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TECHNICAL PROGRESS REPORT

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Title: REVITALIZING A MATURE OIL PLAY:
STRATEGIES FOR FINDING AND
PRODUCING UNRECOVERED OIL IN FRIO
FLUVIAL-DELTAIC RESERVOIRS OF
SOUTH TEXAS

Cooperative Agreement No.: DE-FC22-93BC14959

Institution: Bureau of Economic Geology
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OBJECTIVES

Advanced reservoir characterization techniques are being applied to selected reservoirs in the Frio Fluvial-Deltaic Sandstone (Vicksburg Fault Zone) trend of South Texas in order to maximize the economic producibility of resources in this mature oil play. More than half of the reservoirs in this depositionally complex play have already been abandoned, and large volumes of oil may remain unproduced unless advanced characterization techniques are applied to define untapped, incompletely drained, and new pool reservoirs as suitable targets for near-term recovery methods. This project is developing interwell-scale geological facies models and assessing engineering attributes of Frio fluvial-deltaic reservoirs in selected fields in order to characterize reservoir architecture, flow unit boundaries, and the controls that these characteristics exert on the location and volume of unrecovered mobile and residual oil. The results of these studies will lead directly to the identification of specific opportunities to exploit these heterogeneous reservoirs for incremental recovery by recompletion and strategic infill drilling.

Project objectives are divided into three major phases. Phase I, reservoir selection and initial framework characterization, consisted of the initial tasks of screening fields within the play to select representative reservoirs that have a large remaining oil resource and are in danger of premature abandonment and performing initial characterization studies on selected reservoirs to identify the potential in untapped, incompletely drained, and new pool reservoirs. Phase II will involve advanced characterization of selected reservoirs to delineate incremental resource opportunities. Subtasks here include the volumetric assessments of untapped and incompletely drained oil along with an analysis of specific targets for recompletion and strategic infill drilling. The third (III) and final phase of the project will consist of a series of tasks associated with technology transfer and the extrapolation of specific results from reservoirs in this study to other heterogeneous fluvial deltaic reservoirs within and beyond the Frio play in South Texas.

SUMMARY OF TECHNICAL PROGRESS

Work during the second project quarter of 1994 focused on continuation of Phase II tasks associated with characterizing stratigraphic heterogeneity in selected Frio fluvial-deltaic sandstone reservoirs. Playwide reservoir assessment continued as reservoir engineering data from fields throughout the Frio Fluvial-Deltaic Sandstone trend were grouped within stratigraphic sub-intervals in order to characterize general reservoir heterogeneity, evaluate production behavior, and assess remaining resource potential in middle Frio, lower Frio, and upper Vicksburg reservoir sandstones.

Characterization studies of individual reservoirs in Rincon field are continuing. Digitized log data from approximately 200 wells in Rincon field have been depth-adjusted to correspond with core analysis data and normalized to account for baseline drift in SP response. Detailed maps of the distribution of oil production and initial flow rates were completed and compared with maps illustrating net sandstone thickness and reservoir facies for each of the three major reservoir intervals in Rincon field. Differences in sandstone depositional styles and production behavior were assessed to identify zones with significant stratigraphic heterogeneity and a high potential for containing unproduced oil. The details of the internal physical architecture in the most heterogeneous reservoirs will be used to identify the dimensions of individual flow units, delineate remaining recoverable reserves, and identify specific incremental recovery opportunities. Evaluation of reservoir production behavior and identification of heterogeneity style in selected reservoir zones from T-C-B field is also proceeding using similar methods.

In addition to these ongoing tasks, an abstract and manuscript entitled "Integrated reservoir characterization of mature oil reservoirs: an example from Oligocene Frio fluvial/deltaic sandstones, Rincon field, South Texas"¹ were submitted and accepted for presentation at the 1994 Gulf Coast Association of Geological Societies Meeting to be held in October. A technical poster session "Targeting the unrecovered oil resource in mature field areas: an example from Oligocene Frio fluvial-deltaic reservoirs of South Texas"² was also prepared and presented at the

1994 American Association of Petroleum Geologists Meeting on 15 June 1994. The first annual project report³ and a topical report⁴ for this project were also published by the DOE. A manuscript detailing geological and engineering reservoir characteristics and additional oil resource potential in Frio fluvial-deltaic sandstone play reservoirs in South Texas was also prepared for a Bureau of Economic Geology Geological Circular with a target publication date in early 1995.

Stratigraphic Distribution of Additional Recoverable Oil Potential in Frio Fluvial-Deltaic Sandstone Reservoirs

Methodology

The stratigraphic positions of important reservoir units in Rincon field within the context of the larger scale Frio-Vicksburg genetic stacking sequence were evaluated during the last project quarter to assess the importance of reservoir stratigraphy on hydrocarbon production, recovery efficiency, heterogeneity style, and the potential for compartmentalization of additional oil resources⁵. The differing stratigraphic context of middle Frio, lower Frio, and upper Vicksburg reservoirs results in different engineering attributes and degrees of internal heterogeneity that affect reservoir quality, flow unit architecture, and therefore hydrocarbon recovery efficiency and the future potential for additional recovery. In this project quarter, reservoir data collected from fields throughout the play were grouped into similar stratigraphic subdivisions to evaluate remaining potential represented by each of these reservoir intervals at the scale of the play. This analysis provides a regional context that should facilitate the transfer of results from our field-specific reservoir studies to other fields and reservoirs in the play.

Strategies for reservoir classification

Reservoir sandstones in fields throughout the play that have produced over 1 MMBO (Figure 1) have been preliminarily identified as belonging to either the middle Frio, lower Frio, or upper Vicksburg stratigraphic interval (Figure 2). Vicksburg reservoirs are not targets for resource delineation and additional recovery in this project, but some reservoir zones originally classified within the "Frio Fluvial-Deltaic Sandstone Play"⁶ in fact represent wave-dominated deltaic sandstones belonging to the Vicksburg Formation. Classification was based on regional geologic setting as well as various reservoir data available from files at the Texas Railroad Commission, as well as other public sources. Basic criteria such as reservoir depth, geographic and structural location of the field, and depositional environment interpreted from log profiles were used to separate Vicksburg units originally grouped within the Frio Fluvial-Deltaic Sandstone Play from Frio reservoirs that are the main focus of this study.

Upper Vicksburg reservoirs

Data presented here from Vicksburg sandstones include only those reservoirs originally classified as belonging to the Frio Fluvial-Deltaic Sandstone Play⁶. Vicksburg reservoirs along the play trend in South Texas have a shorter development history than shallower Frio zones and are still actively being exploited and explored for by many operators. Resource assessment in this project focuses on more mature Frio reservoirs that are in more danger of being abandoned before they have produced a majority of their mobile oil. Limited reservoir data from Vicksburg sandstones are shown here to illustrate some basic differences in reservoir geometry between Vicksburg reservoirs and those reservoirs in the overlying Frio section (Figure 3). Vicksburg sandstones are characterized by greater net pay thicknesses (mean value of 25 ft) and smaller reservoir areas (mean of 1,228 acres). Thicker development of reservoir sand facies, as compared to that observed in Frio reservoirs, is expected in delta front facies that characterize Vicksburg sedimentation. The smaller areal distribution of these reservoir sandstones is most likely a result of the significant faulting associated with Vicksburg deposition that serves to isolate reservoirs into multiple structural compartments.

Lower Frio reservoirs

Lower Frio reservoirs reside in the stratigraphic section immediately above the Frio-Vicksburg contact and represent an interval of mixed progradational and aggradational fluvial-deltaic sedimentation. Reservoir sandstones are predominantly dip-elongate, delta-plain, distributary-channel sandstones that stack to combined thicknesses of up to 50 ft. These

composite units commonly display an upward-thickening trend that reflects net progradation of the fluvial-deltaic system. Average net pay thicknesses and reservoir areas for lower Frio sandstones are 17 ft and 3,313 acres respectively (Figure 3). Some of the lower Frio reservoirs included within the play are located in a distal position relative to the Vicksburg Fault Zone (basinward from the ancient Frio shoreline) where the lower Frio section becomes expanded and is complicated by faulting. These reservoirs include more deltaic facies and have greater thicknesses than their distributary and fluvial channel counterparts.

Middle Frio reservoirs

The majority of reservoir sandstones in the Frio Fluvial-Deltaic Sandstone Play are aggradational fluvial channel sandstones located within the middle Frio section. These reservoirs consist predominantly of dip-elongate, upward-fining, channel-fill facies with individual thicknesses ranging from 5 to 30 ft and composite stacked thicknesses between 20 and 60 ft. Average net pay and reservoir size for 118 reservoirs from throughout the play are 12.5 ft and 2,643 acres. Mean values for porosity (24%) and initial water saturation (31%) are similar for both lower and middle Frio reservoir sandstones, although the distributions of values for these data are distinctive for each (Figure 3).

Distribution of Remaining Recoverable Oil in Frio Fluvial-Deltaic Sandstone Reservoirs

Overall estimates of the remaining mobile oil resource in reservoirs from middle and lower Frio stratigraphic intervals throughout the play trend in South Texas were calculated by subtracting the volume of oil produced and an estimated residual oil volume from an estimate of original-oil-in-place (OOIP) calculated for each group of reservoirs in the play. OOIP and residual oil for individual reservoirs were calculated using values of acre/ft, porosity, S_w , and Bo_i data specific to each reservoir, and, where data were unavailable, mean values derived from the middle Frio and lower Frio reservoir data populations were substituted. From these calculations, it is estimated that nearly 1.5 billion barrels of remaining mobile oil, representing over 40% of the OOIP, are still present in these reservoirs (Figure 2).

Evaluation of Stratigraphic Heterogeneity and Production Behavior in Selected Middle Frio Reservoirs in Rincon Field, Starr County, Texas

Identification of additional oil resources in selected Rincon field reservoirs is currently being pursued through the evaluation of existing oil production trends, facies mapping, and analysis of abundant petrophysical data from wireline cores. Major Frio oil reservoirs in Rincon field represent deposition in broad, dip-elongate fluvial systems that consist of either narrow channel fills isolated vertically and laterally by very low permeability overbank facies and floodplain mudstones or as large channel complexes with multiple laterally coalescing sand lobes. These large dip-elongate channel-sandstone complexes provide ideal conditions for the isolation of oil accumulations in multiple reservoir compartments, many of which are now incompletely drained or completely untapped.

Data from two of the most prolific reservoirs in the field shown here provide examples of how different reservoir architectural styles may directly impact recovery efficiency (Table 1, Figures 4 and 5). Maps comparing the distribution of oil production with trends in reservoir facies and sandstone thickness illustrate the updip strike-oriented component of the E sandstone channel system (38% estimated recovery efficiency) that increases the likelihood for communication between individual channels (i.e., reservoir flow-units) along the crest of the structure (Figure 4). This is in contrast to the more depositionally complex, strongly dip-oriented, and likely more compartmentalized D sandstone that has an estimated recovery efficiency of only 29% (Figure 5).

Preliminary assessment of the remaining mobile oil resource in each of these reservoirs was performed by using mean values of acre/ft, porosity, S_w , and Bo_i specific to each reservoir to calculate an estimate of original-oil-in-place. The playwide probability distribution of S_o values was then used to generate a range of possible residual oil values. Cumulative production was

subtracted from this residual oil distribution to predict the range of the remaining mobile oil resource that may be present in these reservoirs (Figure 6). The mean results of this simulation (at 50% probability) shown in Figure 6 suggest that more than 15 MMBO of additional recoverable mobile oil may be present in Frio D and E reservoirs. A more conservative estimate at the 95% probability level indicates that nearly 5 MMBO of mobile oil is remaining. At least 10% of the volume of original-oil-in-place for the stratigraphically heterogeneous D sandstone, or more than 3.3 MMBO, is expected to be present as remaining mobile oil. This significant remaining oil resource is the target of our future detailed reservoir characterization studies in Rincon field.

Table 1: Summary of reservoir data for two major reservoir sandstones in Rincon field

	Frio D Sandstone	Frio E Sandstone
CURRENT STATUS:	95% of completions abandoned	85% of completions abandoned
DEPTH INTERVAL:	3,700-3,800 ft	3,800-3,900 ft
DEPOSITIONAL ENVIRONMENT:	D-3,4,5 zones: Fluvial channels with strong dip-oriented geometry D-6 zone: Strike-oriented transgressive bar	E-1,2,3,4 zones: Dip-oriented fluvial channels with moderate strike-oriented component
PETROPHYSICAL ATTRIBUTES: (wireline core data)		
Mean porosity	25.3% (range 21-26%)	26% (range 22 - 28%)
Geometric mean permeability:	50 md (range 23-91 md)	59 md (range 31-116 md)
Mean Initial water saturation:	40.5%	37.5%
TOTAL PRODUCTION (1940-1990):	> 9,811 MMBO	> 14.0 MMBO
SECONDARY PRODUCTION:	200 MSTB from waterflooding (2% of total D zone production)	2.5 MMSTB from waterflooding (21% of total E zone production)
ORIGINAL ESTIMATED OOIP:	33.85 MMBO	37.04 MMBO
RECOVERY EFFICIENCY:	29% (based on 27.5% / 40.5% Sw)	38% (based on 26.5% / 37.5% Sw)
ESTIMATED RESIDUAL OIL:		
@ 50% probability	15.37 MMBO (45% OOIP)	16.01 MMBO (43% OOIP)
@ 95% probability	20.76 MMBO (61% OOIP)	21.65 MMBO (58% OOIP)
ESTIMATED REMAINING MOBILE OIL:		
@ 50% probability	8.67 MMBO ((26% OOIP)	7.03 MMBO (19% OOIP)
@ 95% probability	3.28 MMBO (10% OOIP)	1.39 MMBO (4% OOIP)

PLANNED ACTIVITIES

The Frio D reservoir in Rincon field is the current focus of detailed studies to characterize the heterogeneity of the various productive reservoir facies. Detailed mapping of the internal physical architecture of individual reservoir flow units will be followed by simulation of petrophysical attributes using 3-D computer visualization to document internal geometry and heterogeneity within the Frio D reservoir. These results should lead to an understanding of reservoir flow-unit boundaries, their control on oil production, and the identification of untapped

and incompletely drained zones that may be targeted for incremental recovery by recompletions and strategic infill drilling.

In conjunction with these efforts, studies of whole core from the D and E reservoir zones in Rincon field are also underway. Evaluation of production data and identification of heterogeneity style in selected reservoir zones from T-C-B field is also continuing.

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Figure 1: Location map of major oil and gas fields in the Frio Fluvial-Deltaic Sandstone Play in South Texas. Reservoirs from these fields have been subdivided according to stratigraphic position and depositional facies into middle Frio (fluvial) reservoirs and lower Frio (fluvial-deltaic) reservoirs to identify differences in heterogeneity style and better estimate remaining oil potential in each type of reservoir facies.

Figure 2: Stratigraphic subdivisions for reservoirs in the Frio Fluvial-Deltaic Sandstone Play and summary of genetic sequence context, reservoir characteristics, oil production, and estimates for remaining oil potential in middle and lower Frio reservoirs.

Figure 3: Cumulative frequency histograms illustrating the differences in the distribution of values of porosity, initial water saturation, net pay, and reservoir area for middle Frio, lower Frio, and Vicksburg reservoir sandstones in the Frio Fluvial-Deltaic Sandstone Play.

Figure 4: Cumulative oil production map for the entire Frio E reservoir zone, and a representative isopach map from one of four E sandstone sub-units showing distribution of net sandstone thickness and depositional geometry. The strike-oriented component observed in the updip portion of the mapped channel units may be responsible for increased flow-communication between channels along the crest of the structure and therefore explain the relatively high recovery efficiency (38%) of the E reservoir.

Figure 5: Cumulative oil production map for the middle Frio D reservoir zone, and isopach maps from the D-4, D-5 and D-6 sandstones showing variety in depositional patterns from broad dip-oriented channels characteristic of the D-4 and D-5 zones to strike-oriented bar deposition in the underlying D-6. The complex nature of D sandstone deposition increases likelihood for compartmentalization in this reservoir zone that has an overall recovery efficiency of only 29%. See Figure 5 for legend explanation.

Figure 6: Mean (50% probability) and conservative estimates (95% probability) of remaining mobile oil present in Frio D and E reservoir sandstones in Rincon field. The highly heterogeneous Frio D sandstone zone has recovered nearly 10 MMBO to date, but has potential for recovering over 3 MMBO of additional oil that is presently residing in untapped and incompletely drained compartments

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