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RESERVOIR CHARACTERIZATION OF UPPER DEVONIAN GORDON SANDSTONE, JACKSONBURG, STRINGTOWN OIL FIELD, NORTHWESTERN WEST VIRGINIA

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ABSTRACT

The Jacksonburg-Stringtown field was discovered in 1895. It is located on the western flank of the Burchfield syncline, in southeastern Wetzel, eastern Tyler, and northwestern Doddridge counties, West Virginia. Over 500 wells were drilled in the field between 1897 and 1901; most were plugged by 1910. Primary recovery has been estimated to lie between 1454 and 1590 barrels of oil per acre. Primary production was a result of solution gas drive and gravity drainage through the mid-1920's and resulted in production of an estimated 13 million barrels of oil.

Gas injection began prior to the 1940's. Recovery attributed to gas injection averaged 154 BOPA over a limited portion of the field. The pilot waterflood of the Gordon was installed in 1981 as an approximately 34 acre dual five-spot. Since 1990, more than 100 new wells have been drilled for water injection and 40 new wells drilled for production. Between January, 1991 and February, 1999, 1,864,782 barrels of oil have been produced as a result of the full-scale waterflood.

Three statistically significant, positive correlations involving Permeability is significantly correlated with primary porosity, secondary porosity, and potassium feldspar content. Potassium feldspar grains weather relatively easily into clay, leaving intergranular porosity and hence, permeability. Potassium feldspar content is positively correlated with both secondary porosity and clay content.

Four Electrofacies identified in the Gordon are: Electrofacies 1, corresponding to shales within the Gordon; Electrofacies 2 and 3, corresponding to Non-Pay Sandstones (sandstones of Electrofacies 3 are coarser that 2); and Electrofacies 4, corresponding to Pay Sandstones of the reservoir. Conglomerates are found interbedded with the sandstones of Electrofacies 3 and 4. In vertical cross-section, Electrofacies 3 and 4 are observed to be asymmetrically distributed within the Gordon Reservoir and to be concentrated on the east side of the field.

Lithology and sedimentary structures observed in outcrop are similar to features observed in Non-Pay sandstones in the reservoir. Consequently, the minimal permeabilities measured in outcrop are analogous to those in the Non-Pay sandstones in the Gordon. The outcrops as a whole cannot be used as a model of the Pay sandstones in the reservoir.

A relationship between core plug permeability values, mini-perms, and geophysical well log data was developed through an Artificial Neural Network. Permeability was predicted with R-squared values greater than 76% with the exception of one well.

Redefinition of flow units improved simulation results in the pilot area. Flow unit I consisted of the lower part of the conglomerate-sandstone sequence and the upper part of the sandstone section. This Flow Unit has a slightly lower porosity but much lower permeability. Flow unit II is defined as the lower part of the sandstone. It has higher porosity and permeability.

EXECUTIVE SUMMARY

The Jacksonburg-Stringtown oil field contained an estimated 88,500,000 barrels of oil in place, of which approximately 20,000,000 barrels were produced during primary recovery operations. A gas injection project, initiated in 1934, and a pilot waterflood, begun in 1981, yielded additional production from limited portions of the field. The pilot was successful enough to warrant development of a full-scale waterflood in 1990, involving approximately 8,900 acres in three units, with a target of 1,500 barrels of oil per acre recovery. However, PennzEnergy (now East Resources) encountered technical barriers to production that must be overcome if they are to reach this enhanced production goal.

The West Virginia University Research Corporation is assisting PennzEnergy by developing a three-dimensional model of permeability for the Upper Devonian Gordon sandstone reservoir in the field. Two approaches are being used: analysis of geophysical and core data, and direct measurement of permeability in core and in outcrops that are analogous to the subsurface reservoir. The goal is to establish relationships among permeability, geophysical and other data by integrating geologic, geophysical and engineering data into an interdisciplinary quantification of reservoir heterogeneity as it relates to production.

This report documents achievements made during the fifth six-month period of the contract. During this interval of time, project focus was on reservoir description (Task 2), outcrop permeability study (Task 3), and reservoir characterization (Task 4).

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developed through an Artificial Neural Network. Permeability was predicted with R-squared values greater than 76% with the exception of one well.

Redefinition of flow units improved simulation results in the pilot area. Flow unit I consisted of the lower part of the conglomerate-sandstone sequence and the upper part of the sandstone section. This Flow Unit has a slightly lower porosity but much lower permeability. Flow unit II is defined as the lower part of the sandstone. It has higher porosity and permeability.

The project is on schedule, and we anticipate all milestones scheduled for the upcoming six-month interval to be accomplished as planned.

INTRODUCTION

Discovered in 1895, the Stringtown field is located on the western flank of the Burchfield syncline, in southeastern Wetzel, eastern Tyler, and northwestern Doddridge counties, West Virginia. Over 500 wells were drilled in the field between 1897 and 1901, most plugged by 1910. Average well spacing was 13 acres per well. Average initial potential of these wells was 72 BOPD, with a range of 0 to 300 BOPD (King, 1980). The wells were initially stimulated ("shot") with nitroglycerine. Many wells have been shot several times to increase production. Average production life of the wells was approximately 20 years. Based on an effective area of 4,388 acres, primary recovery has been estimated to be between 1454 (King, 1980) and 1590 (Morrison, 1991) BOPA. Primary production was a result of solution gas drive and gravity drainage through the mid 1920's and resulted in production of an estimated 13 MMBO (Morrison, 1991) from the waterflood area (8,900 acres). Primary production has been calculated from lease production records to range between 824 and 2,700 BOPA. Whieldon and Eckard (1963) estimated primary production to equal 20 MMBO and original oil in place to equal 88.5 MMBO for the entire Jacksonburg-Stringtown field, an area of 15,386 acres.

Gas injection began in 1934 (Boone and others, 1986) or mid 1920's (Putscher and King, 1983). Limited development and testing continued through the 1950's, with five injection wells spread out through the field. Recovery attributed to gas injection averaged 154 BOPA over a limited portion of the field (Boone and others, 1986).

The pilot waterflood of the Gordon was installed in 1981, as an approximately 34 acre dual five-spot An average of 1300 BOPA was recovered in 4 years. Water injection rates were limited due to supply. Lower than predicted (1500 BOPA) recovery is believed to be due to dump flooding of the eastern five-spot (Boone and others, 1986).

The full-scale waterflood began in 1990. Since 1990, more than 100 new wells have been drilled for water injection and 40 new wells drilled for production. Of these newly drilled wells, 24 of them have been drilled with low angle deviations, to accommodate surface topographic and logistical constraints. PennzEnergy divided the field into 3 areas or units for their waterflood development. Unit I, consisting of 1,815 acres, was formed in 1981, and contains the pilot waterflood. Unit II, 5,723 acres, was formed in 1986 and is located north of and adjacent tothe first. Unit III, 1,360 acres, was formed in 1995 and is located south of Unit I. From January, 1991 through February, 1999 1,864,782 barrels of oil have been produced as a result of the full-scale waterflood. Water for injection in the full-scale flood is transported from shallow water wells drilled near the Ohio River to the field via a 15-mile long pipeline constructed for that purpose.

New well drilling and secondary recovery operations led to the following observations: 1) early breakthrough in water floods; 2) multiple sand bodies within the reservoir; 3) difficulties in converting old, shot wells to injection wells; 4) areas of unusually high production within the field; 5) growth faults in one part of the field; and 6) unexpected vertical communication between sand bodies.

This project includes four scientific and engineering tasks: database development, reservoir description, a study of permeability in outcrop, and reservoir characterization. Task 1 was completed before this reporting period; and tasks 2 through 4 are in progress, with a number of subtasks complete.

Work reported previously showed that in the pilot waterflood area, the Gordon can be subdivided into three stratigraphic intervals, designated from top to bottom: A, B, and C. Each interval is heterolithic, consisting of a combination of conglomerate, pay sandstone, nonpay sandstone, and shale. Pay sandstone comprises only part of the total Gordon, creating isolated flow-units occurring within each of the stratigraphic intervals.

In addition, previous reports detailed our efforts to predict permeability from geophysical logs. Because of the heterogeneous nature of the formation, more detailed formation characteristics such as grain size, lithology, and depositional environments might need to be incorporated in the development of the relationship between permeability and well log data. Application of a neural network, which has been found to be powerful tool for identifying the complex relationships, was to be investigated.

This report gives results of our efforts to determine electrofacies from logs; measure permeability in outcrop to study very fine-scale trends; find the correlation between permeability measured by the mini-permeameter and in core plugs, define porosity-permeability flow units; and run the BOAST III reservoir simulator using the flow units defined for the Gordon reservoir.

RESULTS AND DISCUSSION

TASK 2: RESERVOIR DESCRIPTION

Subtask 2.3 - Stratigraphy

Milestone 25 – Petrographic study summarized and reported (**STATUS:** *Complete*)

Preliminary examination of 41 (10 from outcrop; 31 from core) petrographic thin sections consisted of a microscopic "reconnaissance" of each section to gain information on grain contacts, cements, stratification, and unusual features. Areas within each section requiring further examination were noted at this time.

Next, mean grain size and sorting was established for each thin section on the basis of 300 point counts. Mean grain size value was reported in both millimeters and Φ units (Krumbein, 1934); a numerical value for sorting was computed using the Inclusive Graphic Standard Deviation of Folk (1974, p. 46). This index is based on a comparison of the grain size in Φ units for various percentiles (95th, 84th, 16th, and 5th) of the grain size distribution of the entire sample. Values that are close to or less than 0 indicate good sorting; larger values indicate poorer sorting. In a number of instances, the distribution of grain size in individual thin sections was found to be distinctly bimodal. In these instances, the point counting procedure was repeated for "coarse" and "fine" fractions and results were reported for each size class. Finally, for thin sections taken from core material, permeability values measured by minipermeameter at the core interval closest to the thin section position were placed in an Excel spreadsheet along with grain size and sorting data. Bivariate correlations (SPSS, 1999) were performed between permeability, grain size (both millimeter and Φ units) and sorting index. In general, permeability is negatively correlated with grain size and is positively correlated with sorting. However, neither of these correlations was determined to be statistically significant at the 95% confidence level.

Finally, each thin section was again point counted to 300 points but grains and pore space (identified in thin section by infilling with blue epoxy) were classified into one of ten categories (Monocrystalline Quartz, Polycrystalline Quartz, Secondary Quartz, Potassium Feldspar, Primary Porosity, Secondary Porosity, Micas, Opaques, Clays, and "Other"). At the end of the point counting session for each thin section, category totals were converted to percentages. These data were placed in Excel spreadsheet created earlier and statistical correlations were investigated between permeability, grain size, sorting, and grain components. Three statistically significant, positive correlations involving permeability were found; permeability and Primary Porosity (≥ 99% confidence level), permeability and Secondary Porosity (≥ 95% confidence level), and permeability and the Potassium Feldspar content (≥ 95% confidence level). The correlation between porosity and permeability was expected but that between permeability and feldspar content was not. The later correlation is probably due to the propensity of potassium feldspar grains to weather relatively readily into clay leaving intergranular porosity and hence, permeability. Note that Potassium Feldspar content is positively correlated with both Secondary Porosity (≥95% confidence level) and Clay content (≥ 95% confidence level). Other statistically significant correlations observed are shown in Figure 1. A summary of this information will be distributed to all team members.

Subtask 2.4 - Electrofacies

Milestone 27– Database of three-dimensional electrofacies created for entire field (**STATUS**: *Complete*)

Digitized geophysical logs (gamma ray and density) from eight of the cored wells in the field (095-741, 095-859, 095-1124, 095-1125, 095-1126, 095-1532, 103-1315, and 103-1547) were used to establish parameters for recognition of electrofacies within the Gordon reservoir. K-Means Cluster Analysis (SPSS, 1999) was used to identify closely related groups of data based on a linear combination of density and "scaled" gamma ray (range: 0.0 to 1.0). Each geophysical sample from the logs for the cored wells was classified as belonging to either electrofacies 1, 2, 3, or 4 during the clustering procedure. Discriminant Analysis (SPSS, 1999) was performed on the classified dataset for the cored wells. This procedure produced a set of Fisher's coefficients for each electrofacies. Fisher's coefficients are used to compute the classification "score" (ie., Electrofacies 1, 2, 3, or 4) using a linear equation of the form: $D = B_0 + B_1X_1 + B_2X_2$, where D is the group membership, B_0 , B_1, and B_2 are the computed Fisher's coefficients, X_1 is the value of density response, and X_2 is the value of scaled gamma ray response (Norusis, 1993). These coefficients were applied to all the other logged wells in the field allowing the classification of their density and scaled gamma ray responses into one of the four electrofacies.

Two, separate, field-wide, electrofacies data sets were created. Both contained the facies classifications for all wells in the field with gamma ray and density logs. Within one set of data, well depths were converted to metric, subsea elevations and individual wells correlated to the top of the Gordon interval as picked in well 095-1124 (Thompson Heirs #8). In the second data set, all well depths were converted to metric, subsea elevations, but wells were not correlated. To create the final, three-dimensional data sets, the UTM coordinates of each well location were added to well depths; the final structure of the field-wide electrofacies data is Well Code, UTM easting, UTM northing, Depth, and Electrofacies Number.

Milestone 28 – Electrofacies cross-sections and slice maps created for entire field (**STATUS**: *Complete*)

Horizontal slice maps were created from the three-dimensional electrofacies data sets. In general, slices were made every 0.5 m (1.6 ft) from the top of the Gordon interval to the bottom. In these maps, individual electrofacies were "color-coded" and displayed at the appropriate well location as discrete points. No attempt was made to interpolate electrofacies between wells as the electrofacies classification numbers do not represent a continuous series of numerical values. Figure 2 shows an example of one of the horizontal slice maps.

Figure 3 shows a structural contour map of the top of the Gordon interval for the Jacksonburg field. As reported previously (Semi-Annual Report, April 1999), the Gordon sandstone in the field has been folded into a broad syncline that plunges to the northeast. A synclinal axis has been superimposed on the contour map shown in Figure 3. This axis was used as a reference for orienting vertical cross-sections. Vertical cross-sections were constructed parallel to (NE-SW) and at right angles to (NW-SE) the synclinal axis. Figure 4 and 5 show examples of vertical cross-sections.

Milestone 29 – Completed three-dimensional electrofacies model for entire field (**STATUS**: *Complete*)

Geostatistical methods were used to generate 3-d realizations of electrofacies and permeability in the pilot area using software contained in Deutsch and Journel (1998). Sequential Indicator Simulation (Hohn, 1999) was used to generate realizations from the database of electrofacies developed under milestone 27, and compared with realizations created by Sequential Gaussian Simulation from values of permeability computed with use of Artificial Neural Networks (Milestone 37). There was some correspondance between the two realizations in that some electrofacies matched with particular electrofacies. In general the similarity was low because of the limited parts of the reservoir in which permeability could be estimated with any reliability. Stratigraphic and geographic relationships between electrofacies in these parts of the reservoir are relatively simple.

Milestone 30 – Petrophysical characteristics for each electrofacies compiled (**STATUS**: *Complete*)

Figure 6 summarize petrophysical characteristics of each of the four electrofacies identified within the Gordon reservoir in the Jacksonburg field. In general, Electrofacies 1 corresponds to Shales within the Gordon; Electrofacies 2 and 3 correspond to Non-Pay Sandstones (sandstones of Electrofacies 3 are coarser that 2); and Electrofacies 4 corresponds to the Pay Sandstones of the reservoir. Conglomerates are not identified as discrete units, rather they are found interbedded with the sandstones of Electrofacies 3 and 4.

Milestone 31 – Electrofacies study summarized and reported (**STATUS**: *Complete*)

On February 6, 2001, all members of the Jacksonburg Project met with representative of East Resources, the current owner and operator of the Jacksonburg field. At that time, the results of electrofacies analyses for the field were presented. Subsequently, the Projects' engineering personnel requested a new set of electrofacies cross-sections reoriented with reference to the structural axis of the field. These cross-sections have been completed, examined, and presented to project personnel for scrutiny.

	PERMEABILITY	MEAN GRAIN SIZE (mm)	SORTING	%MONOCRYSTALLINE QUARTZ	%POLYCRYSTALLINE QUARTZ	%SECONDARY QUARTZ	%POTASSIUM FELDSPAR	%PRIMARY POROSITY	%SECONDARY POROSITY	%MICAS	%OPAQUES	%CLAYS	%"OTHER"
PERMEABILITY													
MEAN GRAIN SIZE (mm)													
SORTING		- -											
%MONOCRYSTALLINE QUARTZ													
%POLYCRYSTALLINE QUARTZ		+	- -										
%SECONDARY QUARTZ													
%POTASSIUM FELDSPAR	+				-								
%PRIMARY POROSITY	++												
%SECONDARY POROSITY	+		+		-		+	++					
%MICAS		-	++	-					+				
%OPAQUES													
%CLAYS					-		+						
%"OTHER"				- -		- -		- -	- -			-	

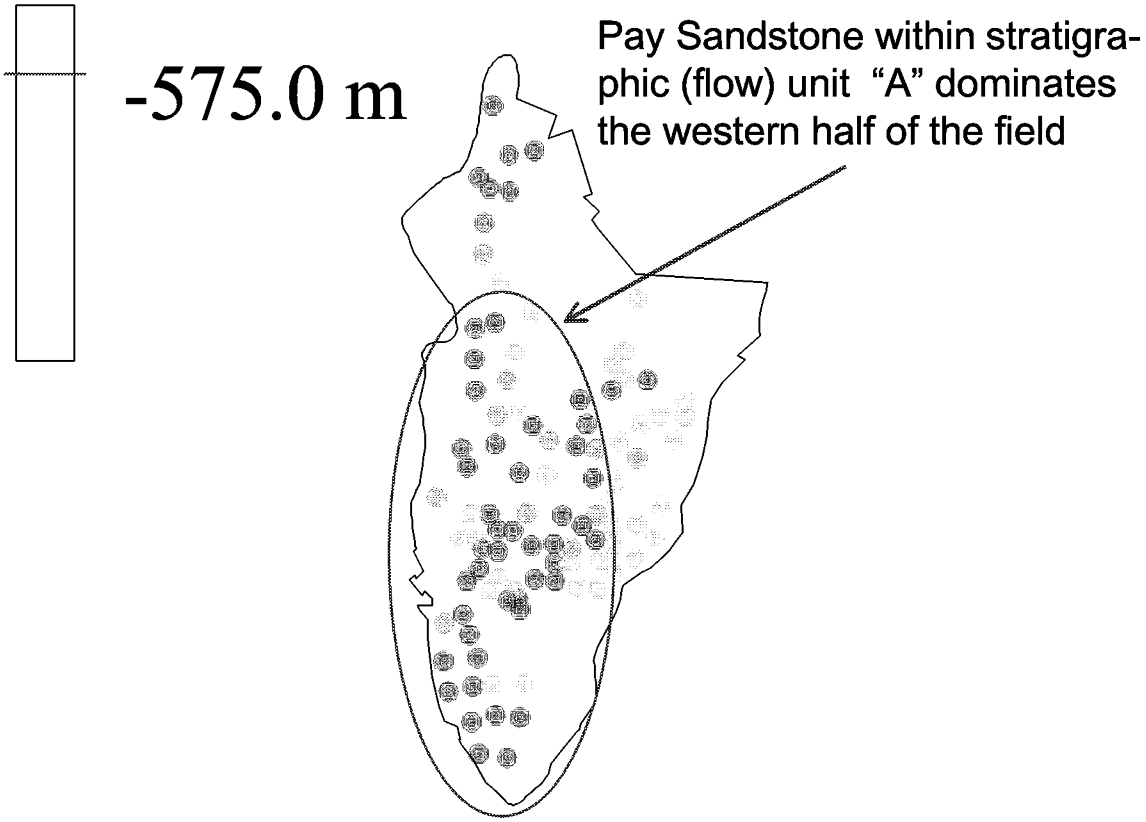
++ positive correlation significant at ≥ 99% confidence level

+ positive correlation significant at ≥ 95% confidence level

- - negative correlation significant at ≥ 99% confidence level

- negative correlation significant at ≥ 95% confidence level

Figure 1 – Bivariate correlation matrix for variables measured in thin section.



Pay Sandstone within stratigraphic (flow) unit "A" dominates the western half of the field

Figure 2 – Horizontal slice map for the correlated electrofacies data set, Jacksonburg field. Slice taken at –575.0 m below sea level. Position with respect to the top of the Gordon interval is shown graphically in the upper left corner of the Figure. Electrofacies have been color-coded (Electrofacies 1 - red; Electrofacies 2 – green; Electrofacies 3 – yellow; Electrofacies 4 – blue). NOTE: Electrofacies 4 corresponds most closely to the Pay Sandstone within the reservoir.

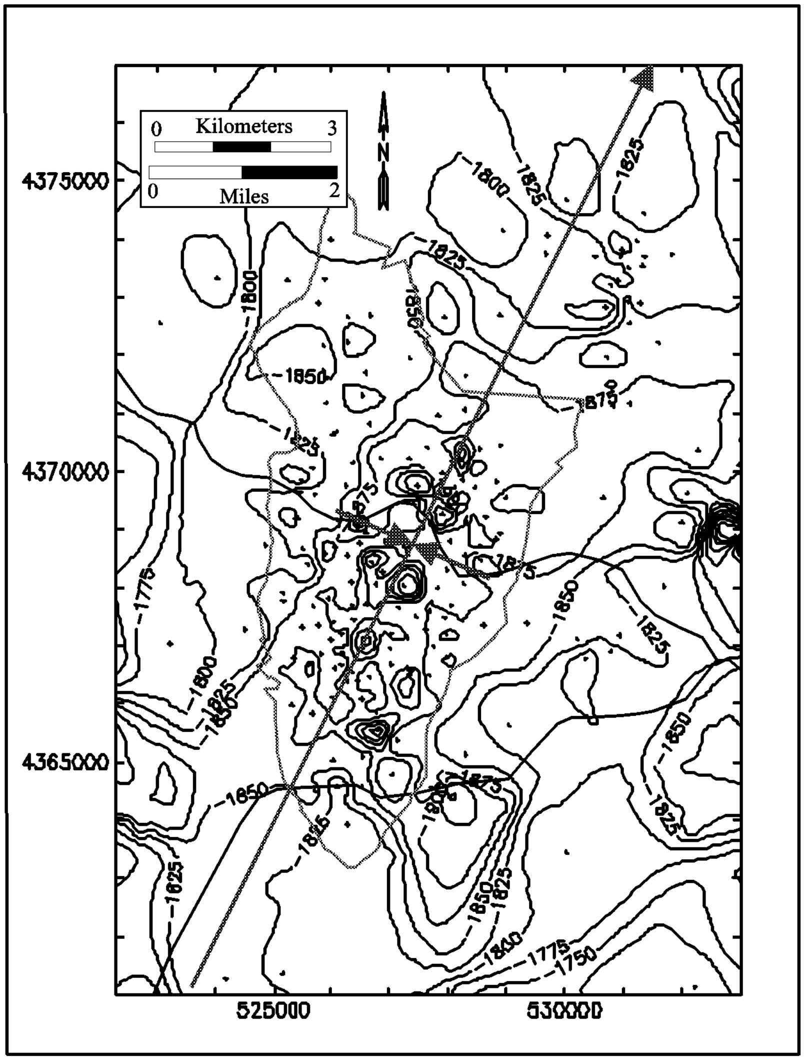


Figure 3 – Structural contour map on the top of the Gordon interval in the Jacksonburg field. A structural axis has been superimposed on the field showing the direction of plunge the syncline. Contour interval is 25 feet.

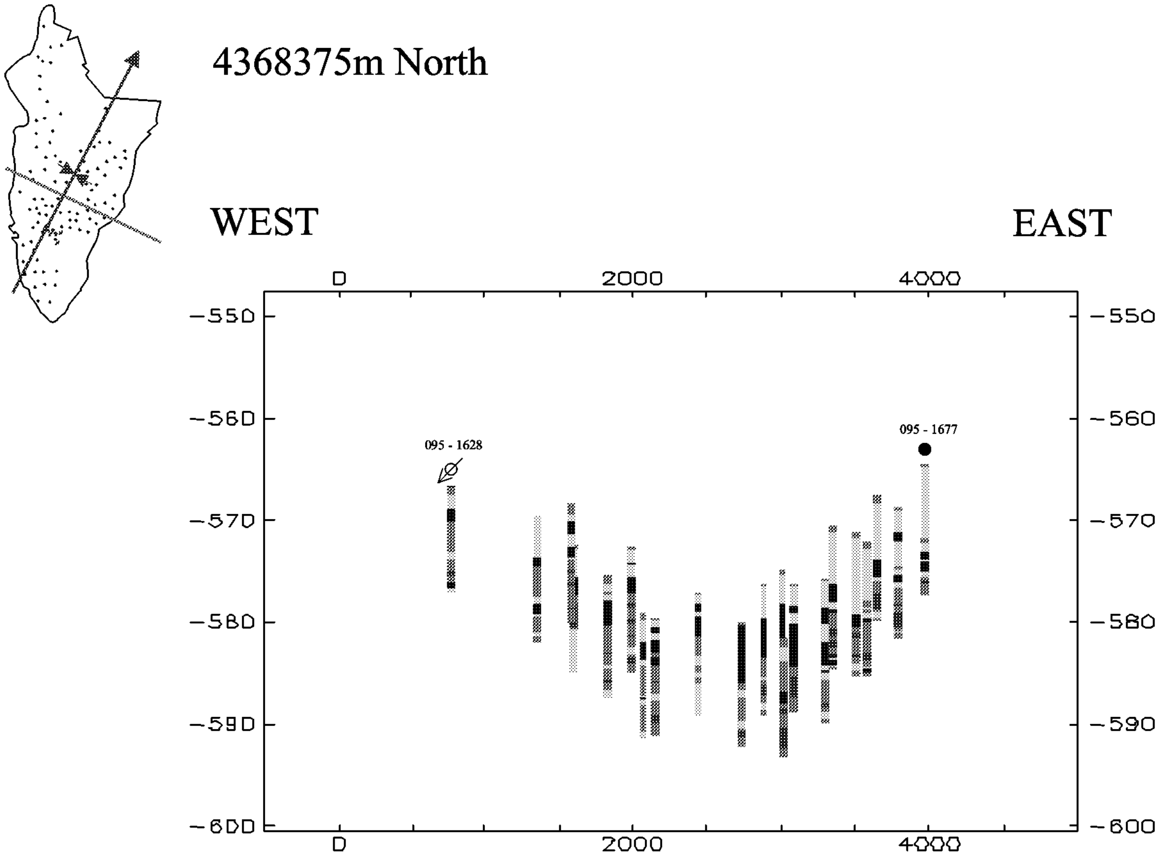


Figure 4 – Vertical cross-section through the uncorrelated, electrofacies data set for the Jacksonburg field. Section is oriented approximately NW-SE, at right angles to the synclinal axis of the field. Position of the section is shown graphically in the upper left corner of the Figure. Electrofacies are color-coded using the same colors as in Figure 2. Notice the asymmetrical distribution of Electrofacies 3 and 4, which are concentrated on the east side of the field.

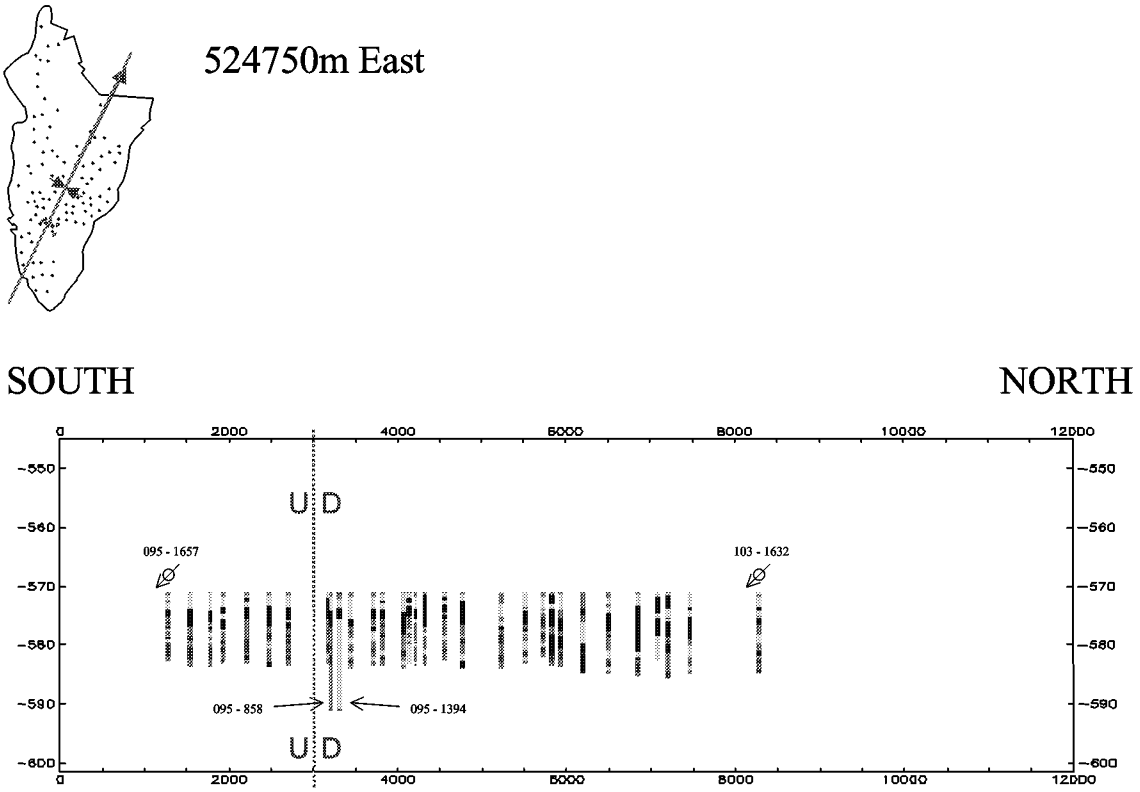


Figure 5 – Vertical cross-section through the correlated, electrofacies data set for the Jacksonburg field. Section is oriented approximately NE-SW, parallel to the synclinal axis of the field. Position of the section is shown graphically in the upper left corner of the Figure. Electrofacies are color-coded using the same colors as in Figure 2. The approximate location of a fault within the Gordon interval is shown on the cross-section along with the interpreted sense of motion.

		Mean Gamma Ray	Mean Density	Mean Permeability	Mean Grain Size
Shale	● Electrofacies 1	135.529	2.682	0.000	Coarse Silt
Non-Pay Sandstone	● Electrofacies 2	79.175	2.555	2.651	Very Fine Sand
	● Electrofacies 3	39.576	2.519	3.154	Medium Sand
Pay Sandstone	● Electrofacies 4	47.026	2.352	30.989	Very Fine Sand & Granule

NOTE: Conglomerate is not represented by any single Electrofacies. Most typically it is found to be a lithologic "component" within Electrofacies 3 and 4.

Figure 6 – Petrophysical characteristics of Electrofacies based on core analysis, thin section analysis, geophysical log response, and permeability sampling using the minipermeameter.

Subtask 2.5-Petrophysics

Milestone 35- Completed porosity and permeability analysis of core plugs taken from outcrop **(STATUS:** *Complete***)**

Milestone 36- Begin comparison of core and outcrop permeability **(STATUS:** *Complete***)**

Porosity and permeability measurements of the outcrop samples(plugs) have been completed. The results indicate that porosity values are very low and permeability values are zero. This is compatible with the mini-permeameter measurements.

Milestone 37- Determine Statistical correlation between direct permeability and core plug analysis **(STATUS:** *Complete*)

Comparison of the core permeability distribution measured by the mini-permeameter and the core plug analyses indicate very different values. The permeability values measured by the mini-permeameter (mini-perms) are much lower in value and are much more sporadic in nature than core plug analysis. The differences are probably caused by a number of factors including damage to the core surface, the scale of measurements by the different tools, and the fact that the measured permeability value by the mini-permeameter is a combination of horizontal and vertical permeability values. Variability in mini-perm data is due to scale of measurement. The mini-permeameter measures the permeability at one spot on the surface of the core. Therefore, the measured permeability represents very small volume of the rock. The core plugs generally represent somewhat larger volume (a 1-inch diameter by 1-inch long). It should be noted that only one core plug is obtained from every one-foot interval of the core. Furthermore, the plug is obtained from the high porosity and permeability section of the interval. As a result, mini-perms more accurately represent the small-scale permeability variations in the core. In a heterogeneous formation, mini-perms are therefore more variable. However, the mini-perms are much more affected by core surface conditions since the depth of investigation is very limited. The core used in this study appear to have been coated by an unknown substance which has apparently reduced the permeability.

The objective of this task was to predict the small-scale permeability variation in the formation based on the measured core mini-perms. To achieve this objective, a relationship between core plug permeability values, mini-perms, and geophysical well log data must be developed. It should be noted that well log data are obtained at quarter of foot scale which is more representative of the formation than the core plugs scale. Due to good results obtained with Artificial Neural Networks (ANN) for permeability prediction, two separate ANNs were trained and tested to develop this relationship. Six wells which had both core plug permeability values and measured mini-perms available, were utilized in this study. The first ANN utilizes the data from the Bulk Density and Gamma Ray logs as well as well location and mini-perms as input and core plug permeability as output. Due to differences in the scale, the mini-perms were first averaged out using moving average technique and then the average mini-perm and log data corresponding to the depth at which core plug were taken were used as inputs. A measure for accuracy of the network is correlation coefficient (R-squared) between the target output and network predictions. A reliable network provides high R-squared (close to 1.0) value for a set of data not used as part of training, generally called the verification set. The verification set in this study consisted of all data from one well.

The first network provided R-squared values exceeding 76% for all wells when used as a verification set. The first network was then utilized with detailed log and mini-perm data to generate a detailed permeability profile for each well. The generated detailed permeability profile was then used as target output for the second network. The second network had detailed log data and well location as input. The second network provided accurate prediction of the permeability. The verification sets resulted in R-squared values greater than 76% with the exception of one well.

Milestone 38- Complete Comparison of core and outcrop permeability **(STATUS:** *Complete*)

Milestone 39- Established criteria for creating three-dimensional permeability database **(STATUS:** *Complete*)

Neural networks developed for permeability prediction from well log data has been utilized to predict and establish the three-dimensional permeability distribution in the reservoir.

Milestone 40- Petrophysical results summarized and reported **(STATUS:** *Complete*)

Results of our analysis of porosity and permeability data collected during this project are reported above.

Task 3 – Outcrop Permeability Study

Milestone 47 – Outcrop permeability study summarized and reported (**STATUS:** *Complete*)

No outcrop permeability within the range of that for the Pay Sandstone (≥ 20 mD) has been obtained. One inch plugs taken by core drill from outcrop localities have been analyzed and have shown no permeability. The lack of outcrop permeability makes modeling impossible. The outcrops chosen as analogs to the Gordon reservoir, although similar in grain size, grain sorting, grain composition, and sedimentary structures appear to be too tightly cemented to represent the Pay Sandstones within the Gordon. Consequently, no further work on or with the outcrop data will be carried out.

TASK 4. Reservoir Characterization

Subtask 4.0 and 4.1

Milestone 48- Mini-permeameter permeability from cores and outcrop integrated into fluid flow modeling **(STATUS:** *Complete*)

The core plugs as well as mini-perms from outcrops have indicated that the outcrops do not have significant porosity and permeability. Therefore, results from outcrops can not be used to develop fluid flow model for the reservoir. The flow modeling has been accomplished based on the 3-D permeability predictions of as discussed under Milestones 37 and 39.

Milestone 49-Modification to fluid flow modeling software completed.**(STATUS:** *Complete*)

The modification to fluid flow modeling software was not found to be necessary.

Milestone 50- Completed three-dimensional modeling of porosity-permeability flow units **(STATUS:** *Ongoing*)

Permeability and porosity distributions are the most critical factors in development of the Flow Unit model. The petrophysical studies on the core samples had revealed that the formation consists of three distinct lithologies: sandstone, conglomerate, and shale. Definition of Flow Units based on sandstone and conglomerate did not generate the reasonable results in simulation of waterflood in pilot area. Further investigations revealed that the conglomerate is a sequence of sandstone with interbedded conglomerate. As a result, two new flow units were defined. Flow unit I consisted of the lower part of the conglomerate-sandstone sequence and the upper part of the sandstone section. This Flow Unit has a slightly lower porosity but much lower permeability. Flow unit II is defined as the lower part of the sandstone. It has higher porosity and permeability. This definition of flow units provided significantly better simulation results in the pilot area. Presently, the study is focused in another part of the reservoir where the Flow Unit definitions are being verified with simulation results.

Subtask 4.2

Milestone 52- Compiled and report suggestions for modification of flow units **(STATUS:** *Ongoing*)

Data from waterflooding operations in other parts of the reservoir has been collected and analyzed to evaluate the flow unit model developed previously. The preliminary results appear to support the reservoir description based on the defined Flow Units.

Milestone 53- Complete final runs of BOAST simulator **(STATUS:** *Ongoing*)

The three-dimensional flow unit model and injection pressure-rate information were used with BOAST simulator to predict the oil and water production performance for the pilot area successfully. These results clearly indicate that the simulator can be used accurately to predict the performance of the secondary recovery. Additional runs are planned in other parts of the reservoir for further verification.

Milestone 54- Complete modifications to BOAST programs specific to field/reservoir
(STATUS: ***Ongoing*****)**

The flow unit model has been successfully used with the BOAST simulator to predict the reservoir performance during the waterflooding period. No reservoir specific modification to the simulator was found necessary. Additional runs are planned for further verification.

Milestone 55- Complete comparison of BOAST simulator results and production history
(STATUS: ***Ongoing*****)**

The available data from the primary recovery period are insufficient for simulation purposes. However, the secondary (waterflood) performance can be used for history matching. The runs with BOAST simulator have indicated that the predicted production performance during waterflooding period can be closely matched with reservoir performance history if the flow unit model is correctly described. This study is being further expanded to evaluate the flow unit in different part of the reservoir.

TASK 6. Technology Transfer

A workshop cosponsored by PTTC was presented in October on determining and modeling permeability in the Appalachian basin.

CONCLUSIONS

Three statistically significant, positive correlations involving permeability were found; permeability and Primary Porosity (≥ 99% confidence level), permeability and Secondary Porosity (≥ 95% confidence level), and permeability and the Potassium Feldspar content (≥ 95% confidence level). The correlation between porosity and permeability was expected but that between permeability and feldspar content was not. The later correlation is probably be due to the propensity of potassium feldspar grains to weather relatively readily into clay leaving intergranular porosity and hence, permeability. Note that Potassium Feldspar content is positively correlated with both Secondary Porosity (≥ 95% confidence level) and Clay content (≥ 95% confidence level).

Four Electrofacies have been identified within the Gordon reservoir. In general, Electrofacies 1 corresponds to Shales within the Gordon; Electrofacies 2 and 3 correspond to Non-Pay Sandstones (sandstones of Electrofacies 3 are coarser that 2); and Electrofacies 4 corresponds to the Pay Sandstones of the reservoir. Conglomerates are not identified as discrete units, rather they are found interbedded with the sandstones of Electrofacies 3 and 4.

In vertical cross-section, the sandstones of Electrofacies 3 and 4 are observed to be asymmetrically distributed within the Gordon Reservoir and to be concentrated on the east side of the field.

Outcrop permeability modeling cannot be completed because insufficient permeability is present. While the lithology and sedimentary structures observed in outcrop are similar to those seen in core, they are similar to features observed in the Non-Pay sandstones in the reservoir. Consequently, the minimal permeabilities measured in outcrop are analogous to those in the Non-Pay sandstones in the Gordon. The outcrops as a whole cannot be used as a model of the Pay sandstones in the reservoir.

A relationship between core plug permeability values, mini-perms, and geophysical well log data was developed through an Artificial Neural Network. An initial ANN utilizes Bulk Density and Gamma Ray logs as well as well location and mini-perms as input, and core plug permeability as output. This network was then utilized with detailed log and mini-perm data to generate a detailed permeability profile for each well. The generated detailed permeability profile was then used as target output for the second network, which provided prediction of permeability with R-squared values greater than 76% with the exception of one well.

Redefinition of flow units improved simulation results in the pilot area. Flow unit I consisted of the lower part of the conglomerate-sandstone sequence and the upper part of the sandstone section. This Flow Unit has a slightly lower porosity but much lower permeability. Flow unit II is defined as the lower part of the sandstone. It has higher porosity and permeability.

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