Identification of Bypassed Gas Reserves Through Integrated Geological and Petrophysical Techniques: A Case Study in Seeligson Field, Jim Wells County, South Texas


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ABSTRACT

Bypassed gas zones can be identified and developed by integrating advanced geologic methods and petrophysical techniques into field development strategies. These reservoirs may provide incremental gas reserve additions at relatively low cost to the operator. Seeligson field was studied as part of a Gas Research Institute-sponsored program designed to develop, test, and verify technologies and methodologies for maximizing the recovery of gas from conventional reservoirs in mature fields.

Detailed geologic evaluation of middle Frio reservoirs in Seeligson field reveals a stratigraphic framework composed of multiple, stacked fluvial channel-fill and splay deposits interstratified with floodplain mudstones. Channel-fill deposits are 10 to 40 ft (3 to 12 m) thick and approximately 2,500 ft (750 m) wide. Splay deposits are up to 20 ft (6 m) thick proximal to channels and extend several thousand feet away from the channel. Channel-fill and crevasse-splay sandstones are reservoir facies; levee and floodplain mudstones are thought to be barriers to flow, separating individual reservoirs vertically and laterally.

Recently developed cased-hole log evaluation techniques tested in Seeligson field demonstrate their superiority for locating bypassed gas. Based on geological and spatial considerations, 14 key wells within a 4 mi² (10 km²) area of the field were selected for cased-hole petrophysical analyses. Pulsed-neutron and gamma-ray logs were recorded in these wells. After preliminary analyses, five wells were selected for full waveform acoustic logging. Porosity was calculated from the acoustic log and compared to pulsed-neutron porosity to determine gas effect. The logs were corrected for shaliness and combined with sigma (capture cross section) data to calculate water saturation. Long-normal resistivity curves from electric logs were digitized and integrated with the newly acquired data to calculate original open-hole water saturation. Plotting and comparing the logs graphically enabled gas-productive sands to be identified.

Five successful recompletions were made as a result of this study. By estimating reserves from current and initial production, using net present value of the gas, and dividing by the cost of the project, a highly favorable return on investment is estimated.

INTRODUCTION

Since 1987, the Gas Research Institute (GRI) has supported a cooperative, field-oriented research program designed to develop and test technologies and methodologies that can be used to improve ultimate recovery of gas from conventional reservoirs in mature fields. Accomplishing this goal requires techniques that will allow gas producers to improve evaluation of bypassed gas reservoirs in existing wells and to identify untapped or incompletely drained compartments within known reservoirs in producing fields. Evaluating bypassed gas-bearing zones within producing intervals or unidentified productive zones located updip from a producing interval requires utilization of state-of-the-art logging tools and new interpretational techniques. Identifying untapped or incompletely drained compartments within established reservoirs involves advanced geological characterization of selected gas-bearing reservoirs.

Essential to the success of the program is the involvement of operators active in the targeted areas. In late 1987, the Bureau of Economic Geology and ResTech, Houston entered into an agreement with Sun Exploration and Production Company (now Oryx Energy Company) to study Seeligson field, located within the highly prolific FR-4 gas play (Frio fluvial and deltaic sandstones along the margin of the Vicksburg Fault Zone1; fig. 1). Seeligson field includes an Oryx-operated unit that produces gas from multiple, stacked fluvial sandstones of the Oligocene Frio Formation. This setting provides an excellent opportunity to study heterogeneous fluvial reservoirs and to focus on integrating geological reservoir-characterization methods and cased-hole log-evaluation techniques in order to identify potentially bypassed gas zones.
Sun had been actively evaluating recompletion opportunities within Seeligson in a systematic manner by dividing the unit into smaller Package areas and studying each one individually. The strategy of the repletion program was to define target reservoirs by evaluating pulsed-neutron logs recorded in selected, temporarily abandoned wellbores and by incorporating geologic and engineering assessments with those results. The project’s research effort focused on Package VI, an area encompassing approximately 4 mi² (10 km²) in the east-central part of the field. Sun welcomed input from the project on development-strategy decisions in Package VI and offered the project workers the opportunity to recommend repletion candidates based on the results of our research. Our evaluation and recommendations were separate from, but in conjunction with, Sun’s ongoing evaluation of the package area.

Five successful well repletions were made in Package VI following this research. Total cumulative production through March 1990 for the completed zones is more than 1.4 Bcf of gas. The completions were made in zones within wellbores logged as part of the project and identified as containing bypassed gas opportunities, or in zones within wellbores that are offset and structurally higher than those that were logged by the project.

Study area and data base

Seeligson field is located in Jim Wells and Kleberg Counties, South Texas, north of the town of Premont (fig. 2). The field was discovered in 1937 when the Magnolia A. A. Seeligson No. 7 well was drilled to a total depth of 8,141 ft (2,442 m) and encountered hydrocarbons in the upper Vicksburg. The field encompasses more than 40 mi² (102 km²) and more than 1,000 wells have been drilled. Cumulative production totals more than 2.5 Tcf of gas from 130 Frio and Vicksburg fluvial and deltaic sandstone reservoirs. More than 150 electric logs were used for geologic and petrophysical control in the study area. Pulsed-neutron logs were recorded in 14 selected wells and cased-hole sonic logs were recorded in 5 wells in Package VI for petrophysical evaluation. In addition, 30 ft (9 m) of slabbled core from the Sun P. Canales No. 141 well, located about 1 mi (1.6 km) south of the study area, was used for petrophysical and petrographic analyses, to characterize facies, and to calibrate wireline-log curve responses.

GEOLOGIC FRAMEWORK

Stratigraphy

The Oligocene Frio Formation in South Texas has been divided into three operational units informally designated the lower, middle, and upper units. The middle Frio is composed of lenticular sandstones encased in mudstones that represent the Guaydan Fluvial depositional system. The middle Frio was selected for analysis because it is highly productive. It also coincides with the Oryx-operated unit, and it possesses sufficient lithologic heterogeneity that may result in bypassed gas zones and untapped or incompletely drained reservoir compartments.

The middle Frio at Seeligson is defined as the sandstones and mudstones occurring from reservoir Zone 7 to Zone 20C-4, which corresponds to the Oryx-operated unit (fig. 3). The productive section has a depth range of approximately 4,000 to 6,200 ft (1,200 to 1,860 m) and includes more than 50 reservoirs.

Depositional Environment

The middle Frio is composed of sand-rich channel-fill and splay deposits interstratified with floodplain mudstones, all forming part of the Guaydan Fluvial System. Channel-fill deposits are typically 10 to 40 ft (3 to 12 m) thick but often amalgamate into units up to 80 ft (24 m) thick. Widths of individual channels approximate 2,500 ft (766 m), but where channels coalesce, the width of the channel complex can exceed 1 mi (1.6 km). Splay deposits are as much as 20 ft (6 m) thick proximal to channels and can extend several thousand feet from channels. Channel-fill and splay sandstones are reservoir facies, with porosities averaging 20% and permeabilities ranging from 10’s to 100’s md; floodplain mudstones and levee silty to sandy mudstones are thought to be barriers to gas flow, separating individual reservoirs both vertically and laterally.

Trapping Mechanism

Seeligson field is situated along the downthrown margin of the Vicksburg Fault Zone (fig. 1). The major bounding Vicksburg growth fault defines the western extent of the field. Synthetic and antithetic faults occur within the field but are most extensive in the deeper Vicksburg and lower Frio section, leaving middle Frio reservoirs relatively unaffected. Deformation related to the Vicksburg fault has produced a broad, northeast-trending rollover anticline with several subsidiary structural highs. Middle Frio gas reservoirs at Seeligson field produce from sandstones located over the crest of the rollover anticline. Structural relief of reservoirs is commonly less than 400 ft (120 m). Several gas caps occur in the field; the primary gas cap is just north and updip of the Package VI study area. Although production is dominantly structurally controlled, stratigraphic trapping of gas due to lateral and vertical permeability barriers such as sandstone pinch-outs or facies changes occurs in Seeligson field. More than one-third of the production in the Frio fluvial gas play may be from stratigraphic traps.

RESERVOIR STUDIES

Reservoir studies focused on the description of the geometry and distribution of sandstone bodies and analyses of facies within the reservoir. Detailed stratigraphic analysis of each selected reservoir helped to define discrete stratigraphic intervals composed of genetically related facies. Subdivision of the reservoir into genetic units allows inferences to be made regarding potential lateral or vertical segmentation of a reservoir due to facies changes or the superposition of separate genetic units.

Cross sections and detailed electric-log correlations were used to establish the stratigraphic framework of the reservoirs studied. Stratigraphic cross sections were referenced to correlative fieldwide resistivity or conductivity markers. Amalgamated sandstone bodies were subdivided into discrete genetic units (facies deposited approximately contemporaneously) through detailed correlation of SP and resistivity curves. Log facies were mapped by interpreting characteristic SP- and resistivity-curve shapes that correspond to particular depositional environments. The four log-facies types recognized include upward-fining channel-fill deposits (bell-shaped log curves); generally upward-coarsening crevasse-splay deposits (funnel-shaped log curves, but can be variable); levee deposits (thin, spiky or serrate log curves); and floodplain deposits (generally baseline log response).
Previous stratigraphic analyses of several Seeligson reservoirs demonstrate an architectural style that is potentially suited to the addition of gas reserves. Facies heterogeneities that may result in incompletely drained compartments have been described in middle Frio reservoirs. Most of the middle Frio reservoirs in Seeligson field are complex heterogeneous zones composed of multiple superimposed channel sandstones. These complex zones may have reserve-growth potential due in part to what may be partial barriers formed at sandstone-on-sandstone contacts. Permeability contrasts of up to four orders of magnitude are observed between mud-intraclast-rich zones at channel bars and adjacent middle channel-fill facies in middle Frio fluvial sandstones at nearby Stratton field.

**Zone 14B**

Zone 14B occurs at depths ranging from 4,960 to 5,150 ft (1,488 to 1,545 m) in Package VI. At least three genetic intervals are recognized in Zone 14B and are informally named the upper, middle, and lower operational units. The middle and upper operational units were mapped in detail in an area where the channel system of the 14B upper unit has eroded into the channel system of the 14B middle unit (virtually throughout the map area) may contain mud intraclasts at basal scour surfaces that could act as partial permeability barriers. Lateral compartmentalization due to facies heterogeneities may occur in the 14B middle unit.

**Zone 19B**

Zone 19B occurs at depths ranging from 5,620 to 5,900 ft (1,686 to 1,770 m) in Package VI. The reservoir is composed of at least three genetic units in the map area and are informally named the upper, middle, and lower operational units. The 19B lower operational unit is composed primarily of channel-fill sandstones. The width of an east-west-trending channel is generally about 2,000 ft (600 m) in the area. Net-sandstone thicknesses reach only 12 ft (4 m) due to downcutting by the overlying unit, resulting in incomplete preservation of the channel-fill sequence. Complete erosion of the 19B lower unit is observed in the northwestern corner of the map area (fig. 5). The middle unit of the 19B zone is developed in the map area as channel and splay sandstones, with channel sandstones reaching net sand maxima of 27 ft (8 m). Levee or splay deposits are indicated in the northeastern corner of the map area (fig. 6). The upper unit is developed in the southwestern part of the study area as the edge of a channel and its associated splay sandstones. There is also a thin stringer present in one well in the north-central part of the area, which may be part of a splay channel.

The channel system of 19B middle overlies and erodes into the channel system of the 19B lower unit. Potential vertical permeability barriers most likely occur at channel-on-channel contacts where low permeabilities exist in mudstone intraclast zones. The channel and splay sandstones of the upper operational unit overlie floodplains of the 19B middle interval in the southwestern part of the map area. Reservoir sandstones may form compartments separate from the underlying units.

**FORMATION EVALUATION**

**Open-hole logging**

Electrical surveys and occasionally micrologs were typically recorded in wells drilled in Seeligson field prior to 1960. Unfortunately, the lateral resistivity curve is difficult to interpret in this environment because of the thickness of many sandstones in the middle Frio section is less than the 18-ft, 8-in electrode spacing on the tool. However, the short- and long-normal curves are useful as resistivity indicators. With no porosity logs available for the pre-1960 wells, quantitative petrophysical analysis is difficult. Whole and sidewall cores were frequently collected to determine productive intervals.

Open-hole logging programs that typically include dual-induction, density, neutron, and gamma-ray logs were recorded in wells drilled after 1970 in order to calculate porosity and water saturation. Wireline pressure tests are frequently recorded to assess formation pressures. Sidewall cores are routinely taken to evaluate porosity, permeability, and fluid saturations. This log suite is adequate to determine new potential pay horizons or to identify established pay zones still having significant formation pressure.

**Cased-hole logging**

Cased-hole logs have been used primarily for obtaining perforating depth and, to a limited extent, in well-recompletion programs. A typical cased-hole logging program consists of a gamma ray/neutron log with collar locators and a cement-bond log for evaluating cement integrity.

In this project, pulsed-neutron logs were recorded to obtain neutron-capture cross-section data, followed by an acoustic log to determine porosity. The acoustic log normally recorded in an open hole may be used in a cased-hole environment if the casing is adequately cemented. Use of these two logs provided a combination that identified gas by comparison of the curve responses and by calculating water saturations.

Acoustic and neutron-porosity logs respond similarly in oil zones and in zones with higher water saturation; however, in gas zones, the curves diverge. Overlays to normalize the data and observe these divergences were used at Seeligson to identify gas. Near and far count rates were used in the same manner from the pulsed-neutron logs. Combining these methods with the capture cross-section curve from the pulsed-neutron log provides a powerful cased-hole formation evaluation tool.

**Evaluation of the Sun P. Canales No. 141**

Petrophysical data used to improve petrophysical modeling was obtained when Sun drilled the P. Canales No. 141 well just south of the Package VI study area. In addition to the standard dual-induction, density, and neutron logs, the project recorded a long-spaced sonic log, supplemental wireline pressure tests, and obtained conventional whole-core. The sonic log enabled comparison to the cased-hole sonic log, which was recorded at a later date during completion of the
well. Wireline pressure tests provided pressure data in zones where formation pressure was unknown. The conventional core provided calibration for porosity and permeability calculations, cementation and saturation exponents, and facies and petrophysical information. After casing, the digital sonic log was run to test its applicability in the area. A comparison of the data from the two runs showed the cased-hole sonic to be reliable, with cement bonding as low as 50%. This was critical information because the cement quality in the old wells targeted for the cased-hole logging program was unknown.

**PACKAGE VI EVALUATION**

Fourteen key wells were selected in Package VI for pulsed neutron logging. These wells were selected on the basis of available wellbores, lithological heterogeneities of unit reservoirs, and comparison of offset-well production. The selected wells were also distributed across the area to obtain optimum areal coverage.

Each of the fourteen wells was evaluated for water saturations based on estimated porosity. The gas shows in the fourteen wells were compared, and the wells were ranked to decide where the cased-hole sonic should be run. Cased-hole sonic logs were recorded in five wells.

After acquiring cased-hole sonic data, porosity could be calculated from the pulsed-neutron log and compared to sonic porosity to determine gas effect. These two porosity values were used along with capture cross-section (sigma) data to calculate cased-hole water saturation. Long-normal curves from old electric logs were used to estimate resistivity and combined with newly acquired porosity data to calculate open-hole water saturation. The results were plotted to include both original open-hole water saturation and cased-hole water saturation along with porosity from the sonic and neutron logs. Plotting the logs graphically enabled gas-productive sandstones to be identified.

The Oryx Seeligson Unit No. 1-168 well best illustrates how this approach is used. Figure 7 includes field-acquired pulsed-neutron, acoustic, and resistivity data. Also included are computed values for shale content and open- and cased-hole water saturations. Sonic and neutron porosity values are overlain to illustrate the gas effect in Zones 14B and 15. Notice that the response is very similar throughout the log except in the gas zones of 14B and 15. This is caused by the reduction of hydrogen, which causes neutron porosity to read low. The same effect is noticed to a lesser degree on the near and far count rates (fig. 7).

The open-hole water saturation was computed from a combination of long-normal curve values from the electric log and porosity values from the neutron and sonic log curves. This allows use of the pre-1960 technology (electrical survey without a porosity log) and the new-generation through-casing sonic tool to calculate original open-hole water saturation. The cased-hole water saturation is calculated from the capture cross-section (sigma) curve of the pulsed-neutron log along with neutron and sonic porosity data. In Zone 14B, cased-hole water saturation is not significantly higher than open-hole water saturation (fig. 7). This is an indication that hydrocarbons have not been thoroughly flushed. In this zone, gas effect is observed on the neutron sonic porosity overlay and the near and far count overlay. This is clearly a gas productive zone if formation pressure is high enough. In a field where a low-pressure gathering system is in place (such as Seeligson), the reservoir can be produced effectively even when nearly depleted.

**Results**

Five successful recompletions were based on the Package VI evaluation (Table 1). Two of the recompletions (wells 1-94 and 1-168) were made in wells where the full cased-hole logging suite of pulsed-neutron and digital sonic logs were recorded. Three other recompletions were made in offset wells either on along strike or updip from these two wells.

The combined logs across the completed zone in the 1-94 and 1-168 wells are shown in figures 8 and 9 across the completed zone. The upper half of each figure displays the neutron porosity from the pulsed-neutron log (PHIN) and the sonic transit time (DTCO). These are displayed at a compatible scale to illustrate gas effect. Other curves displayed are shale-corrected neutron (PHNE) and sonic (PHSE) porosities and pulsed-neutron near and far count rates (TSCN and TSCF). All sets of curves indicate gas (shaded areas). The lower half of each figure includes lithology, gamma ray (GR), SP, SIGMA, long normal, open hole water saturation (SWOH), cased hole water saturation (SWCH), and porosity (PHI).

The 1-94 well was completed in Zone 14B from 5,138 to 5,182 ft (1,514 to 1,555 m). The completion was made in an interval composed of superimposed channel sandstones from the 14B middle and upper operational units. Gas effect is seen on all curves. The open-hole water saturation averages 42%. The cased-hole water saturation averages 52%, indicating some production in other wells and movement of gas. This reservoir has had gas production in the area, but a significant amount likely remains on the underdeveloped gas cap. The indication of bypassed gas in this zone is primarily due to the location of the logged well on the gas cap, upstructure from current and past hydrocarbon production. Two other successful completions were made in the same genetic intervals and same facies in this zone from nearby wells in similar structural positions (wells 1-202 and 1-236; fig. 4).

The 1-168 well was completed in Zone 19B from 5,805 to 5,818 ft (1,741 to 1,745 m). The perforations are in channel sandstones of the 19B lower operational unit (figs. 5 and 10). Open- and cased-hole water saturations are nearly the same, and gas effect is seen on all logs (fig. 9). This successful completion was based on indications of bypassed gas in the 19B lower interval at this wellbore, as the closest past production was from channel sandstones of the 19B middle operational unit. In addition, a successful completion was made in channel sandstones of both the 19B lower and middle intervals at the 1-35 wellbore (figs. 6 and 10).

**Economics**

Production through March 1990 from the five recompletions has been 1.4 Bcf. Using current and initial production, ResTech, Houston estimates reserves at 4.2 Bcf for the five wells. Using net present value of the gas ($1.80/MCF) and dividing by the approximate costs of the project ($476,000), an undiscounted return on investment of 10 to 1 is approximated. Using a more conservative estimation of reserves (3 BCF), this relation is reduced to 4 to 1.
CONCLUSIONS

Integrating reservoir-characterization methods with state-of-the-art petrophysical techniques is an effective mechanism for identifying bypassed gas zones. Evaluating gas potential in a bypassed or untapped zone can be accomplished by utilizing a cased-hole logging program that includes pulsed-neutron and acoustic logs and by applying advanced reservoir-characterization methods.

In Seeligson field, reservoirs were studied for bypassed gas potential and evidence of incomplete drainage due to compartmentalization. Middle Frio sandstones were described and mapped, identifying reservoir-quality facies. Pulsed-neutron, gamma-ray, and acoustic logs were recorded in selected cased holes and interpreted using new techniques that demonstrate their effectiveness in identifying gas-bearing zones. Five successful recompletions were made in two zones that have produced more than 1.4 Bcf of gas in approximately 18 months.

ACKNOWLEDGMENTS

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REFERENCES


TABLE 1—Successful Recompletions in Package BI, Seeligson Field

<table>
<thead>
<tr>
<th>Well</th>
<th>Zone</th>
<th>Cumulative Gas (MCF) to March 1990</th>
<th>Current Rate MCF/Day</th>
<th>BHSIP* (Original)</th>
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<tr>
<td>1-94</td>
<td>14B</td>
<td>399,683</td>
<td>614</td>
<td>240</td>
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<td>1-202</td>
<td>14B</td>
<td>298,900</td>
<td>743</td>
<td>240</td>
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<td>1-236</td>
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<td>403,607</td>
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<td>1-168</td>
<td>19B-03</td>
<td>96,855</td>
<td>230</td>
<td>210</td>
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</tbody>
</table>

*Average BHSIP based on 1988 Data

FIGURE 2. Index map of Seeligson field, Jim Wells and Kleberg Counties, Texas.
FIGURE 3. Type log illustrating unitized middle Frio reservoirs in Seeligson field. Zones 14B and 19B (not developed at this well) are described in this study. See figure 2 for location of well.

FIGURE 4. Log-facies and net sandstone-map, middle operational unit, Zone 14B. Wells 1-94, 1-202, and 1-236 were recompleted in channel-fill sandstone facies of this zone.
FIGURE 5. Log-facies and net sandstone map for the lower operational unit of Zone 19B. Wells 1-168 and 1-35 were recompleted in channel-fill sandstone facies of this zone. Cross section AA' given in figure 10.

FIGURE 6. Log facies and net-sandstone map, middle operational unit, Zone 19B. Well 1-35 was recompleted in channel-fill sandstone facies of this zone. Cross section AA' given in figure 10.
FIGURE 7. Combined logging suite of pulsed-neutron log and sonic log identifies gas in Zones 14B and 15, in the Oryx Seeligson No. 1-168 well.

FIGURE 8. Combined cased-hole log suite, Oryx Seeligson No. 1-94 well, shown with porosity and water-saturation analyses.
FIGURE 9. Combined cased-hole log suite, Oryx Seeligson No. 1-168 well, shown with porosity and water-saturation analyses.

FIGURE 10. Stratigraphic cross section illustrating channel-fill facies in the lower and middle operational units of Zone 19B. See figures 5 and 6 for location of section.