36

AN INTEGRATED STUDY OF THE GRAYBURG/SAN ANDRES RESERVOIR,

FOSTER AND SOUTH COWDEN FIELDS, ECTOR COUNTY, TEXAS*

James J. Reeves, Ph.D., P.E.,
Texas Tech University, Center for Applied Petrophysical Studies
W. Hoxie Smith, M.S.,
Dawson Geophysical Company
Robert C. Trentham, D.G.S.,
Muskoka Consultants
Richard Weinbrandt, Ph.D., P.E.
Jackson Hole, Wyoming

ABSTRACT

A cooperative study of the Grayburg/San Andres reservoir is being conducted in response to the United States Department of Energy's (DOE) Class II Oil Program. The project is cost shared by Laguna Petroleum Corporation (operator), and the DOE. The purpose of this study is to preserve access to existing wellbores by identifying additional reserves. Production problems associated with shallow shelf carbonate reservoirs are being evaluated by a technical team integrating subsurface geological and engineering data with 3-D seismic data. Engineering analysis, subsurface control from wireline logs, and 3-D seismic data will be integrated using a network of state-of-the-art software on a high performance computer workstation. The results of the integrated effort will be a recommendation for infill drilling locations and the design of an effective waterflood. It is expected that this study will demonstrate a methodology for reservoir characterization and subsequent development of the Grayburg and San Andres reservoirs that is feasible for even small independent operators. The integrated multi-disciplinary approach of reservoir evaluation is relevant to many shallow shelf carbonate reservoirs throughout the United States. Furthermore, this study will provide one of the first public demonstrations of the enhancement of reservoir characterization using high resolution 3-D seismic data. This paper discusses the geological makeup of the Grayburg and San Andres reservoirs and the acquisition, processing, and interpretation of the 3-D seismic data set acquired for the project. The 3-D seismic volume will be utilized for optimization of a reservoir simulation model through a quantitative study to extract reservoir properties from seismic attributes.

INTRODUCTION

The area contained in this study encompasses approximately 1,000 acres with more than 60 wells drilled. An index map showing the location of the study area in the southern portion of the Foster Field is shown in Figure 1. Two main producing reservoirs are included in the study: the Grayburg and San Andres Formations.

*This paper will be presented at the South West Petroleum Short Course, 1996 Conference, April 17-18, at Texas Tech University, Lubbock, Texas and at the Society of Petroleum Engineers/U. S. Department of Energy 10th symposium on improved oil recovery, April 21-24, 1996 in Tulsa, Oklahoma.

Reservoir Description

A total of 18 tops (Santa Rosa through San Andres), including detailed parasequence sets within the Grayburg, are being correlated for wells in the immediate area of the project. All of the available wireline logs in the project leaseholds have been digitized in the Grayburg/San Andres intervals, including depth shifting, normalization and generation of pseudo sonics (when feasible) to support the 3-D seismic interpretation.

The reservoir description is an integration of the 3-D seismic interpretation with the geologic model derived from the core description, thin section study and cross section work. The presence of clinoforms, in both the reservoir portion of the Grayburg and the San Andres is significant. These clinoforms correlate to facies changes (the presence of the grainstone shoal) seen in the core and on the cross sections. The extent seems to be influenced by the presence of paleostructures identified by both seismic and geologic mapping. These facies changes have lateral continuity, as identified in the 3-D seismic volume, which would have been difficult to predict from well control alone. Identification of the facies belts will impact the design of the waterflood.

Grayburg

The Grayburg was deposited as a carbonate ramp on the eastern margin of the Central Basin Platform. The carbonate ramp slowly deepened across the study area from west to east into the Midland Basin. The Grayburg within the project area was deposited as numerous packages of sediments (parasequences) ranging from 5 to 30 ft thick that act as flow units in the reservoir. These shallowing-upward units are composed of siliciclastic bases and carbonate tops. The siliciclastics range from dolomitic to highly dolomitic and were deposited only as part of some parasequences. The carbonate portion of each unit has been heavily dolomitized.

On the deeper portion of the ramp (most eastern part) the Grayburg dolostones are composed of deeper water fusulinid wackestones. Higher on the ramp, the dolostones are composed of thicker bedded, higher energy grainstones and packstones. Landward, in a quiet lagoon behind the grainstone shoals, the dolostones are composed of thinner bedded, muddier packstones and wackestones with significant amounts of primary anhydrite. In between, the thicker and thinner units interfinger. The individual flow units are, therefore, thicker down dip and thinner and more numerous up dip.

The siliciclastic basal beds are thicker and more numerous in the upper third of the Grayburg which corresponds to the main pay interval. The fine grained siliciclastics were originally transported from the sabka onto the shelves during sea level lowstands. Once the sea level rose and flooded the shelf, the sands were reworked along with the dolomitic rubble and any soil which formed during the lowstand.

Porosity distribution within the Grayburg is controlled by both depositional facies and diagenesis. The thicker bedded grain-rich facies, most often seen in the high energy shoal portion of each sequence, have the best porosity; whereas, the thinner bedded mud-rich facies both up dip in the lagoon and down dip in the fusulinid wackestones have the poorest. Subaerial exposure of the individual units, though short lived, created additional secondary dissolution porosity. Deep burial diagenesis both enhanced and reduced interparticle porosity and permeability. Anhydrite has been mobile during both the depositional (and early burial) and during the burial diagenetic phase.

San Andres

The San Andres was deposited in a similar environment as the Grayburg. There is, however, a lack of siliciclastics in the San Andres and the distinctive basal beds are absent. Consequently, the "shaley" gamma ray signature is also absent. Much of the San Andres in core was composed of higher energy packstones and grainstones. Unlike the Grayburg, there are capping intertidal and supratidal facies in the San Andres.

Although the San Andres and Grayburg reservoirs have a similar depositional history they have very dissimilar diagenetic histories. This resulted in the subsequent hydrocarbon accumulations being quite different. At the end of San Andres time there was a major (+/- 250 ft), long term sea level drop which subaerially exposed the porous intervals and caused extensive dissolution, reprecipitation, and infilling with debris (karstification). The upper San Andres in the study area was above the water table and undergoing major dissolution and collapse. The blocky character of the porous zones in the upper San

Andres is believed to be a result of this process. Erosion of the San Andres also resulted in an angular unconformity with truncation of the porous intervals against the unconformity. This may have resulted in the development of separate oil water contacts within the different porous zones, a possibility which is under review. A type-log showing both the Grayburg and upper portion of the San Andres Formations is given in Figure 2.

GEOPHYSICS

In recent years a major breakthrough has occurred in exploration geophysics with the development of 3-D seismic technology. The reason is the truly remarkable difference in resolution between 2-D and 3-D seismic data. A 3-D seismic data volume samples the subsurface at a much greater density than a normal 2-D seismic grid. This greater subsurface sampling enables 3-D seismic methods to resolve the overall structural and stratigraphic framework in the reservoir including major and minor faults and sequence boundaries that control fluid flow.

The most important advantage of 3-D seismic techniques is that reflections can be migrated to their true position in the subsurface. In principle, seismic migration is a three dimensional problem that can only be handled properly in a 3-D data volume. For this reason seismic attributes extracted from 3-D seismic data are much more sensitive to petrophysical parameters in the reservoir that effect reservoir flow geometry. For example, an accurate measure of seismic amplitudes, related to changes in acoustic impedance, may allow estimation of reservoir parameters such as porosity and lithology.

Seismic Data Acquisition

During the month of August, 1994, the 3-D seismic survey over the project area was acquired by Dawson Geophysical Company. The high resolution survey covered over 3.25 sq. mi. of the South Cowden and Foster oil fields in Ector County, Texas. The objective was the Permian Grayburg and San Andres Formations at depths of roughly 3,800 ft to 5,000 ft. To avoid cultural obstructions (including a number of houses, buildings, and wells) the entire 3-D seismic survey was initially designed using an aerial photograph covering the study area. During the acquisition of the 3-D seismic survey any deviated location for a source or receiver group greater than 10 ft from the original station was resurveyed. Each source/geophone station and well location in the project area was accurately surveyed using conventional surveying equipment and/or satellite GPS instruments.

Initially, a sweep test was designed to determine the proper sweep parameters for the survey. An 8 Hz to 110 Hz nonlinear 6 dB per octave sweep was selected from the test. A 10 sec sweep with a 13 sec listen time was used. Four vibrators were used with each VP, sweeping a total of 8 times at a fixed location. Typically, the receiver line spacing was 660 ft and the source line spacing was 1,320 ft. Source and geophone groups were spaced 220 ft along these lines.

Source and receiver lines were positioned to allow a bin fractionization technique to give an option of two different bin sizes (110 ft x 110 ft or 55 ft x 55 ft) for seismic imaging. Imaging done with the smaller bin size has maximum fold of about 6 or 7 whereas with the larger bin size the maximum fold is about 25. The advantage of the smaller bin is that it increases the subsurface sampling of the 3-D seismic image by a factor of 4. For reservoir characterization studies this can be very desirable provided the data has adequate signal to noise ratio. A summary of the seismic data acquisition parameters is shown in Table 1.

Seismic Interpretation

Seismic interpretation, reservoir description and reservoir simulation is being conducted at the offices of GeoSpectrum, Inc., Midland, Texas, using Schlumberger GeoQuest's IESX software and Scientific Software Intercomp's (SSI) WorkBench software. Data loaded into the computer workstation and PC network includes: the 3-D seismic volume; digital basemaps containing block and section lines, streams, and roads; well locations; digital well log suites for approximately 67 wells, and a comprehensive well information database. About 23 of the wells located in the 3-D seismic volume have sonic logs.

The project geologist has used the WorkBench software for picking tops for the Yates, Queen, Grayburg, San Andres, and Glorieta Formations and the high frequency sequence boundaries including porosity zones in the Grayburg/San Andres reservoirs. Both the project geologist and geophysicist are working together using the IESX and WorkBench software to integrate their interpretations from digital well logs and the 3-D seismic data.

Only one velocity survey is available in the study area. This survey from the Blair French No. 1 Moss well (FM-1) was evaluated. After computing appropriate datum adjustments to tie the velocity survey to the 3-D seismic volume, a mistie of about ~22 ms exists between the velocity survey and the interpreted seismic tops (it is not unusual for velocity surveys to mistie within 1 leg of the interpretation). Formation tops for the Yates, Seven Rivers, Queen, Grayburg, San Andres and Glorieta are being interpreted by correlating the seismic data to synthetic seismograms available in the seismic volume. Interval times in the interpretation agree with the interval times from the velocity survey.

The velocity survey in the Blair French No. 1 Moss well (FM-1) has check shots taken above and below the Grayburg/San Andres reservoir; however, because of casing, reliable sonic log readings in this borehole are not available in the Grayburg or the shallow section above. Interval velocities computed from the velocity survey were used to pseudo check shot correct the synthetic seismogram obtained from the Foster 3X-B well (FP-3X) located nearly on strike approximately 3,000 ft to the northeast of the Blair French No. 1 Moss well. The Foster 3X-B well contains reliable sonic log coverage from the Grayburg interval to the top of the Yates Formation. A series of phase-rotated seismic sections through the Foster 3X-B well were generated in 15 deg steps. A good character tie between the seismic and the synthetic seismogram occurs when the seismic is rotated about 180 deg. Consequently, the entire 3-D seismic volume was rotated 180 deg for interpretation.

The top of middle San Andres sequence boundary is defined to be the bottom of the Grayburg/San Andres reservoir as the middle San Andres is typically tight and non-productive in this area. The location of the upper San Andres shelf break has been mapped in the 3-D seismic volume which strikes to the northwest through the area. The location of the Grayburg shelf break lies nearly parallel and above the upper San Andres shelf. Basinward of the shelf break prominent stratigraphic wedges in the Grayburg/San Andres reservoir can be seen. In the shelfward direction these wedges thin and the reservoirs are eventually sealed by anhydrite mineralization. Some preliminary work has been done to map the more prominent wedges in the 3-D seismic volume.

Interpretation of detailed sequence stratigraphy in the 3-D seismic volume for the Grayburg/San Andres reservoir requires depth to time conversion of the subsurface interpretation from the well control. This will allow simultaneous interpretation of well log and 3-D seismic data. Apparent correlations between production and seismic attributes, such as sagging dim spots seen in the upper Grayburg and porosity in the "A" zone of the Grayburg reservoir may then be more thoroughly evaluated.

The integrated interpretation of the reservoir sequence stratigraphy from the well control and 3-D seismic data will complete the initial 3-D seismic interpretation for the study. Porosity zones will then be correlated through the reservoir and input into reservoir simulation models assuming that reservoir compartments mostly conform to the sequence stratigraphy.

Application of Seismic Attribute Analysis to Reservoir Development

The quantitative extraction of reservoir properties (such as structure (ft), net and gross thickness (ft), and porosity (%)) from seismic attributes will be addressed in the next phase of the study. Field implementation of the study results will include drilling up to six new infill wells. Modern log suites are planned for each well and a full set of core through the reservoir will be extracted from three of the wells. Tying modern log suites and the 3-D seismic data to detailed core descriptions and measurements will be important for developing statistical relationships between seismic attributes and reservoir properties. To date only two wells, the Cox No. 1 Moss and the Brock No. 5, have sonic measurements through the entire Grayburg/San Andres reservoir.

Geostatistical relationships of seismic attributes to reservoir properties will be evaluated using Schlumberger GeoQuest's Reservoir Modeling software. Additional attributes from seismic inversion may also prove useful. Consideration will be given to reprocessing the 3-D seismic volume to 55 ft bins for greater spatial resolution. The final reservoir model derived from the interpretation will be validated using SSI's WorkBench black oil reservoir simulator and seismic modeling conducted with GX Technology's 3D-AIMS modeling software.

RESERVOIR ENGINEERING

To develop an accurate 3-D reservoir model. various engineering data and reports have been obtained from Phillips Petroleum Company. Laguna Petroleum Corporation. and other companies having production near the study area. These engineering reports include:

AMOCO Foster Field Waterflood Study
FINA Emmons Unit Waterflood Study
UNOCAL Moss Unit Waterflood Study

A discussion of available core analysis. initial reservoir conditions. and production histories is provided in the SWPSC paper presented last spring by the project team (Smith et. al.. 1995).

Reservoir Simulation

Portions of the following two sections were taken from the U. S. Department of Energy Continuation Application submitted November 1995 by Laguna Petroleum Corporation.

A simple two-layer. 3-D reservoir simulation model for the Grayburg/San Andres reservoir was developed using the integrated geological and geophysical interpretation. The top layer of the model consists of the upper and middle Grayburg and the lower layer consists of the lowermost Grayburg and upper San Andres. To date. 80% of the production has been obtained from layer 1 (4.551 MMBO) with an estimated recovery factor of 10.7%. Approximately 1.27 MMBO have been produced from layer 2 (mostly upper San Andres). Oil saturations for most of the lower Grayburg and upper San Andres (layer 2) are near 50% average oil saturation. Under these conditions (oil saturations less than 50%) the remaining oil in layer 2 cannot be economically displaced by waterflooding. These conclusions were supported by the finite difference reservoir simulation model. in which no significant oil was moved in layer 2.

Since results from the two layer model indicate that layer 2 cannot be flooded economically. layer 2 was removed from the simulation model and a single layer model for the productive upper Grayburg was analyzed. Several grid dimensions were tried in the initial simulation runs. The final grid dimension selected was a 12 by 12. multi-dimensional grid for the full Section 36 (Figure 3). This model was used to evaluate Section 36 under three different operating schemes.

Initially, the production and injection as recorded over the span of 55 years was simulated. This mainly involved achieving a match of pressures and water-cuts over the period of operations. A reasonably good match of both parameters was obtained after making several runs with the WorkBench software. A "base case" prediction run was then made assuming operations would continue as in the past with no new wells drilled nor any remedial work of existing wells other than normal rod. tubing and pump repairs currently employed. The results showed a profitable recovery of an additional 332 MBSTO with abandonment occurring in approximately nine years.

The next prediction run was designed to obtain maximum waterflood recovery using a ten-acre well density. Twenty-eight new wells were drilled and nine existing wells were recompleted so as to include all flow compartments as delineated in the reservoir description.. This model was used to calculate the recovery obtained by implementing infill drilling and full-scale waterflood. The total expected recoverable oil is calculated to be 2.073 MBSTO. This amounts to an increase of 1,741 MBSTO over that predicted for the base case. The time required to deplete the field for the 10-acre spacing is estimated to be 19 years.

The model was then used to attempt to optimize profitability of the lease as opposed to optimizing oil recovery as examined in the previous case. In this effort only five carefully selected new wells will be drilled and nine existing wells recompleted in Section 36 for profit optimization purposes. In this instance. the venture shows an additional recovery of 1.397 MBSTO. or an increase of approximately 1.065 MBSTO over the do-nothing case. The time to reach field abandonment is 20 years.

INFILL DRILLING AND RESULTS

Based on the results of the simplified reservoir simulation model developed in the WorkBench software program, the Grayburg reservoir shows definite waterflood potential. The Grayburg can be developed by infill drilling, improvement of existing injection power and by selective completions. The San Andres does not appear to have waterflood potential because it is currently above 50% water saturation due to its proximity to the water-oil contact, as well as the extent of the capillary transition zone. Its potential is limited unless high spots can be found that are sufficiently isolated from the water to allow development.

The technical team recommends drilling a well in the L.E. Brock lease on the seismic high amplitude anomaly (NW quarter of Section 36) and another well to be drilled in the H.C. Foster lease to test the structural high located in the SW quarter of Section 36. This well would be drilled into the top of the San Andres where core and log analyses would evaluate the San Andres for present day water saturations. A third well location in 1996 would be based on the results of the first two wells and subsequent workover/recompletion results. The three wells to be drilled in 1997 would be guided by results of the 1996 field program and additional information gathered from new log and core analyses.

Serious consideration should be given to initially flooding the reservoir with CO_2 in addition to water. With the amount of work that is being done in the reservoir description and waterflood design, the incremental work to consider CO_2 is minimum. CO_2 is a proven recovery process in similar reservoirs and offers a higher ultimate recovery efficiency than waterflooding. This could allow recovery of oil from both the Grayburg and the San Andres Formations (if a water saturation of 50% is truly found to be present in the San Andres). CO_2 is definitely applicable for the Grayburg reservoir. Preliminary study shows oil saturations in the San Andres are too low to support a waterflood but would be acceptable for CO_2.

After completing the reservoir characterization for the final detailed reservoir simulation model, a thorough economic evaluation of a pilot CO_2 flood should be made; including another reservoir simulation with appropriate compositional logic to predict the response to the CO_2 flood. Economics should dictate the proper flooding procedure.

ACKNOWLEDGEMENTS

Robert Elphick, Scientific Software Intercomp, Denver, Colorado for petrophysical evaluation

David A. Rowland, Advanced Reservoir Technologies, Midland, Texas for reservoir engineering
The United States Department of Energy for its funding of this cost shared project, Cooperative Agreement No. DE-FC22-94BC14982.

REFERENCES

Bebout, D.G. and P. M. Harris, eds., 1990, Geologic and engineering approaches in evaluation of San Andres/Grayburg hydrocarbon reservoirs - Permian basin: The University of Texas at Austin, Bureau of Economic Geology, p. iv.

Laguna Petroleum Corporation, 1995, U. S. Department of Energy continuation application, An integrated study of the Grayburg/San Andres reservoir, Foster and South Cowden fields, Ector County, Texas.

Smith, W.H., J.J. Reeves, R.C. Trentham, and D.A. Rowland, 1995, An Integrated Study of the Grayburg/San Andres Reservoir, Foster and South Cowden Fields, Ector County, Texas: Southwestern Petroleum Short Course, 1995 Conference, April 19-20, Texas Tech University, Lubbock, Texas, p. 463-494.

Table 1
3-D Seismic Data Acquisition Parameters

Shot by Dawson Geophysical Company. Party 19	Vibrator Locations: 438
Recorder/Format: I/O System II. SEG D	Number of Channels: 679
Filter: Low cut filter - out	Geophone Array: 55-0-55 ft
Energy Source: Vibroseis (a trademark of Conoco)	Sweep: 8-110 Hz Non-Linear. 6db per octave. 10 sec
Number of Sources/Sweeps: 4/8	Source Array: In-line. bumper to bumper. no move up
Sample Rate: 2 ms	Data Length: 3 sec
Shot Point and Group Intervals: 220 ft	Spread: Fixed

Seismic Data Processing

The 3-D seismic data was processed at Dawson Geophysical Company in Midland. Texas. using SSL Phoenix Vector 3-D seismic data processing software. Particular emphasis was placed on preserving true seismic amplitude and on designing a deconvolution operator to insure a uniform broadband seismic wavelet in the data for stratigraphic interpretation. Processing was completed in February. 1995. A summary of the seismic data processing sequence is shown in Table 2.

Table 2
Generalized High Resolution 3-D Seismic Processing Sequence

Demultiplex
Geometry Definition
Refraction Statics
Spherical Divergence Correction
Minimum Phase Filter
Spiking Deconvolution
Trace Balance
Weathering Statics
Normal Moveout Correction
Trace Muting
Datum Statics
Surface Consistent Residual Statics
Dip Move Out
Stack
FX Deconvolution
One Pass Finite Difference Migration (checkshot velocities used)
Phase Rotation (to match synthetics from sonic logs)

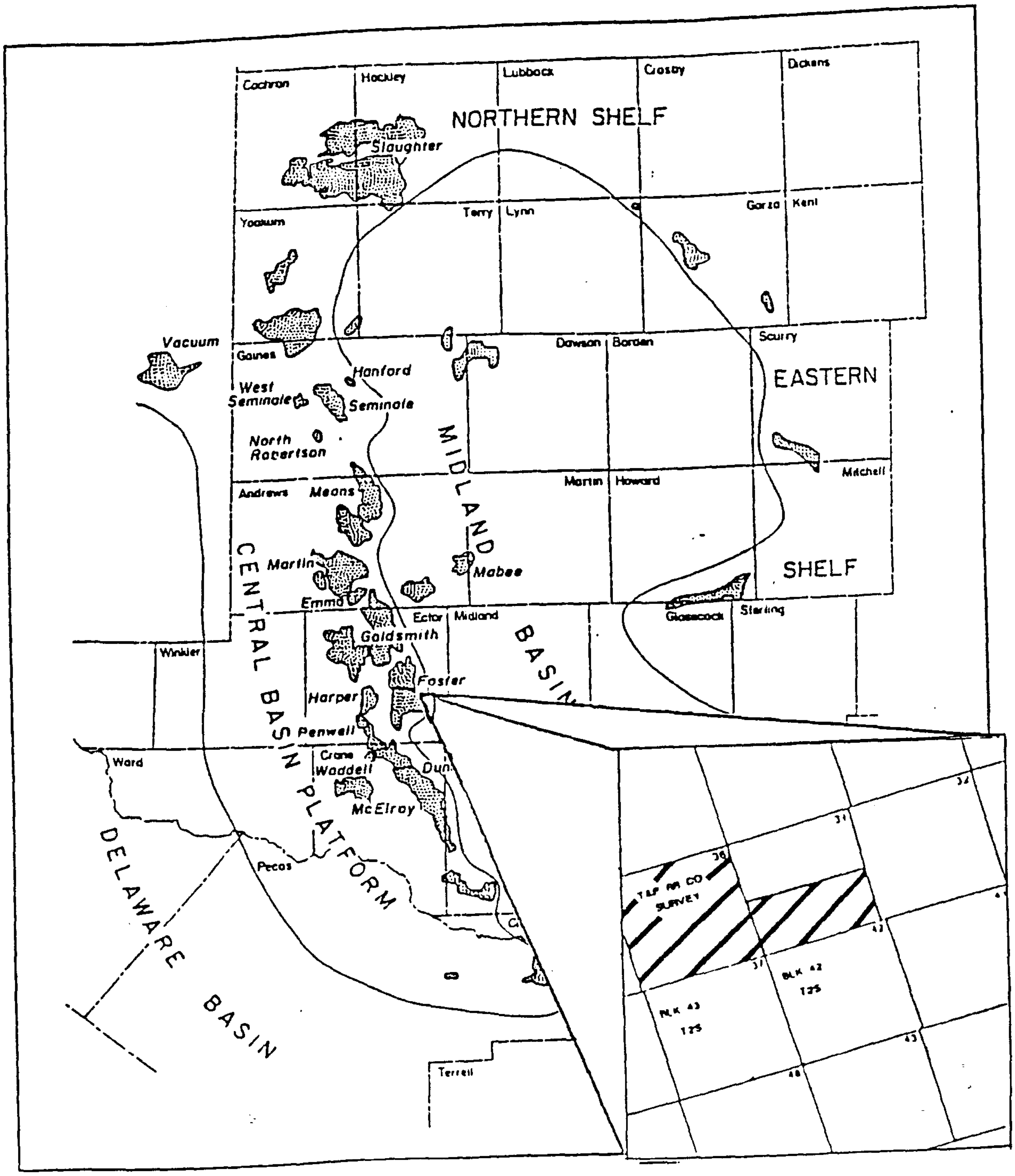

Figure 1 - Index Map of the Study Area (After Bebout and Harris, 1990)

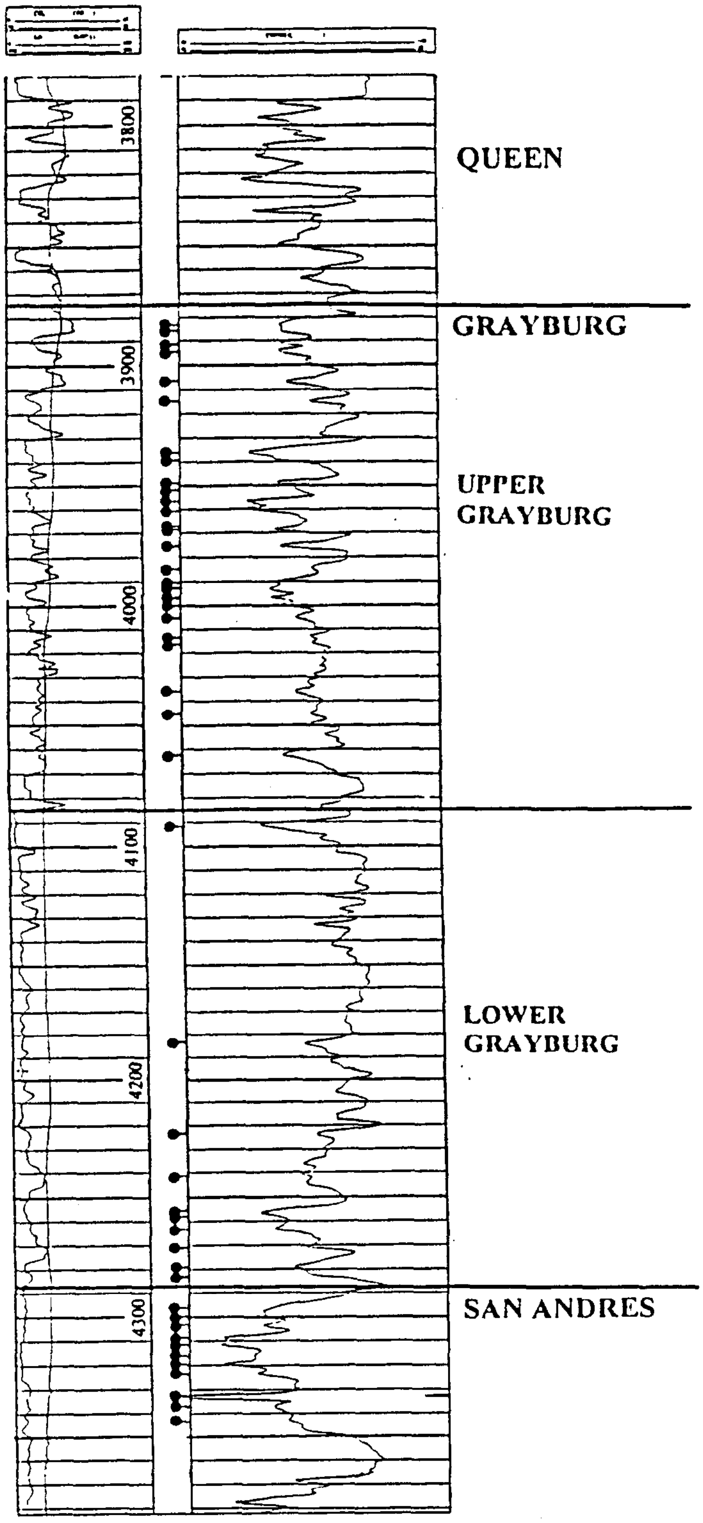

Figure 2 - Type-log of Well Drilled in Study Area