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Risk Reduction with a Fuzzy Expert Exploration Tool

(Second Annual Technical Progress Report)

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Executive Summary

Objectives

Incomplete or sparse information on types of data such as geologic or formation characteristics introduces a high level of risk for oil exploration and development projects. “Expert" systems developed and used in several disciplines and industries have demonstrated beneficial results. A state-of-the-art exploration “expert” tool, relying on a computerized database and computer maps generated by neural networks, is being developed through the use of “fuzzy” logic, a relatively new mathematical treatment of imprecise or non-explicit parameters and values. Oil prospecting risk can be reduced with the use of a properly developed and validated “Fuzzy Expert Exploration (FEE) Tool.”

This FEE Tool can be beneficial in many regions of the U.S. by enabling risk reduction in oil and gas prospecting as well as decreased prospecting and development costs. In the 1998-1999 oil industry environment, many smaller exploration companies lacked the resources of a pool of expert exploration personnel. Downsizing, low oil prices, and scarcity of exploration funds have also affected larger companies, and will, with time, affect the end users of oil industry products in the U.S. as reserves are depleted. The FEE Tool will benefit a diverse group in the U.S., leading to a more efficient use of scarce funds and lower product prices for consumers.

This second annual report contains a summary of progress to date, problems encountered, plans for the next quarter, and an assessment of the prospects for future progress.

Summary of Progress

During the second year of the project, data acquisition of the Brushy Canyon Formation was completed with the compiling and analyzing of well logs, geophysical data, and production information needed to characterize production potential in the Delaware Basin. A majority of this data now resides in several online databases on our servers and is in proper form to be accessed by external programs such as Web applications.

A new concept was developed and tested in well log analysis using neural networks. Bulk volume oil (BVO) was successfully predicted using wireline logs as inputs. This concept provides a new tool for estimating the potential success of a well and determining the productive interval to be perforated.

Regional attributes have been gridded to a 40-ac bin (gridblock) size, and our fuzzy ranking procedures were applied to determine which attributes are best able to predict production trends in the Delaware Basin. The production indicator was the average of the first 12 full producing months of oil production as the value to be predicted.

A study to determine the ability of an artificial intelligence system to predict depth using seismic attributes in a Delaware field was completed and the results were published.[1] Significant improvements over standard techniques were found, particularly when test wells were on the dataset boundary where extrapolation is required.

Programming the expert system was undertaken, and a decision tree program was coded in Java Expert System Shell (JESS) that allows development and tabulation of rules and relationships between rules that can be used by our expert system. This important program allows lists of rules to be entered and easily tested and verified.

The design of the expert system itself was clarified and an expanded system was created where several distinct factors such as geologic/geophysical data, trap assessment, and formation assessment can be operated on in parallel to increase efficiency of the overall system.

Coding of the Java interface, which users can use to access data in the online databases and run the expert system, was completed. Development of the interface ties together the data and the expert system programs coded in JESS while allowing user customization and informative reports of results to be retrieved.

Technology transfer continued to be an important aspect of this project. Research and progress to date was presented to a group of industry and academic professionals at the second annual consortium meeting held November 2, 2000 in Hobbs, NM. Key technical results from the project were reported in nine papers and posters that were presented during the second year of the project.

Progress and Discussion of Results

Geology

Geologic Data Acquisition and Analysis

During the reporting period from March 2000 to March 2001, geologic work continued on five main tasks.

1. Identification of wells that unsuccessfully tested the lower part of the Brushy Canyon Formation.
2. Correlation of lithology and reservoir distribution with areas of known production.
3. Correlation of petroleum source rocks with production from the lower Brushy Canyon.
4. Development and mapping of a database of cumulative oil and gas production from the lower Brushy Canyon Formation.
5. Development and mapping of a database of oil quality (oil viscosity and specific gravity) of lower Brushy Canyon oils.

Each of these tasks is designed to provide partial input of a major geologic variable into the fuzzy logic system for risk analysis and reduction. Work on the five tasks is summarized below.

Identification of wells that unsuccessfully tested the lower part of the Brushy Canyon Formation.

Drilling and completion records of more than 10,000 wells that were drilled within the Delaware Basin were examined to determine which of these wells tested the lower part of the Brushy Canyon Formation but were unable to establish production (Fig. 1). In those 75 wells, casing was perforated in an attempt to establish production. In most of the wells in which casing was perforated, attempts at stimulation such as acidizing or artificial fracturing were also employed. These wells identify locations where the lower Brushy Canyon Formation will not yield commercially viable quantities of oil and gas. Each well was correlated with the regional network of cross sections in order to positively ascertain that the completion attempt was made within the lower Brushy Canyon.

Correlation of lithology and reservoir distribution with areas of known production.

Work continued on correlation of lithology and reservoir distribution with areas of established, known production as well as with areas where wells have been unsuccessfully tested in the lower Brushy Canyon. During the first project year, it was determined that trends of sandstones with porosity exceeding 15 percent exhibited a first order control on production. Most Brushy Canyon oil fields are located along trends and in areas where net thickness of sandstone with 15 percent porosity (reservoir quality sandstone) exceeds 25 ft (Fig. 2). During the year 2000-2001, additional work revealed that much of the established production coincides with trends of percentage of reservoir quality sandstone within the lower Brushy Canyon (Fig. 3). Figure 3 essentially denotes areas where reservoir quality sandstones pinch out into non-reservoir quality sandstones and siltstones. In the central and eastern parts of the basin, most areas of production lie along trends that indicate a northwestward, updip pinchout. Figure 4 is a wire-frame structural relief map that shows the thickness of porous sandstone map of Fig. 3 superimposed on Bone Spring structure, indicating major updip regional trends of reservoir pinchouts.

Work during the current reporting year also involved correlation of reservoir trends with areas where the Brushy Canyon has been unsuccessfully tested. This work clearly shows that areas without significant reservoir quality sandstones are not productive of oil and gas (Fig. 2). The data also indicate, however, that large areas along the western and northern parts of the basin with thick sections of reservoir quality sandstones are nonproductive even though many attempts have been made to establish production.

There have been several explanations put forth by industry geologists as to why these areas of thick sandstone accumulation are non-productive but none of the explanations appears to have been rigorously tested. These explanations include:

1. There is a lack of adequate hydrocarbon seals in a northwestward, updip direction between the unsuccessfully tested areas and the surface outcrop belt of the Brushy Canyon. This lack of seals has either let oil and gas leak out to the northwest or has let influent recharge waters flush oil and gas out of traps.
2. The sandstones in the northern and western parts of the basin are finer grained than the sandstones in the central part of the basin even though porosity is similar. The finer grained sandstones are characterized by smaller pore spaces with higher capillary entry pressures. Existing hydrocarbon columns within the Brushy Canyon petroleum system exerted insufficient buoyant forces to enable entry of hydrocarbons into these reservoirs. The reservoirs with smaller pore sizes, therefore, remain water filled.
3. There is a lack of hydrocarbon source rocks with sufficient generative potential in the unproductive areas.

Explanation No. 3 (lack of source rocks) was tested in the present year. Results are discussed below but it appears that distribution of hydrocarbon source facies does not exert a first-order control on production in the lower Brushy Canyon. Explanation No. 1 has been only partially evaluated thus far (Figs. 2 and 3) by maps that indicate regional updip pinchouts of reservoir quality sandstones, and explanation No. 2 awaits evaluation during the next year of the project.

In order to ascertain the validity of explanations No. 1 and No. 2, more detailed work has been undertaken in two local areas of the basin (Fig. 5). The eastern of these areas is characterized by significant production from the lower Brushy Canyon and by very few wells that have unsuccessfully tested the lower Brushy. The western area is characterized by a small area of low-volume production and by a number of wells that represent unsuccessful attempts to establish production. Both areas contain substantial thickness of sandstone with at least 15 percent porosity. To date, work has concentrated on mapping of log-derived sandstone attributes in finely-subdivided sequence stratigraphic units in each of these areas. These attributes include thickness and percentage of porous sandstones as well as hydrocarbon seals. Mapping has been done at a finer scale than the previous regional work, and additional work will involve mapping of log-derived attributes that will yield factors related to bulk-volume oil, oil saturation, and pore-size distribution within the reservoir facies.

Correlation of petroleum source rocks with production from the lower Brushy Canyon

Hydrocarbon source facies were analyzed in the current and previous reporting years. Source facies in both the lower Brushy Canyon and in the underlying Bone Spring Formation have been considered to be the source of oils produced from the lower Brushy Canyon with the exact source varying from place to place within the basin.[2] As such, source rocks were analyzed in both formations as a means of determining controls on hydrocarbon accumulation and production. Source facies in the Bone Spring Formation consist of fine-grained, organic-rich, fetid lime mudstones. These underlie the lower Brushy Canyon reservoirs and in some cases are stratigraphically separated from productive reservoirs by one or more seals. Source facies in the Brushy Canyon Formation consist of fine-grained siltstones that contain substantial quantities of algal kerogens. These siltstones are interbedded with productive reservoirs in the lower part of the Brushy Canyon and form the seals for most, if not all, of the known productive reservoirs.

Bone Spring source facies. Eighteen samples of well cuttings and cores were analyzed from the uppermost part of the Bone Spring Formation. All samples were of black, organic-rich, fetid lime mudstones and therefore represent Bone Spring rocks most likely to be hydrocarbon sources. These analyses indicate that the Bone Spring is thermally mature and within the oil window throughout the entire basin (Fig. 6). A region of higher TMAX values, and therefore higher thermal maturity, is present along a northwest-southeast trend in the basin. A similar trend exists in values of total organic carbon (TOC; Fig. 7). Neither of these trends has any apparent, first-order correlation with production.

Brushy Canyon source facies. Thirty-five samples of drill cuttings and core were analyzed from the organic-rich siltstones interbedded with sandstone reservoirs in the lower Brushy Canyon Formation. Again, the entire lower Brushy Canyon is thermally mature and within the oil window throughout the basin (Fig. 8). However, differences in maturity levels are more accentuated than in the Bone Spring. The Brushy Canyon is most mature along the western flank of the basin where burial depth is shallowest. Again, relative levels of thermal maturity do not exhibit a first-order control on production. This is somewhat surprising because the Brushy Canyon, as a self-sourced petroleum system without regional carrier beds, should exhibit interdependency between oil accumulations and source facies.[3,4]

Trends of TOC in lower Brushy Canyon source facies also do not indicate any first-order correlation with production (Fig. 9).

Development and mapping of a database of cumulative oil and gas production from the lower Brushy Canyon Formation.

Data of cumulative production of oil, gas, and water from reservoirs in the lower Brushy Canyon Formation were assembled and mapped during the reporting year 2000-2001 (Figs. 10-13). The goal of this task is to integrate the volume of production into the fuzzy logic system rather than just the presence or absence of production. This task was nontrivial since reported production data are identified by well and indicate that production is obtained from within the Delaware Mountain Group but do not identify which formation in the Delaware provided the production. Because there are two other formations in addition to the Brushy Canyon that comprise the Delaware and because minor amounts of Brushy Canyon production are obtained from the middle and upper parts of the formation, it was necessary to ascertain which Delaware wells produce from the lower Brushy Canyon. Producing zones in Delaware wells were correlated with our network of regional cross sections in order to identify 400 wells that produce solely from the lower Brushy Canyon and to obtain cumulative production data from the lower Brushy Canyon.

The mapped cumulative production data clearly indicate that the most productive lower Brushy Canyon reservoirs reside in the central and north-central parts of the basin (Figs. 10 and 11). Oil-water ratios and gas-oil ratios of wells also appear to be higher in these areas (Figs. 12 and 13).

Development and mapping of a database of lower Brushy Canyon oil quality.

Oil quality is an important variable to be considered in prospect development and risk assessment. Factors such as oil viscosity and specific gravity affect not only the product price but also govern ease of production. Low viscosity oils are generally easier to produce and command a higher product price than high viscosity oils. Oils with low specific gravity generally contain hydrocarbons with lower molecular weights and lower sulfur contents, factors that affect ease and expense of refining.

Reported values of API gravity of lower Brushy Canyon oils were collected, collated and mapped from 299 producing wells within the Delaware Basin (Fig. 14). API gravity is an inverse measure of specific gravity. As such, the API gravity generally varies inversely with sulfur content and viscosity; that is, high API gravity oils have very low specific gravity and therefore are generally characterized by low viscosity and low sulfur contents, which are desirable traits.

The basin-wide map of API gravity of lower Brushy Canyon oils (Fig. 14) indicates an east-west trend of higher gravity oil across the southern part of the basin and another north-south trend of higher-gravity oil within the east-central portion of the basin. Correlation of these data with other variables that will enable prediction will be done in the next year of the project.

Geophysics

Depth mapping using seismic attributes

Accurate depth maps are useful for reservoir development, particularly for stratigraphic and structural trap location, drilling depth, and reservoir modeling. During this reporting period, three velocity-to-depth transforms were evaluated.

Well log and 3-D seismic data were used to construct three depth maps for the top of the target L horizon of the Nash Draw field in southeastern New Mexico. The first two depth maps were made using Landmark™ software packages TDQ and Z-map. The third depth map was made using a multilayer perceptron (MLP) neural network to regress for velocity at each seismic bin. At Nash Draw most of the wells are confined to the central region of the seismic survey, and conventional geostatistics reliably interpolates depths in the region defined by well control. The MLP approach used the best three of 28 "fuzzy" ranked seismic attributes to predict the average velocity field from the surface to the L horizon. Each map was constructed using 15 wells as control points, with three wells excluded for testing. Test wells 1 and 2 were located away from the control wells and had anomalous average velocities/depths.

The three test wells were used to compare the robustness of the computed depth maps, and all depth predictions were compared to the true depths determined from gamma ray logs for each well. TDQ, Z-map and MLP predicted values within 229.4, 104.7 and 7.6 ft, respectively, at test well 1; 129.4, 47.7 and 43.7 ft, respectively, at test well 2; and 12.4, 4.1 and 16.5 ft, respectively, for test well 3. Results are illustrated graphically in the Fig. 15 bar chart.

Grid geostatistical methods underestimate the depths to the top of the L for the test wells lying outside the central clustering of control wells, but the MLP solution calculates a relationship that should be valid in each seismic bin in the field. Details of this study are available in D.M. Hart's thesis entitled "Evaluation of a Multi Layer Perceptron Neural Network for the Time-to-Depth Conversion of the Nash Draw "L" Seismic Horizon using Seismic Attributes" (May 2001) New Mexico Tech or at http://baervan.nmt.edu.

Depth filtering of gravity data

Renewed interest in the Delaware Basin and surrounding area gravity and aeromagnetic data sets has been sparked with the advent of new computing tools. Current computing technology (processor speed and memory size) permits larger data sets to be used in combination with advanced modeling software to produce results that offer renewed interest in geophysical prospecting with potential field methods. The goal in this study was to offer an unbiased 3-D differential density model for the Delaware Basin and adjoining Central Basin Platform region covering 31–34° north latitude; -102– -105° east longitude. Tikhonov regularization inverse techniques were applied to solve for the unknown density distribution of a model space described by rectangular blocks of dimension 16 × 16 × 3 (x, y, z). The Tikhonov regularization technique is the most widely used technique for regularizing discrete ill-posed problems. Because of the size of the model space (768 grid blocks) and the data space (1700 surfaces measurements), the system matrix, which relates the data to the unknown model parameters, is considered slightly ill-posed. Tikhonov regularization provides a way of performing the inversion in a quick and stable manner, at a low cost.

This method and current computer computing capability allowed this approach to be implemented on large gravity data sets with a sizable model space. Other advantages of the method include:

1) Existing geologic information is used to constrain the solution with a starting model.
2) Subjective user input is minimized.
3) No problems are encountered related to wave number domain transforms (as in the upward/downward continuation problem).

Applying this method to a gravity data set covering southeast New Mexico and west Texas showed geologically believable results when compared to previous geologic work describing the basement structure. The current realization of this method is too coarse for application to the Brushy Canyon interval in the Delaware Sands but the methodology is established and may be further developed. Details of the gravity filtering work can be found in PRRC Report 01-30 entitled “Tikhonov Linear Inversion of Gravity Data to Determine 3-D Differential Density Distribution – Case Study of Southeast New Mexico and West Texas,” or at http://baervan.nmt.edu.

Engineering

Bulk Volume Oil Prediction

Determining the water saturations in thin-bedded turbidites such as the Lower Brushy Canyon using wireline logs is difficult. For example the cross plot in Fig. 16 shows that bulk volume oil (ϕS_o) calculated from log estimates of S_w results in BVO values much greater than those measured in a core. These errors in S_w calculation frequently result in uneconomical completions as shown by the non-commercial completions in the Fig. 17 map of Lower Brushy Canyon wells. Consequently, current Brushy Canyon completion decisions include expensive core information to provide an acceptable indicator of oil saturation to compensate for the S_w calculation problem. Completion decisions can be improved and less core data is needed using a method that correlates wireline logs with core measured BVO.

An interactive Web-based neural network, PredictOnline, was developed in-house so that predictions can be made in a user-friendly manner. Coded in Java, PredictOnline is an interface to the actual neural network software that is used for prediction. PredictOnline was used to train a complex 4-6-5-2-1 neural network to 90+ % correlation coefficient using density porosity, neutron porosity, and shallow and deep resistivity logs as input variables. The neural network was trained and tested to predict the BVO product from the Nash Draw Well #23 whole core analysis. The neural network BVO log is shown in Fig. 18. It is noteworthy that several networks trained to ~ 90% correlation coefficient provided that the records to weights ratio exceeded 2.5.

The trained neural network was then used to predict the core plug BVO measurements that were available from 14 additional wells in the field. The BVO log statistical parameters were later correlated with a production indicator, which is the average of the first 12 full months of production.

The BVO logs constructed with the neural network predictions are shown in Figs. 19-23. The measured bulk volume oil calculated from sparse sidewall core plug data is included with the BVO curve (dark curve). The gamma ray log (fine line) is included on all plots for completeness. The plots are intended to illustrate the goodness of the predictions or perhaps a problem with relying on sporadic core plugs (compared to whole core data). Nash Draw #23 well information was included with the 14 wells as an aid to visually correlate the measured values with the predicted BVO log. The visual correlations indicate that the BVO log rarely captures the measured data exactly, but trends are evident.

The BVO log statistical parameters (Average, Standard Deviation, and Sum) are shown in the upper left hand corner of the BVO logs. Intuitively a high Average or Sum of BVO should correlate with high production. The standard deviation of the BVO log says something about the spread in the BVO values. Table 1 shows the statistical values of each well's BVO log and a production indicator. The production indicator is the average of the first 12 full producing months.

Table 1. BVO Log Statistics

Well	Average	STD	Sum	Average BOPM
5	214.7	113.3	99854	1117
6	195.7	110.4	98036	1652
9	199.2	102.9	79878	388
10	196.6	110.2	64277	648
11	224.1	109.4	88503	2085
12	38.9	21.2	17917	1039
13	257.7	94.5	104889	1820
14	218.9	118.2	95653	2177
15	193.7	102.0	98183	3460
19	179.8	109.5	82892	2867
20	197.5	109.6	91036	1023
23	223.2	82.6	61130	1703
24	218.7	105.1	110469	2501
29	37.9	25.2	16026	560
38	36.6	27.0	31144	536

The plot in Fig. 24 shows that the Sum BVO generally correlates with monthly oil production as the production indicator. The addition of the Average and the Standard Deviation to Sum as correlating parameters improves the correlation coefficient considerably as seen in Fig. 25.

The trained neural network also was used to predict BVO logs using the density porosity, neutron porosity, and shallow and deep resistivity logs from 19 additional lower Brushy Canyon wells as input variables. The statistical parameters (Average, Standard Deviation, and Sum) were calculated and used to generate plots of actual first year production versus predicted production for the entire 34 wells (Fig. 26).

Computational Intelligence

Regional data analysis

A key component of this study is the analysis of regional data to provide a baseline to correlate with production potential, as well as to provide a source of heuristic rules for the expert system. Four major categories of regional data were selected and compiled during the course of the last year. Regional gravity surveys cover the entire area of the Delaware basin and have been compiled with an accuracy of a few milligals. The survey measurements are on the order of a few thousand feet apart, but highly variable as gravity is measured in easily benchmarked locations, such as along roadways. Gravity measures variations in density and tends to highlight large-scale regional structures in basement materials. If structure has an impact on maturation, migration or trapping of hydrocarbons in the basin, useful information can be obtained. Regional aeromagnetic data, primarily collected via over-flights with 1 mile spacing re-gridded to 0.296 miles longitude and 0.346 miles latitude, also exist for the region. Aeromagnetic data highlights contrast in the magnetic susceptibility between rocks and can help indicate basement blocks, large-scale faults, and possible large-scale alluvial deposits. The structure of the lower Brushy Canyon was picked on 729 wells in the basin covering a geographically large area. Large-scale maps of structure covering the region were constructed with a kriging algorithm using this data. Structure can play more than one role in trapping and migration of hydrocarbons. Two potentially helpful attributes for this study are structural highs and flexures that may induce fracturing along the flanks of structures. Finally, the wells used to compute structure were used to generate an isopach map for the Brushy Canyon in the region. Thickness may indicate areas of greater potential production and also can indicate pinch-outs and other nonstructural features that may form hydrocarbon migration pathways or traps.

A number of attributes were calculated from the four core data types. These attributes are 1st and 2nd derivatives along latitude and longitude; dip azimuth and magnitudes; and curvature azimuths and magnitudes. These values were computed to expose finer scale features in the basic data types that might be useful for correlating back to a production indicator. A total of 36 maps were generated using the Zmap tool of Landmark Graphics Release 98 plus interpretation package.

Each of these maps was gridded at a scale of 1320-ft (quarter section) because that is the regulatory spacing for wells in the Brushy Canyon in New Mexico. The gridded data were exported and loaded into the project production database. Our current production database is a subset of the state of New Mexico’s Oil and Natural Gas Administration and Revenue Database, or ONGARD, furnished courtesy of the SW PTTC, which contains production information on all New Mexico wells. In our database, Brushy Canyon wells were also identified and, using grid locations from the Zmap maps, producing wells were correlated with grid numbers. This essentially allows regressions to be formed using the production data as control points (training and testing) and the attribute data as variables. Any regression formed in this manner could then be used to predict production in all other 40-ac bins in the basin.

There are two primary considerations when trying to form regressions: the first involves the quality of the data used to predict with the generated regression model, and the second deals with the choice of attributes or variables that will be used in forming the regression model. An optional consideration is the application of linear models (least squares regression) or more complicated non-linear solutions such as polynomial regressions or neural networks. An average of the first 12 producing months Hydrocarbon Equivalent (BO + MCF/6) calculated at each well was chosen as the data to be modeled. Figure 27 shows a histogram of average hydrocarbon equivalent produced per month in barrels for the 2257 identified Brushy Canyon wells. The trend of the histogram is approximately an exponential decay function. A more ideal data distribution that simplifies modeling is data that follow a Gaussian distribution. The production data was conditioned with a $\log_{10}$ filter; Fig. 28 shows a histogram of the production indicator after $\log_{10}$ conversion. The bulk of the data now follow a roughly Gaussian distribution with some notable outliers on the low end. It is desirable to remove outliers from the training data if those data are not significant to the solution. In this case, a cut-off of 50 barrels of oil per month was applied to remove the outliers, and the filtered data were conditioned for either linear or non-linear regression analyses.

There are a number of ways to determine which of a set of inputs (attributes) would best be used to form a regression for a particular output. Simply crossplotting each input against the output can give an indication of the quality of linear or multiple linear regression models that could be formed. For this study each of the 36 data and data attributes calculated and loaded into the database were analyzed using fuzzy ranking.[5] It is both statistically dangerous and not computationally feasible to use all 36 attributes to form a regression relationship; therefore, software was developed based on a fuzzy-ranking algorithm to select attributes best suited for predicting production indicators. The algorithm statistically determines how well a particular input (regional data or data attribute) could resolve a particular output (production indicator) with respect to any number of other inputs using fuzzy curve analysis.

To illustrate the technique a simple example is given. Consider a set of random numbers in the range {0,1} using $x=\{x_i\}$, $i=1,2,\ldots,99$, and $x_i=0.01*i$, and plot each value (y_I= Random(x_i)) as seen in Fig. 29. Next add a simple trend to the random data ($y_i=(x_i)$^0.5+Random (x_i)) and plot those values shown in Fig. 30. For each data (x_i, y_i) a “fuzzy” membership function is defined using the following relationship

$$F_i(x) = \exp(-(\frac{x_i - x}{b})^2) * y_i$$

Sample fuzzy membership functions are shown in Figs. 29 and 30. Here, b=0.1, since b is typically taken as about 10% of the length of the input interval of x_i. A fuzzy curve was constructed using a summation of all individual fuzzy membership functions in (x_i, y_i), and this final curve can prioritize a set of inputs for linear or non-linear regressions. The fuzzy curve function is defined below:

$$FC(x) = \frac{\sum_{i=1}^{N} F_i(x)}{\sum_{i=1}^{N} F_i(x) / y_i}$$

where N is the size of the data set or the total number of fuzzy membership functions. Figure 31 shows the curves for the data sets shown in Figs. 29 and 30. This simple example illustrates the ability of the fuzzy ranking approach to screen apparently random data for obscure trends such as the correlation between seismic attributes and reservoir properties.[6]

Based on the deviation from a flat curve, each attribute is assigned a rank, which allows a direct estimation of attributes that contribute the most to a particular regression. The fuzzy ranking algorithm was applied to select the optimal inputs (data or attributes) for computing an average of the first 12 months of hydrocarbon equivalent production in the Brushy Canyon wells. Experience[7] suggests that numerical rank can best be used to eliminate attributes that have low rank, but that a direct visual inspection of the curves themselves is needed to select attributes for use in forming regressions. Figures 32-40 show the individual fuzzy curves for all 36 data attributes. In examining these curves, two factors are considered: 1) the rank which is defined as the vertical difference between the maximum and minimum points, and 2) the shape of the curve itself. Monotonically increasing or decreasing curves with relatively high rank are optimal and are the most easily modeled data.

There are several basic patterns that occur in the curves. The majority of the data are essentially flat or flat with noise, and these curves have no real correlation to the production indicator. Other curves are generally flat or have a monotonically increasing or decreasing portion, but the rank is inflated because of a discontinuous data point. Some curves are flat in the middle and monotonically increase and decrease on both ends. The most desired attributes are those few that have a distinct monotonic trend including Structure DY2, Gravity DY, Gravity Dip Azimuth, Magnetism DY and Gravity Curvature Magnitude. Correlations between these attributes and the production indicator are under development.

Web-Based Database Management System (WDMS)

A key component to the success of this project is the development of a dynamic, Web-accessible database for storing, managing, accessing, and analyzing data, including the development of heuristic fuzzy rules. As the data files can be quite large, the system must be efficient and useable by persons with varying degrees of computer literacy.

WDMS consists of three parts (Fig.41):

- Databases built on two different servers administer the static information (gravity, aeromagnetic, etc) as well as dynamic data (production data, well data, etc, monthly updates).
- A group of Java classes that allow the user interface to easily access the databases.

- A Web-based interactive interface (using Java) for accessing the data over Internet.

The version of WDMS under construction was implemented using Java Technologies (Java, Java Server Pages, Java Database Connection, etc. based on Microsoft® SQL Server and Microsoft® Data Source).

WDMS Interface consists of three tiers (see Fig.42).

- A Presentation Layer was written in HTML (or generated by JSP files) and Java Script that implements the interactive interface and presents home pages in any Java capable browser on the user side. The interface accepts user requests generated by clicking on the menu items and buttons of those homepages, and sends them to the Business Logic Layer.
- The Business Logic Layer was written in JSP, Java Bean and JDBC and it translates requests from users to SQL statements. These requests are forwarded to the Data Layer, and answered queries are returned.
- The Data Layer, which is a Microsoft® SQL Server in WDMS, manages the Data of the FEE Tool project by executing SQL statement received from the Business Logic Layer. SQL communicates with JDBC through Microsoft® ODBC. SQL processes the SQL statements and sends the results back to Business Logic Layer through the ODBC driver to the JDBC driver.

Architecture of WDMS

WDMS used with JDBC to connect to the database involves five essential components: JSP/Servlets, JDBC Driver, ODBC SQL drivers and the database management system (DBMS), and Microsoft® SQL Server. The JDBC driver consists of classes that translate requests into SQL queries. It also shields the database from outside adjustments. For user convenience, WDMS is designed to let users access FEE Tool data without any installation, downloads, security permissions or browser option changes on the users machine.

During initial database development, Microsoft® Access was used. However, some important features of JDBC and the ODBC Access driver are not supported and an early shift was made to Microsoft® SQL as the primary database software. The communication between JDBC and the SQL server was implemented by using two drivers, the JDBC-ODBC driver and the Microsoft® Data Source (ODBC) SQL Server driver. In Windows NT, data sources are made visible to application through Microsoft's driver manager (Access lacked this feature). SQL does not require third party JDBC-ODBC bridge drivers. Thus WDMS does not need installations or downloads which provides an added convenience to the user.

Aside from the user interface, the other important feature of WDMS is the API interface. The Applications Programming Interface (API) is a series of JAVA programs which allows the FEE Tool system to directly interface with the databases, and to both examine and mine the data, including the generation of heuristic rules for the expert system to apply regionally. The API also allows the user to indirectly control the responses of the expert system via interpreted user commands (entered via browser menu selection). All API JAVA programs reside, and are executed, on the http://tvr.nmt.edu server. In the overall system architecture the user interface and the API (presentation layer) are parallel with the business logic layer interpreting between the two, and the databases (data layer).

The features of WDMS:

- User simply installs a Java capable browser.
- Developer supplies no software.
- Lower maintenance cost because no user side upgrades needed.
- Simple user GUI.
- Data is stored on a high-performance server. Many data operations are executed on the server, so the user does not need an expensive, high performance machine to store data and execute the complex operations.
- Flexible three-tier design, which by separating presentation, business and data layers into their own components allows changing implementations in one layer without changing the others.

Current Platform: DELL Optiplex GX1p 650MZ/384MB RAM/20GB hard disk.
Window NT v4.0, MS SQL Server v7.0/2000, MS IIS, JSPWK WebsServer v1.0.1, MS Data Source v3.5, JSP 1.0.1 JSPWK WebServer with a built-in Java Engine to work with Web Server software.

Developing Tools: Many kinds of software tools can be used to develop Web-based applications. For rapid entry into the field, pure Java technology was used. The software tools that we use are: Java Develop Kit v1.3, Java Server Pages 1.1.1, JDBC API 2.0. HTML/JavaScript.

Data: To date, the following regional data for the Delaware Basin have been stored in a Microsoft® SQL Server on http://tvr.nmt.edu: aeromagnetic, thickness, gravity, and structure. Production data is linked via the SQL server on http://pontiac.nmt.edu. Log Data, PredictOnline data, correlations, and source data will be loaded soon. The link to the production database is provided courtesy of the SW Regional PTTC.

Interface: The interactive interface provides a simple point-and-click tool to guide the user through data selection, forming and implementing queries, and displaying results. Advanced users can more directly interact with the database using SQL "select" statements. Accounts will be required to run WDMS to increase security and to isolate working parameters by individual or company. When a user starts WDMS by opening http://tvr.nmt.edu with their browser, the user will be asked to register a name, a user ID and a password. Subsequent logins will be password enabled. WDMS will record where the user is from, when the user visits, browser type, computer type, operating system type and other user information. The information will be used for statistics and evaluation. Menus and submenus include the following functionalities:

- **Search Regional Data**
  Currently, users can access data by its reference grid number. Future implementations will allow the user to enter coordinates in latitude-longitude, oilfield x-y, or Township-Section-Range. Alternatively, a clickable map can be used to select data for a particular area of interest.
- **Browse Regional Data**
  When the user clicks on "browse" on the menu page of WDMS, a new window opens that lets the user chose which type of map data the user wants to browse. After clicking on the type desired, the user sees the requested data (Figs. 43–45).
- **Search Local Data**
  When the user clicks on "Local Data", WDMS shows four items: Production, Log, PredictOnline, and Correlations. Each WDMS item will show the relevant data. For example, by clicking on the Production item of main menu, WDMS will show all Pool IDs and Pool names (Fig. 46). WDMS also will show all well API numbers in a particular pool (Fig. 47). By clicking a well API number of interest, the user will be linked to production records for that specific well (Fig. 48).
  PredictOnline is written in Java and can be considered a precursor to the Web-based Database Management System described above. The use of PredictOnline is documented by an activity report (courtesy of WEBTRENDS). For March 2001 the average number of hits per day was 31 (Table 2). Use during March was confined to workers at the PRRC/NM TECH.

Table 2. PredictOnline General Statistics

Date & Time This Report was Generated	Thursday April 05, 2001 - 14:18:40
Timeframe	03/01/01 15:07:41 - 03/31/01 16:58:30
Number of Hits for Home Page	N/A
Number of Successful Hits for Entire Site	974
Number of Page Views (Impressions)	0
Number of User Sessions	115
User Sessions from United States	0%
International User Sessions	0%
User Sessions of Unknown Origin	100%
Average Number of Hits per Day	31
Average Number of Page Views Per Day	0
Average Number of User Sessions per Day	3
Average User Session Length	N/A

Technology Transfer

In addition to the second consortium meeting an aggressive technology transfer effort was undertaken. During the last project year the following papers/posters were presented:

- Balch, R.S., Weiss, W.W., and Wo, S.: "Core Porosity Prediction Using Wire-Line Logs, Case Study: Dagger Draw Field, New Mexico," paper presented at the AAPG 2000 Rocky Mountain Meeting, Albuquerque, New Mexico, September 17-20, 2000.
- Hart, D.M., Balch, R.S., Weiss, W.W. and Wo, S.: "Time-to-Depth Conversion of Nash Draw "L" Seismic Horizon Using Seismic Attributes And Neural Networks," paper presented at the AAPG 2000 Rocky Mountain Meeting, Albuquerque, New Mexico, September 17-20, 2000.
- Weiss, W.W., Sung, A.H., and Broadhead, R.: "Risk Reduction with a Fuzzy Expert Exploration Tool," poster presented at the AAPG 2000 Rocky Mountain Meeting, Albuquerque, New Mexico, September 17-20, 2000.
- Balch, R.S., Weiss, W.W., Wo, S., and Hart, D.M.: "Regional Data Analysis to Determine Production Trends Using a Fuzzy Expert Exploration Tool," West Texas Geological Society, Fall Symposium Publication 00-109, DeMis, Nelis, and Trentham ed., October 19-20, 2000, p 195-196.
- Hart, D. M.: “Tikhonov Linear Inversion of Gravity Data to Determine 3-D Differential Density Distribution – Case Study of Southeast New Mexico and West Texas,” West Texas Geological Society, Fall Symposium Publication 00-109, DeMis, Nelis, and Trentham ed., October 19-20, 2000, p 195-196.
- Weiss, W.: “Mining Regulatory Files with Artificial Intelligence to Predict Waterflood Recovery,” presented to the New Mexico Landman’s Association, Roswell NM, March 29, 2001.
- Justman, H. A., and Broadhead, R., 2000, An evaluation of the source rock, reservoir rock, and sequence stratigraphy for the Brushy Canyon Formation's hydrocarbon accumulations of the Delaware Basin, southeastern New Mexico (abstract): American Association of Petroleum Geologists, official program for 2000 Rocky Mountain Section meeting, p. A7. Talk presented to Rocky Mountain Section APG, September 2000, Albuquerque, NM. Talk also presented to Roswell Geological Society, Roswell, NM December 2000.
- Justman, H.A., and Broadhead, R.F., 2000, Source rock analysis for the Brushy Canyon Formation, Delaware Basin, southeastern New Mexico, *in* DeMis, W.D., Nelis, M.K., and Trentham, R.C., eds., The Permian Basin: proving ground for tomorrow's technologies: West Texas Geological Society, Publication 00-109, pp. 211-220. Published paper accompanying talk given to West Texas Geological Society Fall Symposium, October 2000.
- Broadhead, R.F., and Justman, H.A., 2000, Regional controls on oil accumulations, lower Brushy Canyon Formation, southeast, New Mexico, *in* DeMis, W.D., Nelis, M.K., and Trentham, R.C., eds., The Permian Basin: proving ground for tomorrow's technologies: West Texas Geological Society, Publication 00-109, pp. 9-18. Published paper accompanying talk given to West Texas Geological Society Fall Symposium, October 2000.

The Second Consortium Meeting, presenting research results as well as talks from representatives of industry and government, was held at the end of the first year of the project. The following news story on the meeting was provided by the Petroleum Recovery Research Center.

HOBBS, N.M.--The Reservoir Evaluation and Advanced Computational Technologies (REACT) Group at The Petroleum Recovery Research Center of New Mexico Tech held the Second Consortium Meeting November 2, 2000 for their NPTO-funded project, “Reducing Exploration Risk with the Fuzzy Expert Exploration (FEE) Tool,” at New Mexico Junior College in Hobbs, New Mexico. This project employs emerging exploration technologies—fuzzy logic and neural networks—and applies them to finding and developing reservoirs.

Typical data analysis has a primary goal of minimizing errors in input data. This becomes a difficult task when data is sparse, or errors are ill defined. Fuzzy analysis uses the error as a source of additional data and allows the use of non-crisp inputs such as “high on structure” and “medium porosity.” Thus, fuzzy analysis shows great promise for integrating sparse engineering data and geological interpretations.

Area producers and explorationists heard the results of the first year of the project as related by REACT scientists and graduate students. A highlight of the conference was the talk given by Gary Hoose, Exploration Manager at Pogo Production, on the company’s experience in exploring the Brushy Canyon formation of southeastern New Mexico.

Hoose encouraged the exploration of unpromising areas and cautioned against having a biased viewpoint, saying “always keep an open mind in exploration.” He cited several instances when a crucial moment of decision was reached in exploration, where “we had to trust the model or our hunches and be aggressive.”

Project Manager Jim Barnes of the National Petroleum Technology Office (NPTO) of the U.S. DOE followed Hoose with a presentation on the “Technology Development for Independents” Program.

The REACT team presented the results of their first-year research, which included

- Installation of the collected data into the database
- Construction of regional structure, isopach, and thickness-porosity maps
- Training of a neural network to predict the product of porosity and oil saturation (bulk volume oil) based on whole core measurements
- Use of fuzzy ranking to prioritize 3D seismic attributes that were then correlated with depth using a neural network
- Development of a radial basis function neural network for use as a log evaluation tool
- Development of an interactive Web-based neural network, PredictOnline, coded in Java and available to consortium members for beta testing
- Completion of a draft design of the Fuzzy Expert Exploration (FEE) Tool system based on readily available software.

Industry interest in the Delaware formation is increasing as seen in the completion records from March 1999 through October 2000 (Fig. 49). Based on the completion plot activity increased 50% during 2000. While the project is not responsible for the increase in the completion rate it is interesting to note that two consortium members were very active during the time period.

Problems Encountered

Because of the high value of the data, the acquisition of regional seismic lines continues to be a problem. Local datasets are available such as those from the DOE-funded Nash Draw project. The processed data from this 3D data set was used to develop new methods of interpreting the distribution of thickness, porosity, water saturation, and depth throughout the survey area. The methodology can be applied throughout the Delaware Basin.

Coding of the required algorithms is an ongoing problem. Additionally, graduate students working on the project, who gain expertise in developing software, leave for high paying industry jobs following completion of a MS degree. Thus, consideration was given to contracting the work to professional coders. Maintenance of the code is a major drawback to this solution of the Web software problem. Currently, new graduate students are being employed to provide a solution to the problem.

Tasks for the Next Year

September 2001 marks the halfway point in the project schedule at which time the geologic focus of the project will be the Devonian carbonate. The Devonian petroleum system of southeastern New Mexico consists of carbonate reservoirs in the Fusselman Formation and source rocks and regional seals in the overlying Woodford Shale. Fields are present throughout southeastern New Mexico, and production is obtained from depths as shallow as 5,000 ft in Chaves County to more than 14,000 ft in Lea County. Reservoirs are dolostones and traps generally have a structural component. The structural aspect of the traps may be combined in some cases with regional porosity pinchouts to form complex trends of oil and gas accumulations.

Preliminary log analyses from a carbonate reservoir.

Anticipating that log interpretation in carbonates may be amenable to neural network technology, a study of openhole logs and cores from a vuggy carbonate reservoir (not Devonian) was undertaken. The objective of this carbonate study was to correlate bulk volume oil measured in cores with the available logs and to demonstrate that the technology can be applied to carbonates.

Six wells with a full suite of logs and core analyses were made available to the project. The log suite used for evaluation comprised caliper, gamma ray, photoelectric effect, laterolog deep resistivity, laterolog shallow resistivity, microspherically-focused resistivity, density porosity, and neutron porosity logs. Fuzzy curves were generated to rank the connection with each of the logs and the value of bulk volume oil measured in the corresponding cores. The caliper, laterolog shallow resistivity, and the density porosity logs where found to have a strong relationship with bulk volume oil from core analyses. A 2-hidden-layer neural network with 8 and 4 nodes trained to a 95%

correlation coefficient using the four logs as input. Testing with cross validation was consistently about 90%. Neural network training is seen in Fig.50. Despite the small statistical sample the bulk volume oil log statistics were correlated with the average of the first 12 producing months. The results are shown in Fig 51.

The positive results of the preliminary log analysis work with information from a vuggy carbonate reservoir are encouraging. The results suggest that the new interpretation method can apply to the Devonian Carbonate.

The Devonian Petroleum System

The Devonian petroleum system is different from that of the Brushy Canyon Formation in several fundamental ways, which are described below. By concentrating on the Devonian for the second part of the project, work will begin on an expert system shell that is capable of handling oil and gas accumulations in a carbonate reservoir. Key differences between the Devonian and the Brushy Canyon are:

1. The Devonian is a carbonate reservoir and the Brushy Canyon is a sandstone reservoir.
2. The Devonian carbonates were deposited on a shallow marine shelf but the Brushy Canyon reservoirs were deposited on submarine fans in a deep, basinal setting.
3. Porosity pinchouts and porosity trends in the Brushy Canyon are localized and are governed by the depositional limits of submarine fans. Porosity pinchouts and porosity trends in the Devonian are more regional in nature and were controlled by regional sea level fluctuations that caused the quick and widespread migration of lithofacies across the shelf.
4. Most traps in the Devonian (and therefore most oil and gas field locations) are structurally controlled, although trends of porosity pinchouts also apparently play an important role in hydrocarbon trapping. This is fundamentally different from the Brushy Canyon Formation where depositional facies variations play the primary role in hydrocarbon entrapment.
5. The Brushy Canyon Formation is confined to the deep Delaware Basin, but the Devonian carbonates are found over a wider depth range in the deep Delaware Basin (14,000 ft +), the shallow Central Basin Platform, and the shallow Northwest shelf (5,000 ft). The greater depth range for the Devonian means that the Woodford source rocks were subjected to much greater differentials of thermal stress and therefore have a much wider variation in thermal maturity than is true of source rocks in the Brushy Canyon. We expect to see the Woodford source rock vary from an immature, nongenerative facies in the shallowest parts of the basin to a mature oil-generative facies in deeper parts of the basin to an overmature thermal gas facies in the deepest parts of the basin. In some places, the Woodford source may be absent altogether.

The substantial differences between the Devonian carbonate reservoirs and the Brushy Canyon sandstone reservoirs will result in differences in risk assessment and the weights that the neural networks apply to various input parameters. As a result, this will allow fuller development of our fuzzy expert system and will test it under substantially different conditions.

Conclusions

In order to provide input of a major geologic variable into the fuzzy logic system for risk analysis and reduction, work continued on: 1) identification of wells that unsuccessfully tested the lower part of the Brushy Canyon Formation, 2) correlation of lithology and reservoir distribution with areas of known production, 3) correlation of petroleum source rocks with production from the lower Brushy Canyon interval, 4) development and mapping of a database of cumulative oil and gas production from the lower Brushy Canyon Formation, and 5) development and mapping of a database of oil quality of lower Brushy Canyon oils. This work is providing new insight into the accumulation of crude oil and production characteristics of Brushy Canyon reservoirs.

During the second year of the project, data acquisition for the Brushy Canyon project was completed and now resides in several online databases on our servers in a format that can be accessed by external applications. Regional data were gridded to a 40-ac bin (gridblock) size and fuzzy ranking was used to determine which attributes are best able to predict production trends in the basin. Bulk volume oil was successfully predicted using wireline logs as inputs, and this technique provides a new tool for estimating the potential success of a well and determining the productive interval that should be perforated. A non-linear neural network technique was used to predict depth using seismic attributes in a Delaware field, and significant improvements over standard techniques were demonstrated.

The design of the expert system itself was clarified, and coding of the expert system was undertaken. A decision tree program that allows development, tabulation, and testing of rules and relationships between rules was written. A Java Expert System Shell was developed that provides an interface tying together the data and the expert system. The interactive interface provides a simple point-and-click tool to guide a non-expert user through data selection, forming and implementing queries, and accessing and displaying results. The architecture of the Web-based database management system was described in this report.

During the second year of the project, industry and academic interest in the project has grown and technology transfer efforts were accelerated. Research and progress to date was presented in nine technical papers and posters as well as to a group of industry and academic professionals at the second annual consortium meeting held November 2, 2000 in Hobbs, NM.

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7. Weiss, W. W., Wo, S., Weiss, J.: “Data Mining at a Regulatory Agency to Forecast Waterflood Recovery,” paper SPE 71057 presented at the 2000 SPE Rocky Mountain Technical Conference, Keystone CO, May 21–23.

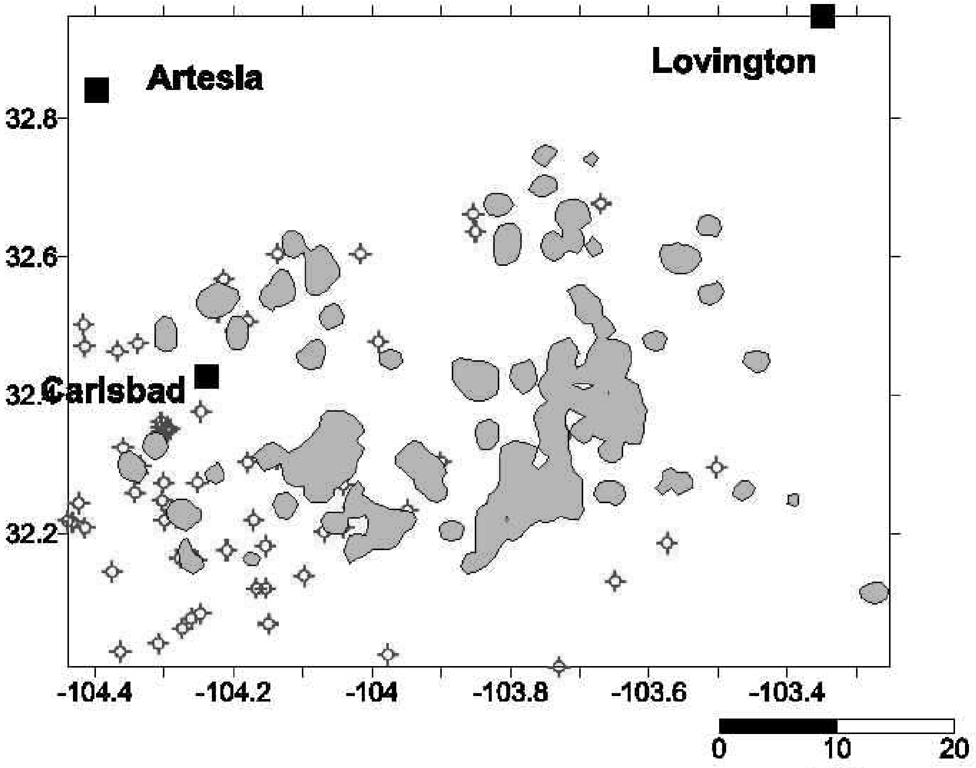


Fig. 1. Productive areas of lower Brushy Canyon Formation and wells that tested unsuccessfully in the lower Brushy Canyon.

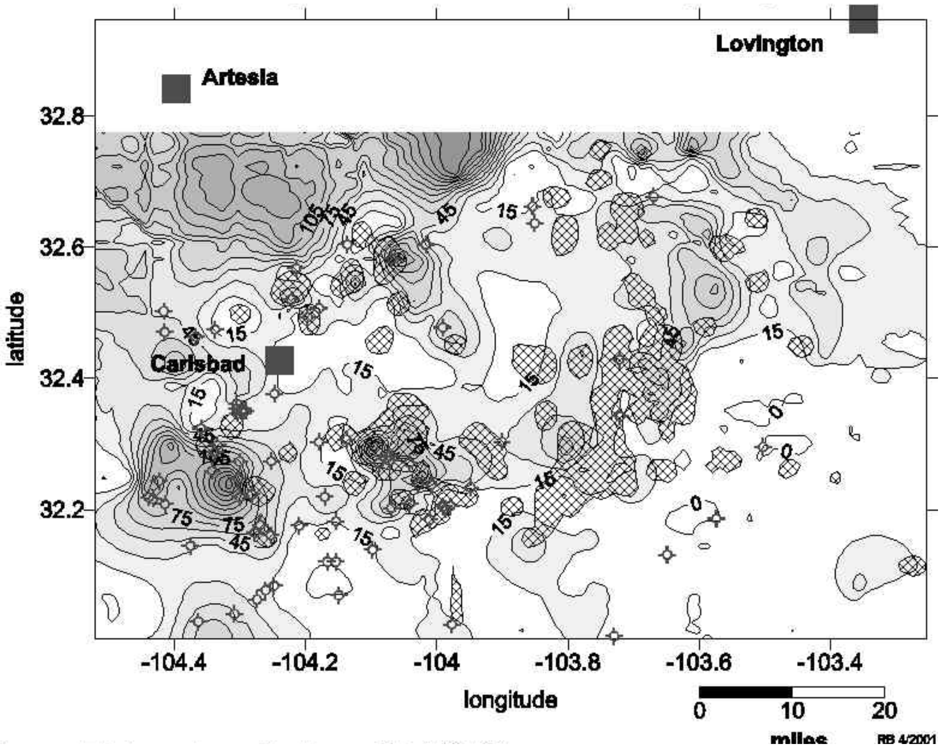


Fig. 2. Net thickness of lower Brushy Canyon sandstone with at least 15% porosity (solid), areas with lower Brushy Canyon production (crosshatched), and wells that unsuccessfully tested the lower Brushy Canyon.

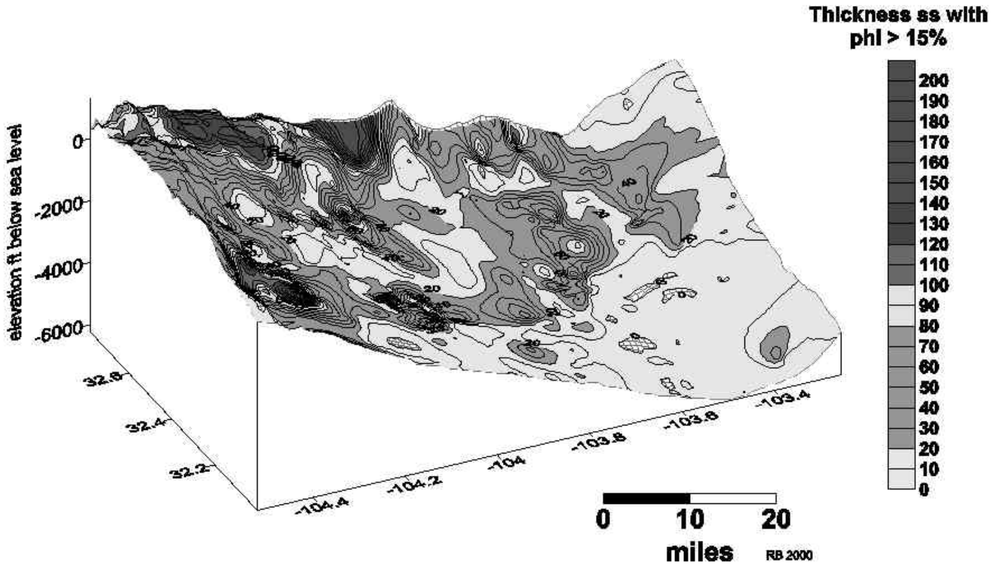


Fig. 3. Percentage of lower Brushy Canyon Formation that is sandstone with at least 15% porosity, areas with lower Brushy Canyon production, and wells that unsuccessfully tested the lower Brushy Canyon.

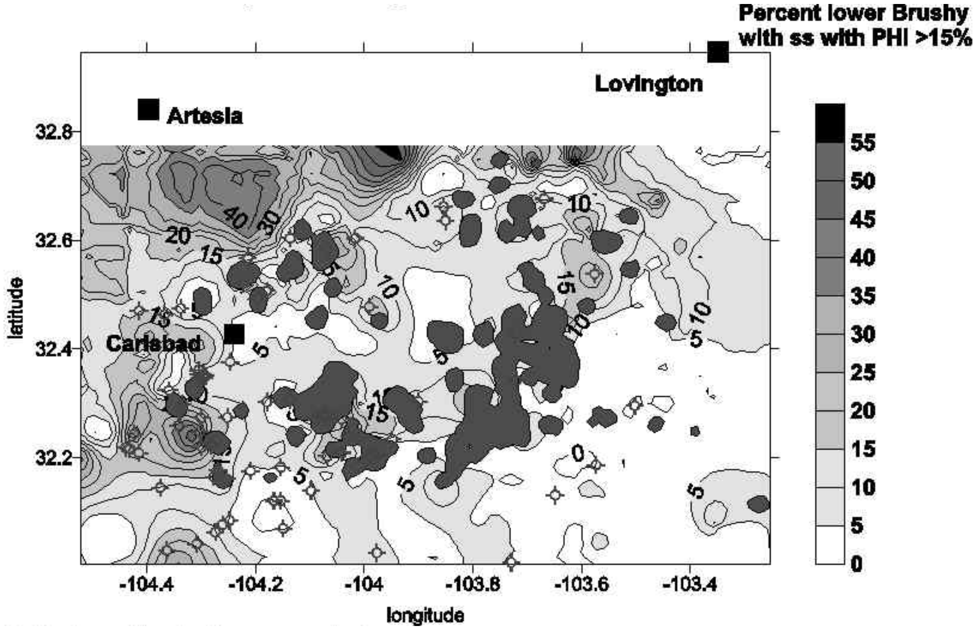


Fig. 4. Isolith map showing sandstone thickness with at least 15% porosity in lower Brushy Canyon, superimposed on structural relief map of Bone Spring Formation.

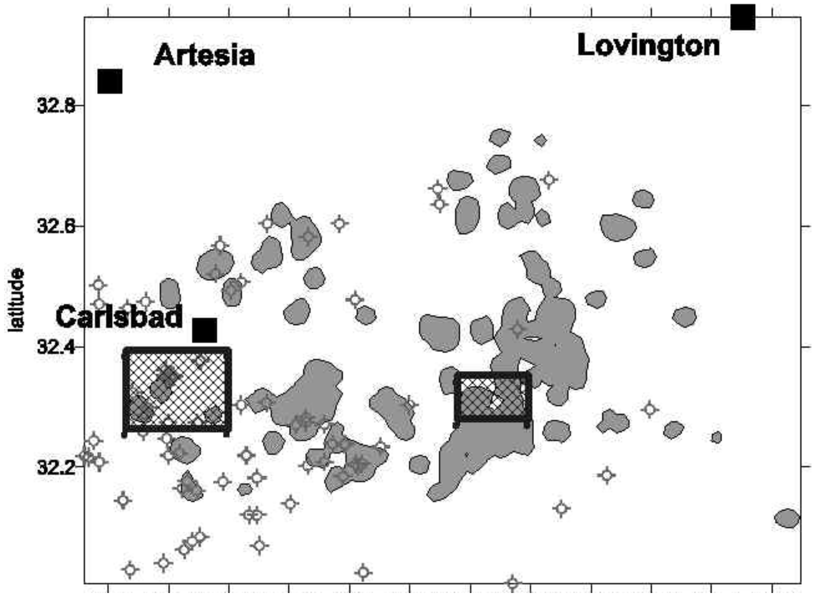


Fig. 5. Map showing areas of lower Brushy Canyon production (grayscale areas), wells that unsuccessfully tested the lower Brushy Canyon, and areas selected for intensive local study (crosshatched areas).

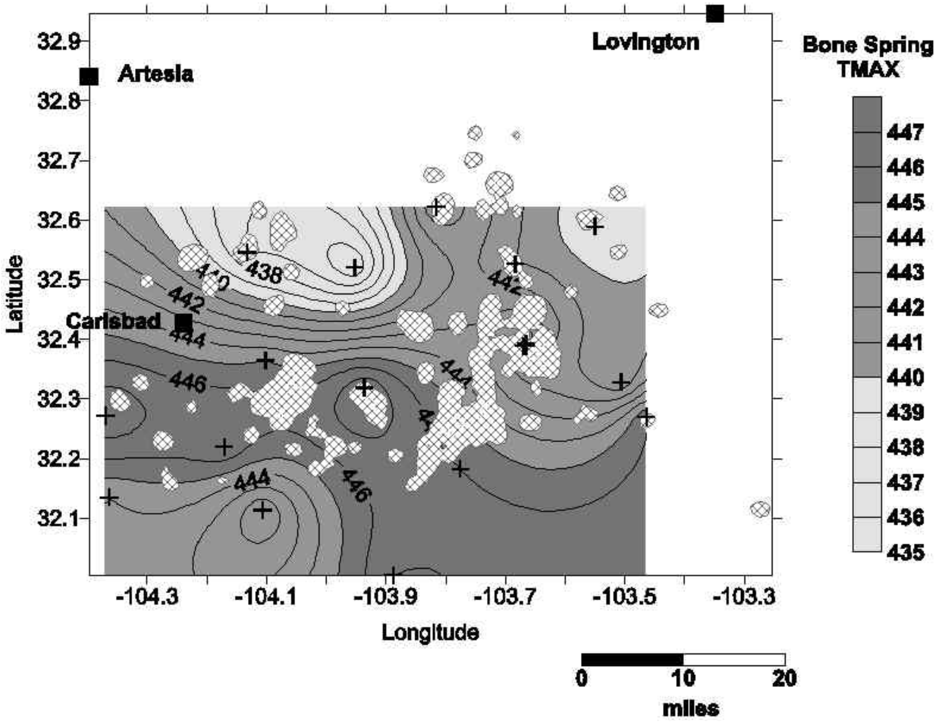


Fig. 6. Contours of Rock-Eval TMAX values from the upper part of the Bone Spring Formation and areas of oil production from the lower Brushy Canyon Formation. TMAX values are indicative of thermal maturity of the source rocks (areas of intensive study indicated by crosshatch).

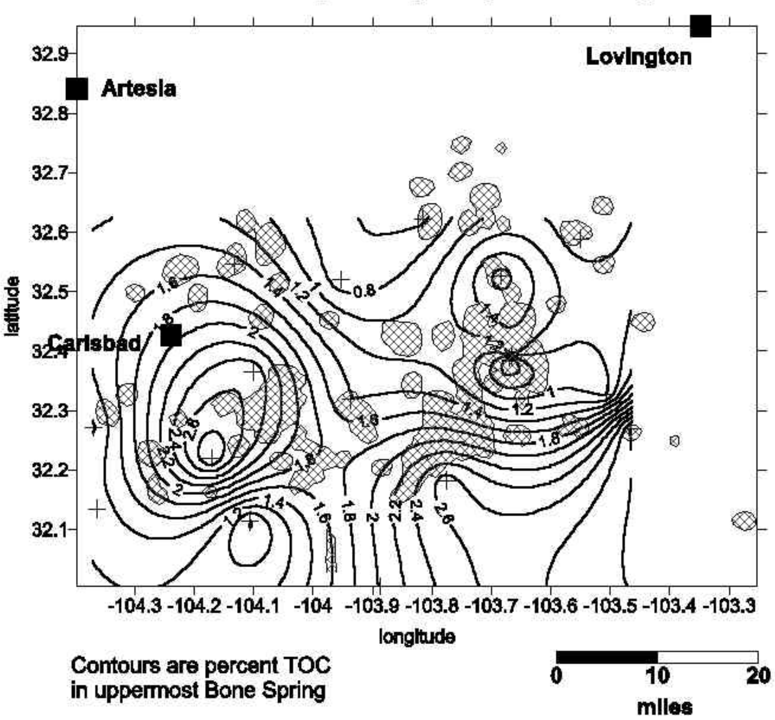


Fig. 7. Total organic carbon (TOC) values for source facies in the upper part of the Bone Spring Formation and areas of lower Brushy canyon production.

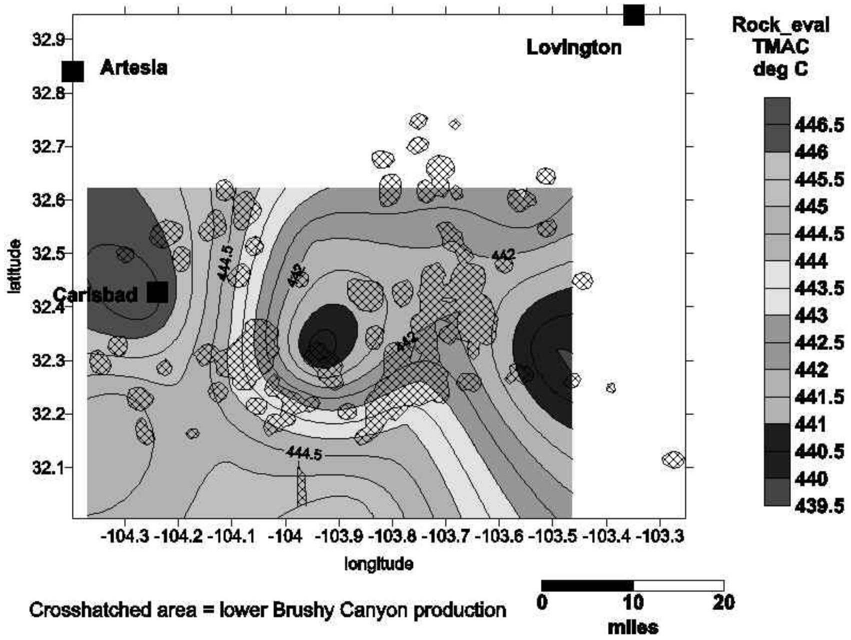


Fig. 8. Rock-eval TMAX values indicative of thermal maturity for source facies within the lower Brushy Canyon Formation and areas of oil production from the lower Brushy Canyon.

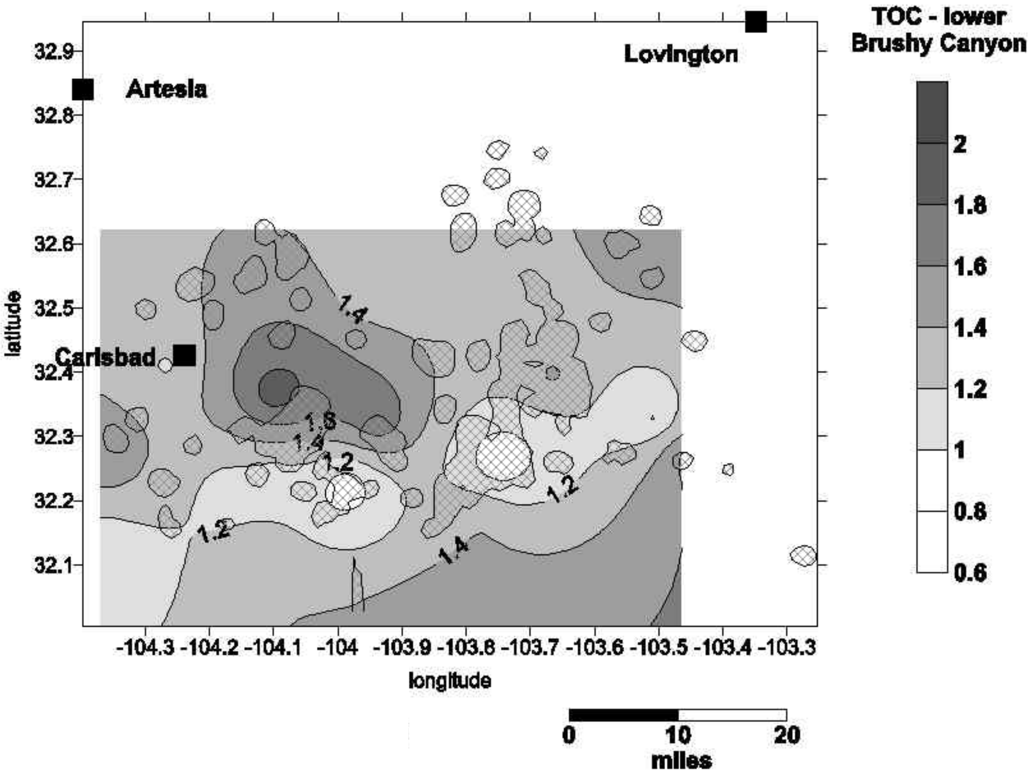


Fig. 9. Contours of total organic carbon (TOC) for source facies in the lower Brushy Canyon Formation (solid) and areas of lower Brushy Canyon oil production (crosshatch).

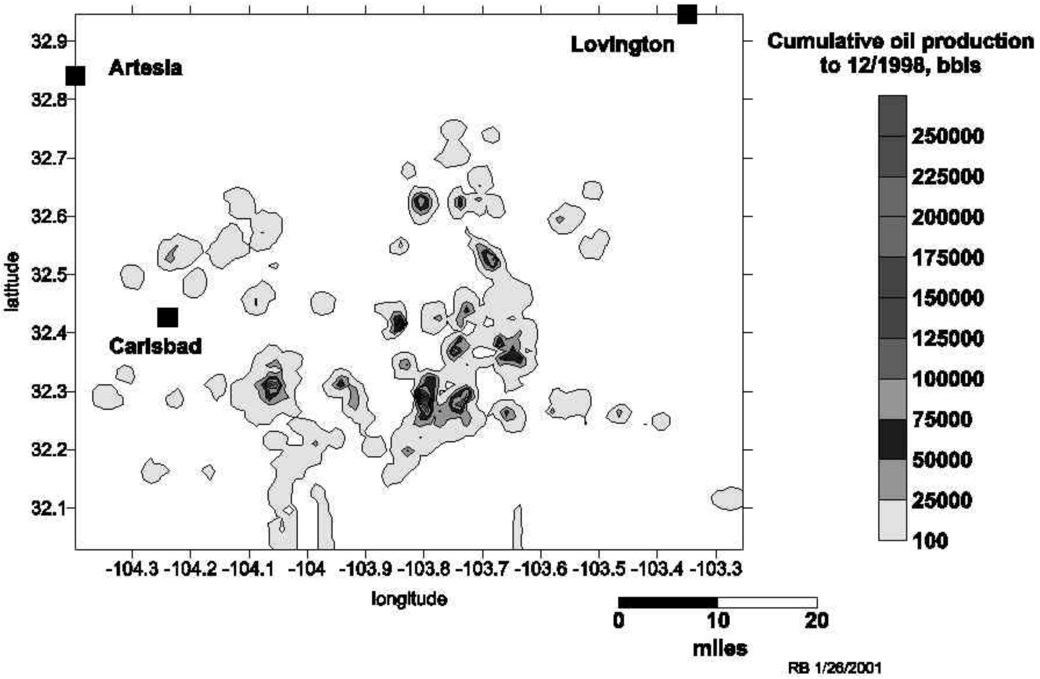


Fig. 10. Contours of cumulative per well oil production from wells producing from the lower Brushy Canyon.

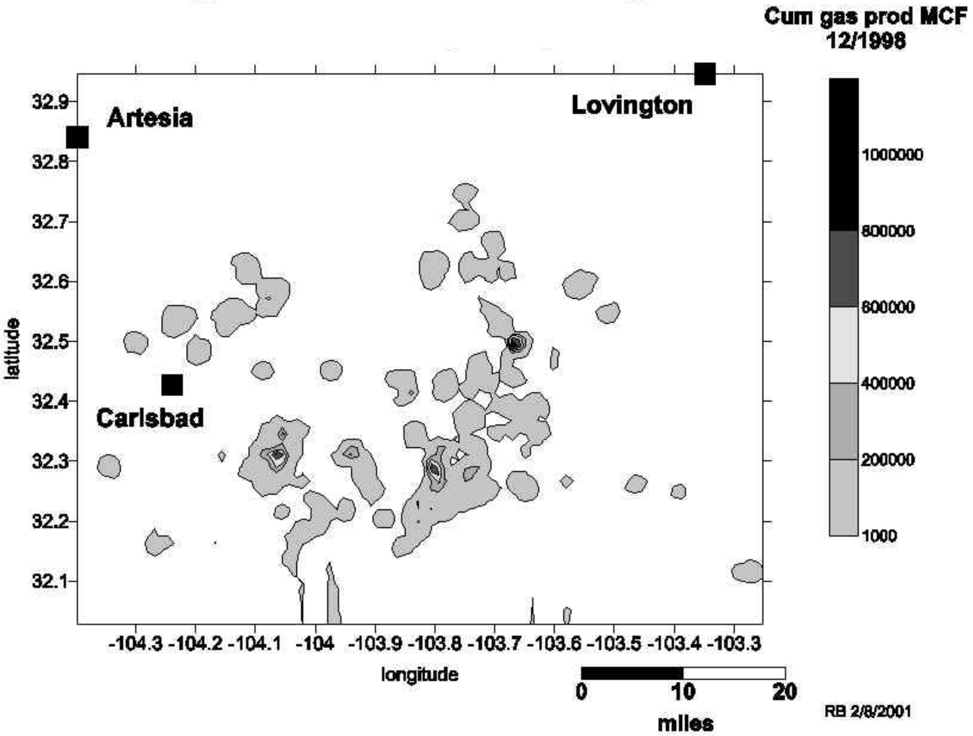


Fig. 11. Contours of cumulative per well gas production for wells producing from the lower Brushy Canyon Formation.

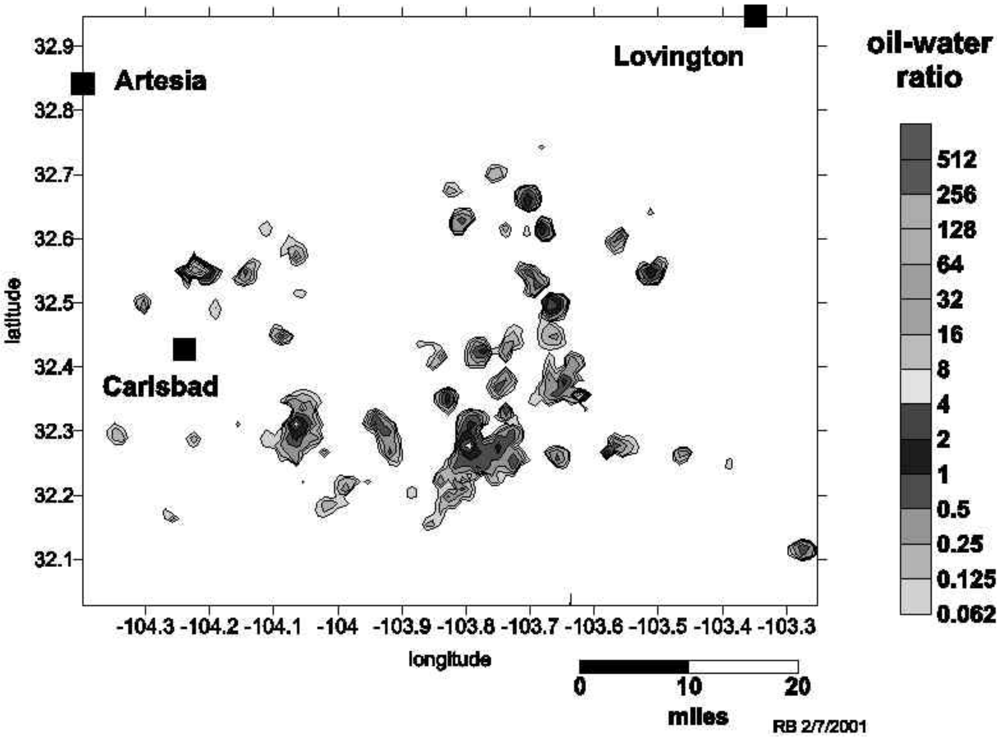


Fig. 12. Contours of oil-water ratio determined from cumulative production for wells productive from lower Brushy Canyon Formation.

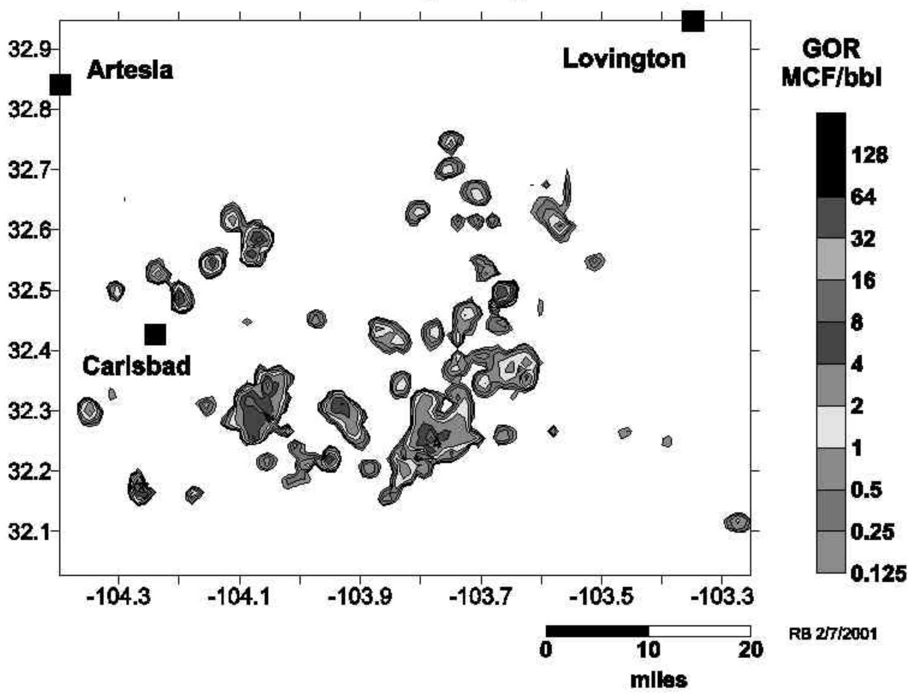


Fig. 13. Contours of gas-oil ratio at cumulative production for wells producing from lower Brushy Canyon Formation.

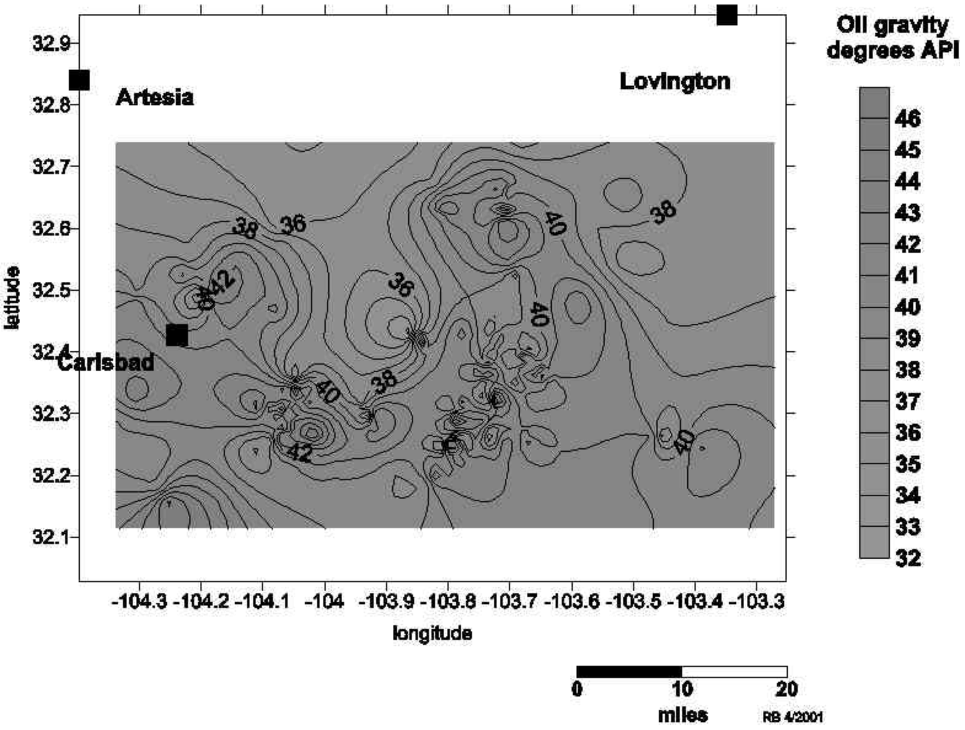


Fig. 14. Contours of API gravity of lower Brushy Canyon oils.

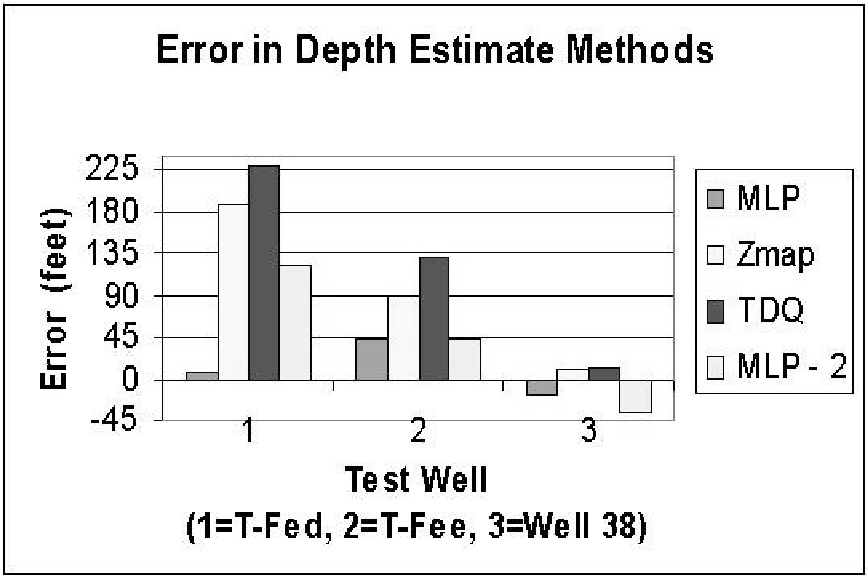


Fig. 15. Comparison of Nash Draw depth model estimates.

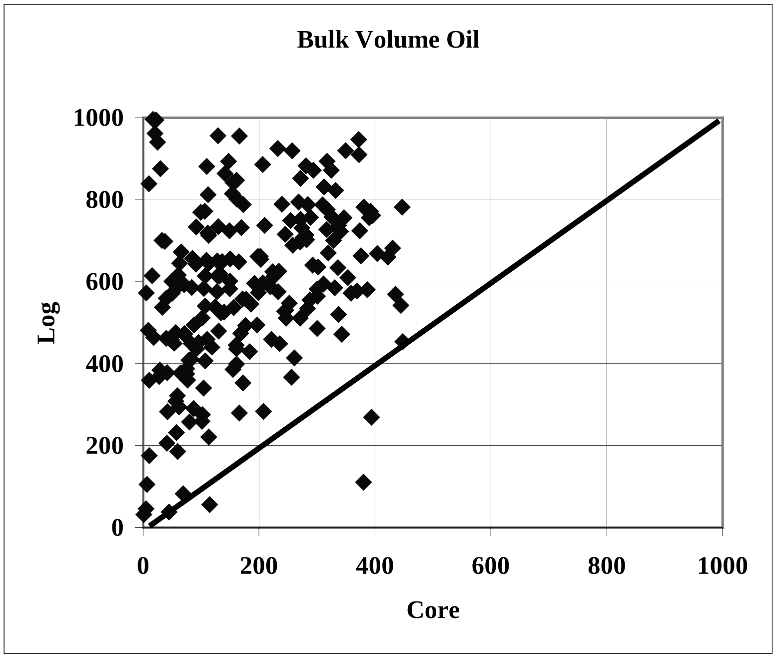
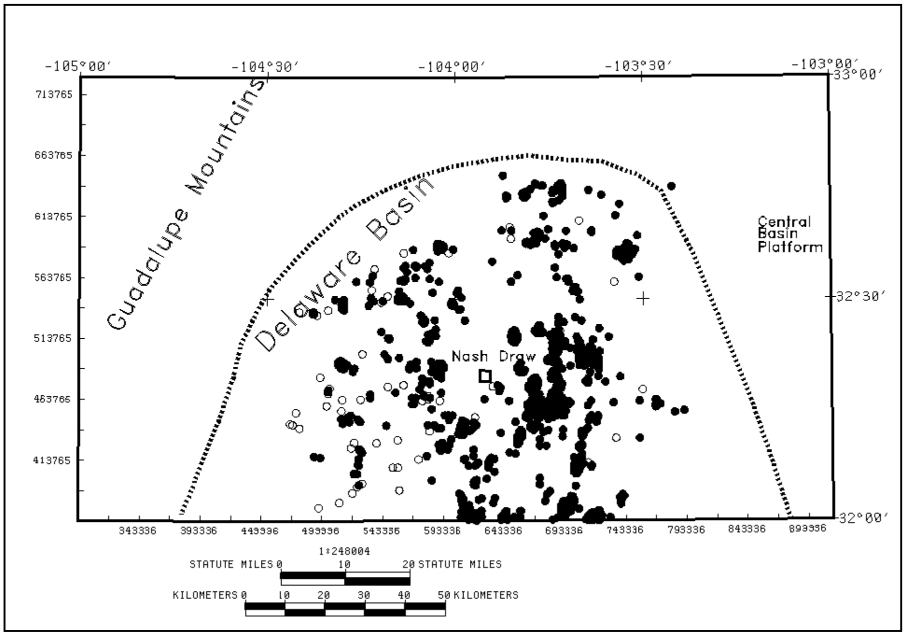


Fig. 16. Extreme difference between log and core ϕS_o values.



17. Dry hole locations.

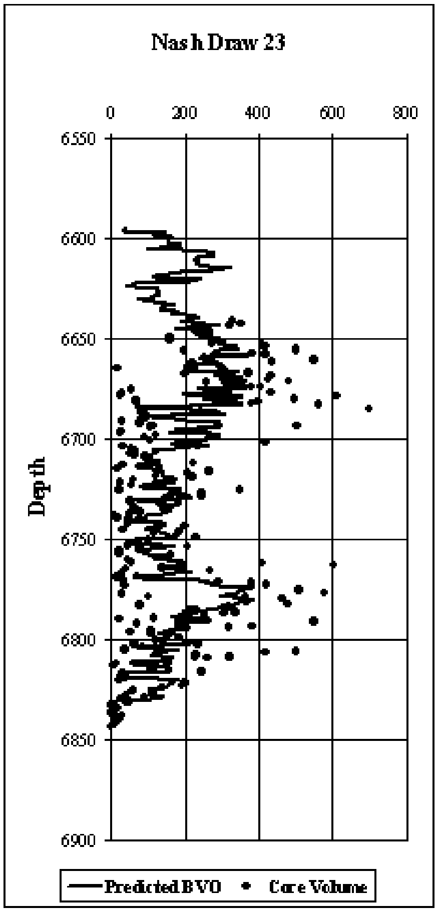


Fig. 18. BVO log from trained neural network.

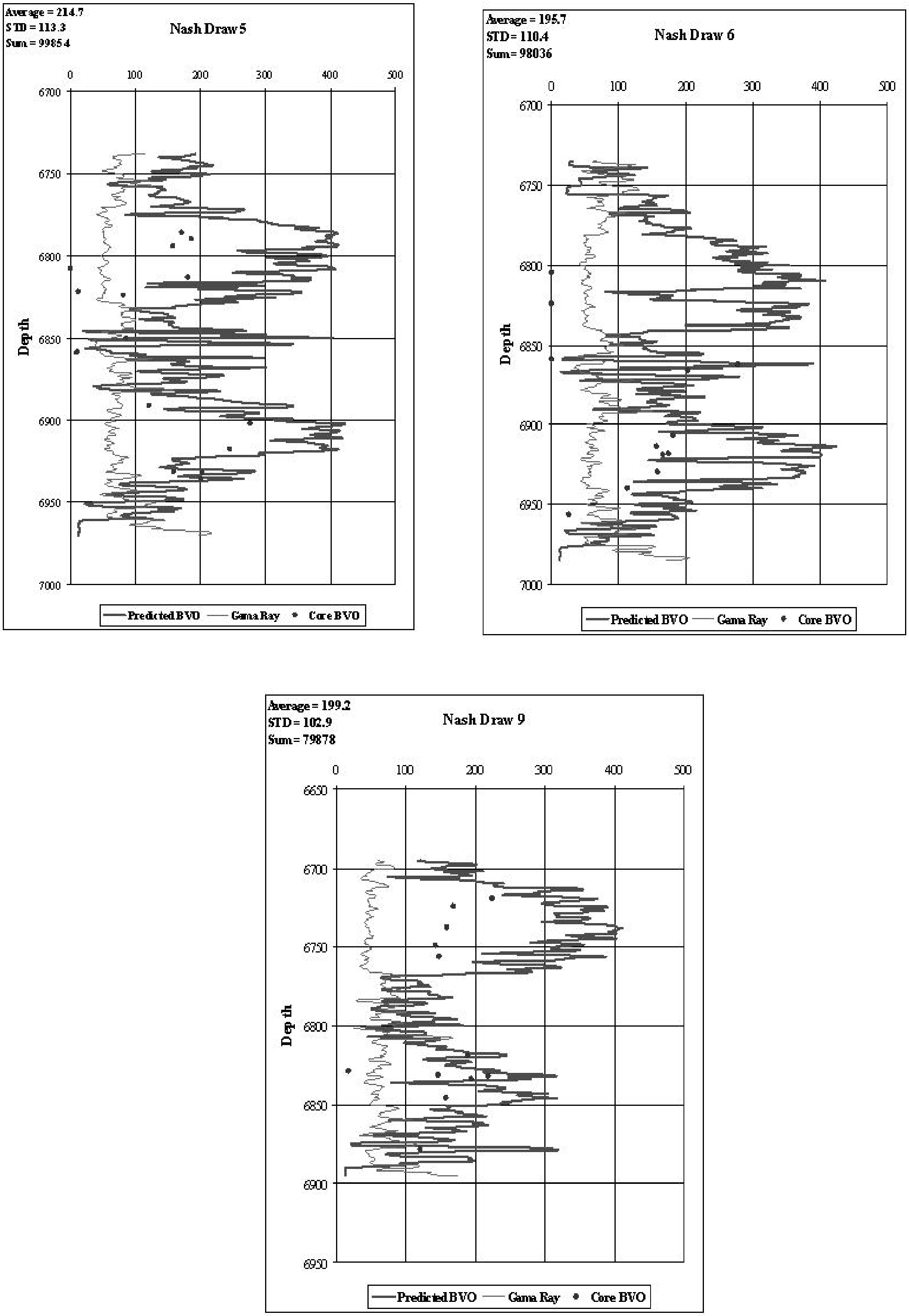


Fig. 19. Neural network predicted BVO, wells 5, 6, and 9.

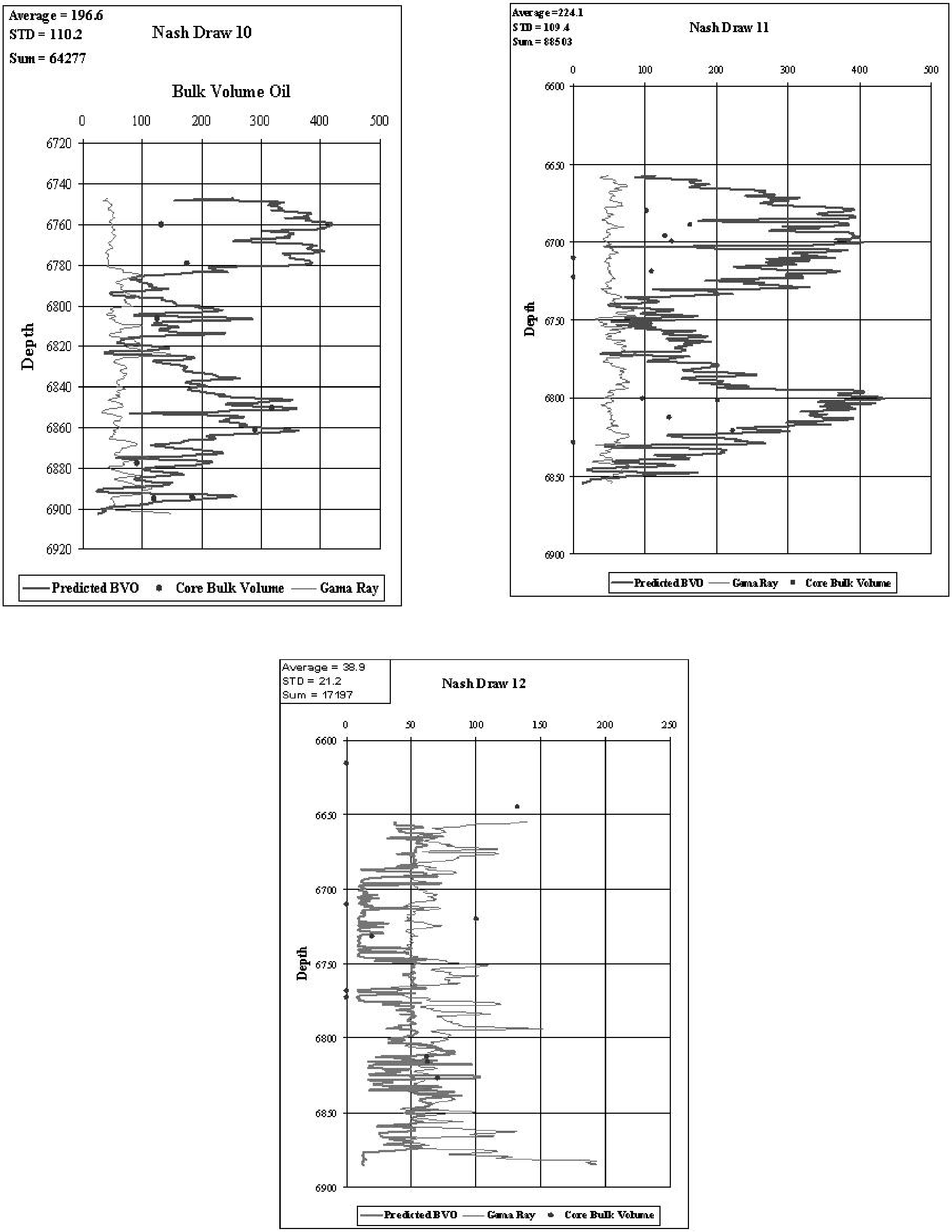


Figure 20. Neural network predicted BVO, wells 10, 11, and 12.

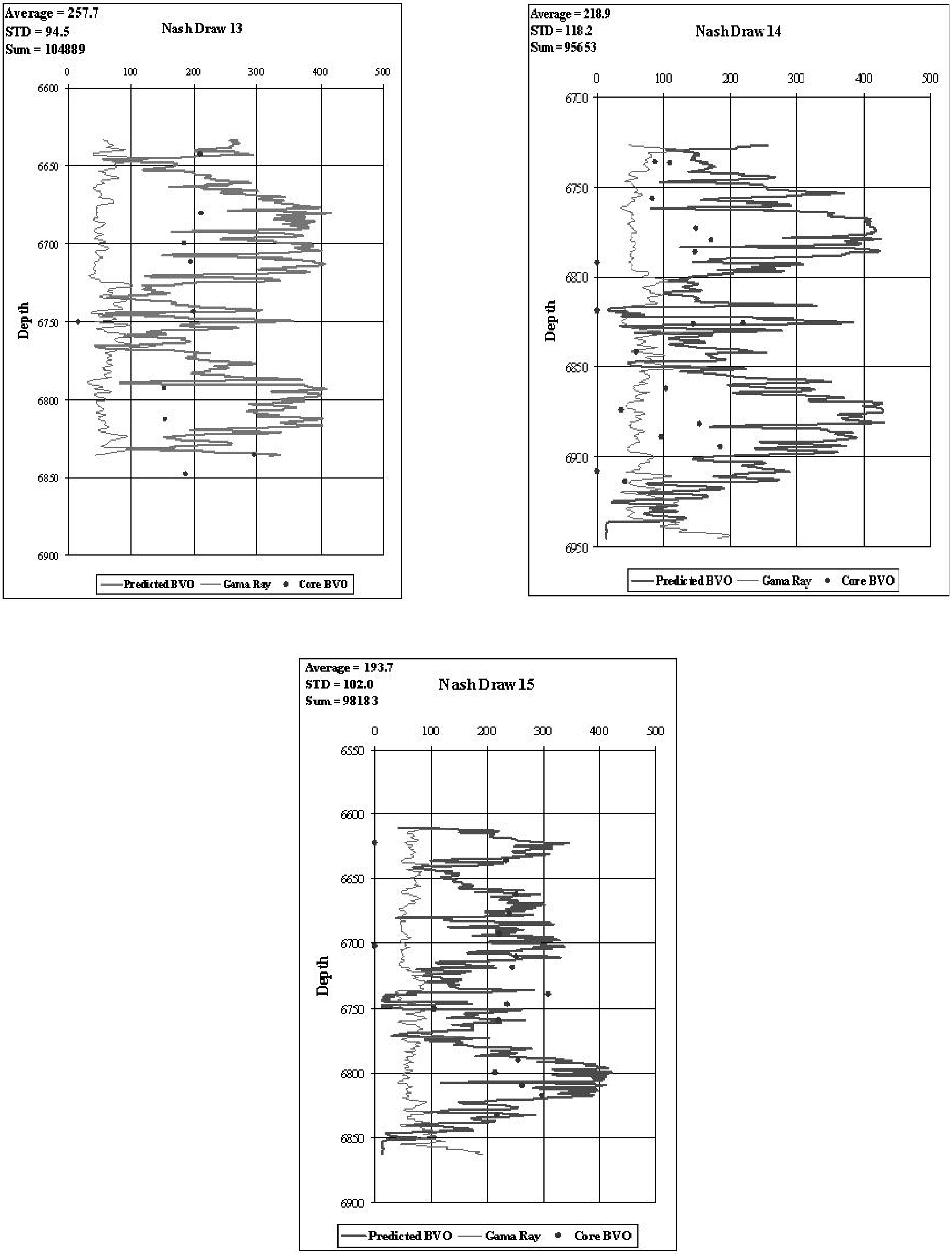


Figure 21. Neural network predicted BVO for wells 13, 14, and 15.

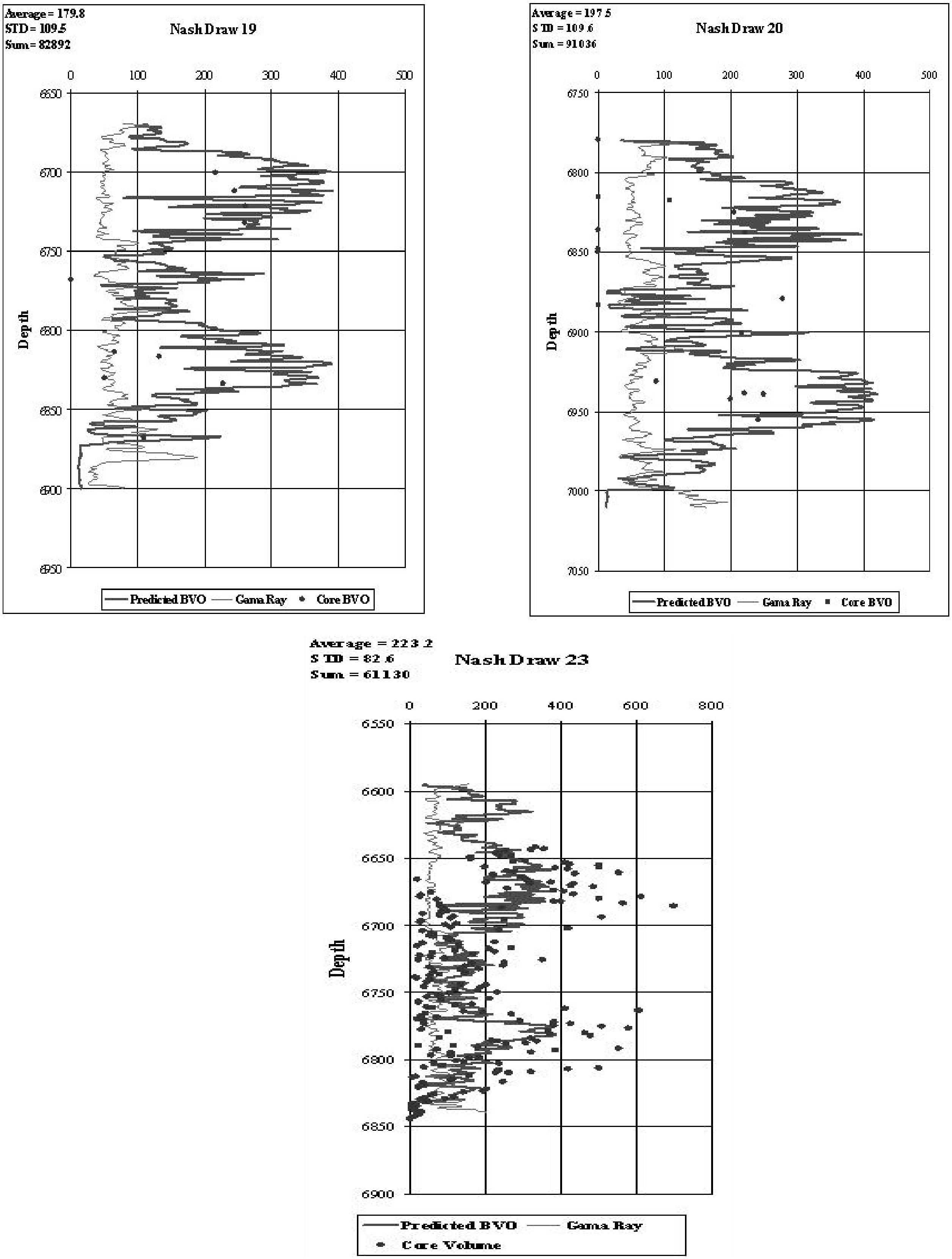


Fig. 22. Neural network predicted BVO for wells 19, 20, and 23.

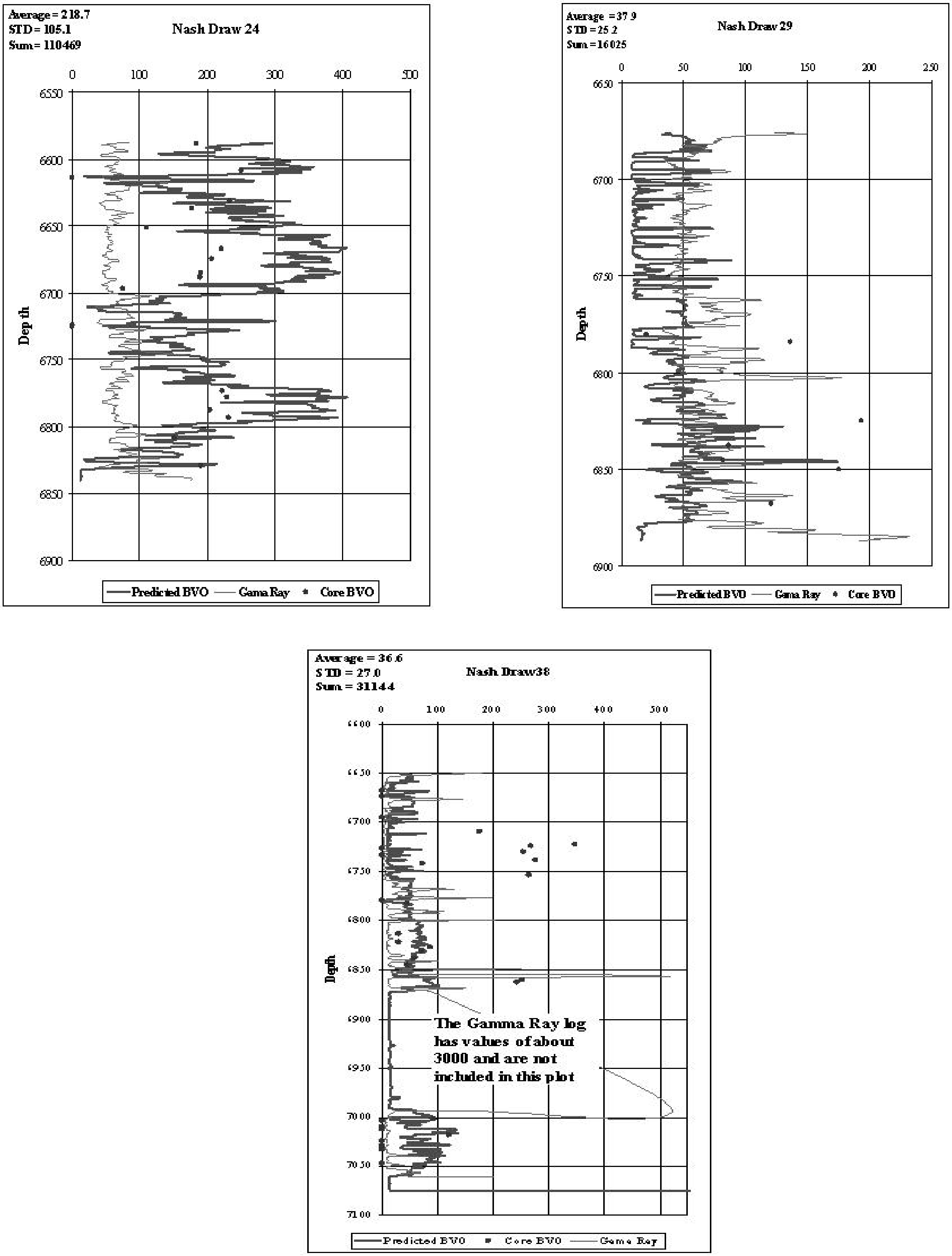


Fig. 23. Neural network predicted BVO for wells 24, 29, and 38.

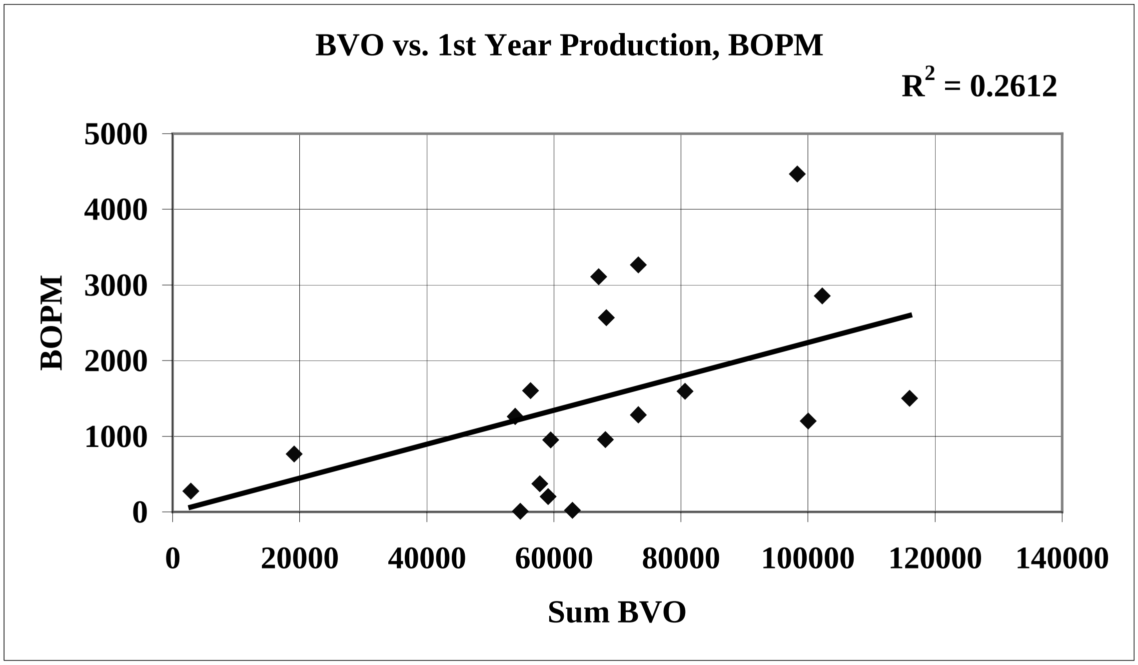


Fig. 24. General correlation between Sum BVO and initial production.

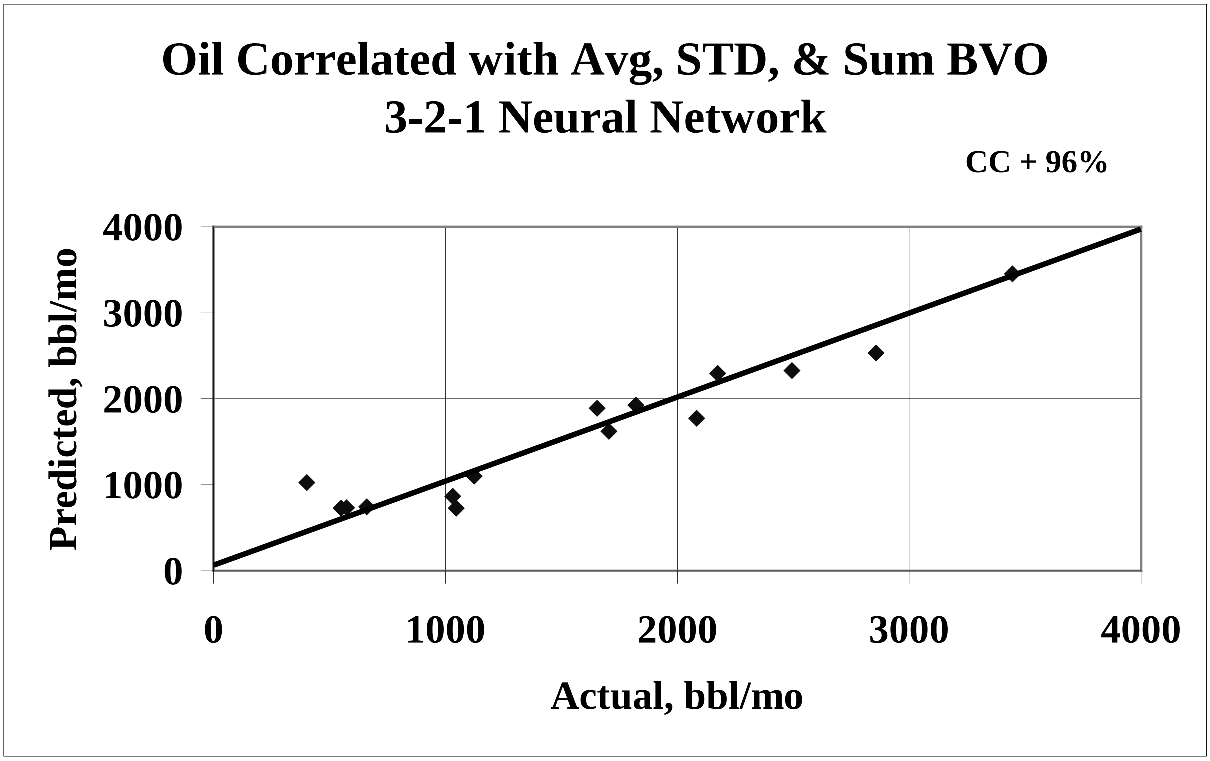


Fig. 25. Neural network correlation using BVO log statistics as input.

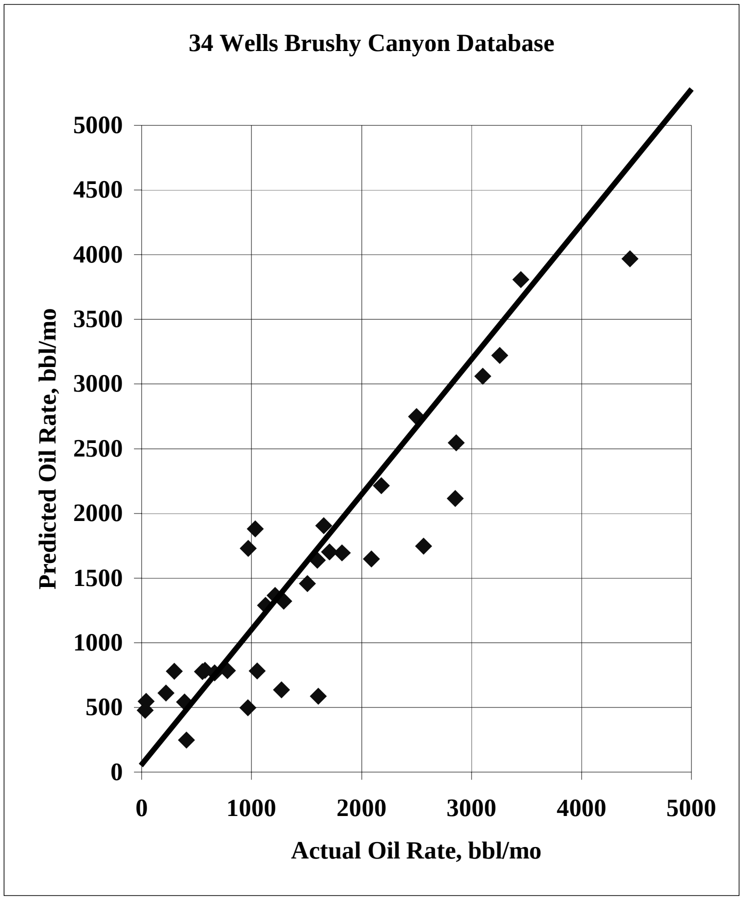


Fig. 26. Correlation based on BVO log statistics and initial production.

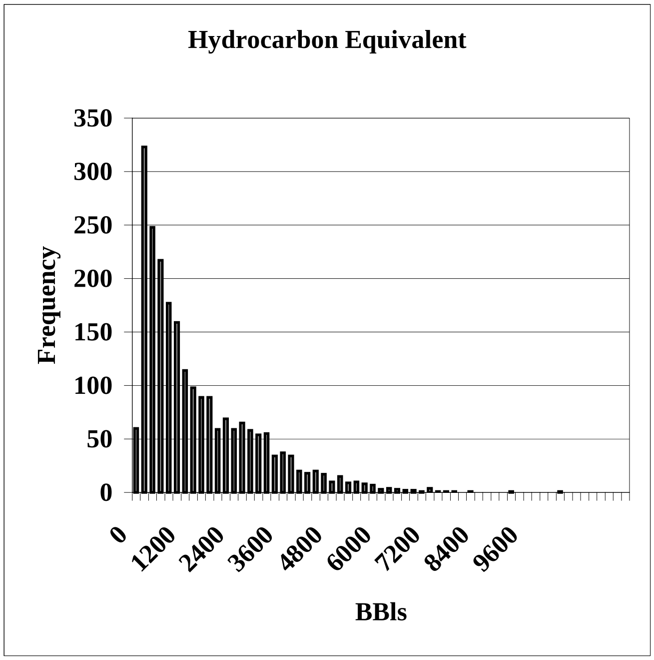


Fig. 27. Hydrocarbon equivalent histogram.

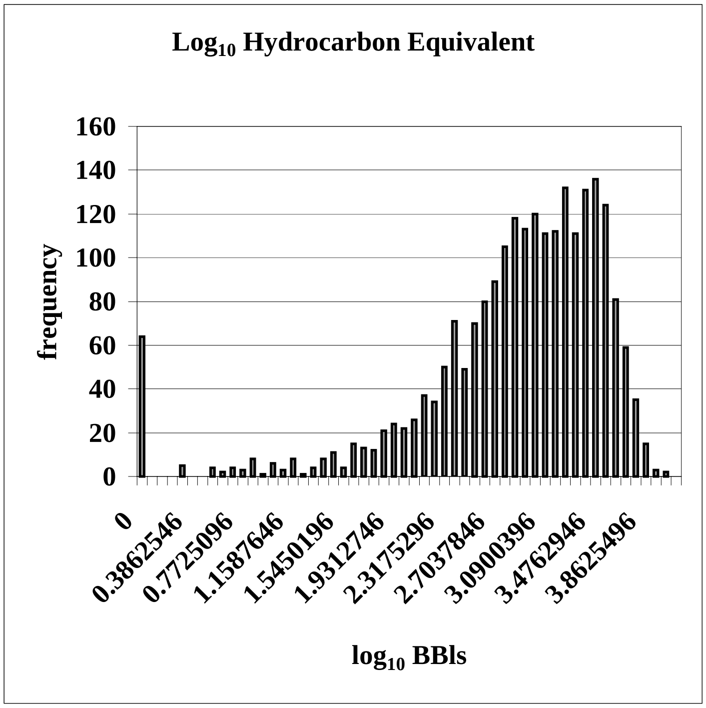


Fig. 28 Log filtered hydrocarbon equivalent.

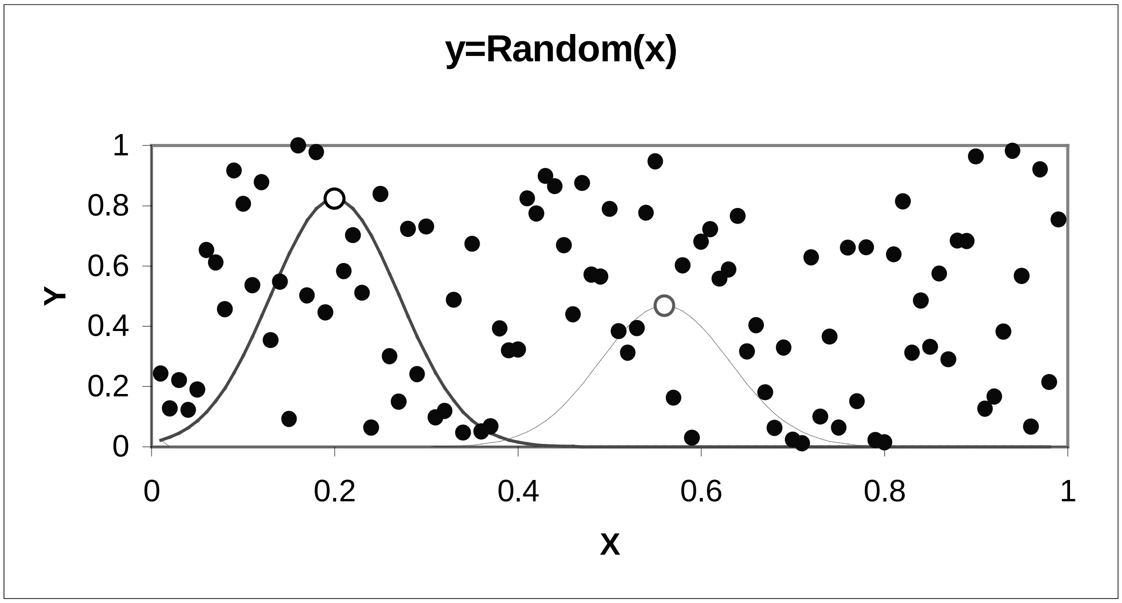


Fig. 29. One hundred random points between 0 and 100. Two sample fuzzy membership functions are illustrated.

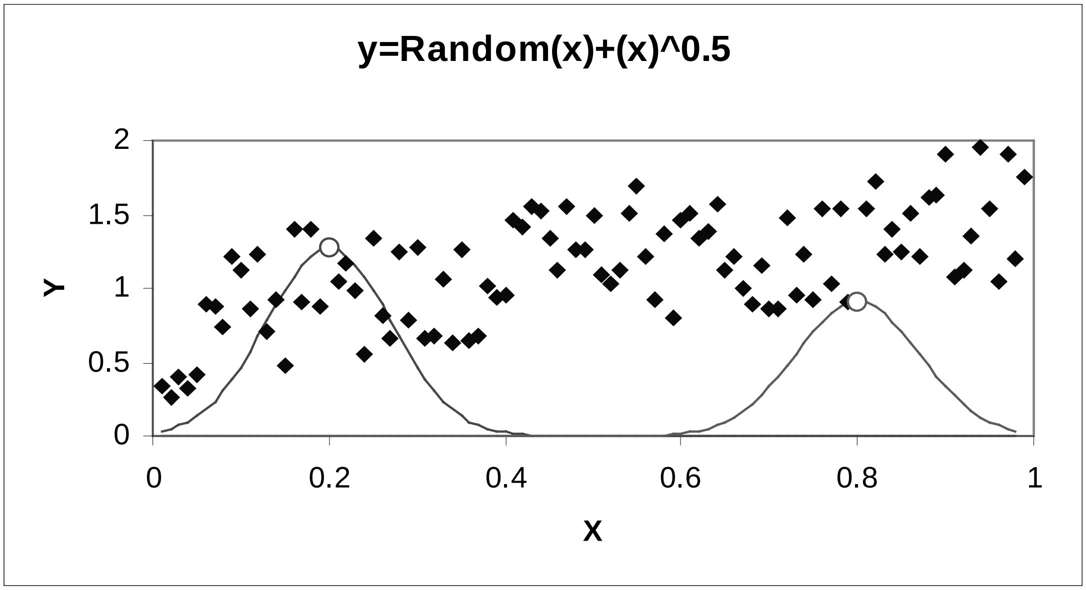


Fig. 30. The same one hundred random points with a simple trend added, two sample fuzzy membership functions are shown.

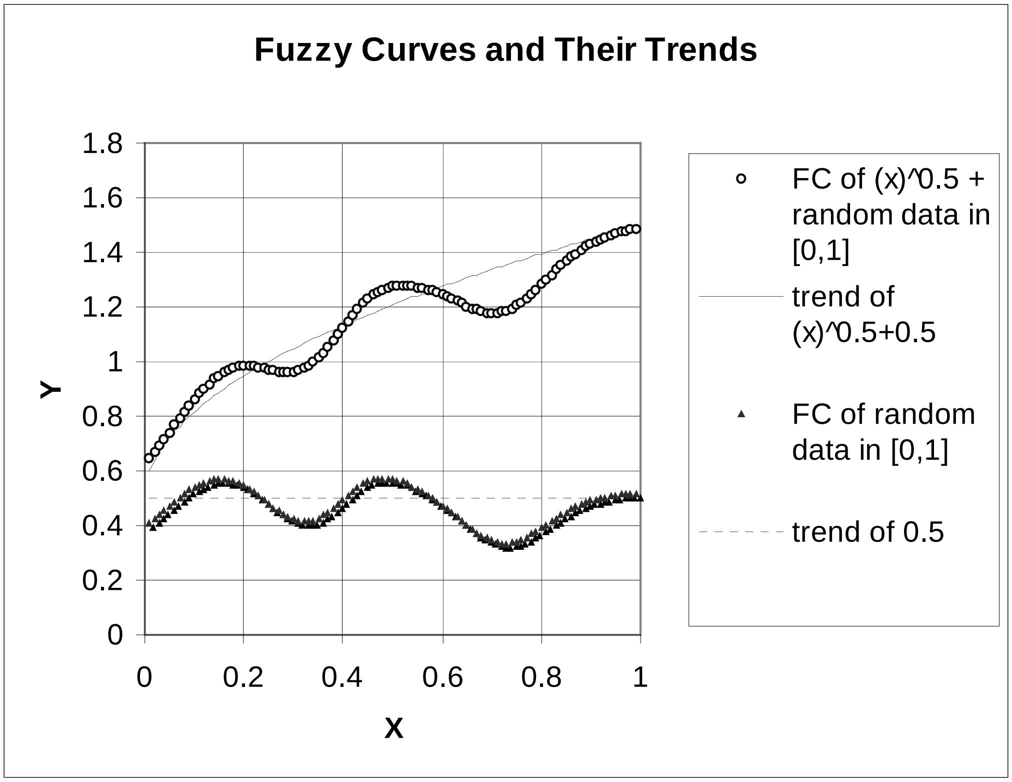


Fig. 31. Fuzzy curves for the two data distributions illustrated in Figs. 29 and 30. Curves are the summation of the fuzzy membership functions for each point. Value is given to trends with monotonic vertical variations.

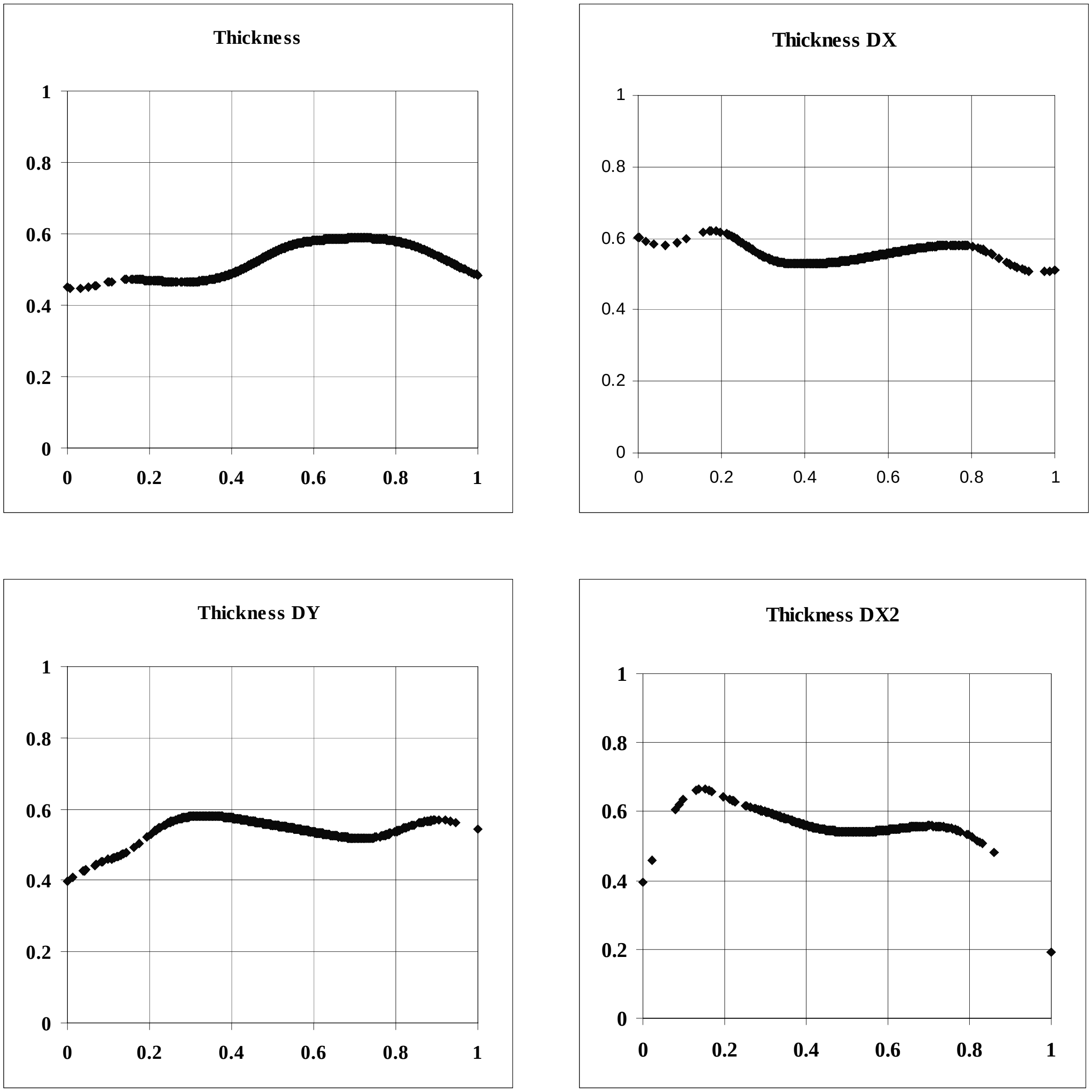


Fig. 32. Fuzzy curves for data attributes: Thickness, Thickness DX, Thickness DY, and Thickness DX2.

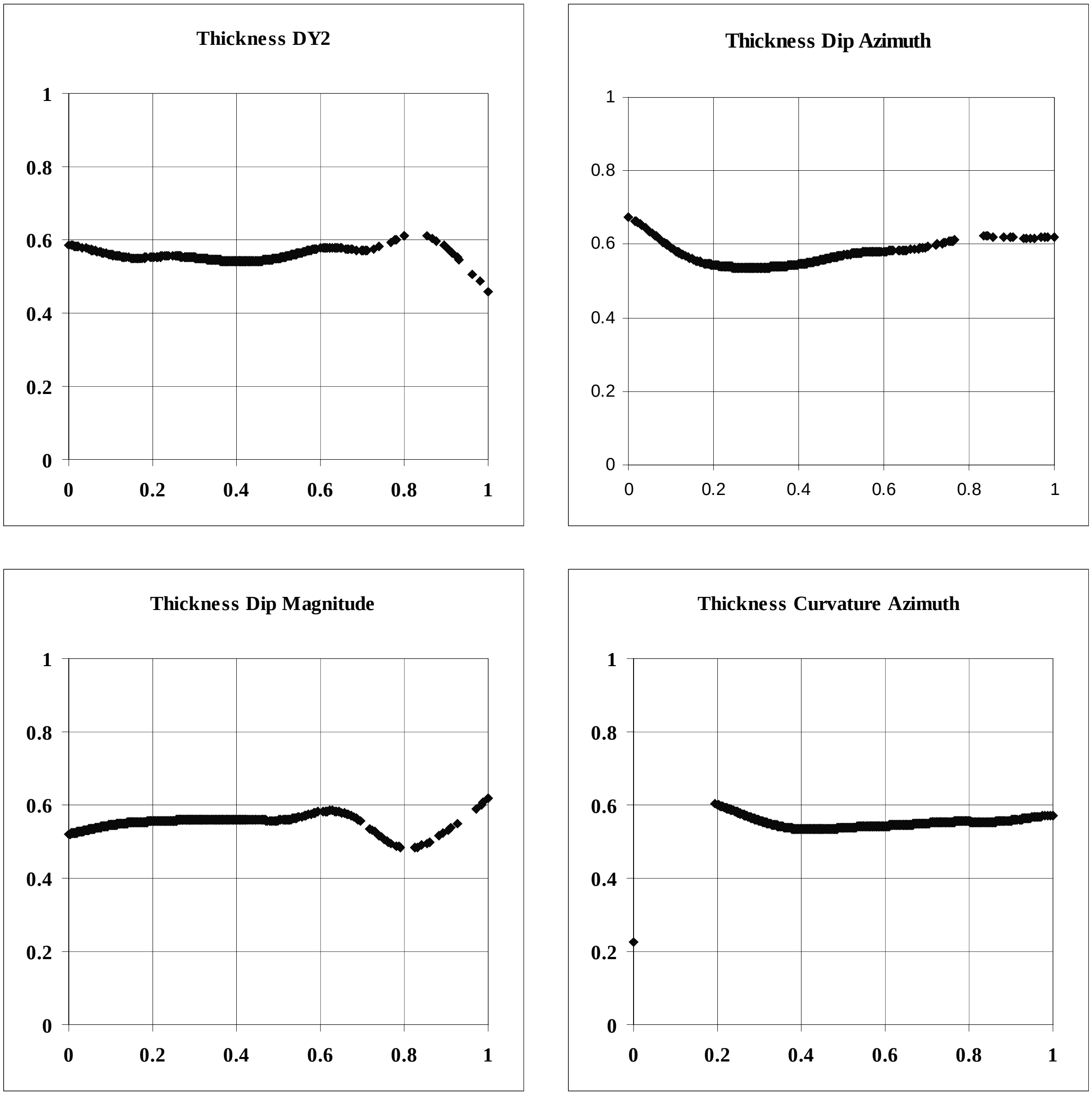


Fig. 33. Fuzzy curves for data attributes: Thickness DY2, Thickness Dip Azimuth, Thickness Dip Magnitude, and Thickness Curvature Azimuth.

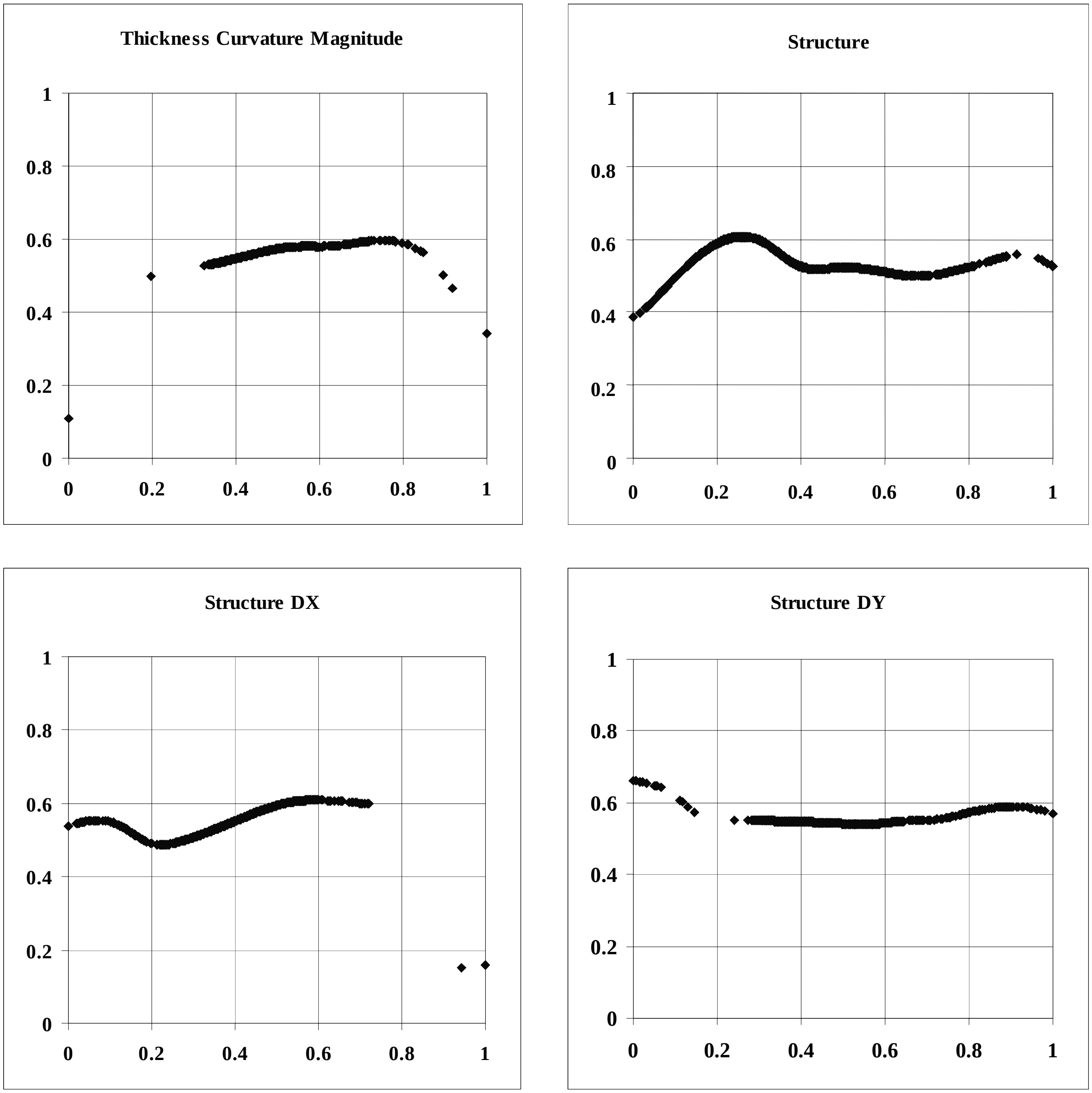


Fig. 34. Fuzzy curves for data attributes: Thickness Curvature Magnitude, Structure, Structure DX, and Structure DY.

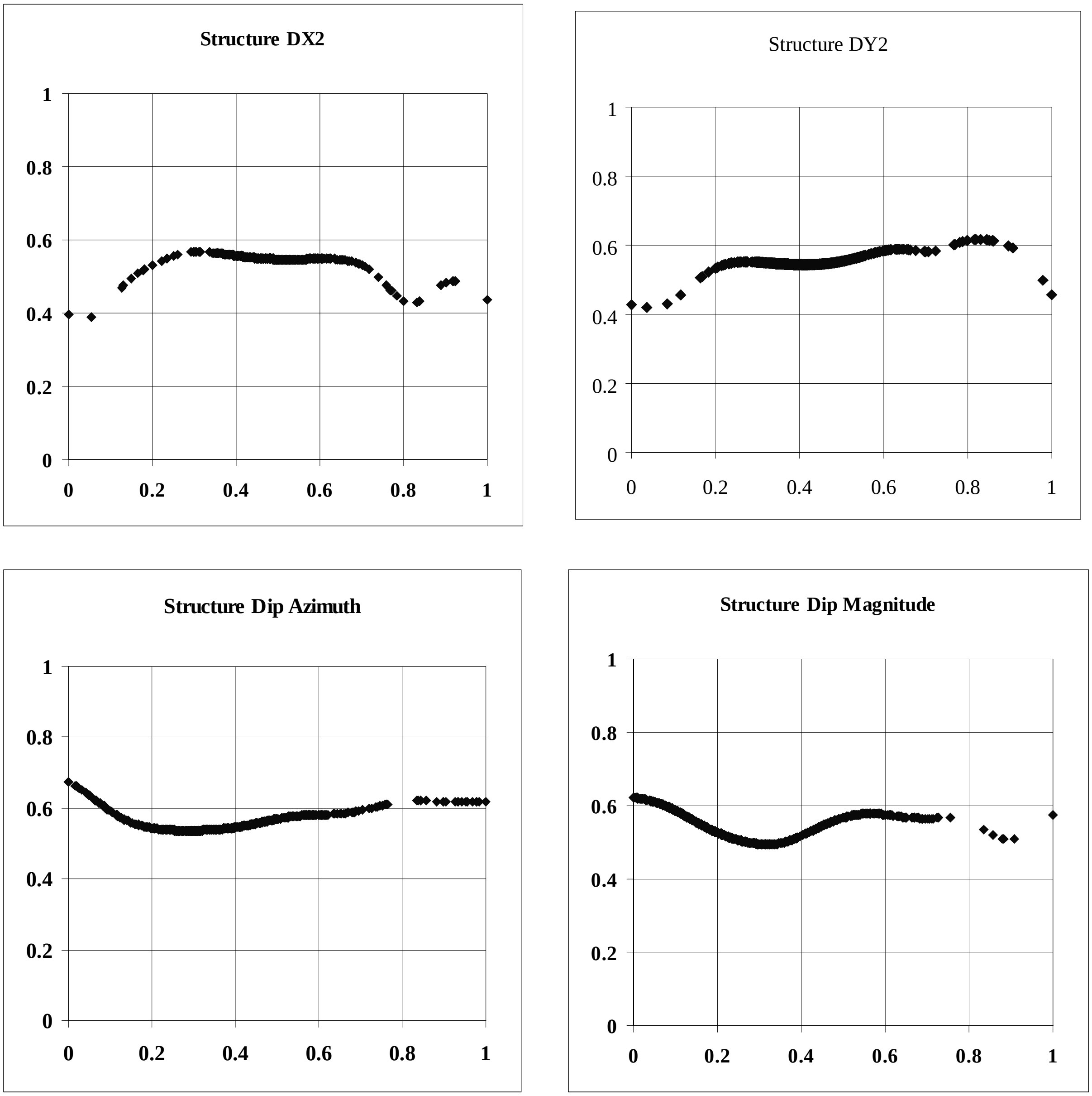


Fig. 35. Fuzzy curves for data attributes: Structure DX2, Structure DY2, Structure Dip Azimuth, and Structure Dip Magnitude.

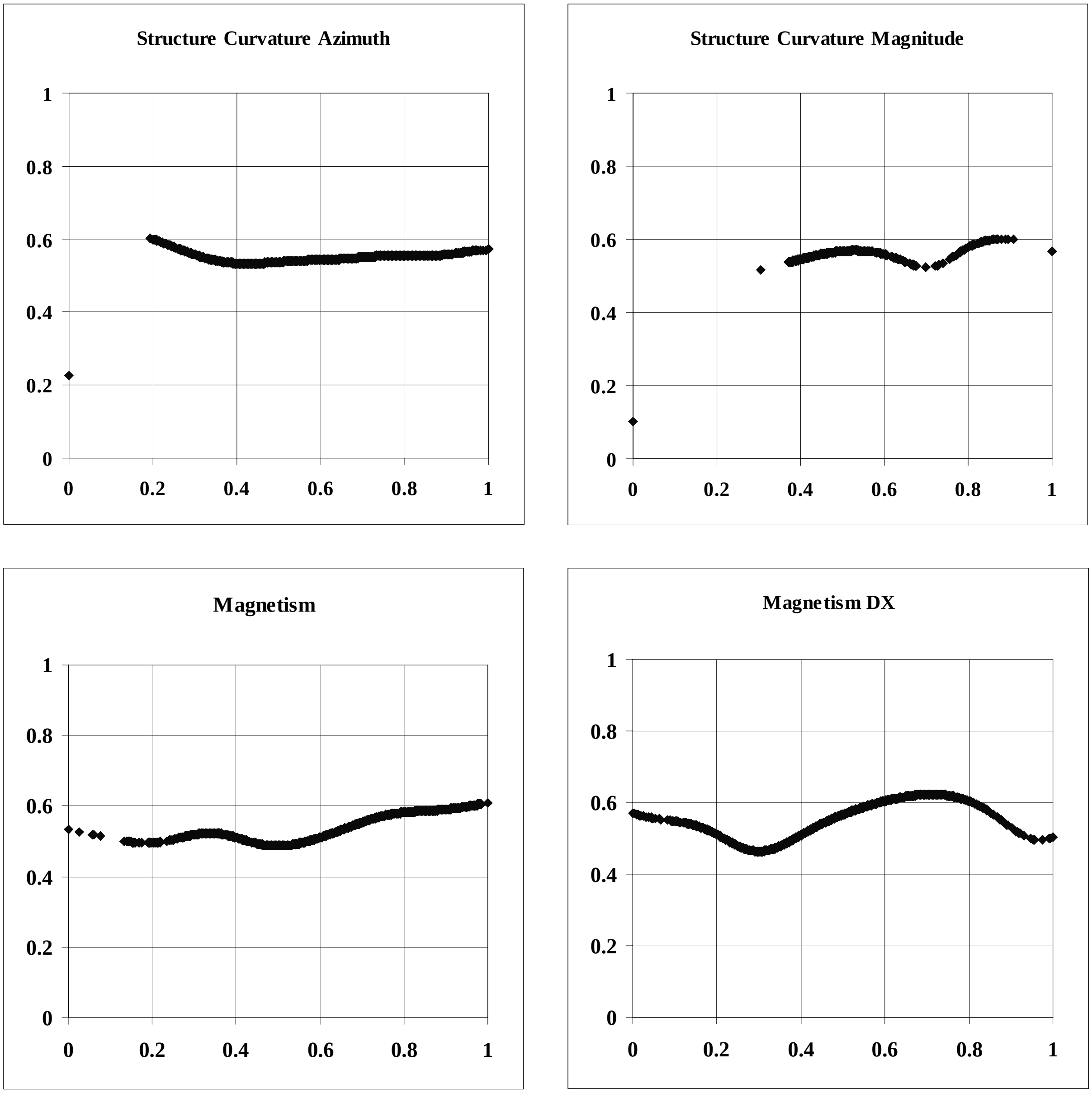


Fig. 36. Fuzzy curves for data attributes**:** Structure Curvature Azimuth, Structure Curvature Magnitude, Magnetism, and Magnetism DX.

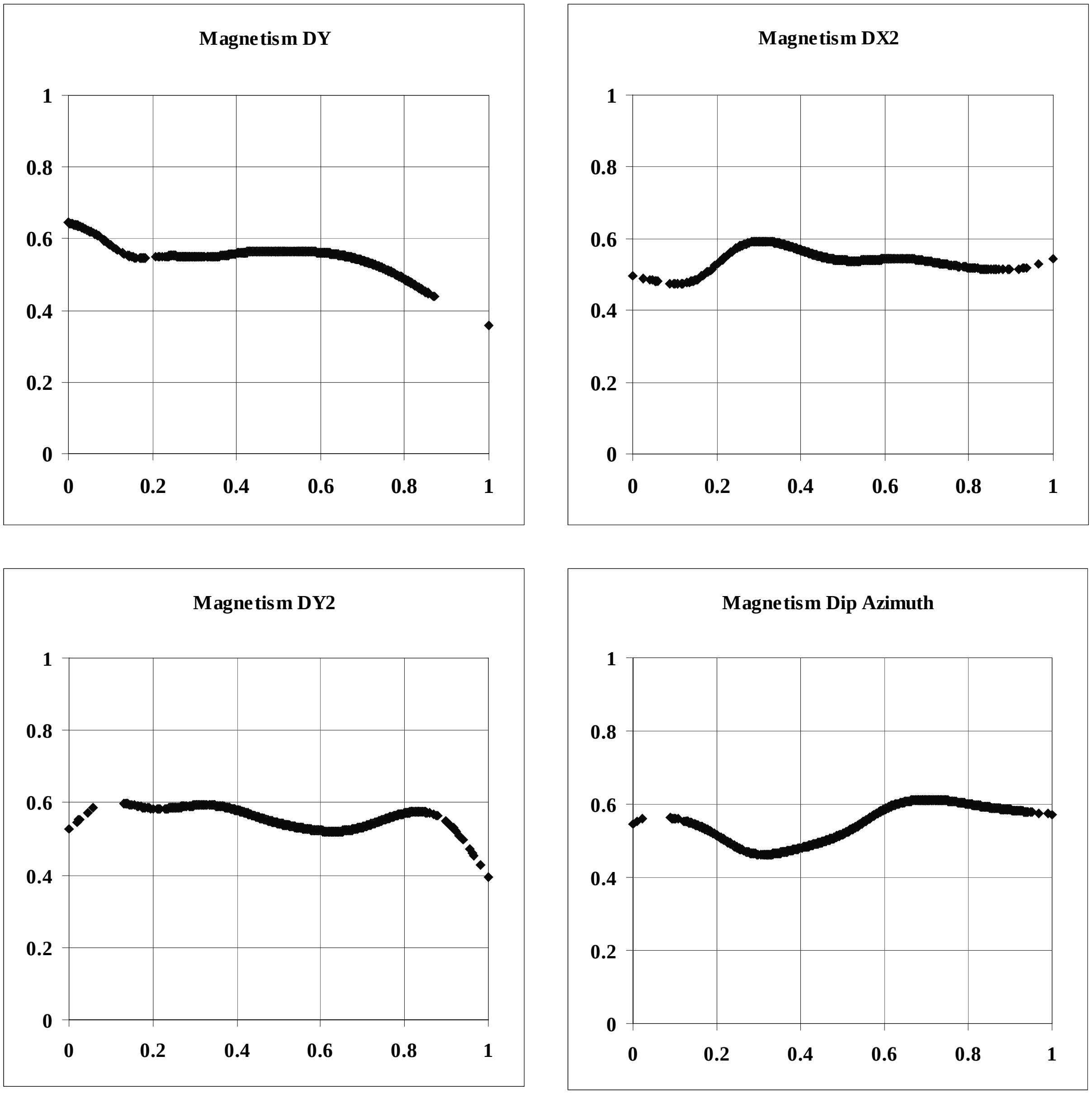


Fig. 37. Fuzzy curves for data attributes: Magnetism DY, Magnetism DX2, Magnetism DY2, and Magnetism Dip Azimuth.

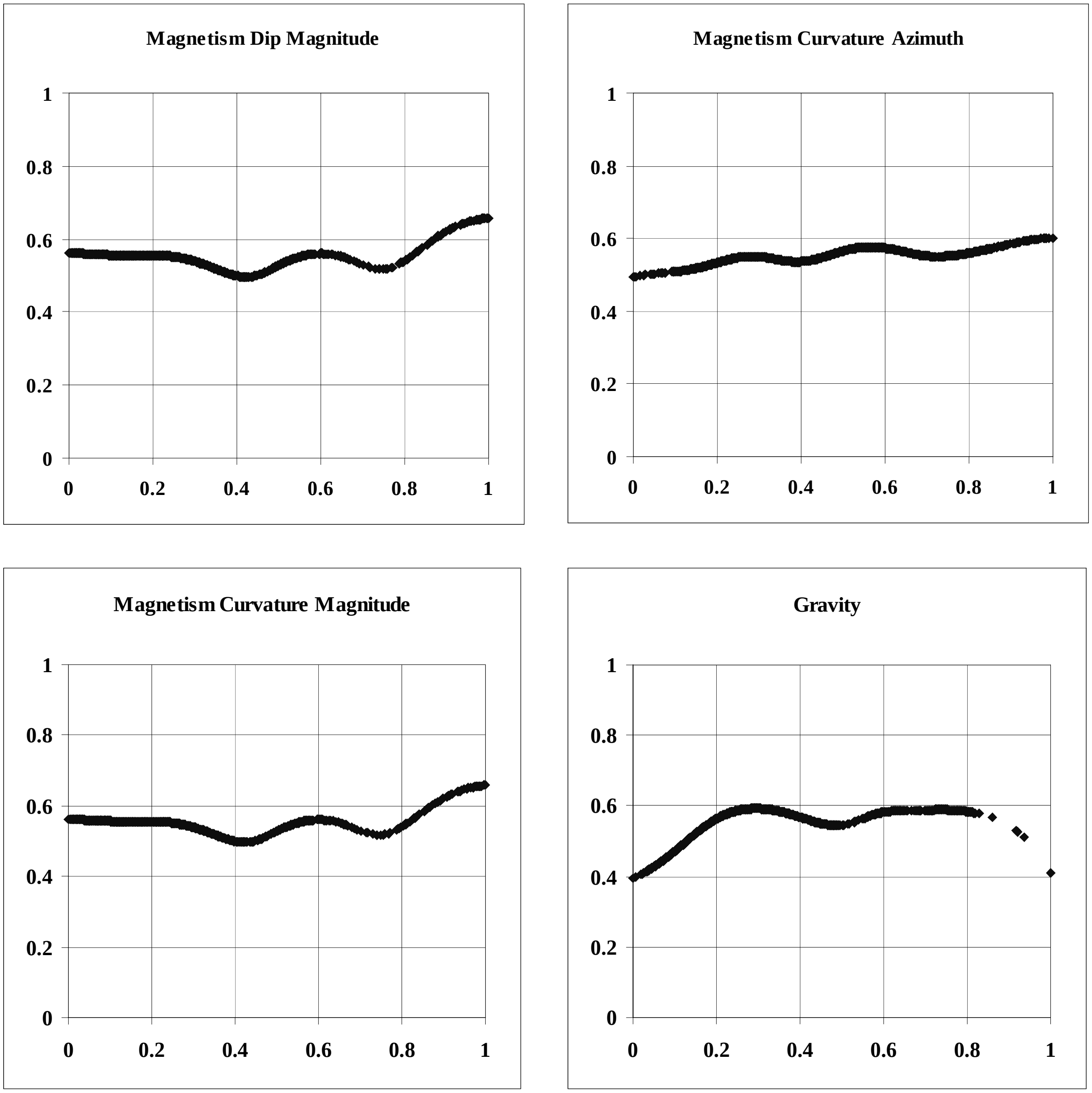


Fig. 38. Fuzzy curves for data attributes: Magnetism Dip Magnitude, Magnetism Curvature Azimuth, Magnetism Curvature Magnitude, and Gravity.

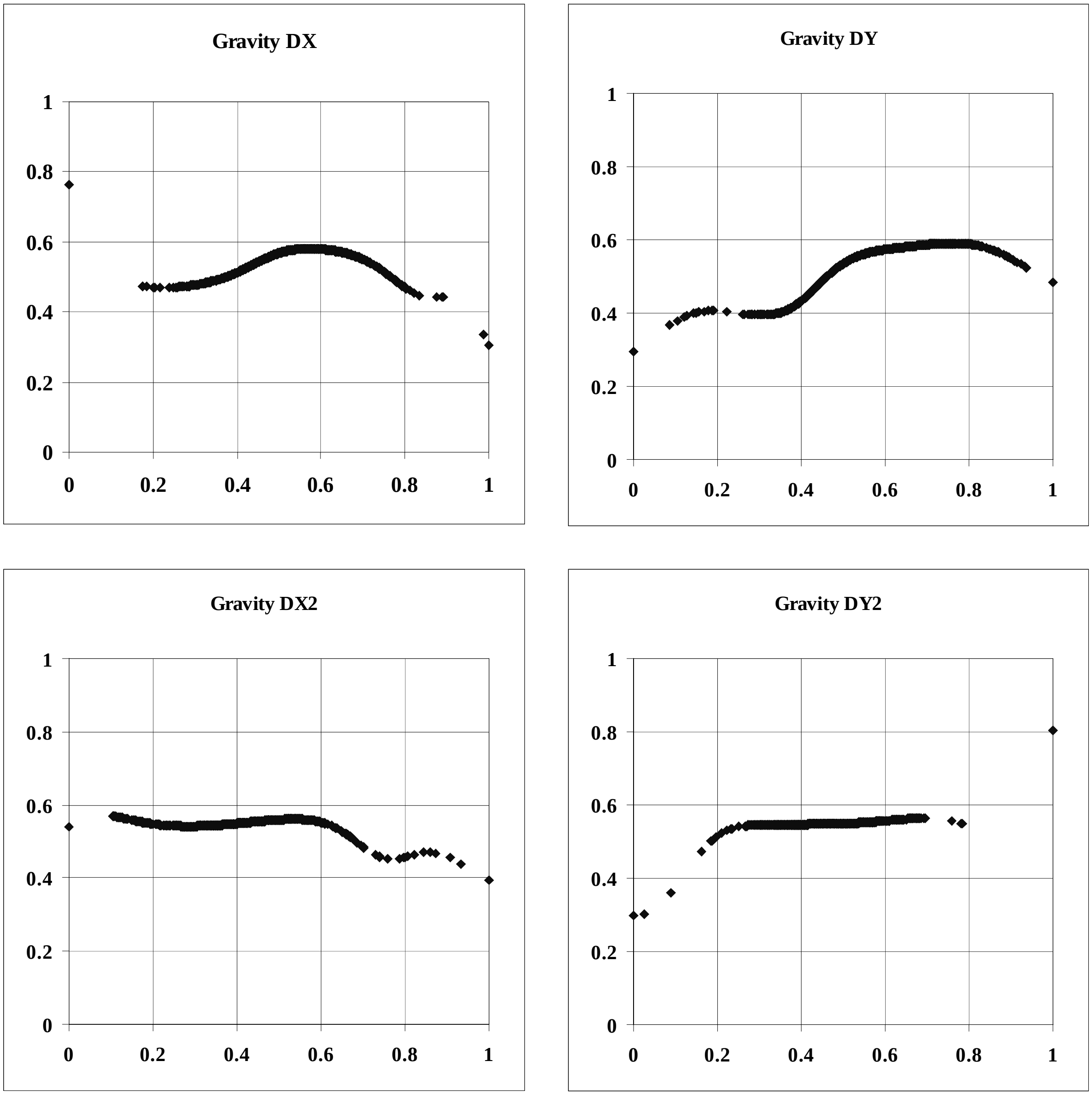


Fig. 39. Fuzzy curves for data attributes: Gravity DX, Gravity DY, Gravity DX2, Gravity DY2.

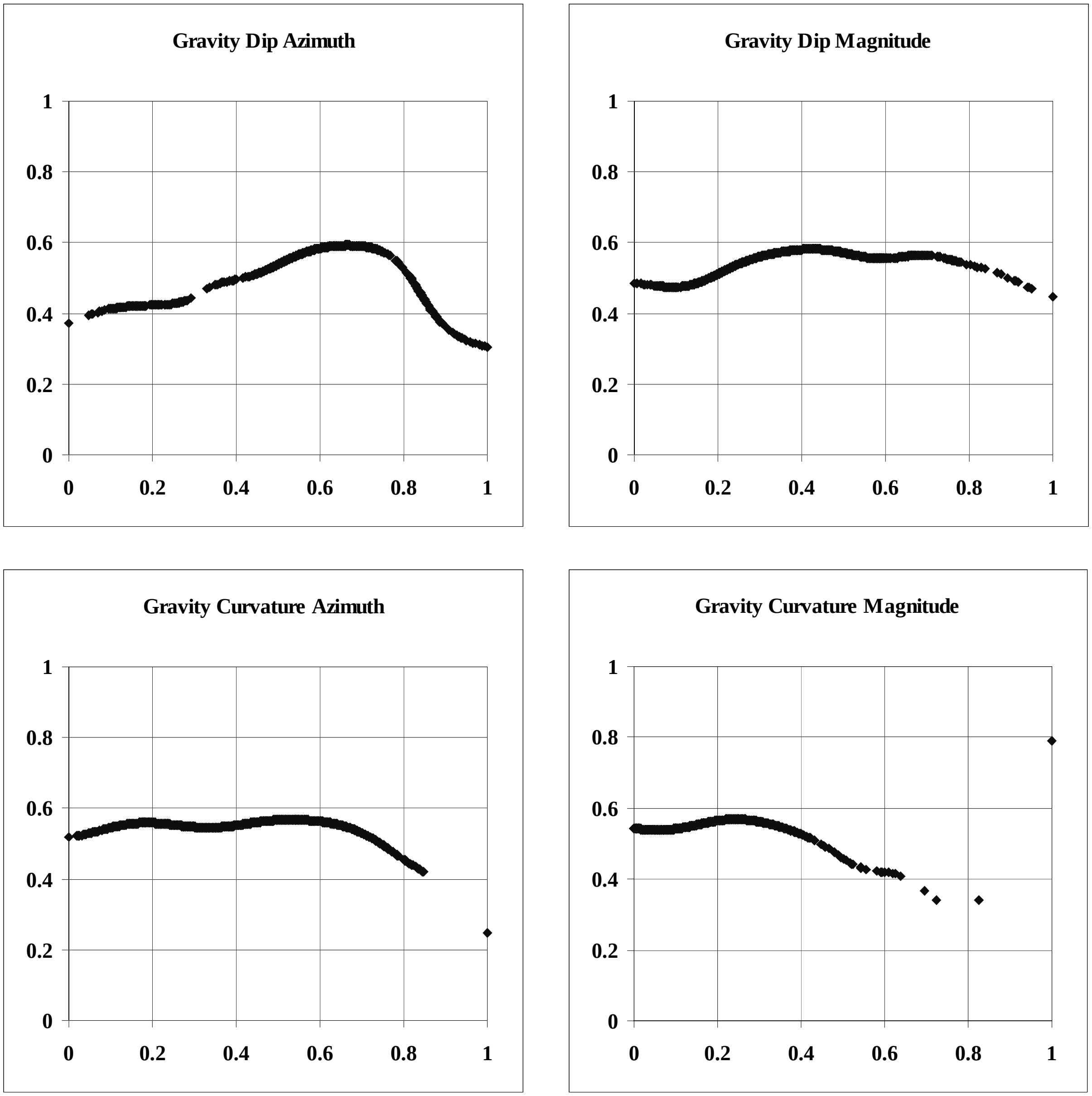


Fig. 40. Fuzzy curves for data attributes: Gravity Dip Azimuth, Gravity Dip Magnitude, Gravity Curvature Azimuth, and Gravity Curvature Magnitude.

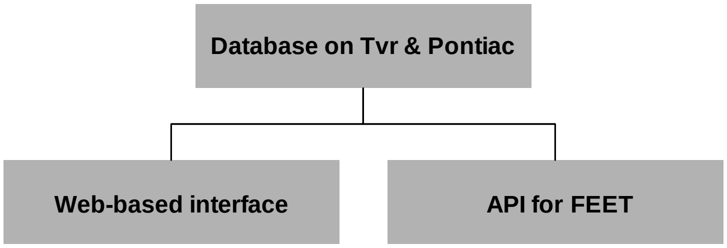


Fig. 41. Three parts of WDMS.

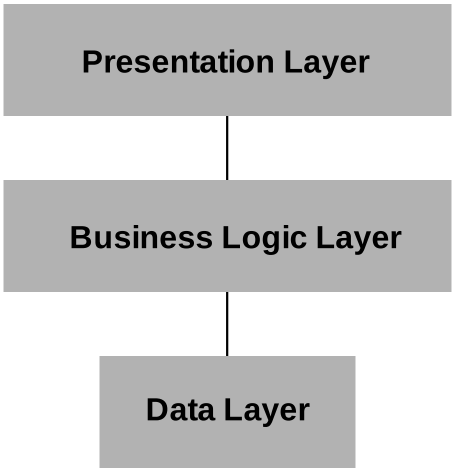
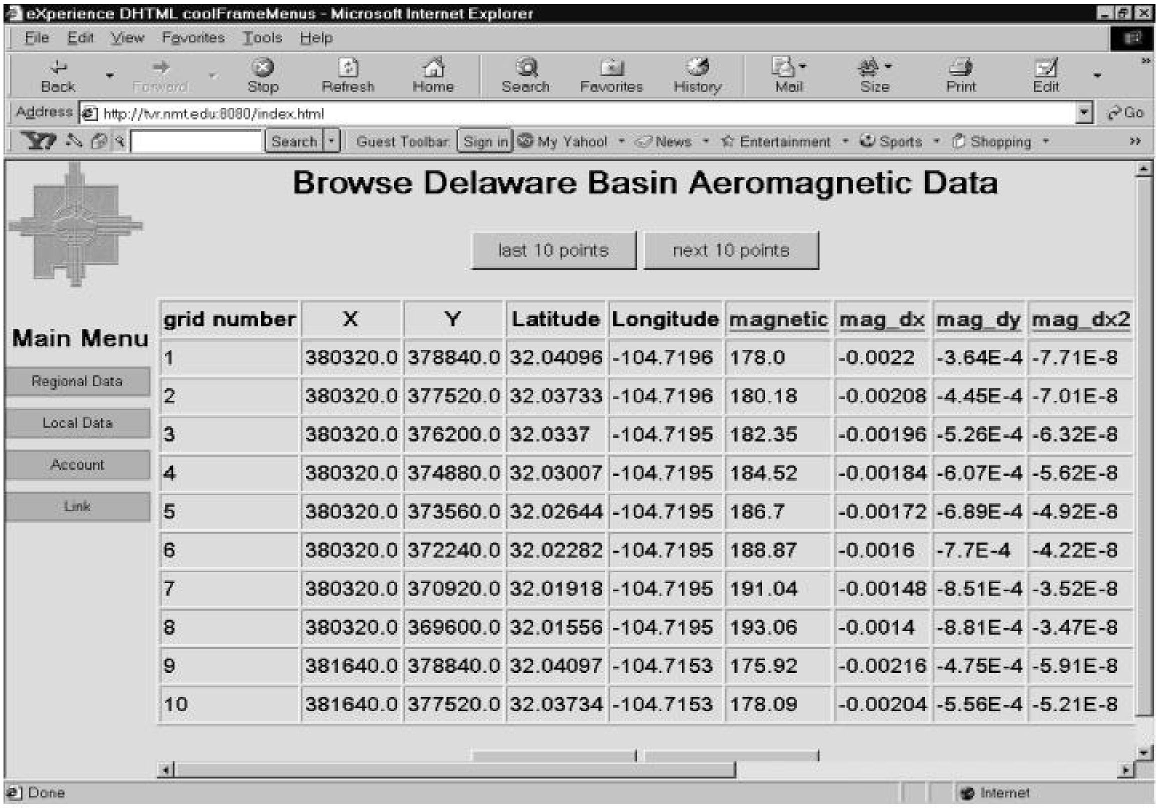


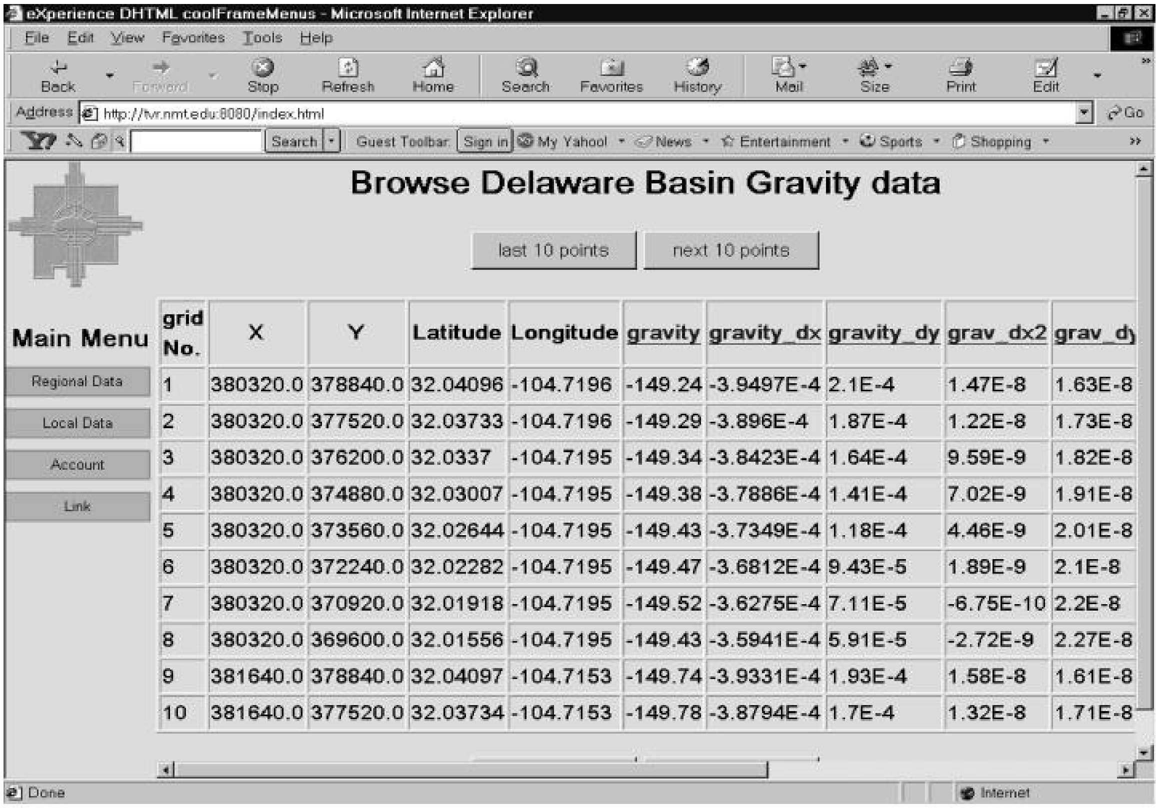
Fig. 42. Three layers of WDMS.



Browse Delaware Basin Aeromagnetic Data

grid number	X	Y	Latitude	Longitude	magnetic	mag_dx	mag_dy	mag_dx2
1	380320.0	378840.0	32.04096	-104.7196	178.0	-0.0022	-3.64E-4	-7.71E-8
2	380320.0	377520.0	32.03733	-104.7196	180.18	-0.00208	-4.45E-4	-7.01E-8
3	380320.0	376200.0	32.0337	-104.7195	182.35	-0.00196	-5.26E-4	-6.32E-8
4	380320.0	374880.0	32.03007	-104.7195	184.52	-0.00184	-6.07E-4	-5.62E-8
5	380320.0	373560.0	32.02644	-104.7195	186.7	-0.00172	-6.89E-4	-4.92E-8
6	380320.0	372240.0	32.02282	-104.7195	188.87	-0.0016	-7.7E-4	-4.22E-8
7	380320.0	370920.0	32.01918	-104.7195	191.04	-0.00148	-8.51E-4	-3.52E-8
8	380320.0	369600.0	32.01556	-104.7195	193.06	-0.0014	-8.81E-4	-3.47E-8
9	381640.0	378840.0	32.04097	-104.7153	175.92	-0.00216	-4.75E-4	-5.91E-8
10	381640.0	377520.0	32.03734	-104.7153	178.09	-0.00204	-5.56E-4	-5.21E-8

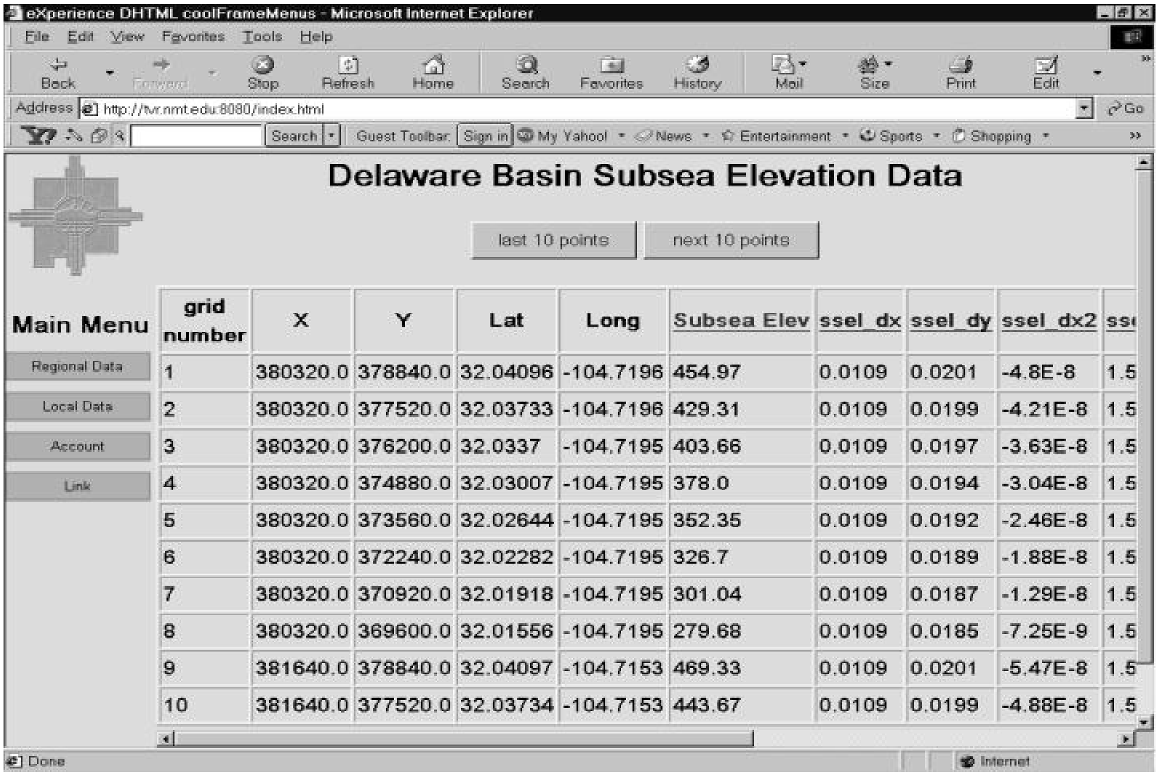
Fig. 43. Browse aeromagnetic data.



Browse Delaware Basin Gravity data

grid No.	X	Y	Latitude	Longitude	gravity	gravity_dx	gravity_dy	grav_dx2	grav_dy
1	380320.0	378840.0	32.04096	-104.7196	-149.24	-3.9497E-4	2.1E-4	1.47E-8	1.63E-8
2	380320.0	377520.0	32.03733	-104.7196	-149.29	-3.896E-4	1.87E-4	1.22E-8	1.73E-8
3	380320.0	376200.0	32.0337	-104.7195	-149.34	-3.8423E-4	1.64E-4	9.59E-9	1.82E-8
4	380320.0	374880.0	32.03007	-104.7195	-149.38	-3.7886E-4	1.41E-4	7.02E-9	1.91E-8
5	380320.0	373560.0	32.02644	-104.7195	-149.43	-3.7349E-4	1.18E-4	4.46E-9	2.01E-8
6	380320.0	372240.0	32.02282	-104.7195	-149.47	-3.6812E-4	9.43E-5	1.89E-9	2.1E-8
7	380320.0	370920.0	32.01918	-104.7195	-149.52	-3.6275E-4	7.11E-5	-6.75E-10	2.2E-8
8	380320.0	369600.0	32.01556	-104.7195	-149.43	-3.5941E-4	5.91E-5	-2.72E-9	2.27E-8
9	381640.0	378840.0	32.04097	-104.7153	-149.74	-3.9331E-4	1.93E-4	1.58E-8	1.61E-8
10	381640.0	377520.0	32.03734	-104.7153	-149.78	-3.8794E-4	1.7E-4	1.32E-8	1.71E-8

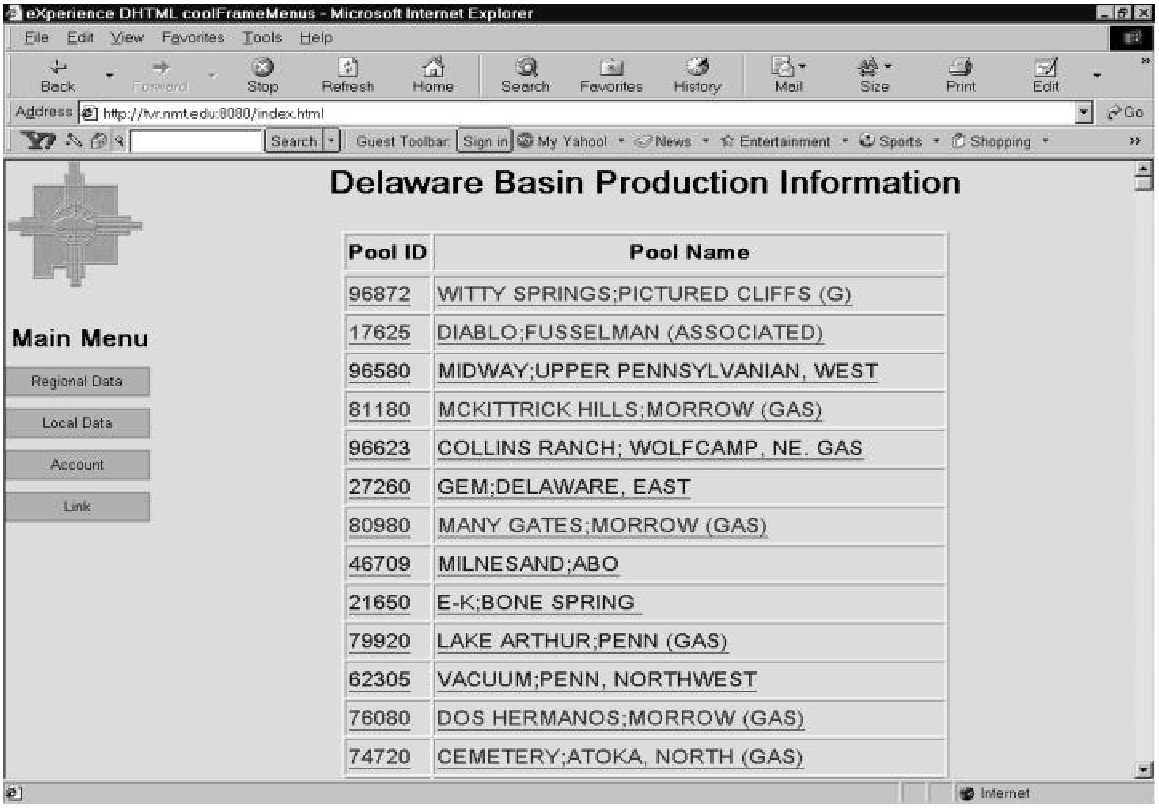
Fig. 44. Browse gravity data.



Delaware Basin Subsea Elevation Data

grid number	X	Y	Lat	Long	Subsea Elev	ssel_dx	ssel_dy	ssel_dx2	ss
1	380320.0	378840.0	32.04096	-104.7196	454.97	0.0109	0.0201	-4.8E-8	1.5
2	380320.0	377520.0	32.03733	-104.7196	429.31	0.0109	0.0199	-4.21E-8	1.5
3	380320.0	376200.0	32.0337	-104.7195	403.66	0.0109	0.0197	-3.63E-8	1.5
4	380320.0	374880.0	32.03007	-104.7195	378.0	0.0109	0.0194	-3.04E-8	1.5
5	380320.0	373560.0	32.02644	-104.7195	352.35	0.0109	0.0192	-2.46E-8	1.5
6	380320.0	372240.0	32.02282	-104.7195	326.7	0.0109	0.0189	-1.88E-8	1.5
7	380320.0	370920.0	32.01918	-104.7195	301.04	0.0109	0.0187	-1.29E-8	1.5
8	380320.0	369600.0	32.01556	-104.7195	279.68	0.0109	0.0185	-7.25E-9	1.5
9	381640.0	378840.0	32.04097	-104.7153	469.33	0.0109	0.0201	-5.47E-8	1.5
10	381640.0	377520.0	32.03734	-104.7153	443.67	0.0109	0.0199	-4.88E-8	1.5

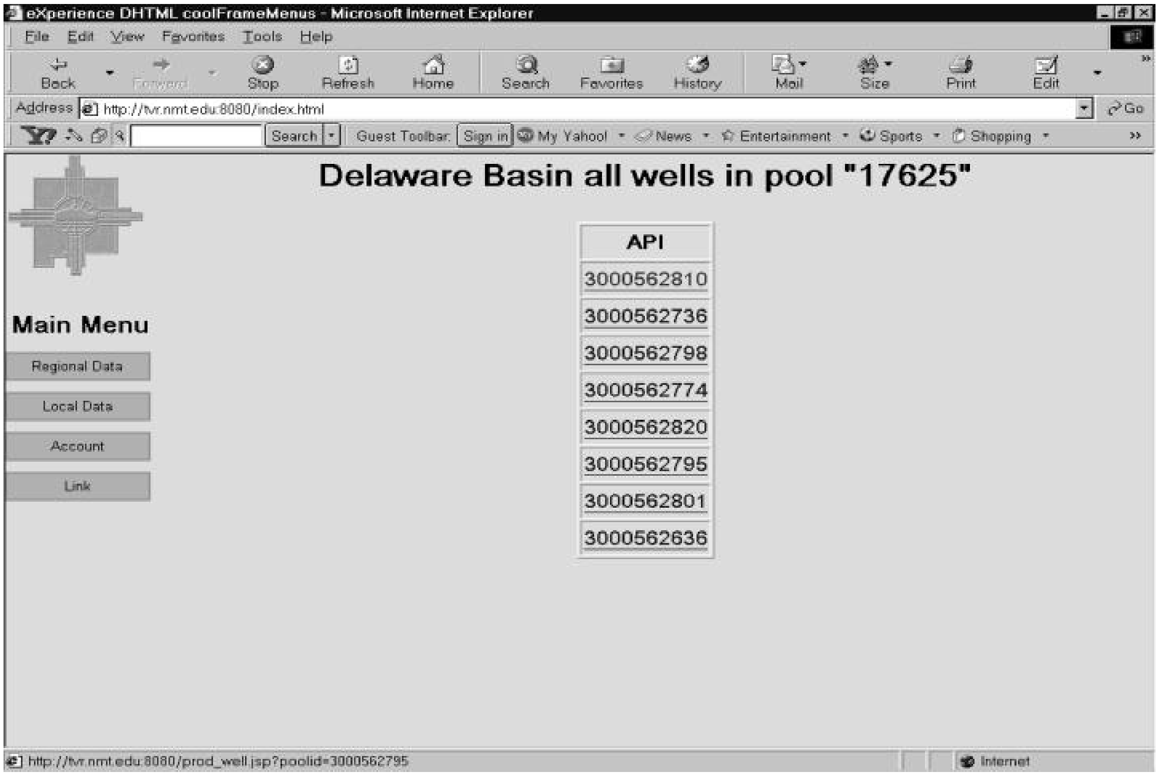
Fig. 45. Browse subsea elevation data.



Delaware Basin Production Information

Pool ID	Pool Name
96872	WITTY SPRINGS;PICTURED CLIFFS (G)
17625	DIABLO;FUSSELMAN (ASSOCIATED)
96580	MIDWAY;UPPER PENNSYLVANIAN, WEST
81180	MCKITTRICK HILLS;MORROW (GAS)
96623	COLLINS RANCH; WOLFCAMP, NE. GAS
27260	GEM;DELAWARE, EAST
80980	MANY GATES;MORROW (GAS)
46709	MILNESAND;ABO
21650	E-K;BONE SPRING
79920	LAKE ARTHUR;PENN (GAS)
62305	VACUUM;PENN, NORTHWEST
76080	DOS HERMANOS;MORROW (GAS)
74720	CEMETERY;ATOKA, NORTH (GAS)

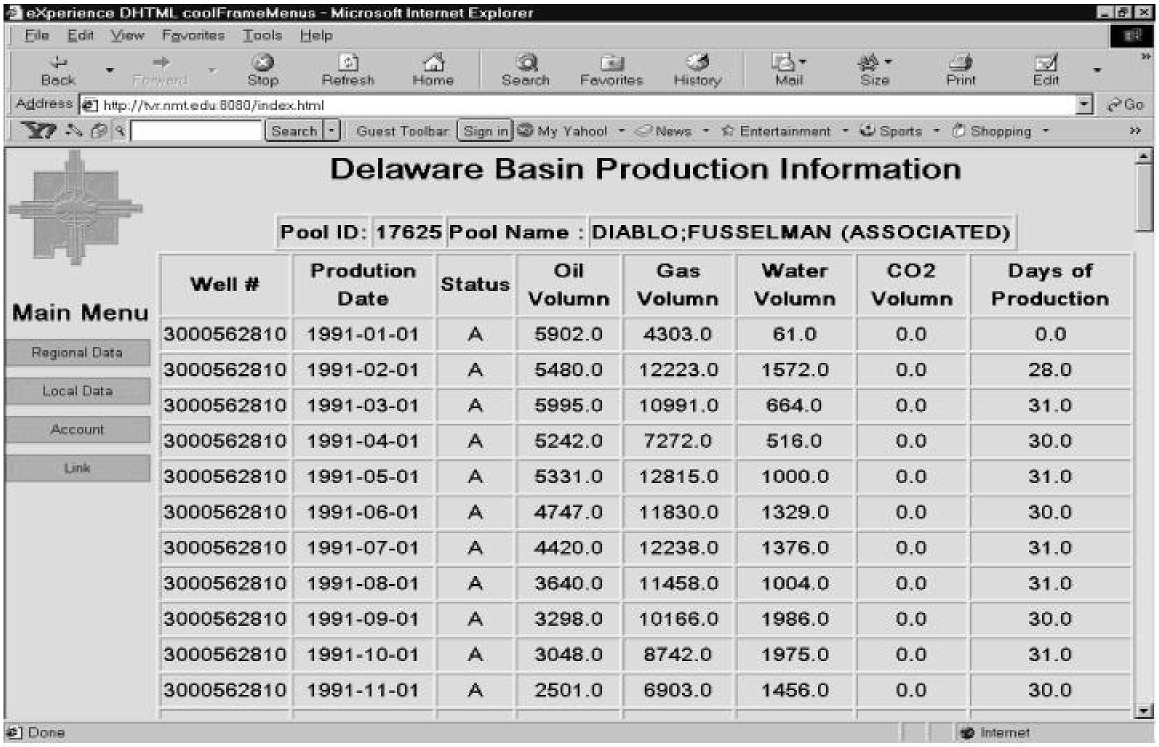
Fig. 46. Pool ID and pool name for all pools.



Delaware Basin all wells in pool "17625"

API
3000562810
3000562736
3000562798
3000562774
3000562820
3000562795
3000562801
3000562636

Fig. 47. API numbers for all wells in pool 17625.



Delaware Basin Production Information

Pool ID: 17625 Pool Name : DIABLO;FUSSELMAN (ASSOCIATED)

Well #	Prodution Date	Status	Oil Volumn	Gas Volumn	Water Volumn	CO2 Volumn	Days of Production
3000562810	1991-01-01	A	5902.0	4303.0	61.0	0.0	0.0
3000562810	1991-02-01	A	5480.0	12223.0	1572.0	0.0	28.0
3000562810	1991-03-01	A	5995.0	10991.0	664.0	0.0	31.0
3000562810	1991-04-01	A	5242.0	7272.0	516.0	0.0	30.0
3000562810	1991-05-01	A	5331.0	12815.0	1000.0	0.0	31.0
3000562810	1991-06-01	A	4747.0	11830.0	1329.0	0.0	30.0
3000562810	1991-07-01	A	4420.0	12238.0	1376.0	0.0	31.0
3000562810	1991-08-01	A	3640.0	11458.0	1004.0	0.0	31.0
3000562810	1991-09-01	A	3298.0	10166.0	1986.0	0.0	30.0
3000562810	1991-10-01	A	3048.0	8742.0	1975.0	0.0	31.0
3000562810	1991-11-01	A	2501.0	6903.0	1456.0	0.0	30.0

Fig. 48. All production data for well 3000562810.

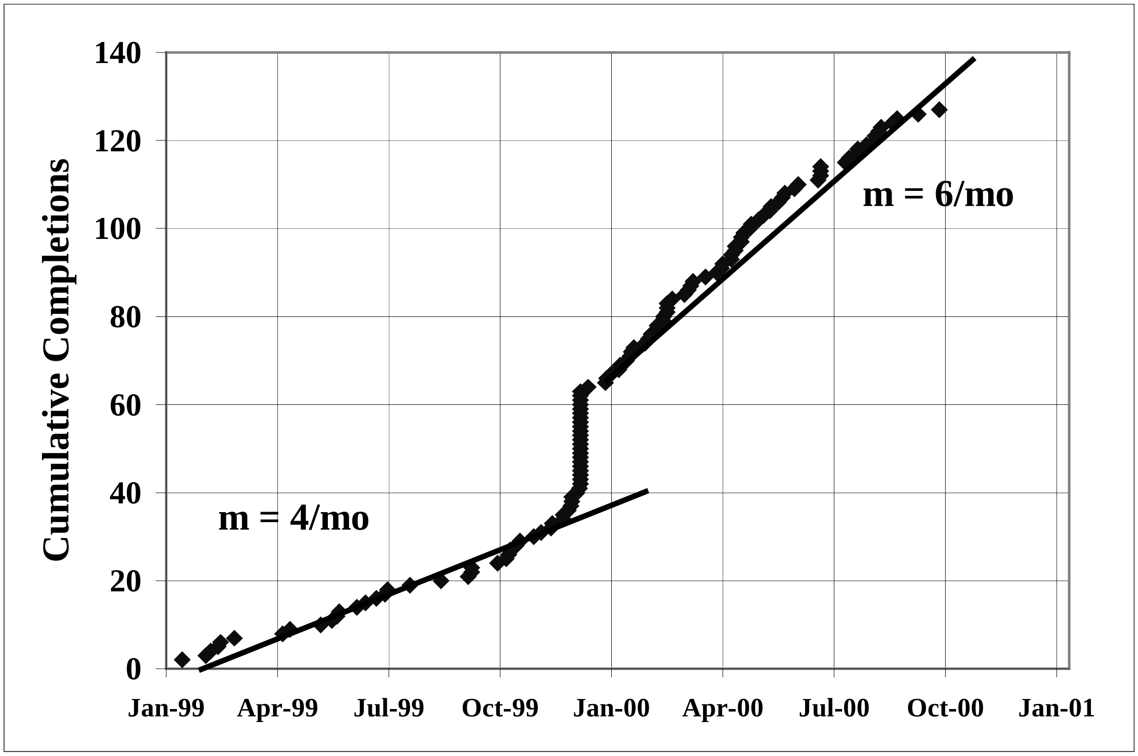


Fig. 49. Delaware completion activity.

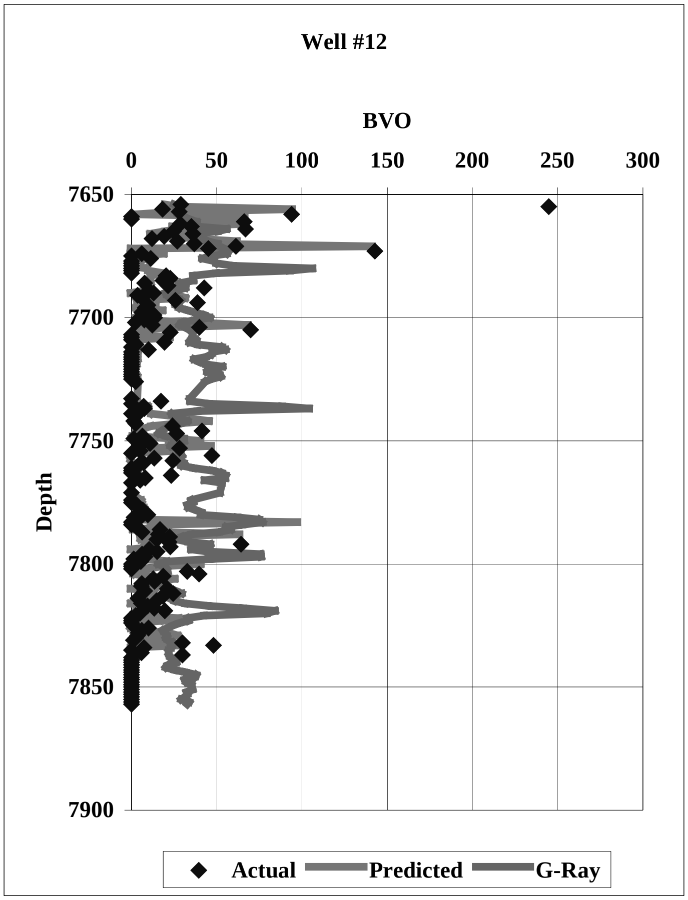


Fig. 50. Actual vs. predicted BVO measurements in a carbonate zone.

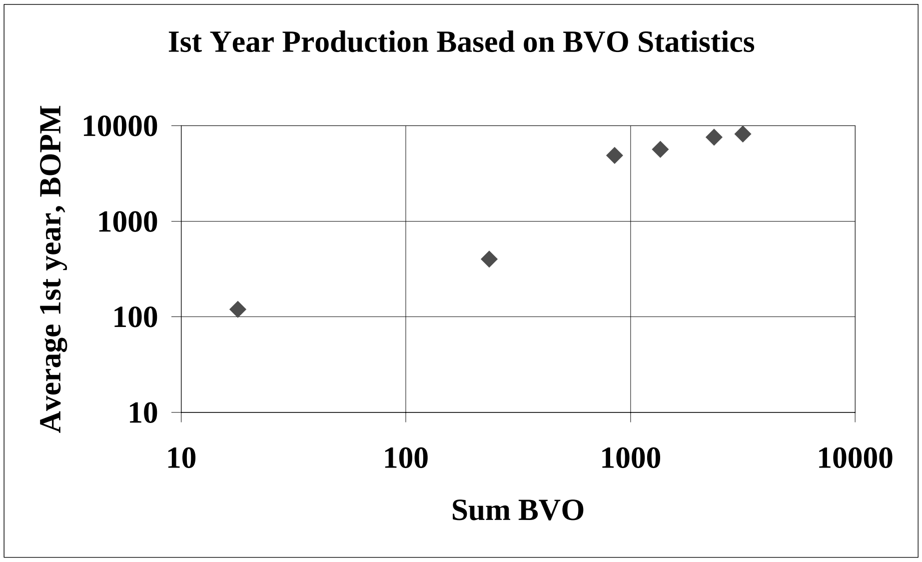


Fig. 51. Average monthly oil rate vs. sum of BVO log.