [473,1-mm] conductor set in 21-in [533,4-mm] hole at 1,388 ft [423 m] TVD, or 1,412 ft [430 m] MD. Pipe to be cemented to surface;
- 13 3/8-in [339,7-mm] surface casing set in 17 1/2-in [444,5-mm] hole at 3,838 ft [1170 m] TVD, or 5,160 ft [1573 m] MD, directly above an overpressured shale interval. Pipe to be cemented to surface;
- 9 5/8-in [244,5-mm] intermediate casing set in 12 1/4-in [311,2-mm] hole at the prognosed Danian D1 top of 6,470 ft [1972 m] TVD, or 10,127 ft [3087 m] MD. Pipe to be cemented to 2,000 ft [610 m] below surface;
- 6 5/8-in [168,3-mm] liner set in 8 1/2-in [215,9-mm] hole, with setting depth at the end of the drainhole completion interval prognosed to be 6,537 ft [1993 m] TVD, or 11,818 ft [3602 m] MD. Liner to be cemented along entire length, across liner hanger and 200 ft [61 m] above, with liner rotation during cementing and displacement.

Drilling Fluids Program

The drilling fluids program for earlier Tyra development wells required the use of a low-toxicity invert-emulsion oil-base mud system through the 12 1/4-in [311,2-mm] interval, which is predominated by a reactive and overpressured Tertiary shale approximately 2,500 ft [760 m] in thickness.

Testing of various water-base drilling fluid formulations identified a composition that appeared to provide satisfactory inhibition of shale swelling and deterioration, relative ease of maintenance, reduced cost, and low environmental risk. These potential advantages were sufficiently compelling, particularly in view of anticipated regulatory changes regarding the use of oil-base mud (OBM) in Danish waters, that a field trial of the water-base mud system was approved for the 12 1/4-in [311,2-mm] interval on well TEB-1.

The drilling fluids program for well TEB-1 is summarized as follows:

- 21-in [533,4-mm] interval: pre-hydrated bentonite and seawater, unweighted;
- 17 1/2-in [444,5-mm] interval: native clay, lime, caustic soda and seawater, 8.5 to 9.5 lb/gal [1,02 m to 1,14 kg/L];
- 12 1/4-in [311,2-mm] interval: lime-treated water-base with asphaltene shale stabilization material, 13.0 to 14.0 lb/gal [1,56 to 1,68 kg/L];
- 8 1/2-in [215,9-mm] interval: low-toxicity invert-emulsion oil-base, 12.0 to 12.5 lb/gal [1,44 to 1,50 kg/L], 80/20 oil/water ratio, 120 000 to 160 000 mg/L Cl^- (water-phase).

Directional Wellplan

The requirements for well TEB-1 directional wellplanning and execution were as follows:

- establish the departure necessary to penetrate the Danian D1 at the prognosed location;
- provide for pilot-hole penetration of the Danian D1 at an inclination suitable for economical coring of the Danian D1 and D2 members, and subsequent confirmation of the desired interval for horizontal completion and appraisal;
- facilitate pilot-hole plugback, kickoff and build-to-horizontal, within a vertical clearance of 30 ft [9 m], using a wellpath curvature that would allow extended liner rotation during cementation without risk of liner failure;
- Minimize the accumulation of drillstring torque and drag in order to provide the most favorable environment for successful realization of the drilling prognosis.

The well TEB-1 target, and beginning of the horizontal interval, was positioned at a departure of approximately 7,240 ft [2207 m], on azimuth 105.5, at a depth of 6,638 ft [2023 m] TVD, or 30 ft [9 m] below the prognosed top of the Danian D1 chalk interval. The tolerance for target entry and subsequent horizontal completion and appraisal interval drilling was as follows:

- in the horizontal plane, a square 200 by 200 ft [61 by 61 m], squarely aligned with the planned wellpath azimuth and centered on the target location;
- in the vertical plane, a rectangle 200 ft [61 m] wide by 20 ft [6,1 m] tall, oriented perpendicular to the planned wellpath azimuth and centered on the target location;
- along the wellpath axis, in the vertical plane, a rectangle 200 ft [61 m] wide by 20 ft [6,1 m] tall, centered on the proposed wellpath.

Horizontal Maastrichtian wells drilled in the Dan field were designed for low drillstring/ wellbore friction (torque and drag), with shallow, intermediate and deep kick-off points, using a build-up rate of 2.5 deg/100 ft [2,5 deg/30 m] through all build intervals. An alternate wellplan was required for well TEB-1, retaining the low-friction characteristics of the Dan field trajectories, but meeting the requirement for initial pilot-hole penetration of the Danian and subsequent drilling of the horizontal section.

The directional wellplan developed for well TEB-1 (Fig. 3A) required shallow and intermediate kick-off points, using conventional build rates of 2.5 and 3.0 deg/100 ft [2,5 and 3,0 deg/30 m] respectively, to establish an inclination of 54 deg through the overpressured shale and 75 deg at the chalk top.

Following pilot hole coring and logging operations, and plugback into the 9 5/8-in [244,5-mm] casing, a third kickoff would be effected using a specially-designed steerable (i.e., rotatable) medium -radius (SMR) drilling motor (PDM), building to the required inclination of 89 deg, at a planned build rate of 8.3 deg/100 ft [8,3 deg/30 m], within the limited vertical clearance between casing shoe and target.

Drilling Assemblies

Previous experience drilling the Dan field horizontal wells showed steerable PDM drilling assemblies to be reliable and cost-effective, permitting the required wellpath trajectories to be established more precisely, and with fewer trips, than was normally possible with conventional directional drilling methods.

The more ambitious objectives for well TEB-1 made careful control of the wellpath trajectory of even greater importance than with the Dan field wells, and drilling assemblies selected for the 21-, 17 1/2-, and 12 1/4-in [533,4-, 444,5-, and 311,2-mm] intervals were all of the steerable PDM variety.

Following pilot-hole coring of the Danian D1 and D2 members, plugback, and cement drillout to the third kickoff point, an SMR/PDM drilling assembly would be picked up to establish the final angle build, at 8.3 deg/100 ft [8,3 deg/ 30 m], to effect the required target interception at an inclination of 89 deg.

Drilling of the horizontal completion and appraisal interval would be accomplished with a steerable PDM drilling assembly and thermally-stable synthetic diamond drill bits.

Dan field horizontal drilling experience had shown that the use of 5-in [127,0-mm] drillpipe for compressive service in the 8 1/2-in [215,9-mm] horizontal interval resulted in significant reductions in torque and drag, and improved hydraulics, when compared to heavy-weight drillpipe (HWDP); indications of drillpipe buckling, such as excessive down-drag and torque while drilling, or drillpipe fatigue failure, were not observed.

A simulation of anticipated torque and drag through the horizontal interval of well TEB-1 indicated that 5-in [127,0-mm] drillpipe would be adequate for the anticipated compressive- service loads, and that the additional resistance to sinusoidal or helical buckling provided by 5-in [127,0-mm] HWDP was not required.

Wellbore Survey Program

Wellbore survey requirements for well TEB-1 were as follows:

- gyro survey of 24-in [609,6-mm] conductor through drillpipe following the first gyro single-shot orientation of the 21-in [533,4-mm] kick-off assembly;
- gyro surveys and orientation of 21-in [533,4-mm] kick-off assembly until clear of possible magnetic interference from nearby wells;
- MWD surveys through the balance of the 21-in [533,4-mm] interval, and through the 17 1/2 - ,

12 1/4 -, and 8 1/2-in [444,5-, 311,2-, and 215,9-mm] intervals;

- magnetic multi-shot surveys (electronic) of 17 1/2-in [444,5-mm] and 12 1/4-in [311,2-mm] intervals during trips at the 13 3/8-in [339,7-mm] surface casing and 9 5/8-in [244,5-mm] intermediate casing setting depths;

- gyro multi-shot surveys inside 18 5/8-in [473,1-mm] conductor, 13 3/8-in [339,7-mm] surface casing and 9 5/8-in [244,5-mm] intermediate casing;

Coring Program

The requirement for improved definition of Tyra field's eastern flank reservoir properties placed particular emphasis on the recovery of cores through the hydrocarbon-bearing Danian D1 and D2 units. Coring planned for well TEB-1 included:

- 8 1/2-in [215,9-mm] pilot hole: 60-ft [18,3-m] oriented core, beginning at the top of the D1 chalk, followed immediately by a 180-ft [54,9-m] conventional core;

- 8 1/2-in [215,9-mm] horizontal hole: 30-ft [9,1-m] conventional core at TD, wellbore conditions permitting.

The taking of sidewall cores was reserved as a contingency alternative.

Logging Program

Requirements for the logging of well TEB-1 were as follows:

- 21-in [533,4-mm] interval: none required;

- 17 1/2-in [444,5-mm] interval : none required;

- 12 1/4-in [311,2-mm] interval: none required;

- 9 5/8-in [244,5-mm] casing: CBL/VDL/CCL/GR from hold-up depth (HUD) to 100 ft [31 m] above the cement top; SDT/GR from HUD to 2,000 ft [610 m] above the chalk top;

- 8 1/2-in [215,9-mm] pilot hole: DIL/SDT/GR/LDL /CNL/CAL from TD to 100 ft [31 m] above the chalk top, drillpipe-conveyed; VSP from TD to surface, drillpipe-conveyed; OBDT or SHDT from TD to 100 ft [31 m] above the chalk top; RFT as indicated;

- 8 1/2-in [215,9-mm] horizontal hole: GR (MWD) or GR/induction (MWD), the latter preferred if available; DIL/LSS/LDL/CNL/GR/CAL from TD to 100 ft [31 m] above the chalk top, drillpipe-conveyed; RFT as indicated, drillpipe-conveyed.

DRILLING OPERATIONS SUMMARY

Well TEB-1 drilling operations commenced on 19 December, 1988 aboard the jack-up Glomar Moray Firth. Lost circulation, subsequent to cleanout of the 24-in [609,6-mm] drive pipe, required remedial cementing prior to initiation of directional drilling operations in the 21-in [533,4-mm] interval.

21-in [533.4-mm] Interval

Well TEB-1 was kicked off at 420 ft [128 m] MD/TVD with a steerable PDM drilling assembly. Initial orientations, to a depth of 668 ft [204 m] MD, were effected with gyro single-shot surveys.

Bit balling problems at circulation rates of 540 to 600 gal/min [2040 to 2270 L/min] were overcome by increasing the circulation rate to 800 gal/min [3030 L/min], but build rates suffered as a result, and persistent orientation of the steerable PDM drilling assembly was necessary to achieve the planned build rate of 2.5 deg/100 ft [2,5 deg/30 m].

Directional drilling continued to 1,430 ft [436 m] MD and 20.0 deg inclination, where 18 5/8-in [473,1-mm] conductor was run, landed at 1,410 ft [430 m] MD, and inner-string cemented to surface.

The 21-in [533,4-mm] interval, from 400 to 1,430 ft [122 to 436 m] MD, was drilled at an average rate-of-penetration (ROP) of approximately 40 ft/hr [13 m/hr].

17 1/2-in [444.5-mm] Interval

The directional wellplan for well TEB-1 required the initial tangent angle of 54 deg to be established in the 17 1/2-in [444,5-mm] interval, maintaining that inclination for 2,500 ft [760 m] to the 13 3/8-in [339,7-mm] surface casing setting depth of 5,160 ft [1573 m] MD.

A steerable PDM drilling assembly, with milled tooth drill bit, was used to drill out the 18 5/8-in [473,1-mm] conductor. Following a leak-off test (LOT) to 12.4 lb/gal [1,49 kg/L] equivalent mud weight (EMW), oriented- and rotary-mode drilling continued to 5,210 ft [1588 m] MD, drilling the entire 3,780-ft [1152-m] interval in one trip at an average ROP of approximately 130 ft/hr [40 m/hr].

The first tangent angle of 54 deg was established as per the directional wellplan, with high-side orientation required throughout most of the angle-build section. Tangent section drilling was completed largely in rotary mode, with oriented-mode drilling totaling about 15% of tangent section footage.

After circulating a small volume of high viscosity drilling fluid and dropping an electronic magnetic multi-shot survey instrument, the steerable drilling assembly was pulled and 13 3/8-in [339,7-mm] casing was run, landed at 5,193 ft [1583 m] MD and cemented to surface without difficulty.

12 1/4-in [311.2-mm] Interval

Maintenance of the previously established tangent angle of 54 deg was required through the first 4,000 ft [1220 m] of the 12 1/4-in [311,2-mm] interval. After passing through the overpressured shale predominating this interval, a second build section was required to reach an inclination of 75 deg at the Danian D1 chalk top, setting depth for the 9 5/8-in [244,5-mm] intermediate casing.

A steerable PDM drilling assembly, with PDC drill bit, was used to drill out the 13 3/8-in [339,7-mm] surface casing float equipment. Following a LOT to 15.9 lb/gal [1,91 kg/L] EMW, this assembly drilled approximately 270 ft [82,3 m] before severe bit balling and resulting low ROP required a trip for bit replacement.

The balance of the first tangent section, to a depth of 8,887 ft [2709 m] MD, was drilled with steerable PDM drilling assemblies and milled tooth drill bits.

The second angle-build interval was initiated at 8,887 ft [2709 m] MD with a steerable PDM drilling assembly, and the required inclination of 75 deg was established just prior to reaching the chalk top, setting depth for 9 5/8-in [244,5-mm] intermediate casing.

The 12 1/4-in [311,2-mm] interval, from 5,135 to 10,260 ft [1565 to 3127 m] MD, was drilled at an average ROP of approximately 50 ft/hr [15 m/hr], with significant portions of that interval drilling at ROP's on the order of 80 to 90 ft/hr [24 to 27 m/hr].

Following two difficult clean-up trips with a rotary reaming assembly, 9 5/8-in [244,5-mm] intermediate casing was run, landed at 10,254 ft [3125 m] MD, and cemented with casing reciprocation, as per the cementing program; partial or complete loss of returns was observed during lead and tail slurry displacement. After CBL confirmation of poor primary cementing results, cement and float equipment were drilled out, gyro multi-shot survey taken, and remedial squeeze cementation performed with satisfactory results.

The experiment with water-base drilling fluid in the 12 1/4-in [311,2-mm] interval was successful, but not without some difficulties. Persistent problems with "gumbo" resulted in swabbing, tight hole and several occurrences of stuck pipe, even when back-reaming with the top-drive. Nevertheless, major operational difficulties were avoided, and further refinement of the water-base drilling fluid composition is expected to substantially reduce these difficulties on future Tyra wells.

8 1/2-in [215,9-mm] Pilot-Hole Interval

After drill-out of the 9 5/8-in [244,5-mm] casing, the water-base drilling fluid from the previous interval was displaced with low-toxicity invert-emulsion OBM.

The 60-ft [18,3-m] oriented core was cut from 10,270 to 10,330 ft [3130 to 3148 m] MD, recovering 26 ft [7,9 m], or 43 %, of the cored interval.

Four additional runs were made with a 60-ft [18,3-m] core barrel dressed for cutting conventional cores. Over the 164-ft [50,0-m] interval from 10,330 to 10,494 ft [3149 to 3199 m] MD, a total of 107 ft [32,6 m] of Danian chalk was recovered, giving a recovery rate of 65 %. Core jamming, due to chert nodules, was principally responsible for the relatively low recovery rate.

Rotary drilling proceeded from 10,494 to 11,290 ft [3199 to 3441 m] MD, where an electronic magnetic multi-shot survey was taken during the trip to pick up drillpipe-conveyed logging equipment.

The 8 1/2-in [215,9-mm] pilot-hole interval was logged down and up with a drillpipe-conveyed logging string (DIL/SDT/GR/LDL/ CNL/CAL) as per the well TEB-1 logging program. No difficulties were encountered with either latching or shearing free the logging cable wet connector, and logs of acceptable quality were obtained over the entire pilot-hole interval.

Drillpipe-conveyed RFT logs were taken over the pilot-hole interval, with 23 good readings from 63 probe settings. A drillpipe-conveyed OBDT log was obtained over the interval 11,260 to 10,254 ft [3432 to 3129 m] MD, followed by a drillpipe-conveyed CET/CBL/VDL/GR log over the cased-hole interval from 10,225 to 9,254 ft [3117 to 2821 m) MD. The CBL/VDL log was subsequently rerun on wireline over the interval from 9,600 to 4,900 ft [2926 to 1494 m] MD.

After conducting a drillpipe-conveyed VSP survey of 100 shots on the interval from 9,600 to 1,500 ft [2926 to 457 m] MD, pilot-hole logging operations were concluded with an SDT survey on the interval from 10,000 to 8,200 ft [3048 to 2499 m] MD.

8 1/2-in [215,9-mm] Horizontal Interval

The limited vertical clearance between the 9 5/8-in [244,5-mm] casing shoe and the target center for the beginning of the horizontal completion and appraisal interval required that the 8 1/2-in [215,9-mm] pilot hole be plugged back into the casing, thereby improving the likelihood of firm cement, directly below the casing, from which to initiate a sidetrack with the SMR/PDM drilling assembly. Plugback was effected with the setting of a 500-ft [152-m] balanced cement plug from 10,345 to 9,845 ft [3153 to 3001 m] MD, which was subsequently dressed to 10,260 ft [3127 m] MD. The last 210 ft [64 m] of cement was sufficiently hard to assure a positive and rapid sidetrack.

The SMR/PDM drilling assembly, with milled tooth drill bit, was picked up and tripped to the top of the cement at 10,260 ft [3127 m] MD. The kick-off was initiated, and oriented-mode drilling proceeded to 10,384 ft [3165 m] MD and an inclination of 87 deg, for an average build rate over the 124-ft [37,8-m] third angle-build interval of approximately 9.4 deg/100 ft [9,4 deg/30 m]. The SMR/PDM assembly was pulled prior to reaching the required 89 deg inclination in order to accommodate some additional "follow-through", due to the influence of wellbore curvature, with the conventional steerable PDM drilling assembly to follow.

The steerable PDM drilling assembly, with thermally-stable synthetic diamond drill bit and RLL logging tool, was picked up, run to TD, and back-reamed to the 9 5/8-in [244,5-mm] casing shoe, checking surveys every 30 ft [9,1 m] while returning to bottom. As drilling proceeded, inclination maintenance became increasingly more difficult, with as much as 30% chert encountered over one 40-ft [12,2-m] interval. The steerable PDM drilling assembly was pulled at 10,730 ft [3271 m] MD, with back-reaming to the 9 5/8-in [244,5-mm] casing shoe indicative of excellent hole conditions.

To facilitate wellpath corrections while minimizing the total requirement for oriented-mode drilling, the SMR/PDM was picked up again. Drilling proceeded without incident to 12,260 ft [3737 m] MD, where a trip was made for a new bit, SMR/PDM and down-loading of data from the RLL logging tool. Back-reaming of the entire open-hole interval was uneventful, and overpull rarely exceeded 10,000 lbs [44 kN]. Rotary torque while drilling averaged approximately 12,500 lbf-ft [16 900 N·m].

Drilling proceeded to 13,349 ft [4069 m] MD, where the SMR/PDM drilling assembly was again pulled for a new bit and RLL data down-loading, with back-reaming to the 9 5/8-in [244,5-mm] casing shoe and check surveys every stand. Inclination through the course of this run was gradually reduced, with low-side orientations, from 89 to 79 deg in order to locate the Danian GOC/GWC, as per appraisal interval objectives. Rotary torque while drilling averaged approximately 15,000 lbf-ft [20 300 N·m].

During the third run with the SMR/PDM drilling assembly, and thermally-stable synthetic diamond drill bit, inclination was further reduced with low-side orientations. Drilling of the 8 1/2-in [215,9-mm] horizontal completion and appraisal interval was completed at 13,660 ft [4164 m] MD, with a final inclination of 74.4 deg, after establishing 3,276 ft [999 m] of horizontal section; departure from the Tyra East platform reference was 10,515 ft [3210 m] (Fig. 3B).

A total of nine days were required to drill the interval from kick-off below 9 5/8-in [244,5-mm] intermediate casing to TD, using one milled tooth drill bit and four thermally-stable synthetic diamond drill bits; two of the latter drilled 77 % of the total interval footage.

The 8 1/2-in [215,9-mm] horizontal completion and appraisal interval was logged down and up over the interval 10,254 to 13,640 ft [3125 to 4158 m] MD with a drillpipe-conveyed logging string (DIL/LSS/LDL/CNL/GR/CAL). A drillpipe-conveyed RFT log was taken over the same interval, with 23 good tests from 31 probe settings. As with earlier drillpipe-conveyed logging operations in the 8 1/2-in [215,9-mm] pilot hole, no significant difficulties were encountered while latching or shearing free the logging cable wet connector.

6 5/8-IN [168,3-mm] LINER CEMENTATION

Prior to liner running and cementing operations, a trip was made to TD with a rotary reaming assembly. Hole conditions going to bottom were excellent, and the 8 1/2-in [215,9-mm] interval was back-reamed to the 9 5/8-in [244,5-mm] intermediate casing shoe without difficulty. Drillstring torque and drag measurements provided calibration data for a torque-and-drag simulation of liner cementing operations, confirming the viability of liner rotation while cementing.

Running of the 4,173-ft [1271,9-m], 6 5/8-in [168,3-mm], 20.00 lb/ft, [29,76 kg/m] P110 liner, with premium-threaded couplings and hydraulically-set rotatable liner hanger with seal-bore extension, was trouble-free. After washing to bottom, the liner was spaced out, liner hanger set and running tool released and confirmed free with drillpipe rotation. The liner hanger running and setting tool was modified to allow rotation and circulation during liner-running operations.

The liner was cemented as per the well TEB-1 cementing program, with full returns and liner rotation throughout the cementing operation. Liner rotation speed was 18 to 20 rev/min, with 12,500 to 13,750 lbf-ft [16 950 to 18 650 N·m] torque throughout liner cementing operations, of which 10,000 lbf-ft [13 600 N·m] was due to rotation of the drillpipe running string. Cement displacement was effected at a rate of 6.0 bbl/min [1.0 m^3/min].

After raising the drillpipe running string 300 ft [91 m], the 9 5/8-in [244,5-mm] casing was circulated clean, with a trace of spacer fluid detected, but no evidence of excess cement. A subsequent trip with bit and scraper assembly confirmed the absence of cement at the liner top, located at 9,494 ft [2894 m] MD.

The liner hanger seal-bore extension ID was polished with a seal-bore mill, and a liner packer, with seal-bore receptacle, was run, landed in the liner hanger extension, mechanically set, and positive pressure-tested to 3,000 lb/in^2 [20,7 MPa].

Well TEB-1 was displaced with 12.3 lb/gal [1,48 kg/L] calcium bromide ($CaBr_2$) brine after displacing the OBM with seawater, and circulating until clean returns were observed.

The interval from the liner top at 9,494 ft [2894 m] MD to 13,437 ft [4096 m] MD was logged down and up with a drillpipe-conveyed logging string consisting of CET/CBL/VDL/CCL/GR. The top of the cement was established at approximately 10,400 ft [3170 m] MD, about 900 ft [270 m] short of the liner top. Additional log interpretation confirmed the presence of fair-to-good cement over most of the 6 5/8-in [168,3-mm] liner interval.

WELL TEB-1 COMPLETION OVERVIEW

Well TEB-1 was selectively perforated and acidized from 13,231 ft to 12,100 ft [4033 to 3688 m] MD using a drillpipe-conveyed combination perforation/stimulation tool string. A permanent packer was then set in the 6 5/8-in [168,3-mm] liner at 12,000 ft [3658 m] MD.

The 4 1/2-in [114,3-mm] completion tubing string with tubing-retrievable packer was run, spaced out and landed in the wellhead. After pressure testing the completion tubing string, the completion packer was set, in the 9 5/8-in [244,5-mm] casing, at 9,356 ft [2852 m] MD, with the tailpipe re-entry guide located some 40 ft [12,2 m] above the 6 5/8-in [168,3-mm] liner top.

SUMMARY OF RESULTS

Well TEB-1 drilling and liner setting operations were concluded in 70 days, requiring an additional seven days over and above the prognosed drilling time of 63 days (Fig. 4). The variance between actual and prognosed drilling time was largely accumulated at the 9 5/8-in [244,5-mm] intermediate casing setting depth, where lost circulation, high levels of background gas and persistant wellbore packoff resulted in significant delays prior to running and cementing casing.

Operations below 9 5/8-in [244,5-mm] casing, including pilot-hole coring and logging, plugback, drilling of the horizontal completion and appraisal interval, logging and setting of the 6 5/8-in [168,3-mm] liner, required a total of 35 days, as per the drilling program time estimate for that interval.

In terms of reservoir and production engineering objectives, well TEB-1 was an unqualified success. The requirements for total displacement and total horizontal section were marginally exceeded, and the cores and logs obtained in the targeted appraisal interval (Danian) were of high quality. Liner cementation in the 8 1/2-in [215,9-mm] interval was sufficiently competent to allow subsequent well stimulation operations (matrix acidizing) to proceed without remedial cementing.

CONCLUSIONS

The successful drilling and completion of Danish Underground Consortium's well TEB-1, in the offshore Denmark Tyra field, has demonstrated the viability of developing certain types of offshore hydrocarbon reserves using long horizontal completion intervals located at substantial displacements from a central platform location.

A combination of long- and medium-radius directional drilling methods can be successfully applied to such a development well configuration. This directional drilling strategy is particularly effective when depth correlation, logs, cores or reservoir pressure data are desireable at a location near the reservoir entry point for the horizontal interval. Precise placement of the horizontal completion interval is possible using MWD formation logging methods.

High-integrity cementations of long horizontal liners, where subsequent completion methods require positive fluid control and zone isolation in the liner/wellbore annulus, are possible with existing liner-hanger technology designed for liner rotation while cementing. Special modifications to such equipment, allowing rotation and circulation during liner-running operations, are recommended. Extended rotation of a liner in curvatures on the order of 10 deg/100 ft [10 deg/30 m] is possible, although improved liner-hanger bearing assemblies may be required to make such operations reliable on highly -deviated and horizontal wells.

Drillpipe-conveyed logging of high-inclination and horizontal wellbores is a reliable but time-consuming technology. MWD recorded resistivity and gamma ray logging is reliable and of high fidelity; the combination of MWD porosity and density measurements with the existing resistivity/GR configuration may soon facilitate significant and cost-saving reductions in the overall requirement for drillpipe-conveyed logging of wells such as TEB-1.

Water-base drilling fluids are a viable alternative to oil-base drilling fluids when drilling reactive and over-pressured shales at high inclinations. Further refinement of water-base drilling fluid composition may permit future Tyra wells to be drilled without oil-base drilling fluids. The use of a top-drive drilling system is essential to the successful implementation of water-base drilling fluids for high-inclination and horizontal wells drilled in Danish North Sea waters.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the DUC partners (Maersk Oil & Gas, Shell and Texaco) and Eastman Christensen for permission to publish this paper. Congratulations for a "job well done" are extended to all parties involved in the drilling of well TEB-1. Finally, special thanks to Yvonne Kabel for her unflagging and persistant efforts to render this story unto the printed page.

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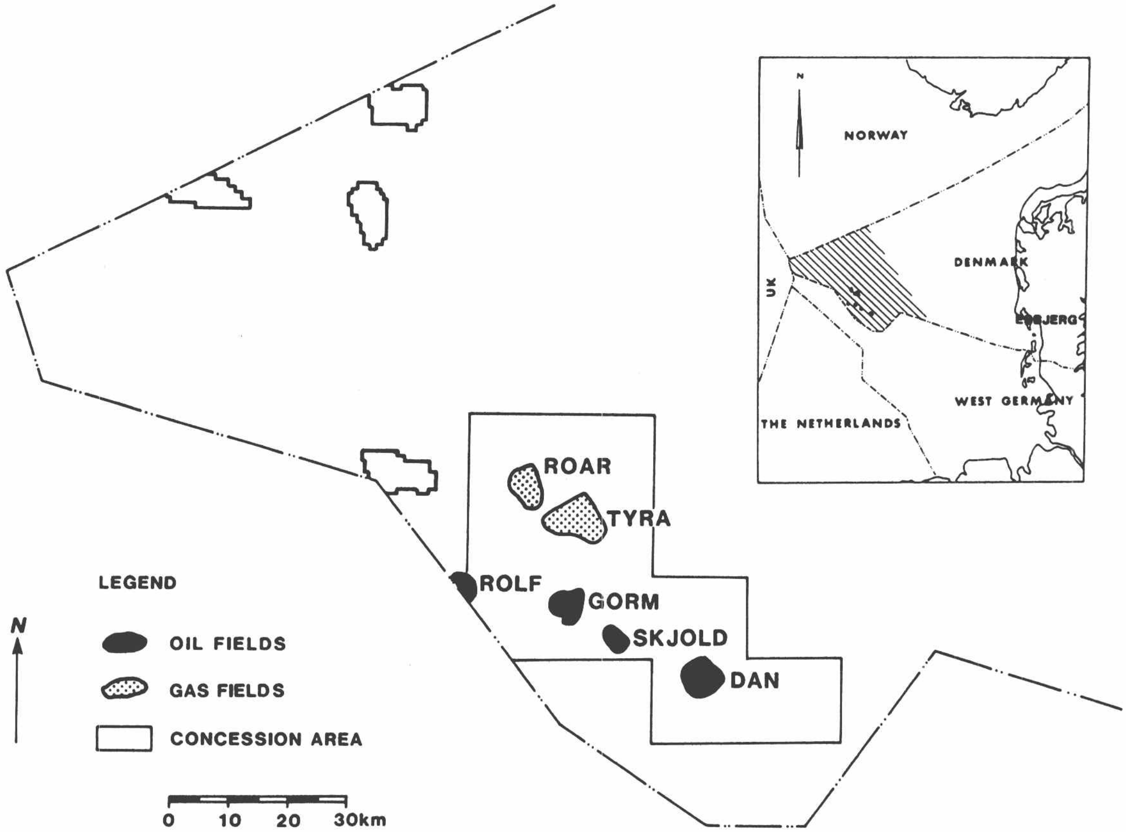

Fig. 1 - Location of Tyra field in Danish North Sea.

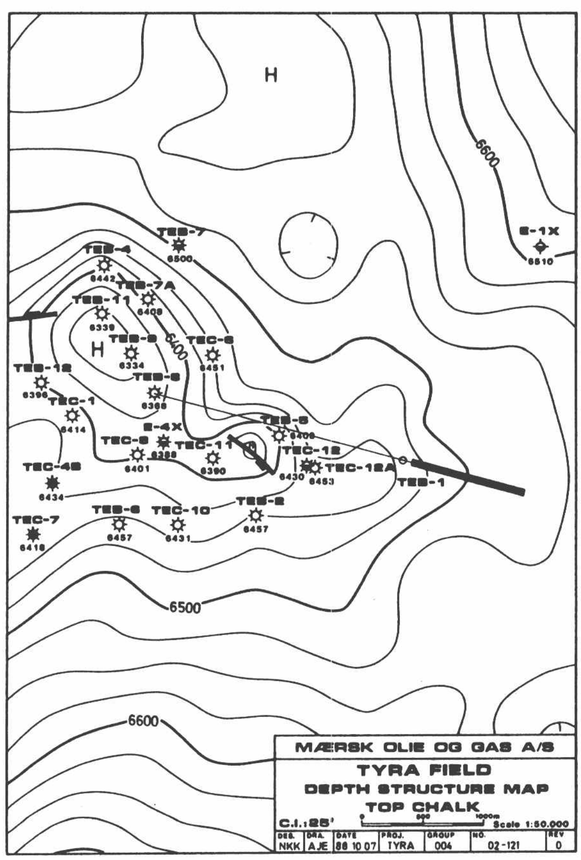

Fig. 2 - Mid-1987 Tyra field development.

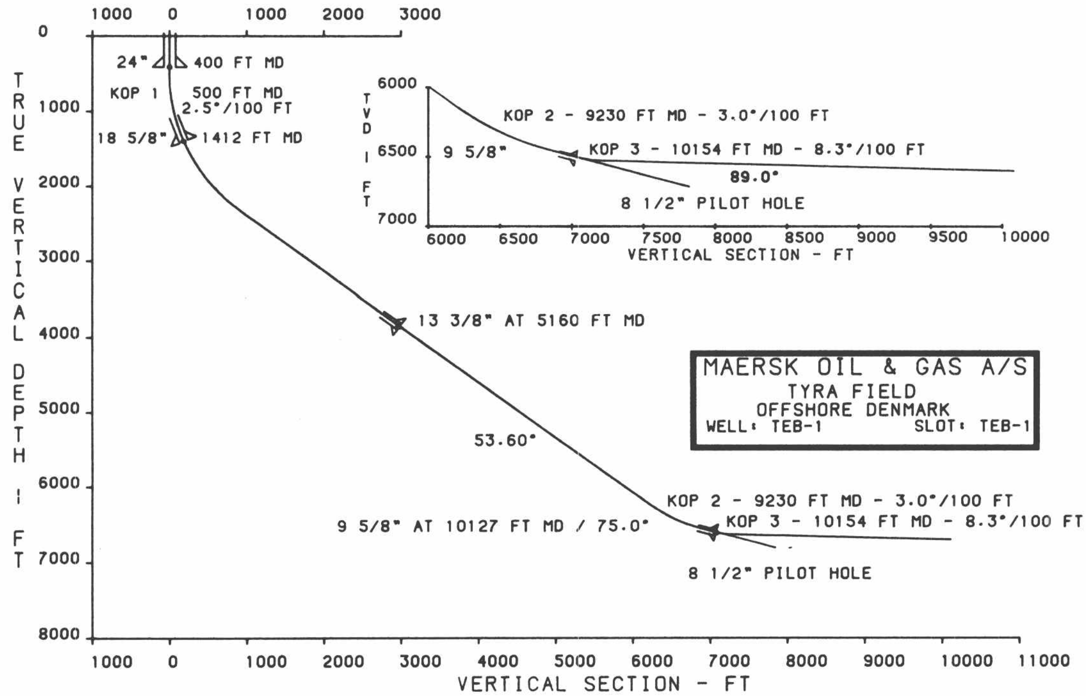

Fig. 3A - Planned trajectory for well TEB-1.

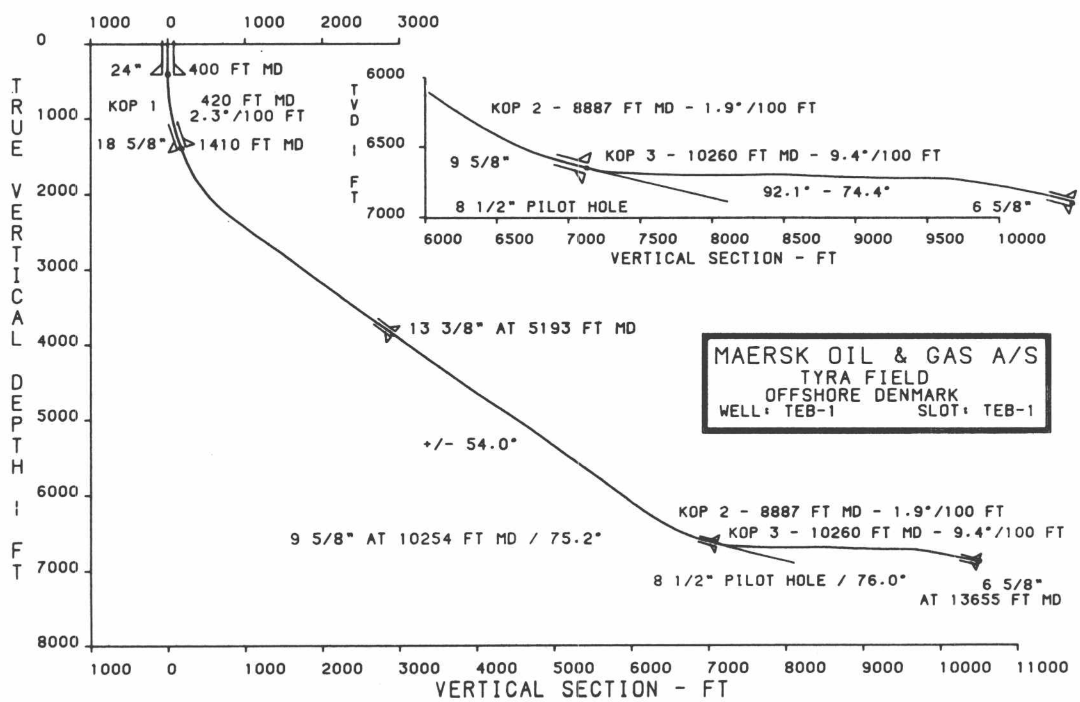

Fig. 3B - Actual trajectory for well TEB-1.