# Deepwater, Subsalt Drilling From Nova Scotia, Canada—Case Study

Offshore eastern Canada is an environment where deep water and the need to penetrate thick salt sheets increase the difficulties faced by drillers. The full-length paper details a deepwater, subsalt-drilling case history and examines the challenges of dealing with high pore pressures and variable fracture gradients. During drilling, conditions were encountered that required use of unconventional borehole sizes and on-the-fly drilling-design modification to deploy unplanned equipment rapidly.

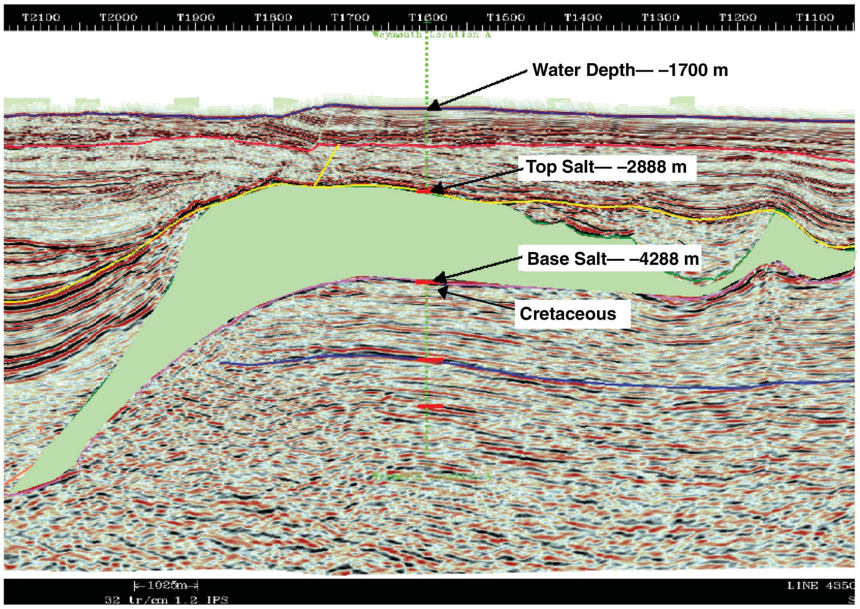
**Weymouth: Preliminary Location**

*Fig. 1—Weymouth Prospect seismic interpretation.*

## Introduction

The Weymouth A-45 well is approximately 160 miles south by southeast from Halifax, Nova Scotia, Canada, in the deepwater area of the Scotian shelf. Seismic analysis identified the presence of a subsalt anomaly, the 150-m-thick Argo salt sequence. This sequence presented a potential drilling challenge and also a problem for prewell pore-pressure and fracture-gradient planning. Because of the challenges posed by the deepwater environment and the thick salt deposit, the well included a complex well design with concentric hole openers and an unconventional casing design. Despite potential hazards and complex well design, the drilling program allowed flexibility in decision processes and in well design to deal with problems encountered. Flexibility was particularly important when drilling through the salt body with a point-the-bit rotary-steerable system (RSS). Although the RSS was not planned for use below the salt, the success of the system in the shallower parts of the well led to its use below the salt and highlighted the flexibility of rotary-steerable technology.

## Planning and Design

In August 2002, three seismic lines and six offset wells were used for initial analysis of the Weymouth Prospect. These data were used to generate overburden, pore-pressure, and fracture-pressure predictions. The six offset wells, including two deepwater wells, showed two different pore-pressure regimes unrelated to water depth.

The first pore-pressure regime was characterized by normal pore-pressure gradients to approximately 2900 m followed by a slow increase in pressure, averaging 22 kg/m$^3$ equivalent circulating density (ECD) per 100 m through to total depth (TD). The second pore-pressure profile had a steeper pressure "ramp" from 3600 m with a rapid pore-pressure increase to 1800 kg/m$^3$ and greater by well TD.

**Seismic.** The Weymouth seismic data highlighted the problems with seismic interpretation through and below the salt. The seismic-data resolution included one data point every 100 m, and the velocity data through the salt were heavily shifted because of the salt-formation density. **Fig. 1** shows a seismic interpretation of the well location. Because of the velocity shift, data points below the salt suggested two pressure scenarios at the base salt. One, a normal pore pressure followed by a rapid ramp; the second, an elevated pore pressure immediately below the salt. All of the seismic lines indicated a rapid pore-pressure ramp followed by a slower pore-pressure increase.

**Salt.** There still remained uncertainty about the pore pressure in the zone direct-

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*For a limited time, the full-length paper is available free to SPE members at www.spe.org/jpt. The paper has not been peer reviewed.*

ly beneath the salt, typically referred to as the "rubble zone." Interpretation of seismic data below salt is less reliable for determining pore pressure and geological structures. A rubble zone is potentially a highly disrupted zone where the principal stress state surrounding the salt is disturbed, which may lead to unexpected borehole collapse and at least, alters fracture pressures. Fracturing and faulting also are common, and these features can lead to pore-pressure compartmentalization. In significantly permeable formations, compartmentalized pore pressures lead to formation charging or depletion, causing influxes or lost circulation and the possibility of differential sticking.

***Stress Fields.*** Deepwater wells, because of lower overburden gradients, have lower formation fracture pressures than wells drilled on the continental shelf. In the Weymouth prospect, there was the additional effect of the thick Argo salt. The 1507-m-thick salt sequence causes a reduction in overburden pressure. The presence of either salt diapirs (vertical) or salt sheets (horizontal) affects the three principal stresses in proximity to the salt body by orienting them so they are perpendicular or parallel to the surface of the salt body. Salt can disrupt stress fields and can disrupt fracture pressures at some distance from the salt body.

**Well Design.** As a consequence of the multiple challenges identified during prewell planning, a more complex bottom-up well design was required to drill to the 6500-m planned TD. The well design had to maximize hole size through the target zone with a contingency casing plan available for unexpected problems. The target section was designed for a traditional $8^1/_2$-in. hole section with six casing-string sections. To achieve this design, the well plan included use of near-bit reamers (NBRs) in four intermediate hole sections. This design maximized borehole and casing sizes to reach TD. Drilling margins (i.e., the difference between pore pressure, mud weight, and fracture pressure) would be narrow, and each hole section would be pushed to a minimum kick-tolerance limit to succeed. The full-length paper shows the initial well plan and the final well schematic.

One potential hazard associated with drilling though salt is poor directional control. Combining the RSS tool with an NBR would provide wellbore verticality control while maximizing rate of penetration (ROP) and eliminating extra trips for hole enlargement. Synthetic-based mud was selected on the basis of Gulf of Mexico (GOM) best practices for drilling salt. The 16-in. casing to be set directly below the salt was engineered to withstand abnormally high loading resulting from salt "creep," the phenomenon of salt formations actually flowing.

### Formation Stability

Wellbore instability in close proximity to salt bodies is well documented. A rubble zone can exist above and below the salt body. In these zones, true fracture pressure may be lowered and drilling windows correspondingly narrowed. Close monitoring of ECD by pressure-while-drilling (PWD) tools is required to determine fracture-opening and -propagation pressures. Mud density must be sufficiently high to overcome pore pressure and salt creep but sufficiently low to limit mud losses caused by open fractures.

The effects of vertical- and horizontal-stress disruptions by salt on underlying formations (near- and far-field stress perturbations) also have been studied in the GOM. This stress disruption can cause a stress-field rotation and a reduction in the minimum horizontal stress. Changes in the stress regime below the salt can reduce fracture pressures by as much as 20%. The presence of wellbore ballooning/breathing and fracturing throughout the formations beneath the salt in this area suggest that the GOM study is applicable to Weymouth.

### Wellbore-Integrity Monitoring

Because of the uncertainty surrounding the pore-pressure estimates, 24-hour monitoring was required to update the models continually with real-time data. Monitoring was provided at the rigsite as well as at shore-based offices to provide information to key decision makers as soon as possible.

During drilling, the fracture-pressure predictions were significantly higher than those actually recorded during leakoff tests (LOTs) and formation-integrity tests (FITs). Initially, these differences were believed to be caused by poor casing-shoe strength resulting in pressure leakage up the annulus. However, squeeze cement jobs did not produce significant improvements in LOT values, so other factors were considered to be responsible for the results.

As drilling proceeded below the salt, mud losses were encountered at ECDs lower than the LOT or FIT pressures. From 5000 m, these losses occurred at ECDs approximately 50 kg/m$^3$ less than expected, causing tight drilling-margin limits. Logging-while-drilling data showed fluid invasion that became progressively worse with depth. Some of the worst loss zones required wellbore/formation seal treatments to continue to drill ahead. It soon became clear that losses would continue to occur with depth, suggesting that, rather than localized fracturing generating mud losses, a more pervasive problem existed below the salt.

The PWD profile observed while drilling the Weymouth well indicated a fracture opening and closing. This two-stage "sharks-fin" PWD profile developed in response to a mud-weight increase but at an ECD lower than the fracture pressures that LOTs or FITs would have suggested.

The low fracture gradients and even lower pressures required to induce ballooning and mud losses meant that the drilling margins were much lower (±100 kg/m$^3$) than LOTs and prewell engineering predicted; therefore, accurate real-time monitoring and pore-pressure updates were critical. Once ballooning had been identified, other related features were identified.

### Well Design and Execution

NBRs were included in the drilling program to enlarge the wellbore while drilling to allow the largest possible casing sizes in each interval. Bottomhole-assembly (BHA) plans called for conventional drilling assemblies with either motors or rotary-steerable tools to maintain directional control. Use of this technology would enable the potential reservoir section to be drilled at $8^1/_2$ in. to maximize well testing. The NBR program also permitted contingency hole sizes to be built into the design.

NBR technology first was used successfully above the Argo salt. Because of a size limitation in the wellhead housing, a 17-in. bit with an NBR was selected. On the basis of salt-drilling practices in the GOM and to help ROP associated with steering a mud motor, an RSS was chosen to allow directional correction if required. The NBR was opened outside the 20-in. shoe and successfully drilled the hole to 20 in. from 2695 to 4102 m. The hole was drilled at a high ROP, drilling 1407 m in 116 hours.

The rotary-steerable tool/NBR combination successfully drilled and opened the borehole from 17 to 20 in. in a single 1407-m, 10-day bit run. The combination of an RSS and the NBR saved 4.2 days rig time. Heavy-walled 16-in. "salt" casing (84 lbm/ft and 97 lbm/ft, P110) was run to just below the rubble zone without encountering any restrictions.

The following hole section was drilled with a 14³/4-in. bit, a mud motor for directional control, and a 17-in. NBR. The NBR was successful in opening the hole; however, directional control was slightly compromised. Therefore, on subsequent bit runs in this interval, the NBR was removed and run after the objective depth was reached.

Cuttings removal and identification were key for the rest of the well. The sections were drilled first with a pilot bit, and then the NBR was run as a separate BHA to open the borehole. The well design called for separate NBR runs deeper in the well to aid with identification of formation changes. If run as part of the drilling assembly, as designed, the NBR could mask indicators of lithology changes and could prevent early detection of potential ROP changes. Although NBRs commonly are run in locations such as the GOM without directional control problems, an unplanned hole-inclination increase to 4.44° led to the decision to stop drilling 38 m early at 4462 m.

The directional complications encountered in the 17-in. section caused a re-evaluation of the drilling assembly. Following a casing cement drillout and squeeze, the rotary-steerable tool and NBR once again were used to drill the 12¹/4×14-in. section. This choice proved successful until 4612 m, where a well-control incident occurred that was followed by severe wellbore instability that forced a sidetrack around lost tools. However, in this short run, the RSS tool corrected the previous hole-inclination build and returned the well to near vertical. This success influenced the use of the rotary-steerable tool for the sidetrack. The sidetrack was performed successfully from 3 m beneath the previous casing shoe by use of a polycrystalline-diamond compact bit. Once the sidetrack was achieved, the well returned to vertical to reach section TD at 4889 m in one 61-hour bit run.

In the 12¹/4-in. section, the lessons learned from the previous hole section were applied; the section first was drilled and then underreamed with an NBR with 14-in. arms. The NBR was successful in opening the 12¹/4-in. section, with a few undergauge intervals.

The lessons learned from previous sections were applied to the 10³/4-in. section, which was opened up to 12¹/4 in. A dedicated NBR run was made to open the borehole from 4889 to 5250 m following wireline logging. The borehole then was extended 200 m using a 10³/4-in. bit and an NBR with 12¹/4-in. arms. The ROP was controlled to 10 m/h for the extra 200 m. At the controlled ROP, the NBR successfully drilled and opened up the extra hole section in one run.

Drilling-margin limits were nearly reached in this hole section, requiring the wellbore to be cased. Real-time pore-pressure calculations using sonic and resistivity logs indicated increasing pore pressure from 5400 m; by 5459 m, the drilling margin and kick tolerance had been reached. The planned depth for this section was 6200 m. However, setting the planned 10³/4×9⁷/8-in. casing string would have limited borehole design, which, in turn, would necessitate the use of much smaller bit and BHA sizes than acceptable for drilling into the reservoir. Therefore, the decision was made to modify the casing program and use 11³/4×9⁵/8-in. expandable casing.

Another reason to use expandable casing was the well-plan modification that set the 11³/4-in. liner at 4889 m rather than the planned 5400 m. The early setting of this casing because of perceived pore-pressure estimates at the rigsite proved to have effects later in the well. The expandable casing saved a hole size and allowed drilling to proceed with only minor changes from the program. However, the expandable casing prevented further use of the NBRs because the NBR body was too wide for the expandable-casing inside diameter.

An underreamer was required to open 470 m of 9¹/2-in. hole to 12¹/4 in. In two separate runs, the conventional underreamer opened up 329 m of borehole. However, wear on the tools was excessive; and after each run, the arms were under gauge and showed evidence of abrasion and wear.

Following the two 12¹/4-in. underreamer runs, two underreamers with 11¹/2-in. arms were used in two subsequent runs. These two runs opened the borehole but only to 5845 m. This shortfall highlighted a major problem with running the planned 9⁷/8-in. at this depth and hole size. The underreamer runs totalled 221 hours, not including tripping time, and the tool proved to be very difficult to run and operate effectively. Underreamer runs had weight-on-bit limits, and ROP was slower than with NBR runs. From TD of the drilled section to running casing, more than 14 days were spent underreaming. Despite problems underreaming, the 8⁵/8-in. tapered casing was run and the target reservoir section drilled effectively by use of a 7⁷/8-in. bit. The well was drilled successfully to a Canada record depth of 6520 m measured depth and 6500 m true vertical depth. JPT