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Risk Reduction with a Fuzzy Expert Exploration Tool

(Ninth Semi-Annual Technical Progress Report)

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DISCLAIMER

Abstract

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 possibly decreasing dependence on foreign oil and lower product prices for consumers.

This ninth of ten semi-annual reports contains a summary of progress to date, problems encountered, plans for the next year, and an assessment of the prospects for future progress. The emphasis during the March 2003 through September 2003 period was directed toward Silurian-Devonian geology, development of rules for the fuzzy system, and on-line software.

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Executive Summary and 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."

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Introduction

In the first 54 months of the FEE Tool Project, an immense amount of data on the Delaware Basin has been accumulated, including data on geology, structure, production, regional information such as gravity, and local data, such as well logs. This data, organized and cataloged into several online databases, is available for the Expert System and users as needed and as appropriate in analyzing production potential. A preliminary map of production potential for the basin has been generated and can now be modified by rules defined both by human experts in exploring the Delaware basin, and by statistical rules defined by the database. We have generated a number of new and useful tools and technologies to support these efforts, including online useable interfaces for neural network analysis (PredictOnline), ranking of potential inputs using fuzzy logic (FuzzyRank), an Expert System able to make prospect evaluations for the lower Brushy Canyon, and a web interface for accessing the databases and Expert System software.

In the remaining six months we will polish the Delaware basin FEE tool, and complete the Devonian carbonate FEE Tool. Both FEE Tools run remotely from a browser on nearly any computer. The system will be able to aid in development and drilling decisions for both the Brushy Canyon and Devonian plays by providing readily accessible public information. An interactive and customizable questionnaire coupled with relevant analyses produce an "Expert" opinion of a prospect in a short time and can enhance and speed the work of a human explorationist. Though this on-line system will be secure, many users will feel more comfortable if an off-line version of the software is also available. Given time, a stand-alone version will be produced.

Results and Discussion

Computational Intelligence

Overview

Basic design changes. The original design entailed the use of a single massive expert system to make decisions about a prospect's potential as a well site (Fig. 1). As we have investigated the process of designing and running expert systems, it has become apparent that a multi-tiered system, with components running in parallel, would be both more efficient and more versatile in actual usage. Figure 2 shows the current design structure for implementing and accessing the various expert systems needed to evaluate production potential. The new design is more efficient for several reasons. First, it allows better organization of software coding, and faster debugging of the rules, resulting in increased run-time efficiency. Second, the parallel expert systems allow the user to seamlessly consider only the data types they feel are most influential, and is easily customizable to their personal or corporate philosophies. Third, database entry from the system occurs in numerous small packets instead of large chunks and extraneous data transfers were reduced.

Implementation. Figure 2 shows the basic layout of the FEE Tool project. Tier 1 is a user interface that allows selection of an area or prospect of interest. Users can select the types of data they are interested in, and can review that data online with their browsers. Tier 2 in Fig. 2 represents the access of the user's browser to the online databases. Advanced users can manipulate the transferred data for personal use. This data resides in 128 bit password secured files on the server and is not available to anyone, including system administrators, nor does it alter the permanent database in any way.

This allows the use of proprietary information with the system. Once the data is accepted or modified, the next step is to run the appropriate expert systems using the available data to answer heuristic questions and accepting user input to answer other questions that "experts" tend to ask when evaluating Brushy Canyon prospects. In Tier 3, there are three expert systems that can be applied based on user wishes. These address *Regional Indications, Trap Assessment,* and *Formation Assessment.* Specifics and starting rules for these three systems are discussed in later sections. Users may elect to not factor in certain aspects, or to dynamically alter database answers to suit their own data.

Types of rules. Two main types of rules are implemented. Heuristic rules are derived directly from our analysis of regional and local data. These rules are interpreted from the data using algorithms, such as distance relationships, and are based on publicly available data. Heuristic rules include elements like proximity of mature source rocks, structural pinchouts, nearest producing well, and formation thickness. Expert rules come from interviews with Delaware explorationists and mimic questions they ask when evaluating prospects. Expert rules include information about position on structure, porosity and thickness ranges, and production at analogous sites. In addition, heuristic rules can be replaced if the user has more detailed knowledge than is publicly available. Both types of rules have been defined by appropriate fuzzy membership sets in the working FEE Tool software. Generally, for sites with less information heuristic rules will be more important and will provide a best "first" estimate of production potential. For sites with sufficient specific or proprietary information Expert rules dominate.

Heuristic rules. One source of rules for the Fuzzy Expert Exploration Tool is statistical analyses of gridded data in our databases. Currently the regional database has four basic data types for the Brushy Canyon: Gravity, Aeromagnetic, Structure, and

Thickness. An additional eight attributes for each of those four basic types has been calculated: DX, DY, DX2, DY2, dip azimuth, dip magnitude, curvature azimuth, and curvature magnitude. Regional maps of TOC and PI were also generated through geologic work. Additional data include location information in latitude/longitude, oilfield X-Y coordinate systems, and a numeric grid number that also functions as a database key. Additionally, in grids that contain a Brushy Canyon well, there is relevant production information for oil, water, and gas. One factor that complicates working with the databases is the fact that the grid is not square: rather, it runs linearly from north to south increasing by integer amounts from the top of the study area to the bottom. The grid then steps over to the next "column." Each gridpoint is separated by a physical distance of 1320 ft that corresponds to an area of 40 acres contained by four adjacent (squared) gridpoints. The gridding system looks something like this:

08 13 18

04 09 14 19 23

01 05 10 15 20 24 27

02 06 11 16 21 25 28

03 07 12 17 22 26 29

Primary uses of the regional database are the organization of the regional data, determination of which bins contain production information, and calculations of a "first guess" map of production potential using the data with the highest fuzzy rank to predict production. This first guess map (Fig. 3) is used as the initial estimate in the Regional component of the Delaware FEE Tool.

Testing. As the primary goal of this project is to evaluate the ability of an expert system to mimic human prospect evaluation, it is also necessary to provide the system with a database of common answers to each expert question at each location in the basin. This "answerbase" was generated using stored regional data.

The overall goal was the **Development of Soft Computing tools to automate and speed prospect evaluation**. To do this the project invested a large amount of time to **Collect Data.** This data can be subdivided into several categories based on how it was collected, and how it is used in the final realization of the expert system software which is designed to produce as an end result an **Evaluation of Risk associated with Prospect**. In subsequent paragraphs each of four major subsections will be reviewed and broken down into their major software development tasks. To accomplish this, the colored boxes in Fig. 4 are each expanded to give more details. Ultimately a list of programming tasks results from each section.

Answerbase

Both the FEE Tool and the model crisp system use a grid system where the Delaware Basin is divided up into 60478 units of 40 acres each. Each of these units is represented by its center point (gridpoint), the coordinates of which are provided in UTM feet and latitude and longitude. For any well or prospect location, the closest gridpoint is located.

The answer base is essentially a database where inputs to the knowledge base rules are computed and stored for each gridpoint in the system. For example, the first set of rules in the trap assessment (see knowledge base section) requires the distance from the prospect to the nearest producing well. The answer base contains these distances for each gridpoint, found by computing the distance between the gridpoint and 911 lower Brushy Canyon producing wells in the Delaware Basin and selecting the minimum. Therefore, when a user selects a location, the closest gridpoint is found and the distance to the nearest producing well and the associated initial estimate is retrieved. Other columns in the answer base include a dip angle between the gridpoint of interest and the nearest producing well, the results of a search for a sand pinchout at each gridpoint, the TOC at each gridpoint, the thickness of the porous sands and other such parameters.

Knowledge Base

The expert system is built on the guidelines of a knowledge base developed for the lower Brushy Canyon formation of the Delaware Basin. A knowledge base has been defined both as a "machine-readable resource for the dissemination of information, generally online, or with the capacity to be put online" (May, 2001) and as "a collection of facts, relations, procedures etc., which constitute the knowledge about a particular domain" (Hart, 1986, p. 173). The knowledge base described here is a collection of rules developed with the help of explorationists familiar with the formation.

Rules serve the purpose of codifying the knowledge and processes used in determining if a potential location is a good prospect for drilling for oil. For example, an explorationist might consider a location to be a good prospect because it is close to a producing well, but then modify that opinion if it is known that the porous sand thins at that location. The knowledge base captures this in a series of rules. All such questions asked by explorationists need to be included and this essentially represents the store of questions asked by explorationists when examining prospects in this play. Ultimately the system will be capable of assimilating new knowledge, though for this study it was hard coded to enable verification testing with the Lower Brushy Canyon (completed) and Devonian (in progress) in SE New Mexico. The flowchart in Fig. 5 expands the center two columns of boxes in Fig. 4 and addresses the development of the knowledge base. Given the completed knowledge base and user interface the inference engines can begin to process data and fire rules.

Interviews with knowledgeable experts gave three broad categories important to lower Brushy Canyon production, *Trap, Formation, and Regional* analyses. Each of these was broken down into a number of distinct sub-questions outlined below.

Trap Step 1 - Proximity Query. Proximity to production or oil shows is an important factor in determining drilling risk according to Delaware explorationists. This first question establishes the distance to the nearest producing well according to the FEE Tool database. If users have more recent information they can adjust this distance and therefore the weight of the initial Trap Estimate.

All answerbase data is related to nearest production, the user, however can modify the answer to represent distance to an oil show.

*Trap Step 2 - Dip Query***.** An important factor for migration and trapping is the dip between the prospect and the Producing well. If the prospect is down-dip from existing production it may have reduced quality compared to a prospect that lays up-dip of a producing well.

Dip is measured in degrees. Users need to be sure to use values in degrees if they enter their own estimate. It is also important to be sure that there are no intervening structural elements, which would negate the dip relationship between the two prospects. If there is no dip relationship the user can toggle the [unrelated structure] radio button in the user interface (see *User Interfac*e section).

Trap Step 3 - Pay Thickness. The FEE Tool has access to two porosity thickness maps for the Lower Brushy Canyon. Prospects deeper in the basin use a porosity greater than 10 % value as default, while prospects in the western margins of the basin use a 15% porosity thickness map by default. The value of porosity is treated differently in these two regions because of expert observations about the nature of thick sands in the two regions. A depth cutoff of 2000 ft sub sea elevation divides the western margin (15% cut-off) and the deep basin (10% cutoff).

The user can customize this line of inquiry by selecting a value that better represents a company value, for example if they normally use can use a 9 % cut-off the 10% toggle should be selected.

Trap Step 4 - Stratigraphic Trap. Stratigraphic traps do much to enhance a prospect. In order to test for stratigraphic traps the Expert System uses the answerbase to look up dip of the prospect location and seeks a thinning of the porosity thickness. There are three possible answers. **A pinchout or thinout exists**, **thickness variation up-dip in the area is insignificant**, and **thickness increases up-dip**. Radio buttons in the interface allow only one possibility to be selected.

The default button selected will vary depending on the location and availability of database answers. The user may customize this selection by simply selecting another radio button.

Trap Step 5 - Structural Strike Analysis. Structural trends are useful for defining fields or other groups of prospects. There is no answerbase value for this, however the user is prompted to examine a pop-up map of structure from the geologic database to see if such a trend exists. Alternatively the user's own map data can be used to make the decision.

*Trap Step 6 - Thickness Trend Analysis***.** The variations of thickness around the prospect can indicate consistency of reservoir quality, or identify anomalous thickness data. In this step the Expert System uses the answerbase to evaluate the average thickness at nearby prospects and reported the standard deviation.

Formation Step 1 - Distance to nearest high quality source rocks. There are strong indications that the lower Brushy Canyon is a self-sourced reservoir based on results of this project, therefore Total Organic Carbon (TOC) is a useful estimate of reservoir quality at a prospect. The Expert System queries the answerbase and reports whether the prospect is within a certain distance of rocks with TOC above a certain threshold, based on TOC analyses and mapping performed for this project.

The database is necessarily limited due to the expense of laboratory measurement of core samples and some generalization is required to map across a large region like the Delaware basin. If the user has information from a nearby well, they are prompted to enter that TOC value in % and the distance from the prospect to customize the data.

Formation Step 2 - Thermal maturity of source rocks. Our research has indicated that most of the lower Brushy Canyon is in the "oil prone", or "mixed" window based on PI measurements. The answerbase is necessarily limited due to the expense of laboratory measurement of core samples and some generalization is required to map across a large region like the Delaware basin.   If the user has information from a nearby well, they are prompted to select what type of maturity estimate was used (PI, TAI, Tmax, or Ro) and enter the value in the corresponding box in the interface.

Formation Step 3 - Migration Potential. The Expert system uses the answerbase to evaluate the potential for migration at each prospect by searching for high TOC rocks down-dip. This section is also customizable by the user.

Regional Step 1 - Initial production. The answerbase queries the map of predicted potential generated using an artificial neural network in an earlier phase of the project. This map only considers a few regional data types, and is used as a “first guess” for the ability of a prospect to generate oil.

If the user has another way of estimating production potential, such as an analog well, they are prompted to estimate the first year’s production and divide by 12, then enter the number in the appropriate box in the interface

Regional Step 2 - Proximity of better production. Whole drilling programs have been designed in the past based on proximity of production/good production and stepping out. The Expert System queries proximity information from the answerbase and provides an estimate of distance to nearest better predicted production in its overall analysis for this reason.

If the user knows of a closer well, or more up to date production data, they are prompted to customize the data by changing the numbers in the appropriate boxes.

Regional Step 3 - Uniformity of production. The Expert System approaches this question for two reasons. First, reservoir heterogeneity can be indirectly measured in this manner, and second, this may help to identify prospects that may be approaching the margins of a field.

The user can customize the answers based on direct knowledge, keeping in mind that the **small area** is nine 40 acre sites with your prospect in the center, and the **large area** is 49 40 acre sites centered on your prospect. Correct inputs include 1, 2, and 3+ standard deviations from the mean.

Regional Step 4 - Gross Thickness. Gross thickness is used by the Expert System differently depending upon if the prospect is in the **western margin** (defined as Sub Sea 2000 ft or shallower) or in the **central Basin**. Thick sands in the western margin can negatively impact a prospect's potential. The answerbase provides an estimate to the user.

If the user wishes to customize this section they can use a pull down menu to change from western margin, or central basin, and modify the gross Brushy Canyon thickness using their own estimate.

Regional Step 5 - Gross Structure. Structural placement can play a role in determining how well a prospect will perform. The Expert System does not have answerbase information for this, as it is subjective. Users can include structural information of this type if they can discern it from the regional map provided, or from their own maps.

Regional Step 6 - Gravity support of structure. Gravity data can be used to verify subtle structures. Users can examine the regional gravity map provided and determine if their structure is supported.

Regional Step 7 - Regional Adjustments. Prospects in the Western Margin of the basin have different characteristics than those in the Deep Basin. The Expert system uses a cut-off of sub sea depth less than 2000 ft to characterize Western Margin prospects and the answerbase provides users with the result, which may be customized.

Each of these lines of analysis is broken down into a number of specific one-line statements or rules. The manner in which these "expert opinions" are codified is addressed next, along with assigning values and weight to each component in the three major categories. Each category has a separate Expert System.

Scoring of rules

A key component to the project is to take the identified rules, and in some manner grade them, so that they have a weigh in the overall analysis similar to that which a human expert would use. In general the values used in each rule were assigned by interpreting the strength for each rule from the composite hierarchy provided by interviewing the group of experts.

There are many methods available to enhance or reduce the estimates provided by an individual rule, a common method being the *method of roots and powers*, a less common method being the *Fractional Shifting method,* and a method derived in-house called the *Sum of Flags Method*. Each is briefly summarized below.

Method of Roots and Powers. This method raises or squares the prospect value to enhance or degrade. This method initially used in our modeling. The way to enhance an estimate was to take roots of the numeric value normalized between zero and one. The cube root was used to strongly enhance the value, and the square root was used to moderately enhance the value. To reduce the estimate, it was raised to the second power and to strongly reduce, it was raised to the third power.

1) Adavantages – easy to compute.
2) Disadvantages – Order of operations is significant.

The essential problem with this method was that rules that fired late in the sequence had inherently more value than those that fired early, and it became quite tricky to order operations in a manner that was true to the expert knowledge.

Fractional Shifting method. This method slides the prospect toward 0 or 1 from the initial (or current) estimate by a scaled amount using an equation of the following form:

$$X_{new} = X + (1 - X)/n \quad n = 2,3,4\ldots.$$

1) Advantages – Fairly easy to compute, and can closely control the value of adjustments.
2) Disadvantages – Again, dependent on order of operations.

For problems that fire relatively few rules this method would be adequate. Our initial modeling however indicated that dozens, from a pool of hundreds of rules could apply to a prospect evaluation and order of operation needed to be insignificant.

Sum of Flags Method. This method has each rule assigned a numeric value, or flag, that is specific to its overall relative value to human experts. All flags are stored, and after all rules have fired for each sectional analysis, the flags were summed. A single root (if the sum was positive) or power (if the sum was negative) is then used to enhance or degrade the prospect based on each of the three major subsystems.

1) Advantages – Very easy to compute.
    a. Able to rapidly compute large numbers of flags.
    b. Independent of order of operations.
    c. Allows precise control over relative value of inputs.
2) Disadvantages – none found to present.

This in-house method was eventually used to model the crisp expert system, and was implemented in the fuzzy inference engine. The following section shows the summary of rules developed using the knowledgebase.

Brushy Canyon Specific Knowledge Base

Each major section, *Trap*, *Formation,* or *Regional* starts with an initial guess scaled between 0 and 1. After the initial value is assigned, a series of rules will be applied, and rules that fire, will have an appropriate flag value stored. At the end of each section of questions the overall evaluation for that section will calculated by applying the sum of the flags to the initial estimate. Flags are listed in parentheses at the end of each potentially modifying rule.

Trap Assessment. The initial value for trap assessment is assigned using the rules in Step 1: below. A graphical version of this can be viewed in Fig. 6.

Step 1: Evaluate Distance between prospect and nearest producing well **OR** oil show.

Available Data in Answerbase: Producing well data available to the year 2000, user can input more recent data:

- If distance to nearest producing well (d) > 5 miles, trap starting estimate (x)=0.05
- If 5280 ft < d ≤ 26400 ft (5 miles), x = 0.2
- If 2640 ft < d ≤ 5280 ft, x = 0.4
- If 1320 ft < d ≤ 2640 ft, x = 0.6
- If 0 ft < d ≤ 1320 ft, x = 0.8

OR

Distance between prospect and nearest oil show: If starting estimate is 0.05 and user provided oil show data exists the following initial rules may apply:

- Distance to oil show (d_s) > 2 miles, starting estimate (x) = 0.05
- 5280 ft < d_s ≤ 10560 ft (2 miles), x = 0.1
- 2640 ft < d_s ≤ 5280 ft, x = 0.2
- 1320 ft < d_s ≤ 2640 ft, x = 0.4
- 0 ft < d_s ≤ 1320 ft, x = 0.5

Step 2: Dip between prospect and nearest producing well, data has been calculated for all potential brushy canyon prospects and is available in the database. User input is allowed.

- If dip angle (α) > 2.75°, estimate enhanced (flag = 2)
- If 1.55° < α ≤ 2.75°, estimate slightly enhanced (flag = -1)
- If –0.85° < α ≤ 1.55°, estimate not changed (flag = 0)
- If –2.05° < α ≤ -0.85°, estimate slightly degraded (flag = -1)

- If $\alpha \leq -2.05°$, prospect estimate degraded (flag = -2)

Step3: Thickness of the Brushy Canyon sand at prospect (net sand 10% or greater porosity for central basin, net sand 15% or greater for western margin), The answerbase provides a response. User input is allowed.

Central basin (Depth of prospect = -2000 ft subsea or greater)

- If thickness (t) > 200, estimate enhanced (Flag =2)
- If $120 < t \leq 200$, estimate slightly enhanced (Flag = 1)
- If $20 < t \leq 120$, estimate not changed (Flag = 0)
- If $t \leq 20$, prospect estimate degraded (Flag = -1)

Basin margins (Depth of Prospect = -2000 ft subsea or less)

- If thickness (t) > 200 estimate not changed (Flag = 0)
- If $120 < t < 200$, estimate slightly enhanced (Flag = 1)
- If 20 < t 120, estimate slightly enhanced (Flag = 1)
- If $t \leq 20$ prospect not changed (Flag = 0)

Step 4: Sand pinchout in the vicinity of prospect, data has been calculated for each potential prospect and is provided by the answerbase or user input.

- If porous sand is less than 15 feet thick at the neighboring gridpoint that is the most updip, enhance estimate. (Flag = 2)
- If thickness at the neighboring gridpoint that is the most updip is larger than thickness at gridpoint, reduce estimate. (Flag = -1)
- If neither condition is met, estimate is not changed (Flag = 0)

Step 5: Structure in region of prospect, User may view pop-up map of structure, or may provide their own information.

- If prospect is on structural strike then enhance estimate (Flag = 1)
- Else (Flag = 0)

Step 6: Sand thickness trends in the vicinity of the prospect, User may view pop-up map of sand thickness, the answerbase will provide data for sand thickness trends.

Central basin (Depth of prospect = -2000 ft ss or greater) use 10% porosity. map.

Western margin (Depth of prospect = -2000 ft ss or less) uses 15% porosity map.

Large area (3 sections)

- If std of thickness (t) ≤ X then enhance prospect (Flag = 1)
- If std X ≤ Y then prospect not changed (Flag = 0)
- If std Y ≤ Z then prospect slightly degraded (Flag = -1)

Small area (1 section)

- If std of thickness (t) ≤ X then slightly enhance prospect (Flag = 1)
- If std X ≤ Y then prospect not changed (Flag = 0)
- If std Y ≤ Z then prospect degraded (Flag = -1)

Basin margins (Depth of prospect = -2000 ft ss or less) use 15% porosity map.

Large area (3 sections)

- If std of thickness (t) ≤ X then enhance prospect (Flag = 2)
- If std X ≤ Y then prospect not changed (Flag = 0)
- If std Y ≤ Z then prospect slightly degraded (Flag = -1)

Small area (1 section)

- If std of thickness (t) ≤ X then slightly enhance prospect (Flag = 1)
- If std X ≤ Y then prospect not changed (Flag = 0)
- If std Y ≤ Z then prospect degraded (Flag = -2)

Formation Assessment. Step 1, below outlines the initial criteria for valuation of a prospect based on formation characteristics.

Step 1: Are potential source rocks with TOC > 1.0% or 0.5% present within 5 miles of the prospect? Data is provided by the answerbase or user input:

Case: Total organic carbon proximal to prospect is high:

- If distance (d_T) to source rock (with TOC >1.0%)> 26400 ft (5 miles), source estimate (s) = 0.25
- If 10560 ft < d_T ≤ 5 miles, s = 0.5

- If 2640 ft < $d_T \leq$ 10560 ft, s = 0.6
- If 0 ft < $d_T \leq$ 2640 ft, s = 0.8

OR

Case: Total organic carbon proximal to prospect is moderate:

- If distance (d_T) to source rock (with TOC >0.5%)> 26400 ft (5 miles), source estimate (s) = 0.10
- If 10560 ft < $d_T \leq$ 5 miles, s = 0.3
- If 2640 ft < $d_T \leq$ 10560 ft, s = 0.4
- If 0 ft < $d_T \leq$ 2640 ft, s = 0.6

Step 2: Thermal maturity of the source rock was computed for each potential prospect location, and is provided by the answerbase in terms of PI, or user input for other estimators.

Oil Prone:

- TAI < 2.3 or (Flag = -1)
- PI < 0.1 or
- Tmax <430 – Immature, reduce prospect

- TAI 2.3 – 3.5 or (Flag = 2)
- PI 0.1 – 0.4 or
- Tmax 430 – 460 – Oil Window, enhance prospect

- TAI > 3.5 or (Flag =1)
- PI > 0.4 or
- Tmax > 460 – Gas Window, slightly enhance prospect

Gas Prone:

- Ro < 0.9 or (Flag = -1)
- TAI < 2.6 or
- PI < 0.1 – Biogenic gas only, slightly degrade prospect

- Ro > 0.9 or (Flag = 0)
- TAI >2.6 or
- PI > 0.1 – Thermal gas possible, prospect unchanged

Inert Kerogen:

- Ro < 2.5 or (Flag = -2)
- TAI < 4.2 – no alteration, prospect is degraded

- Ro > 2.5 or (Flag = 0)
- TAI > 4.2 – Severe alteration possible, prospect unchanged

Step 3: Migration – are source rocks (0.5% or 1.0% from initial estimate) favorably located for migration to the prospect?

Case: Up-dip sand pinch-out or thin-out.

- Self sourced (rocks interbedded at prospect) – greatly enhance (Flag = 3)
- Source rocks downdip of prospect 1360 to 10560 feet - moderately enhance prospect (Flag = 2)
- Source rocks downdip of prospect 10560 to 26400 feet – slightly enhance prospect (Flag = 1)
- Source rocks downdip > 26400 ft – prospect unchanged (Flag = 0)

Case: No up-dip sand pinch-out or thin-out.

- Self sourced (rocks interbedded at prospect) – enhance prospect (Flag = 2)
- Source rocks downdip of prospect 1360 to 10560 feet - slightly enhance prospect (Flag = 1)
- Source rocks downdip of prospect 10560 to 26400 feet – no enhancement to prospect Flag = 0)
- Source rocks downdip > 26400 ft – prospect degraded (Flag = -2)

Regional Assessment. The initial value is provided by the answerbase using the projected production map calculated for the project area (Fig. 3). This initial estimate is based on production potential estimate from Neural Network map which has a prediction for each potential site in the basin. Alternatively, users can provide their own estimate based on an analog well or other approach.

Step 1: Crisp Option (used for modeling the expert system)

- PBOPM < 500, z = 0.1
- 500 < PBOPM < 1500, z = 0.3
- 1500 < PBOPM < 2500, z = 0.5
- 2500 < PBOPM < 4000, z = 0.7
- PBOPM > 4000, z = 0.9

Step 2: distance to higher predicted production than is at the prospect. Answers are provided by the answerbase, or user input.

- Prospect within 10560 ft (2 miles) of much better predicted production (two or more ranks increased) – enhance prospect (Flag = 2)
- Prospect within 10560 ft (2 miles) of better production (1 rank increase) – slightly enhance prospect (Flag = 1)

IF Not, then

- Prospect within 21180 ft (4 miles) of much better predicted production (two or more ranks increased) – slightly enhance prospect (Flag = 1)
- Prospect within 21180 ft (4 miles) of better production (1 rank increase) – prospect not enhanced (Flag = 0)
- No better predictions within 21180 ft (4 miles) – prospect degraded (Flag = -2)

Step 3: uniformity of prediction is sampled for all potential prospects and is provided by the answerbase or user input.

Large area (forty-nine 40 acre sections)

- If std of predicted potential (pp) ≤ X then enhance prospect (Flag = 2)
- If std X ≤ Y then prospect not changed (Flag = 0)
- If std Y ≤ Z then prospect slightly degraded (Flag = -1)

Small area (seven 40 acre sections)

- If std of thickness (t) ≤ X then slightly enhance prospect (Flag = 1)
- If std X ≤ Y then prospect not changed (Flag = 0)
- If std Y ≤ Z then prospect degraded (Flag = -2)

Step 4: Gross Thickness – Net lower Brushy Canyon Interval has been computed and can be provided by the answerbase or user input.

Central basin (Depth of prospect = -2000 ft ss or greater)

- If thickness (t) > 200, estimate enhanced (Flag = 1)
- If 100 < t ≤ 200, estimate not changed (Flag = 0)
- If t ≤ 100, prospect estimate degraded (Flag = -1)

Basin margins (Depth of Prospect = -2000 ft ss or less)

- If thickness (t) > 200 estimate not changed (Flag = 0)

- If 100 < t < 200, estimate slightly enhanced (Flag = -1)
- If t < 100, estimate not enhanced (Flag =0)

Step 5: Gross structure – Is the prospect near a regional structural high? The answer is provided by user input after reviewing a supplied map.

- Prospect is located on flank or crest of structure – Enhance (Flag = 2
- Prospect located off of structure down-dip of regional strike – slightly enhance prospect (Flag =1)
- Prospect located off structure up-dip of regional strike – degrade (Flag = -2)

Step 6: Is the structure supported by gravity data? The answer is provided by user input after reviewing a supplied map.

- Local Bouguer anomaly supports existence of structure – enhance slightly (Flag =1)
- Local Bouguer anomaly doesn't support structure – degrade slightly Flag = -1)

Step 7: Regional adjustments. A final adjustment is made for basin location. The answerbase provides the answer based on prospect depth.

- If prospect is located in the central basin (depth > xxxx) then enhance prospect slightly (Flag = 1)
- If prospect is located in the north or east basin margins (range of gridpoints at shallower than xxxx depth) then do not adjust prospect Flag = 0)
- If prospect is located in the western margin (range of gridpoints with depth less than xxxx) then prospect is slightly degraded. (Flag = -1)

Initial application of the Expert System – The Crisp Model

To convert the ideas and rules from the knowledge base into numerical values, three initial estimates are developed as described above. A series of "flags" were then computed for each modification. The flags are used to indicate the direction (i.e. enhance or reduce) of the modification as well as the strength (i.e. strongly enhance or slightly enhance). For most cases in the model expert system, the set of flags to use for each set of rules is defined in the answer base. The flags are then applied to the modification method chosen to enhance or reduce the initial estimate.

The modification method used in both the crisp and fuzzy versions of the expert systems is the *sum of flags* method. Since the initial estimates are numbers between zero and one, to enhance them, a root is taken and to reduce them a power is taken, depending on the sign of the summed flags. For example, consider an initial trap estimate of 0.6, which would indicate that the prospect is between 1320 and 2640 ft from the nearest producing well. Suppose this location is enhanced with a flag of 2 because it is updip of the nearest producing well, is enhanced with a flag of 1 because the thickness of the porous sand at the point is significantly large, has neither an updip sand pinchout or a significant increase in thickness of porous sand updip (and thus a flag of 0), and finally is reduced with a flag of –1 due to inconsistency in the porous sand thickness in an area surrounding the location of the prospect. The flags are then 2, 1, 0 and –1, and the sum is 2. The final trap estimate is found as shown below.

$$trap\_estimate = \sqrt[2+1]{0.6} = 0.84$$

If the sum of the flags had been negative, indicating a reduction in the initial trap estimate, the following formula would be used, where n is the sum of the flags.

$$trap\_estimate = (initial\_estiamte)^{|n|+1}$$

With the same starting estimate of 0.6, if the sum of the flags is –2, the final trap estimate will be 0.22.

Once the final estimate has been calculated for the trap, formation and regional assessments, the next task is to combine these values into one numerical value and an associated linguistic output, such as very good, good, medium and poor. To combine the numerical values, various methods can be used to weigh each of the inputs. These methods include using fuzzy curves and weighted averaging techniques. For the model system, a weighted averaging method was used. Various weighing schemes were used and the resulting estimates for the entire system were mapped and analyzed. The weighing scheme chosen for the model system is 50% trap, 25% formation and 25% regional. This means that the final estimate is influenced the most by the trap estimate and by the formation and regional assessments equally.

Using the crisp model we were able to fine-tune the response of the system prior to applying formal fuzzy logic to more accurately simulate human thought process.

Numerical Results from Non-Numerical Rules – The Fuzzy Model.

Introduction. Fuzzy set theory is a mathematical approach for working with imprecise data and measurements. In exploration, relevant data such as porosity is sometimes approximated or interpolated from data collected at nearby wells. This example shows how principles of fuzzy set theory are used along with expert opinions to compute a value for a well's potential. The steps involved are: determining the input parameters and obtaining approximate numerical values, developing the linguistic values, fuzzifying the input parameters, firing the appropriate expert defined rules, and defuzzification of the output parameter. Each of these steps is discussed in detail in the example below.

Input parameters. In this example, two variables will be used as input parameters. The variables, total organic carbon (T) and porosity (Φ) are variables for which it is sometimes difficult to get a precise value, and measurements may have to be used from nearby wells. For each of these variables, linguistic values will be defined based on the following criteria:

T=Total Organic Carbon
T: ZERO if $0 \leq T < 0.5$
T: LOW if $0.5 \leq T < 1.0$
T: MEDIUM if $1.0 \leq T < 1.5$
T: HIGH if $1.5 \leq T$

Φ =Porosity (percentage)
Φ: ZERO if $0 \leq P < 5$
Φ: LOW if $5 \leq P < 10$
Φ: MEDIUM if $10 \leq P < 15$
Φ: HIGH if $15 \leq P$

For this example, 0.72 will be used as the best available value for TOC, and 13% will be used for the best available porosity. These two inputs will be used to develop a value for R, the prospect potential on a scale of 1 to 100.

Fuzzification of input parameters. The next step in the process is to "fuzzify" the input parameters. In order to do this, we will define fuzzy membership values for each of the sets; zero, low, medium and high, using a set diagram called a fuzzy membership curve that graphically defines each of the linguistic values. There are many curves that can be used in this process (and a suite was tested and reported later in this report) but the simplest is a trapezoidal graph, which we will use here for purposes of illustration. The process is repeated for each of the input parameters. Figure 7 illustrates the process for the variable T. The value of 0.72 is plotted on the x-axis, corresponding to the following values of membership in each of the linguistic sets:

T(Zero)=0
T(Low)=56
T(Medium)=44
T(High)=0

The process is repeated for the porosity (Fig. 7), using the best value of 13%.

Φ(Zero)=0
Φ(Low)=0
Φ(Medium)=40
Φ(High)=60

Rules. Once the input parameters have been fuzzified, the linguistic sets with non-zero membership can be used to fire a set of rules determined by an expert. The rules for this example are

1. If T is zero then R is zero
2. If Φ is zero then R is zero
3. If T is low and Φ is low or medium, then R is low
4. If T is low and Φ is high then R is medium
5. If T is medium and Φ is low then R is low
6. If T is medium and Φ is medium or high, then R is medium
7. If T is high and Φ is low or medium then R is medium
8. If T is high and Φ is high then R is high

We use the non-zero memberships from the fuzzification process to determine that rules 3, 4 and 6 are applicable.

Defuzzification. The next step in the process is to determine the strength of each of the fired rules using the set theory operators min for "and" and max for "or". Beginning with rule 3, we have T low with membership value of 56, Φ low with membership value of 0 and Φ medium with membership value of 40. So, Φ is low ***or*** medium with a membership value of 40. Rule 3 is then “fired” with a strength of 40, using min (56,40) to arrive at this value.

Following this process for the two other rules, rule 4 and 6, we have rule 4 fired with a strength of 56 and rule 6 fired with a strength of 44. Rule 4 and 6, however, both result in R being medium, so we combine the two using the max operator. In the final results, R is medium with strength of 56 and low with strength of 40.

To obtain a numerical value for R, on a scale of 1 to 100, we consider the median values of 10 for low, 50 for medium and 90 for high. Then using the strengths computed above, we calculate R as follows:

$R = 0.40*(10)+0.56*(50) = 32$

This is a simple example of how the fuzzy set theory approach can be used to determine potential. In a more complex example, multiple input parameters may be used, and the curves used to determine the memberships may be more complex than the trapezoidal curves used here. The basic ideas are the same, however, and were used to build the framework for computer codes that compute potential based on rules written by experts in the field.

Inference Engine

The inference engine is the software that applies the knowledge base to the problem of prospect evaluation, utilizing data in the answerbase, which can be database supplied, user supplied, or a mix of the two sources. For the Brushy Canyon FEE Tool the inference engine is in three parts, one for each major line of questioning, Trap, Formation, and Regional. Each inference engine uses primarily fuzzy rules, but is capable of utilizing crisp rules as well. Fuzzy membership sets were defined using expert opinion. The flowchart for software design of the inference engine can be found in Fig. 8.

Java Software Design – the User Interface

With all data in place and with interviews with Delaware experts completed, design of the FEE Tool was ready to be implemented at the start of this reporting period. As with any large software project it was necessary to break the study into small enough pieces for individual programmers to address in a timely manner. To assist in the organization of the software development it is helpful to examine the Project Design Chart in Fig. 4.

User observations about prospect. This section deals primarily with the user interface, and allowing the user to obtain and customize answers as required. Questions needed to be formalized and finalized, then a proper storage format determined, finally a questionnaire was created to compare our database to answers to the user's answers. The two boxes labeled **Graphical User Interface to record User observations**, and **Prospect Observations** are expanded in Figs. 9 and 10 as flowcharts outlining the required subtasks. A final list of tasks for this step for the **User Interface Design** box of Fig. 10 is listed below:

- **Design questionnaire template**
- **The GUI must have functional similarity to other group web pages**
- **The user enters a prospect location, which may require conversion From T-S-R to Lat-Lon**
  - **This is a non-trivial conversion and requires coding**
- **The questionnaire must display initial answers from databases where applicable**
  - **Requires communication with existing databases**
  - **Requires links to additional information such as on-line log images and production data**
- **The user must have the ability to insert and/or replace these answers with customized answers where applicable**
  - **Not all questions are necessarily answered, some users will want to consider fewer factors**
- **The result of the questionnaire is to form a modified answer base combining data derived and user modified answers**
  - **The answer table needs to be stored as a user and site specific database**

These key factors were integrated in a wholly Java design so that final versions of the software will be usable on any system.

Brushy Canyon FEE Tool

We have implemented a Brushy Canyon FEE Tool and released the software to consortium members for evaluation and testing purposes. This section, and associated figures describes every menu option available to users of the system.

Components of the Delaware Basin FEE Tool. The components of the FEE tool are the user interface, the knowledge base, the answer base and the inference engine. The user interface allows the user to input location information and information about the prospect and to see the results in various formats. The knowledge base contains a listing of the "rules" developed to model expert analysis. The answer base stores the inputs for the rules. These inputs are computed from either geological or production data from the region available to the FEE tool. User inputs may also be used as inputs to the knowledge base rules, either in place of answer base values or in addition to those values. Finally, the inference engine evaluates the rules and produces a measure of production potential. The inference engine uses a combination of crisp and fuzzy reasoning techniques.

Results. The result of the analysis is given as excellent, very good, average, below average, poor or bad. This evaluation is based on a numerical rank between 0 and 1, computed by the inference engine.

In addition to this result, other information available upon completion of the analysis includes a series of pie charts organized with these categories that show the type of production (very successful, successful, marginal or dry) at all wells with estimates in the chosen category. An example of the pie chart for the category "good" is shown in Fig. 11.

In addition to the pie charts, bar charts are available comparing the numerical final estimate at the location of interest to the final estimates for all points in the Delaware Basin and for all the locations of wells producing out of the lower Brushy Canyon.

Tables of the answer base data, the closest wells (geographically and closest in final estimate) and a table defining the ranges for the categories are also available.

System Requirements. The FEE tool is accessed from the http://ford.nmt.edu website. In order to use the FEE tool, the Java plug-in, available from Sun Microsystems, must be installed on your computer. In most cases, if the appropriate plug-in is not installed on your computer, you will be prompted to go to the Sun website to download it. You can download and install it directly by going to the following page:

`http://java.sun.com/products/plugin/autodl/jinstall-1_4_2-windows-i586.cab`

Security. To access the FEE tool and begin using it, a password is required. For information about registering and getting a password, you can go to the REACT homepage, or contact the principal investigator, Dr. Robert Balch, at (505) 835-5305 or balch@prrc.nmt.edu.

Security measures are in place to protect any proprietary data that you may want to use in your analysis. Any data that you use will not be stored in the project databases, and will only be accessible by you.

Getting Started–Creating a Project. To start using the FEE tool, begin at the gateway page, found at http://ford.nmt.edu.

The FEE tool can be accessed by clicking on the "Delaware Basin Fee tool" link. The REACT homepage also provides information about getting a user name and password to use the FEE tool. Three other tools are provided at the REACT homepage, a web-based data management system (WDMS), a fuzzy ranking tool (FuzzyRank) and a neural network tool (PredictOnline). More information about these tools can be found in the appendices.

Once you open the FEE tool, you will be prompted for your user name and password. Upon logging in, you will come to the main page of the user interface. Here you will find the quick start instructions and the menu shown in Fig. 12:

Begin by creating a new project as shown in Fig. 13 using the **Project** pull-down menu and selecting **New**. From this menu you may also open an existing project, close or delete a project or exit the program.

Location of Prospects. Once your new project is created, the next step is to input the location data for the prospect you are interested in. The form to input the location is located in the pull-down menu: **Input data**.

Location information can be entered in two ways, using UTM (feet) coordinates or latitude and longitude. There is also a tool to convert locations from township, section and range to latitude and longitude. Fig. 14 shows the location input pop-up and the T-R-S to Lat-Long converter which requires Township, Range, Section and Offset is shown in Fig. 15.

The offsets are measured (in feet) from the boundaries (north or south, and east or west) as shown in Fig. 16.

*Re-Opening an Existing Project***.** After exiting the program or closing the project, you may return to an existing project by clicking Open in the Project menu. If you then proceed to the trap, regional or formation choices in the Input Data menu, or the Inference or Results menus, you will see the data and results based on any changes you had made to the project. If you instead go to the Input Data menu and select Location, you can use the submit button to resubmit your location data. This has the effect of restoring all of the trap, regional and formation data to the original database values, as well as allowing any updates to the system to be applied.

Help Files. The quick start instructions are available to you on the FEE Tool front page. You can view them by using the scroll bar on the side of the window. Throughout the input screens there are numerous help buttons that provide additional information about each step.

Trap Assessment. In the trap assessment the potential prospect is evaluated based on the following criteria:

- Distance to nearest production or oil show
- Dip angle
- Thickness of the porous sand

- Existence of updip sand pinchouts
- Consistency of formation thickness
- Structure

Answer base values are available for most of the rules based on the criteria above, and these values can be reviewed and modified in the **Trap Info** option found in the **Input data** menu (Fig. 17). Some rules, such as rules relating to recent oil shows, require user input.

Reviewing and Entering Data. For most of the steps in the trap, formation and regional assessments, you will have the opportunity to review the values provided by the answer base and enter your own values. For each step, there is a Help button,  which provides information on the format to use if you input your own values. At the bottom of each screen is a Reset button, which resets the values to the default values from the database.

Distance. The initial trap estimate is based on the distance to the nearest producing well or oil show (Fig. 18). The answer base contains this distance computed using wells completed before March 2000. The wells used are successful wells that have some or all production from the lower Brushy Canyon formation. If you have information about a recent producing well or an oil show, you can input that value instead and it will be used to compute the initial trap estimate. In the first box, you will see the default information about your prospect from the database as shown in Fig. 19. The next box is for user input. Oil show is selected using the pull down menu and the **Reset** button resets the distance to the value in the first box as shown in Fig. 20

Dip Angle. The cutaway graph of the Delaware Basin in Fig. 21 describes how the dip angle is measured by the FEE tool. The depth is measured in relation to sea level and the dip is computed as an angle measured in degrees. A positive value for dip angle indicates that the prospect is updip in relationship to the nearest producing well or oil show. A positive value for depth indicates that the top of the formation at the prospect is above sea level.

If a new distance was provided in step 1, a new dip angle must be computed here. In order for the program to recalculate the dip value, you will need the depth (relative to sea level) to the top of the formation at the well the new distance is based on. To make this conversion, if necessary, subtract the depth reported on the log from the kelly bushing elevation. The depth (relative to sea level) to the formation top at the prospect you selected is provided in the second box of step 2. Once these three values are in place, you can use the "Recalculate Dip" button to compute the new dip angle. The program computes the dip angle as follows:

$$\alpha = \tan^{-1}\left(\frac{sselev_p - sselev_w}{d_w}\right)$$

α= Dip angle (measured in degrees)

$sselev_p$= subsea elevation (depth relative to sea level) at prospect from step 2, box 2

$sselev_w$ = subsea elevation at nearest producing well or oil show

d_w= user supplied distance to nearest producing well or oil show (as provided in the new distance box in step 1).

Porosity Thickness. Step 3 (Fig. 22) involves the thickness (in feet) of the porous sand in the formation at your prospect. There are two possible database provided values for this thickness, based on a 10% porosity thickness or a 15% porosity thickness. The FEE tool selects a value for thickness based on the location of your prospect and the depth (subsea elevation) of the top of the formation. Locations in the northwest margin of the basin use the 10% porosity thickness, while the rest of the basin uses the 15% porosity map.

The user can look at the recommended thickness map by clicking on the **10% (or 15%) Average Porosity**. To navigate the map, use your mouse to find where your prospect is indicated on the map. The left mouse button will zoom in to a location, and the right mouse button will zoom out. To exit the map, just close the window. An example of the 10% porosity map is shown in Fig. 23. To enter your own value for the thickness of the porous sands, use the scroll menu (Fig. 24) to select the appropriate porosity map to use. You might base this on the location of your prospect in the basin, or on the nearest value to a company cut-off porosity. Once the distance, dip angle and porosity thickness values have been entered, proceed to the remainder of the trap assessment input by clicking the **Next** button.

Stratigraphic Trap Search. The FEE tool searches the area around the prospect location looking for an updip thinning (or widening) of the formation, with the result of the search shown in step 4 (Fig. 25). An updip thinning, or sand pinchout, is considered to enhance the prospect's potential. If more information is available, you may change this input by clicking on the button in front of the desired selection. You also have the option of not including this in the analysis.

Structural Strike Analysis. The fifth step allows you to examine a map of the structure by clicking on the link (Fig. 26). A section of the structure map is shown below. The structure map (Fig. 27) functions in the same way as the porosity thickness map described in step 3 (left mouse button zooms in, right mouse button zooms out). After examining that map (or your own structure map of the region), if the prospect is on structural strike, select the **Yes** button. You may also choose to omit this section by leaving the default selection (**Unable to Verify/Don't Use in Analysis**).

Thickness Trends Analysis. The final step to input the data for the trap assessment is the thickness trend analysis step. This step evaluates a mean and a standard deviation of the relevant thickness measurements for a region around your prospect. This provides a measure of formation consistency. At this step (Fig. 28), you again have the opportunity to view the porosity thickness map from step 3, by clicking on the **average porosity thickness** link.

The small area (nine "40-acre" regions including the prospect in the center) is created by stepping out one step (1320 ft) in each direction, is shown in Fig. 29. The large area is defined by stepping out three steps in each direction. It consists of 49 "40-acre" regions. For the small area, the mean thickness and standard deviation of the thickness are found by using the measures of thickness at the nine regions, and for the large area, 49 values are used in the computations. These are then compared to the parameters for the whole region to determine if the thickness varies significantly more or less at your location than at other locations.

Once this data has been reviewed, the input for the trap assessment is complete. At this point, you may use the previous button to review the inputs for steps 1 through 3, or use the **submit** button to exit this form. You may then continue with the Formation Assessment, discussed in chapter 3, or look at the preliminary results from the Trap Assessment before moving on.

Output from the Trap Assessment. The FEE Tool uses the inference engine to compute a numerical value (between 0 and 1) and an associated linguistic value for each of the three branches of the system. You may view this result from the trap assessment by going to the **Inference** pull-down menu (Fig. 30) and selecting **Trap Inference**. At this point, you will be able to see both the numerical value and the associated linguistic value (very bad, bad, average, good, very good, etc.). These values are based solely on the trap assessment. The final output will include the regional and formation assessments as well.

Formation Assessment. The formation assessment is where the potential location is evaluated based on factors relating to the origin and migration of petroleum. The criteria used in this assessment includes:

- Total organic carbon at prospect location
- Thermal maturity
- Distance to high quality downdip source rock

The database has values available for TOC and PI, the production index (also called the transformation ratio). The user may also provide values for T_{max}, R_o or TAI, other measures of thermal maturity. T_{max} is the temperature at which hydrocarbons are expelled from kerogen, as seen during pyrolysis, R_o is the degree of reflectivity, measured by a reflecting-light microscope and TAI is the five-point thermal alteration index.

Reviewing and Entering Data. To begin reviewing and entering data for the formation assessment by returning to the **Input data** option and selecting **Formation info** as in Fig. 31. As with the trap assessment, you will have the opportunity to review the data available in the answer base for your prospect and add to or change the data. The **reset** button is available at the bottom of the screen to reset the data back to the database defaults.

Total Organic Carbon. The initial estimate in the formation assessment is a function of the percentage of total organic carbon (TOC) at the location of the prospect. This value is reported from the answer base in step 1 (Fig 32). As in previous steps, you may modify this value by simply replacing it with a new value.

Thermal Maturity of Source Rock. In this step (Fig. 33), the value of PI (production index) is shown. You may use this value of PI, or replace it with your own. Instead of PI, you may also select a different measure of thermal maturity. (T_{max}, R_o or TAI). Use the radio button to select which measure you wish to use, and enter the appropriate value.

Distance to Down-Dip Source Rock. In this step, the FEE tool searches the region to find the nearest down-dip source rock (Fig. 34). For this analysis, a down-dip source rock location is defined as a location with a subsea elevation lower than the prospect's subsea elevation and a TOC value of at least 1.25%. If the TOC value shown in the first step is already greater than TOC (as is often the case, as it is believed that this is a self-sourced play), then a distance of 0 is returned here. This step also considers the existence of an updip pinchout, a place in the immediate vicinity of the prospect where the formation thins. The existence of a sand pinchout is also part of the Trap Assessment, and the value from the answer base that was shown in step four of the Trap Assessment (Stratigraphic Trap Search) is reported here.

Output from the Formation Assessment. It is possible at this point to see how your prospect scores based on the formation assessment alone. As with the trap assessment, you will find a numerical score and a linguistic value based on the Formation Assessment by going to the **Inference** menu and selecting **Formation Inference** (Fig. 30). Fig. 35 shows an example of formation analysis results. The numerical score is always a value between 0 and 1. (This is the case for all three assessments)

After the formation assessment is completed and you view the results, the final assessment is the regional assessment.

Regional Assessment. The regional assessment focuses on the predicted production at your location. Production is predicted for each location using an artificial neural network (Predict Online – developed for this project). This assessment uses the following criteria:

- Predicted production at the location
- Distance to higher predicted production
- Consistency of predicted production
- Location relative to the margins of the basin
- Thickness of the porous sand
- Structure
- Gravity

Reviewing and Entering Data. As in the previous assessments, the user can review and/or modify the data that the inference engine uses to make computations for the regional assessment. As with the trap assessment, the regional assessment information page consists of two screens. Use the **Next** and **Previous** buttons to move from one to the other, and the **Reset** button at the bottom of each screen if you wish to restore the database formation data.

Initial Production - Predicted Barrels of Oil per Month (PBOPM). The first step of the regional assessment involves the initial production as predicted by the neural network. This value is shown in Fig. 36. You may replace this value using a value of your own, based on any method you use to estimate production potential, such as an analog well.

Proximity of Better Predicted Production. The next step uses the predicted production map (generated by the neural network) to search for the closest area with significantly higher predicted production. As with the other steps, you may use your own values here in place of the values shown. An example is shown in Fig. 37.

Uniformity of Predicted Production. This step is similar to the thickness trends analysis in the trap assessment and is illustrated in Fig 38. In this step, for each prospect, a small and large area surrounding the prospect (using the same definitions for small and large areas as in step 6 of the trap assessment) is used to calculate a mean and a standard deviation. For instance, the small area mean and standard deviation are found using the nine values of predicted production for the prospect and the eight gridpoints around it.

Net Porous Thickness. The next step involves the net thickness of the porous sands at the prospect location. Based on the location of your prospect (margin or central basin) the FEE tool uses either a 15% porosity thickness value or a 10% porosity thickness value (Fig 39). Once this step is complete, click on next to finish the Regional Assessment.

Structure Map. The next step involves observing a structure map (Fig. 40). This map is available by clicking on the **Structure Map** button (Fig 40). This maps function in the same way as other maps connected with the FEE Tool. Use the mouse to maneuver around the map, the left mouse button to zoom in and the right mouse button to zoom out. To exit the map, simply close the window.

Gravity Map. The gravity map (Fig 41) is accessed by clicking on the **Regional Gravity Map** button in Fig. 40. This map can be used to determine if the gravity data supports the structure.

Regional Adjustments. The final step involves a regional adjustment (Fig. 42). This information has been used earlier in the Trap Assessment and is also considered here, as it has been noted that there are different characteristics on the northwestern margin of the basin. The FEE Tool uses the depth of the formation top to differentiate between the margin and the central (or deep) using a cutoff value of –2000 ft subsea elevation.

This finishes the data entry. Use the **Previous** button to review the first screen of the Regional Assessment input, the **Reset** button on the bottom of the screen to reset any changed values on this screen to the database defaults, or the **Submit** button to enter this data.

Output from the Regional Assessment. You may now look at an output from just the Regional Assessment that consists of a numerical and a linguistic variable. As in the other cases, go to the **Inference** menu (Fig. 30) and click on **Regional**. It is possible to view this result (as well as the trap and formation analysis results) prior to reviewing and modifying the data. To do that, simply go to the Inference menu prior to inputting data. This will give you a value based on the database information alone, which can be used to compare to the value after you have modified some of the inputs (Fig. 43).

Inference Results. The inference menu (Fig. 30) provides the numerical results of the computations for the Trap Assessment, Formation Assessment, Regional Assessment and the overall result. The numbers provided in each case are values between 0 and 1, with values close to one indicating a high potential for production. Along with the numerical output, a linguistic variable is provided. The trap, formation and regional values can be obtained upon completion of these steps and have been discussed briefly already. The general (or overall) value is a weighted average of these three values and is shown in Figure 44.

Results Menu. The **Results** menu (Fig. 45) gives you the options of viewing a summary, a series of pie charts, a series of bar charts and various tables. You can also use this menu to download your results to your computer.

Results – Summary. **(**Fig. 46) is an example of a summary page. The summary page provides a final linguistic variable that describes your prospect based on the data from the database and the values you supplied. The summary page also links to the other Results options and to the WDMS and ONGARD, where you can review more information on similar wells.

Results - Pie Charts. The pie charts provided for review look at the success of completed wells with estimates that fall in one of the categories described by the linguistic variables. You can use this pie chart menu by selecting the pie chart that matches the output from the FEE Tool. For example, in the case above, the output is "Very Good". Selecting this option in Fig. 47 brings up the pie chart in Fig. 48. This chart shows the relative production levels for completed wells that were evaluated using the FEE Tool to have "Very Good" potential. For comparison, you may view similar pie charts for other outputs.

Results - Bar Charts. There are two bar charts available. The bar chart in Fig. 49 shows your numerical output (found in Inference - General) in relation to the numerical outputs for the entire system. The bar chart in Fig. 50 shows your numerical output in relation to the numerical outputs for all the wells in the basin producing out of the Lower Brushy Canyon.

Results – Tables. The table menu consists of three tables to help you evaluate your prospect. The available tables are shown in the table menu in Fig. 51. The first two tables provide other wells to compare your prospect to. The first table finds the nearest 10 wells relative to the location of your prospect. The second table finds the 10 wells with FEE Tool estimates closest to the estimate for your prospect. Each of these tables provides the API number for all of the wells it lists as well as oil production data.

The last table provides a summary of the information in the database about your location. This includes the information that has been the default values shown as you have input your data as well as any changes you have made.

Analysis of the Working Brushy Canyon FEE Tool

Data. The FEE tool was used to generate a set of estimates for all 60478 points in the Delaware Basin region. Relevant subsets were also identified and their estimates were evaluated. These subsets include locations with "post-cutoff" wells or wells that were recently completed and not used in trap assessment computations, "pre-cutoff" wells that were used to compute distance to production and unsuccessful wells.

FEE Tool Summary Statistics. The following tables show the descriptive statistics for the estimates generated for the entire region using the FEE Tool. Table 1 gives the parameters, and table 2 provides the five number summary used to generate the boxplots.

Table 1: Parameters of the full set of FEE Tool estimates

Parameters	
Mean	0.476
TrMean	0.473
Standard Deviation	0.124
Variance	0.015

Table 2: Five-number summary of the full set of FEE Tool estimates

Five-number summary	
Min	0.200
Q1	0.387
Median	0.461
Q3	0.562
Max	0.895

Results. The three subsets described above were used for preliminary testing of the performance of the expert system. The values of the mean estimates of each of these sets are encouraging. Recall that for the overall system, the mean is 0.476. For the 911 "pre-cutoff" well set, it was expected that the mean would be significantly higher as these wells were used to produce initial estimates in the trap assessment. The mean estimate for these wells was 0.775. For the most important set, the 89 "post-cutoff" well set, the mean was 0.673, which is significantly higher than the system mean, indicating success at locating potential well sites. Finally, the mean estimate for the set of 75 unsuccessful wells was 0.537. This is a positive outcome, as it is both significantly larger than the system mean, indicating that the expert system performed like the human experts who originally selected these sites, and significantly smaller than the means of the producing well sets, indicating that the expert system shows potential at reducing the number of dry holes. A boxplot of the entire system and the three subsets is shown in figure 52. This graph also indicates the estimate value of 0.65, a preliminary cutoff estimate. Figure 53 shows a histogram of the estimates for the entire system and the producing well estimates, also indicating the 0.65 value.

Geology

During the past project year, work has progressed on geologic data acquisition and analysis of the Siluro-Devonian carbonates. Work progressed on acquiring and mapping structural and stratigraphic data related to Siluro- Devonian reservoirs, traps and source rocks. During the past year, the following personnel have been employed on the geology portion of this project:

Ron Broadhead - *New Mexico Bureau of Geology and Mineral Resources*
Destini Baldonado – *Graduate student in Earth and Environmental Sciences*
Ashley Hall – *Undergraduate student in Earth and Environmental Sciences*
Lynsey Rutherford – *Undergraduate student assistant*.

Geology of Siluro-Devonian Carbonates

Devonian and Silurian carbonates produce oil and associated gas from numerous oil and gas fields in southeastern New Mexico (Fig. 54). The 122 Siluro-Devonian fields in southeastern New Mexico had produced a cumulative 443 MMBO by 1995 (Broadhead and Speer, 1995), 10 percent of the oil produced from southeastern New Mexico. Production is from a number of zones within the Silurian and Devonian sections (Figure 55). Most of the production is obtained from reservoirs of Silurian age. Recent biostratigraphic work (Barrick et al., 1993) indicates that most of the Siluro-Devonian carbonate section in southeastern New Mexico is Silurian in age and that Devonian carbonates are restricted to a relatively thin section (less than 200 ft thick) in southeastern Lea County (Barrick et al., 1993; Ruppel and Holtz, 1994). Depth to Siluro-Devonian carbonate reservoirs varies from less than 7000 ft in the northern part of the Permian basin in Chaves County to more than 15,000 ft in the southern parts of Lea and Eddy Counties.

Traps in the Siluro-Devonian carbonate section are largely structural (Speer, 1993; Hanagan, 2002). Fields discovered to data are present on structures (Figs. 56, 57) that can be identified with the help of 3-D seismic data (Hanagan, 2002). Not all drilled structures are filled with hydrocarbons as some Siluro-Devonian structures are filled with water. Other risk factors include the sealing capacity of faults, migration pathways, and the presence or absence of source rocks. Many structures in Chaves County are only partially filled with hydrocarbons (Hanagan, 2002). This suggests that either proximity to source rocks along migration pathways or the sealing capacity of either roof rocks or faults have significant impact on field location and size.

The Woodford Shale (Upper Devonian) is thought to be the predominant hydrocarbon source rock for Siluro-Devonian reservoirs (Hills, 1984; Ruppel and Holtz, 1994). The Woodford directly overlies the Siluro-Devonian carbonate section in most of southeastern New Mexico. Most productive facies lie directly underneath the Woodford and are separated from the Woodford by a regional unconformity that truncates underlying strata in a northward direction (Canter et al., 1992; Fig. 58).

Geologic data acquisition

Siluro-Devonian carbonates. Geologic data acquisition continued on Siluro-Devonian carbonates. A database of 465 wells that have penetrated the Siluro-Devonian carbonate section was constructed. Geologic and production attributes were obtained for each well include:

1. Depth to top of Siluro-Devonian carbonate section (subsea depth calculated);
2. Location in terms of section-township-range (latitude and longitude calculated via a digital land grid);
3. Identification of productive zones within Siluro-Devonian section;
4. Depth to productive zones within Siluro-Devonian carbonate section;
5. Depth of production below top of Siluro-Devonian carbonates;
6. Unsuccessful tests of Siluro-Devonian carbonates in wells that specifically tested the Siluro-Devonian section through either casing perforations or drill stem tests but did not obtain production.

Attempts to correlate stratigraphic subdivisions of the Wristen and Thirtyone Formations throughout southeastern New Mexico have not been successful.

In addition, an extensive production database was compiled on reservoirs productive from Siluro-Devonian carbonate reservoirs. These data include, for each reservoir:

1. cumulative oil production;
2. cumulative gas production;
3. cumulative water production;
4. depth to production;
5. initial reservoir pressure (where available –63 reservoirs; pressure gradiant calculated)
6. oil gravity (where available – 70 reservoirs)
7. published permeability data (where available – 27 reservoirs; the usefulness of these data is suspect because of differences in the way permeability may be calculated for each reservoir).

From the production data, lifetime gas-oil-ratios (GOR) and oil-water ratios (OWR) were calculated for each reservoir

Woodford Shale. As discussed previously, the Woodford Shale is considered to be the primary source rock for oil accumulated within Siluro-Devonian carbonate reservoirs. As a result, petroleum source rock data were acquired on the Woodford in 25 wells throughout southeastern New Mexico. Source rock analyses were performed on drill cuttings reposted in the Subsurface Library at the New Mexico Bureau of Geology and Mineral Resources. Well were selected for data analysis to ensure an even spatial distribution throughout the Permian Basin in southeast New Mexico as well as to ensure representation of all depth and tectonic/structural domains in the source rock database. Cuttings selected for analysis were carefully prepared to exclude non-Woodford lithologies that may have caved from shallower, younger formations.

Source rock data acquired for each sample include Total Organic Carbon (TOC) as a weight percentage of the rock and Rock-Eval Pyrolysis measurements that yield several parameters related to thermal maturation and oil-source quality. In addition, analyses of visual kerogen that relate to thermal maturity and oil-source quality were acquired on 13 samples so that the results from the Rock-Eval pyrolysis could be evaluated and confirmed.

In addition, the Woodford Shale was correlated on logs in 538 wells throughout southeastern New Mexico. The top and base of the Woodford were calculated. If the Woodford was not present in the well due to either nondeposition or erosion, then the stratal affinity of the formation that directly overlies the Siluro-Devonian section was correlated and identified. The thickness of the Woodford is important for both its role as a source rock and as the seal to most of the oil accumulations on Siluro-Devonian reservoirs. Where the Woodford is present in substantive thickness it may be a source rock, providing it contains sufficient oil-prone organic matter and is sufficiently mature.

The Woodford also acts as a seal for Siluro-Devonian reservoirs where it is present. If post-Woodford faulting has affected a trap, then the Woodford may act as a seal only if the thickness of the Woodford exceeds the vertical displacement along the faults. Otherwise, oil may leak across the fault into younger strata juxtaposed across the fault plane unless those strata are sufficiently impermeable to prevent oil entry. Therefore, areas with thick Woodford should correlate with traps that are filled with hydrocarbons.

Results

Geologic data were used to construct a structure contour map on the top of the Siluro-Devonian carbonate section throughout southeastern New Mexico (Fig. 59). At a contour interval of 500 ft, the map accurately portrays regional structures but does not show lower-amplitude structures that form oil traps in the Siluro-Devonian carbonates. Many of these smaller structures have amplitudes less than 100 ft (Hanagan, 2002). Localized contour maps with contour intervals of 50 ft or less may indicate these low amplitude structures.

A map was also constructed that shows wells that are productive from the Siluro-Devonian carbonates and wells that have unsuccessfully tested the Siluro-Devonian, either through drill stem tests or casing perforations (Fig. 60). The data used in the construction of this map will be essential in determining the presence or absence of oil in the fuzzy expert system.

Maps were also constructed that show the locations of oil reservoirs classified by production. One map shows the reservoirs classed by cumulative oil production (Fig. 61). A second map shows reservoirs classed by their gas-oil ratio (GOR) at cumulative production (Fig. 62). A third map shows reservoirs classed by their oil-water ratio (OWR) at cumulative production (Fig. 63).

Yet another map was constructed that indicates thickness of the Woodford Shale (Fig. 64). This map shows the Woodford has been removed by erosion from the highest parts of the Central Basin Platform in Lea County in the southeastern part of the study area. This erosion took place during the latest Pennsylvanian when the Central Basin Platform was uplifted and structures associated with traps were formed. The map also shows a gradual decrease in thickness of the Woodford to the north and northeast where it pinches out in Chaves and Roosevelt Counties. In the southeast, however, the map indicates thickness of the Woodford may locally exceed 600 ft in some wells. These excess thicknesses are apparent thickness caused by wells that intersect steeply dipping Woodford on the flanks of structures. Examination of dipmeter logs available in the area indicates that true thickness of the Woodford probably does not exceed 300 ft in this area. Therefore, a second Woodford isopach map was prepared that eliminated all wells with measured Woodford thickness exceeding 300 ft (Fig. 65). Although dipmeter logs are available for only a few wells, this map shows consistent trends of Woodford thickness and eliminates local irregularities of anomalously thick Woodford that are probably caused by steep dips. This map, referred to as the *Woodford Isopach (pseudo-corrected thickness) map*, indicates that the Woodford thins to a regional pinchout in the north and northwest and attains a maximum depositional thickness of just under 300 ft in the southeast. In the eastern part of the project area just south of Hobbs, the map indicates removal of Woodford strata by erosion on the Central Basin Platform. The map indicates that the Woodford is less than 50 ft thick along an extensive band in the northwest part of the area; if structures in the area are penetrated by post-Woodford faults that exceed 50 ft of vertical offset, then the seals in this area may have been breached by faults unless the overlying Mississippian section is shale rich.

The supercrop map of the Siluro-Devonian carbonate section (Fig. 66) shows the stratigraphic units that immediately overlie the Siluro-Devonian carbonate section. This type of map has also been referred to as a “worms-eye map” because it depicts the geology on the top of a stratal unit that would be seen by a worm looking upward through the earth. Throughout most of the project area, Siluro-Devonian strata are overlain by Woodford Shale. However, to the north and northwest, the Siluro-Devonian carbonates are successively overstepped by Mississippian, Pennsylvanian, and Permian strata. The Siluro-Devonian carbonates are also overlain Permian strata on the highest parts of the Central basin platform, where pre-Permian units have been removed by erosion. This map indicates the stratal unit that will act as the seal for reservoirs in Siluro-Devonian strata at any given place on the map.

The source rock data were used to construct maps of source rock parameters for the Woodford Shale. The map of Total Organic Carbon (TOC) content in the Woodford indicates a general and regular increase in TOC toward the southeast (Fig. 67). Therefore, without considering other source rock parameters, the source quality of the Woodford increases to the southeast. Qualitative source quality based on TOC content is given in Table 3. Based on TOC content, the Woodford has good to very good source quality everywhere it is present in southeast New Mexico.

Table 3. Generation potential of petroleum source rocks based on TOC content. From Jarvie (1991).

Generation potential	TOC in shales (weight percent)	TOC in carbonates (weight percent)
Poor	0.0 - 0.5	0.0 - 0.2
Fair	0.5 - 1.0	0.2 - 0.5
Good	1.0 - 2.0	0.5 - 1.0
Very good	2.0 - 5.0	1.0 - 2.0
Excellent	> 5.0	> 2.0

Multiplying TOC by thickness of the source rock will result in a parameter that is more reflective of the generative potential of the source rock than either TOC or source rock thickness alone. This parameter (called ***TOC ft*** in this project) is reflective of the relative total quantity of organic matter available for oil and gas generation. Because both Woodford thickness and organic content increase to the southeast, the parameter TOC ft also increases, but the effects of increasing thickness and organic content compound each other so that the generative potential of the Woodford increases at a greater rate toward the southeast than either thickness or TOC do separately (Fig. 68).

Thermal maturation of organic matter in the source rock within a source rock is essential to evaluate when considering oil and generation. Rocks that are thermally immature will have generated little, if any, hydrocarbons. Some biogenic generation of oil and gas is possible in thermally immature source rocks. Thermally mature source rocks will have generated oil and associated gas (Fig. 69). For this project, Rock-Eval pyrolysis was used to obtain most maturation parameters. The maturation parameters most often obtained from the Rock-Eval method are TMAX, or temperature attained at the height of the S_2 peak (Fig. 70) and the Productivity Index (PI) which is the ratio of the Rock-Eval S_1 peak to the sum of the S_1 and S_2 peaks. In general, TMAX and PI increase with maturation (Table 4). When TMAX was plotted against PI for the analyses used in this project (Fig. 71), these two parameters were found to be in disagreement.

The Thermal Alteration Index (TAI) is a third maturation parameter was obtained for 13 samples in this study. TAI is derived from the color of kerogen in transmitted light, which changes from yellow to orange to brown to black with increasing thermal maturity of the kerogen. Standardized color charts are used to quantify this color and a TAI scale of 1 (immature – yellow kerogen) to 5 (overmature – black kerogen). It is generally recommended that maturation parameters obtained from Rock-Eval pyrolysis be conformed with either TAI or vitrinite reflectance (Peters, 1986). It was found that most

Table 4. Correlation of maturation parameters with zones of hydrocarbon production. Based on Geochem Laboratories, Inc. (1980), Sentfle and Landis (1991), Peters (1986), and Hunt (1996).

Maturation level (products generated)	**Visual kerogen Thermal Alteration Index (TAI)**	**Rock-Eval Productivity Index (PI)**	**Rock-Eval TMAX (^oC)**
Immature (biogenic gas)	1.0 - 1.7		
Moderately immature (biogenic gas and immature oil)	1.8 - 2.1	< 0.1	<435
Moderately mature (immature heavy oil)	2.2 - 2.5		
Mature (mature oil, wet gas)	2.6 - 3.5	0.1-0.4	435 - 470
Very mature (condensate, wet gas, petrogenic dry gas)	3.6 - 4.1	> 0.1	
Severely altered (petrogenic dry gas)	4.2 - 4.9		>470
Metamorphosed	5.0		

kerogen populations in the Woodford lack a vitrinite component, so TAI was used. When TAI was plotted against both TMAX and PI (Figs. 72,73), it was found that TAI supports the Rock-Eval PI parameter and not the TMAX parameter. Therefore, PI was used as a maturation parameter for the Woodford in this project.

The reason for TMAX decreasing with increasing maturation is that the programs (the heating curves generated during the Rock-Eval analyses) of the Woodford indicate a bimodal S_2 peak for the Woodford (Fig. 74). The first peak is probably caused by volatilization of heavy hydrocarbons already generated and present within the Woodford shales (see Peters, 1986). The second peak is caused by generation of hydrocarbons from the kerogen in the source rock and can be considered to be the real S_2 peak. The Rock-Eval instrument equates the temperature at the height of the first S_2 peak with TMAX when the temperature at the height of the second S_2 peak is the valid TMAX. Therefore, TMAX values reported from the Rock-Eval analyses are not a valid measurement of maturation for the Woodford Shale in southeast New Mexico.

A map of the Productivity Index (PI) indicates that the Woodford is thermally mature everywhere it was assessed in southeastern New Mexico. Maturation increases to the south. The Woodford source rock is overmature and is in the gas and condensate window in large portions of the southernmost part of the project area. When the Woodford PI is superimposed in Woodford structure (Fig. 75), a general correlation between thermal maturity and burial depth is apparent, with the overmature areas generally occurring in the deepest parts of the basin. However, this correlation is not exact and the most mature regions are located somewhat updip and to the west of the deepest parts of the basin. The same trend was seen when assessing Brushy Canyon source rocks in the earlier phase of this project (Justman and Broadhead, 2000). It is apparent that paleogeothermal gradients must have been higher to the west and resulted in higher thermal maturation in the western, slightly shallower parts of the basin. When the GOR of Siluro-Devonian reservoirs is overlain on structure (Fig. 76), it is found that the reservoirs with the most gassy reservoirs are located in the deepest, most mature parts of the basin and that GOR values decrease regularly toward shallower depths. The shallowest reservoirs on the Northwest Shelf are more gassy, however, perhaps either as a function of migration of gas in an updip direction or as a function of a change to gas-prone kerogen suites in a northwesterly direction.

Current ongoing work

Geologic data acquisition is still ongoing. Work is currently progressing on acquiring additional stratigraphic data. These data include the depth to the top of the Fusselman Formation (Silurian) in wells across the basin. The depth to the top of the Fusselman will allow us to calculate the thickness of the post-Fusselman Siluro-Devonian carbonate section (combined Wristen and Thirtyone Formations). Data are also being acquired on the depth to the top of the Abo Formation (Permian) and depth to the top of the Mississippian limestones in wells throughout the basin. This additional stratigraphic information will allow for the detection and mapping of paleostructure, which has proven to be very useful in exploration for traps in Siluro-Devonian carbonates (Hanagan, 2002).

Experimental

There are no experiments associated with this project.

Technology Transfer

During this six-month period (April 2003–September 2003) the following three presentations were made to disseminate the results of the project:

1. Balch, R. S. Project update at NPTO office, Tulsa Oklahoma to a mixed group of DOE project managers and members of the Tulsa Geological Society, August 7th, 2003.
2. Balch, R. S., "Risk Reduction with a Fuzzy Expert Exploration" Tool West Texas Geological Society Lunch Talk, September 9, 2003 Midland
3. Balch, R. S., Schrader, S., and Cather, M. "Delaware Basin Fuzzy Expert Exploration (FEE) Tool", Workshop, Roswell, NM, August 27, 2003.

The focus of the technology transfer efforts were in hands on demonstrations, direct corporate interactions, and on-line demonstrations. The August 27th workshop in Roswell was particularly successful. The following letter was sent out to a select list of about 150 people who have been following the progress of the FEE Tool.

July 31, 2003

New Mexico Tech
Petroleum Recovery Research Center
a division of
New Mexico Institute of Mining & Technology
801 Leroy Place ■ Socorro, NM 87801-4796
Phone: 505-835-5142 ■ Fax: 505-835-6031

July 31, 2003

PTTC
Technology Connections
Southwest Regional Lead Organization

Dear

I announce with great pleasure our group's completion of an intelligent software tool to aid prospecting in the Lower Brushy Canyon Formation, and I would like to invite you to a hands-on workshop demonstrating the use of our Delaware Basin Fuzzy Expert Exploration (FEE) Tool.

After more than four years of data gathering, programming, and testing, the Reservoir Evaluation and Advanced Computational Techniques (REACT) group at the New Mexico Petroleum Recovery Research Center is now ready to go public with the showpiece of our NPTO-sponsored project, "Risk Reduction with a Fuzzy Expert Exploration Tool." This tool provides an easy-to-use Internet interface to the databases and related useful software developed during the project.

The Brushy Canyon pool in the Delaware Basin was chosen as the initial target for the project. The approximately 800 million bbl/oil recoverable remaining in the lower Brushy Canyon make it an enticing area for independent exploration, particularly if finding costs can be lowered.

A massive database of public domain information for the Lower Brushy Canyon has been compiled, and additional Brushy Canyon data has been generated by the project, creating a knowledge base for this formation. A model employing expert knowledge of the reservoir was developed, along with a graphical user interface and fuzzy inference engine using those expert rules, resulting in a speedy, multi-tiered system with components running in parallel that can be customized for personal or corporate philosophies while maintaining the integrity of proprietary information.

This tool has accurately and blindly predicted the results of 89 new wells drilled since the training data set was developed, and using the basic public domain database has estimated that about 4500 high quality 40 acre prospects remain un-drilled . While not intended to replace a real human expert, we believe the FEE Tool offers a very good simulation of an expert Delaware explorationist. It can provide a quick-look tool for prospect analysis. Prospect location should become faster and more consistent. And even if a user decides not to use the entire FEE Tool, the knowledge base of maps, logs, production, and well data will make it a valuable resource. This software will be adapted to the Devonian carbonate play during the next six months, and a future proposed project may address the Strawn and Bone Springs.

The workshop will be held at Eastern New Mexico University in Roswell, New Mexico, on August 27, 8 am until noon. It will be in the Instructional Technology Center, Room 127. Registration is $15 and includes the cost of the instruction manual. Trainees will have access to the online tool after the workshop. We encourage all who are interested in New Mexico exploration, in any formation, to attend this workshop and try out the tool. We hope that feedback from individuals and companies of all sizes will assist the design of future tools for other formations and regions.

Please contact Elizabeth Bustamante at 505-835-5406 or email her at lizb@prrc.nmt.edu to reserve a spot at the training session. Seating is limited.

Sincerely,

Dr. Robert Balch
Reservoir Evaluation and Advanced Computational Techniques (REACT)

The workshop was attended by 17 professionals from companies of all sizes, including: Pecos Petroleum Engineering, Clayton Williams Energy Inc., Chevron Texaco, Yates Petroleum Corp., Providence Focus, Harvard Petroleum Corp., Devon Energy, Bass Enterprises Production Co and several consultants.

Currently there are 19 registered users in the system and the project webpage ford.nmt.edu has seen nearly 900 hits in its first month of live operation.

Problems Encountered

Personnel changes at the Petroleum Recovery Research Center required changing the Project Manager to Dr. Robert Lee and the PRRC PI to Dr. Robert Balch. The transition has been smooth and no delay or changes were made to the project or its time-line.

Next Year's Tasks

Continue Expert System Development

The Brushy Canyon FEE Tool

On schedule delivery of the Brushy Canyon FEE Tool was accomplished with the release in late August of the web-version of the software to public testing. Continuing refinements to the system are being made available as live software updates on a bi-weekly basis, incorporating changes requested by users, and repairing bugs found in day to day use. It is expected that by the end of project we will have reports of how well the tool identifies new prospects, as several companies are planning new wells based in part on the Tool.

The Devonian FEE Tool

Work has begun on interviewing Devonian experts, and the Devonian expert system will be markedly different from the Brushy Canyon FEE Tool. Development will begin as soon as rules are finalized and is projected for the end of they year. Important factors already identified for the Devonian FEE Tool are:

- Regional map of DST vs. realized production would be useful
- Alternately scout ticket shows/perfs
- Permeability is a key factor
- Best wells are on structure, though some on flank do alright.
- Cherts seem to provide the largest reservoir porosity.
- Woodford shale source rock
    - No Woodford, no well
- The Devonian needs to be divided into 4 or 5 vertical units
- Existence of regional fractures or a fault can cause water problems
- Paleo Structures are very important, though not always the same as modern structures.
    - How to id paleostructures? We will subtract Pennsylvanian rocks (Abo).
- Brecciated facies is a key component, and core information, much of it public is very valuable.

- Develop using horizontal wells, can be very effective.
- Perform up to 5 successive fracs per well, so high completion costs.

Geology

During the next project year, we will finish acquisition of all geologic data. This will include:

1. Obtaining a limited number of source rock analyses on post-Woodford source facies that directly overlie the Siluro-Devonian carbonates north and west of the Woodford pinchout in order to assess their contributory role as a source for oil and gas in the Siluro-Devonian carbonates in the northern and western reaches of the basin.
2. Construct source-rock attribute maps of possible post-Woodford sources identified as a result of step 1, above.
3. Construct a worms-eye map of strata that overlie the uppermost surface of the Siluro-Devonian carbonates.
4. Use Woodford data to produce an isopach map of the Woodford Shale.
5. Use Woodford thickness and source rock data to produce maps related to the generative potential of the Woodford.
6. For each of the Siluro-Devonian oil and gas fields, produce a map that indicates the Siluro-Devonian stratal unit that is the primary productive unit in that field.
7. Produce isopach maps of the major productive Siluro-Devonian stratal units and relate them to structure, stratigraphy, source rocks, and oil and gas production.
8. Relate source rock thermal maturity to gas-oil ratios in Siluro-Devonian carbonate reservoirs.

Conclusions

Substantial progress has been made towards a finished Expert System that will run remotely from a browser on nearly any computer and be able to aid in development and drilling decisions for both the Brushy Canyon and Devonian plays by providing readily accessible public information that simulates an "Expert" opinion of a prospect in a short time, to enhance the work of a human explorationist.

The emphasis during the April 2003 through September 2003 period was directed toward Silurian-Devonian geology, development of rules for the fuzzy system, and on-line software. A working Brushy Canyon FEE Tool, including extensive documentation and on-line manuals was released, and is being used by Explorationist's at more than 10 companies.

We have generated a number of new and useful tools and technologies to support construction of the Expert System, including online useable interfaces for neural network analysis (PredictOnline), ranking of potential inputs using fuzzy logic (FuzzyOnline) and an on-line database of project generated data (WDMS).

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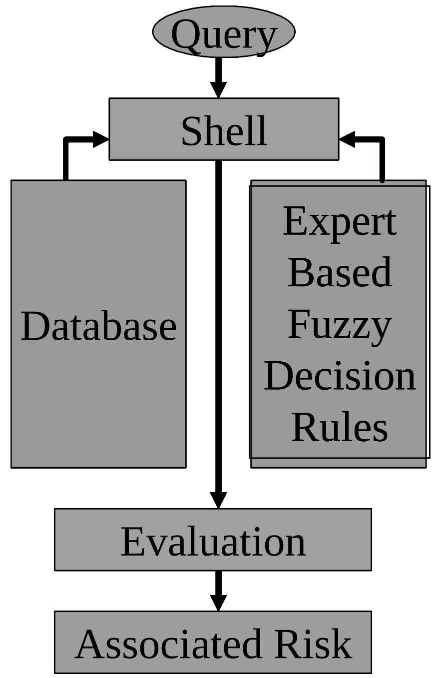

Fig. 1. The original schematic for the fuzzy expert system shell.

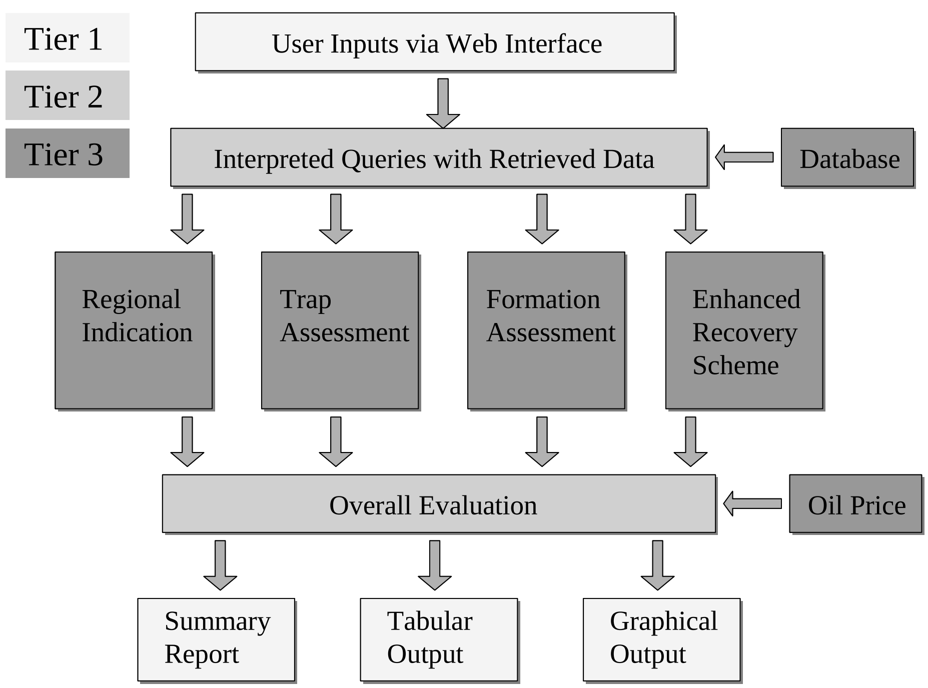

Fig. 2. More complicated system, which breaks the analysis into several separate categories to simplify calculations and customization.

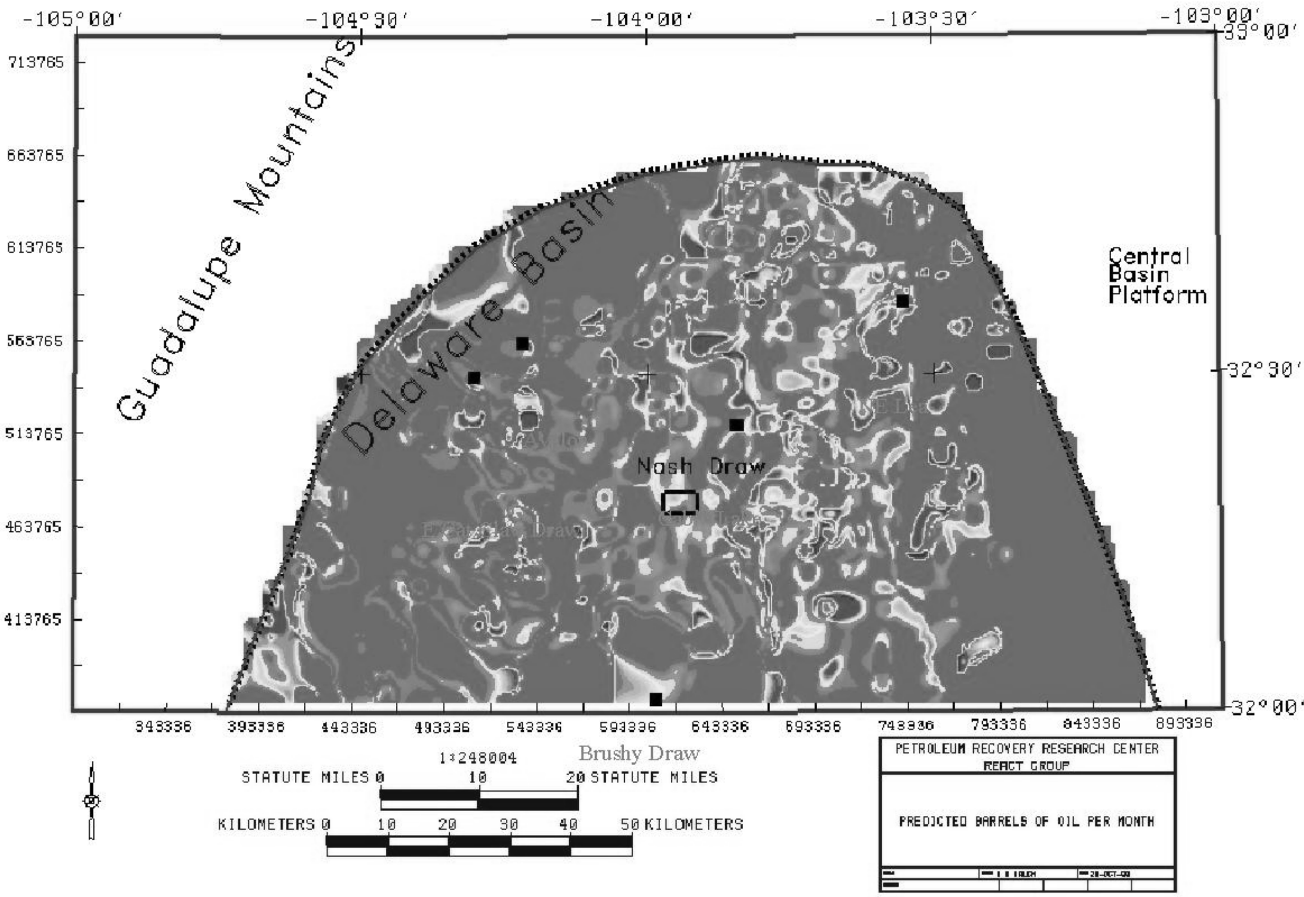

Fig. 3. Map of predicted production potential based on the trained and tested neural network regression.

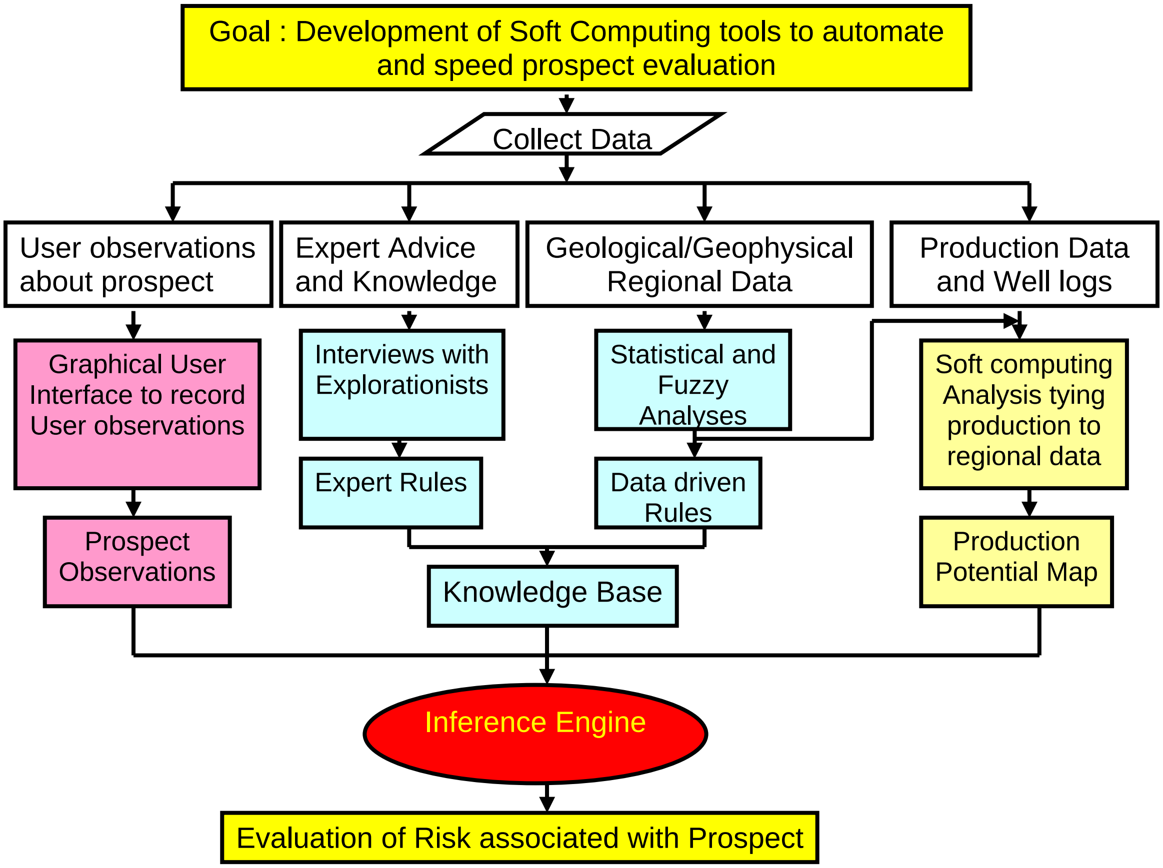

Fig. 4. Chart showing basic processes needed to execute design of the Expert System.

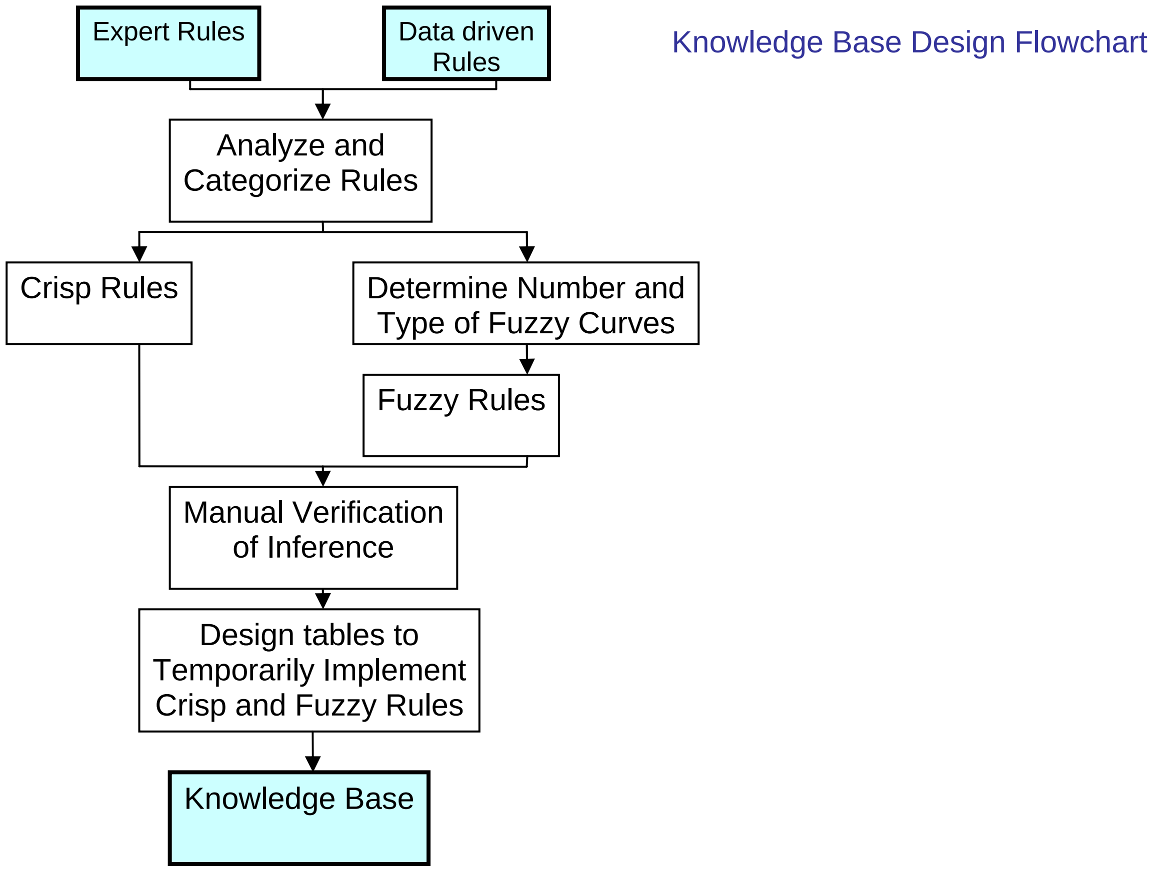

Fig. 5. This flowchart shows the steps and organization of the knowledge base design process and expands on the center boxes in Fig. 4.

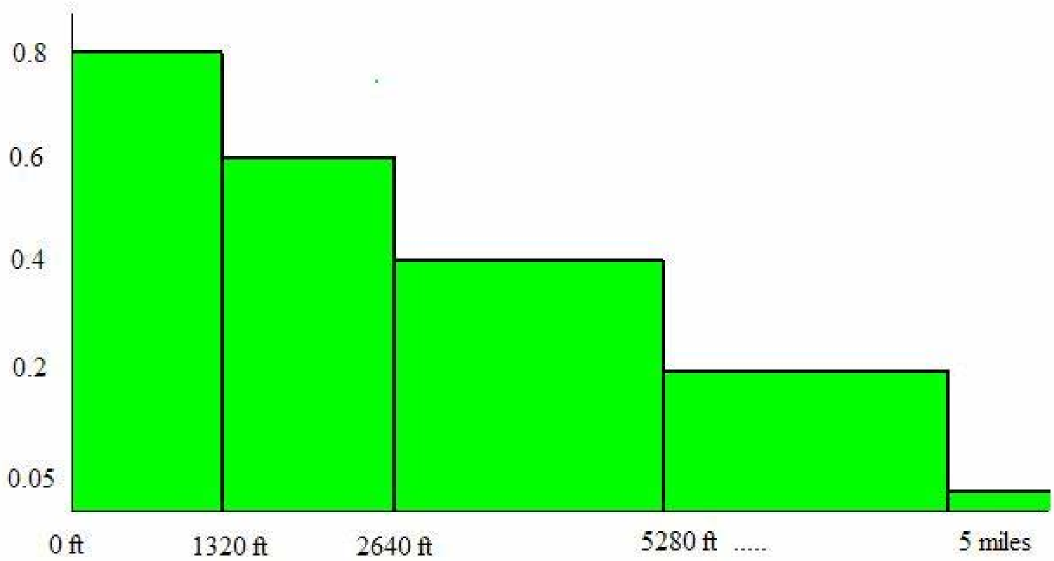

Fig. 6. Graphical representation of distance function.

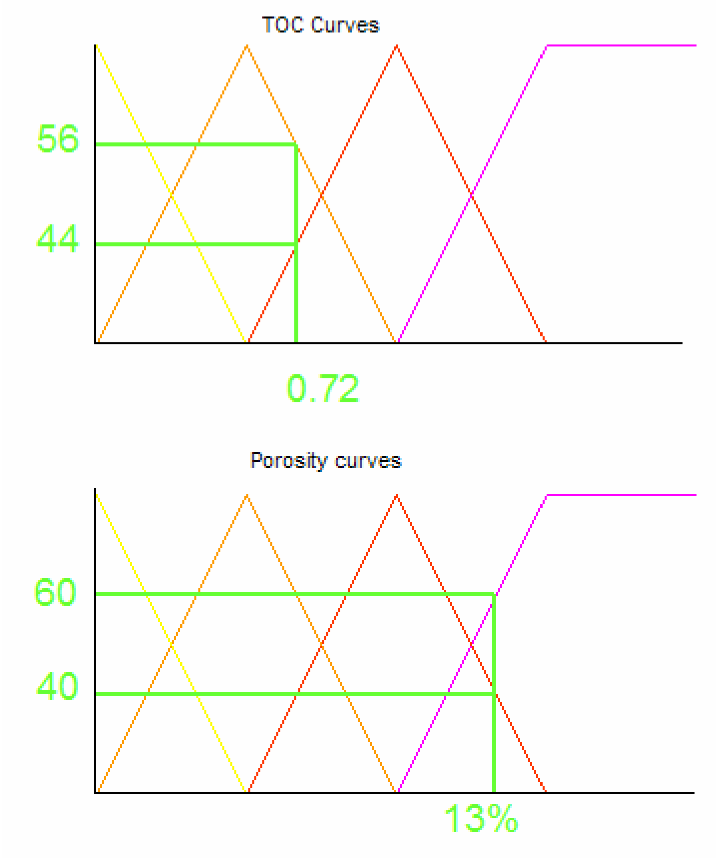

Fig. 7. Fuzzy curves for TOC and porosity.

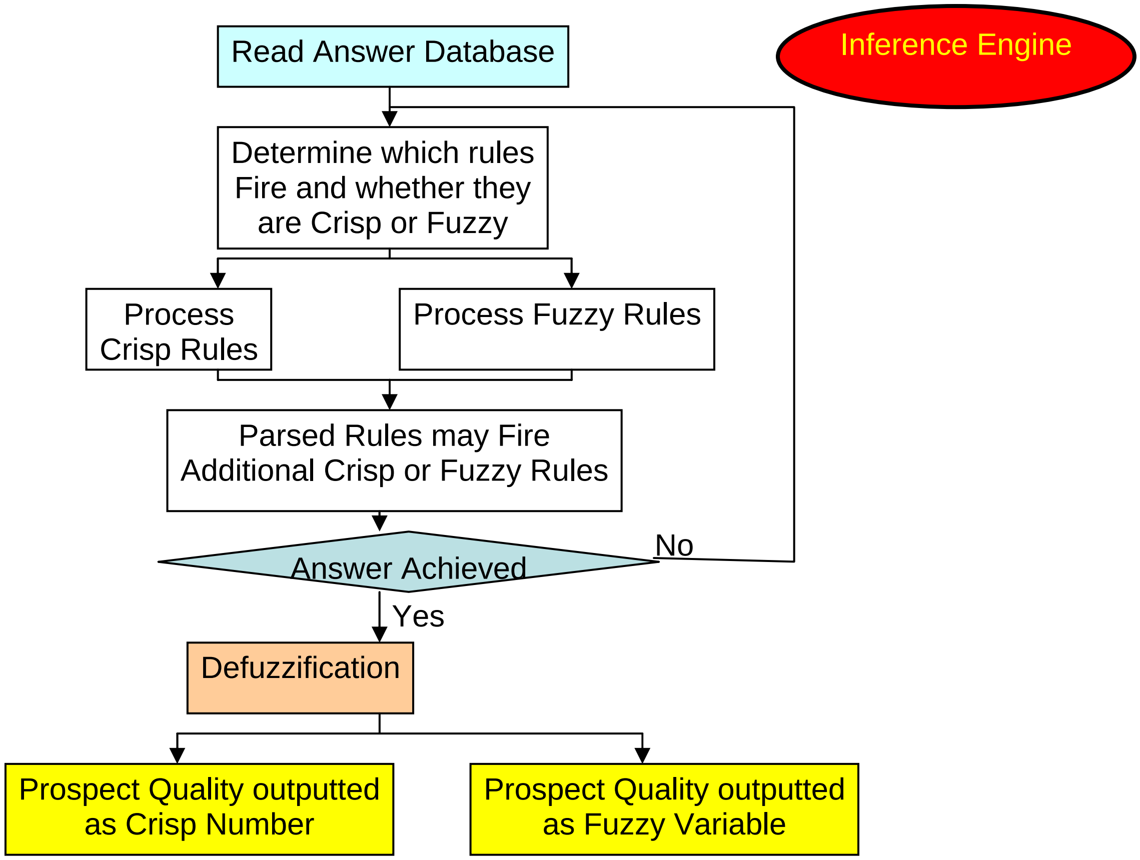

Fig. 8. Flowchart for the design of the Inference engines, used to power the Expert Systems.

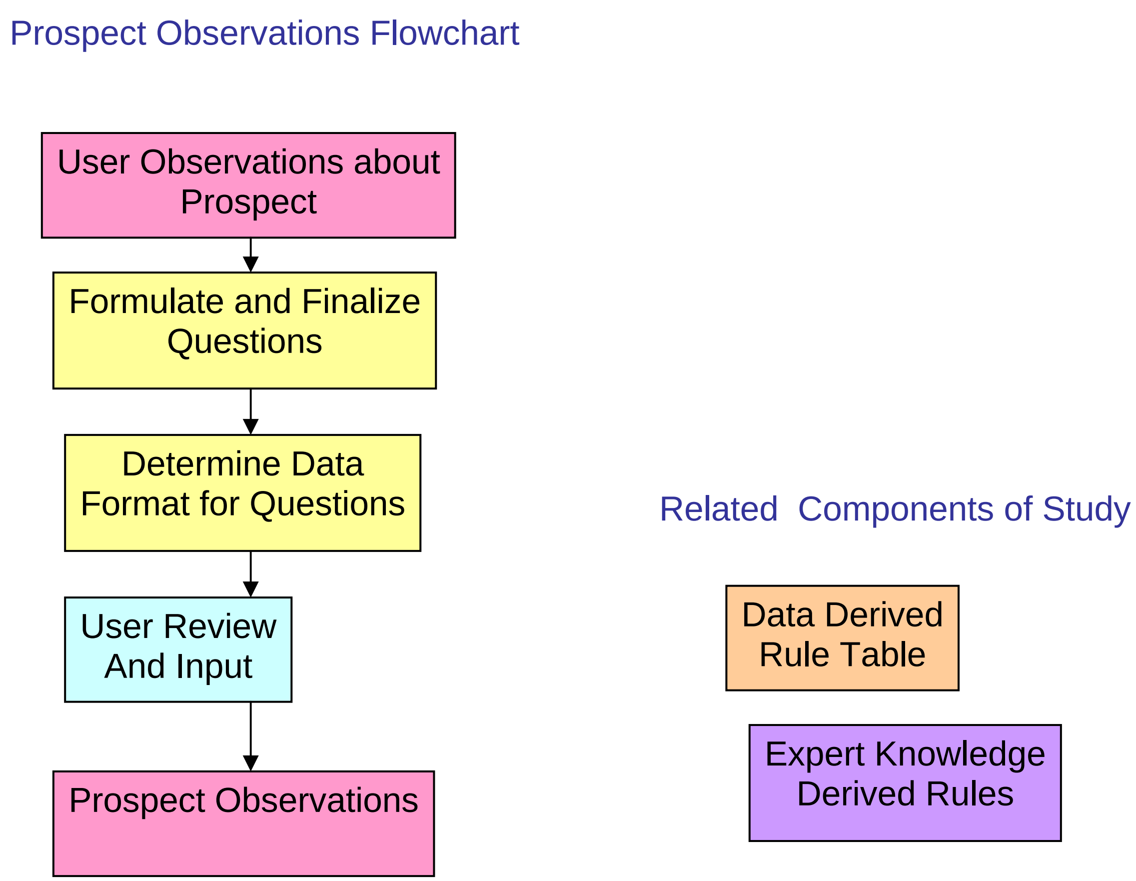

Fig. 9. Expanded flowchart for the **Users Observations about Prospect** section of Fig.4.

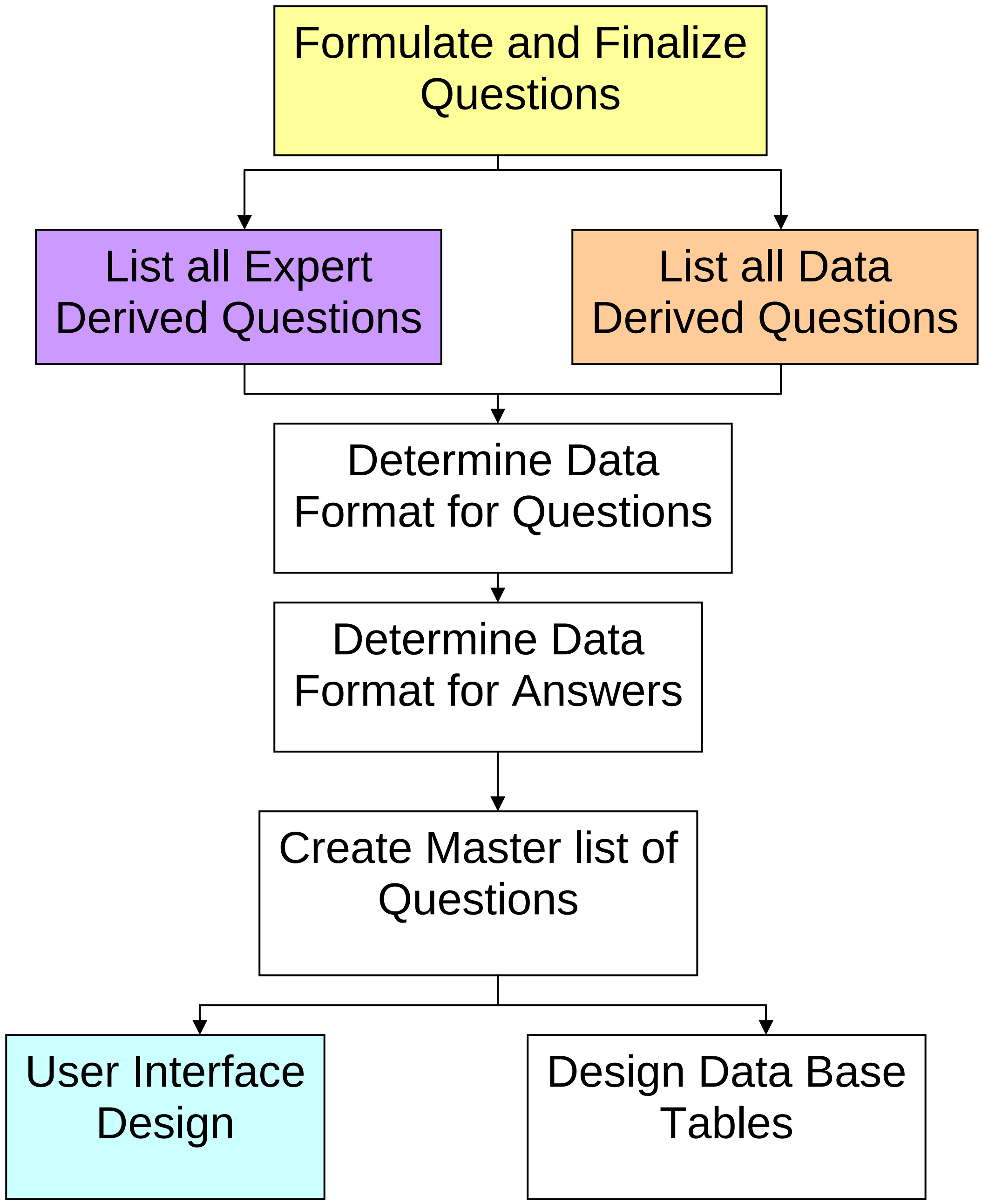

Fig. 10. Expanded flowchart for the **Formulate and Finalize Questions** section of the flowchart in Fig. 5.

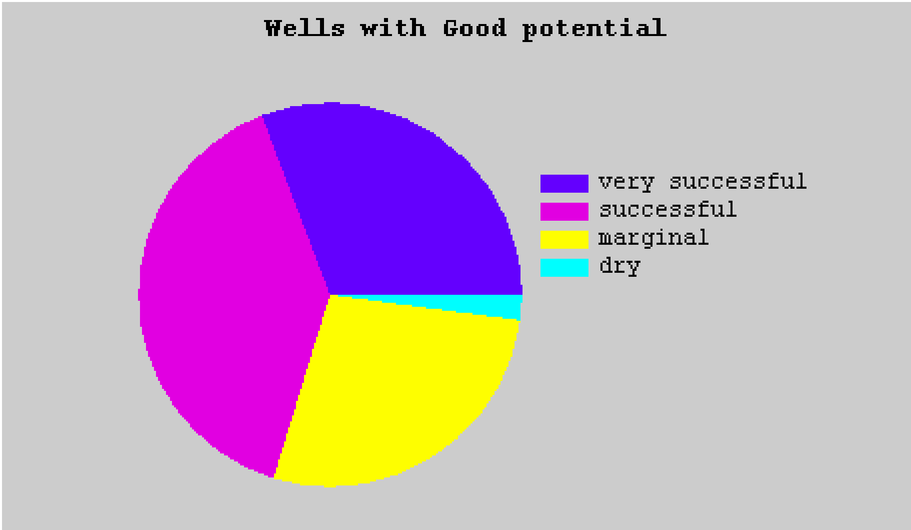

Fig. 11. Pie chart for “Good” category.

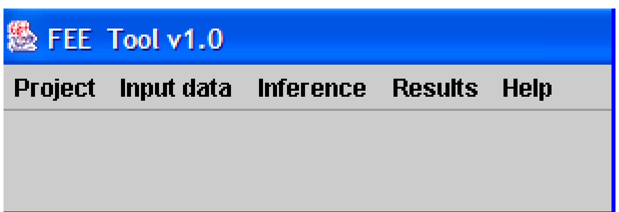

Fig. 12. FEE Tool menu.

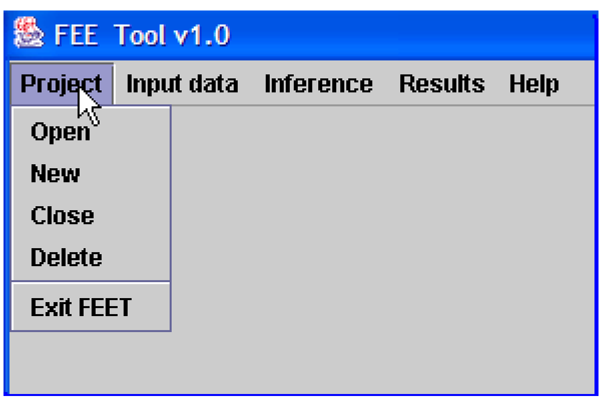

Fig. 13. Project menu.

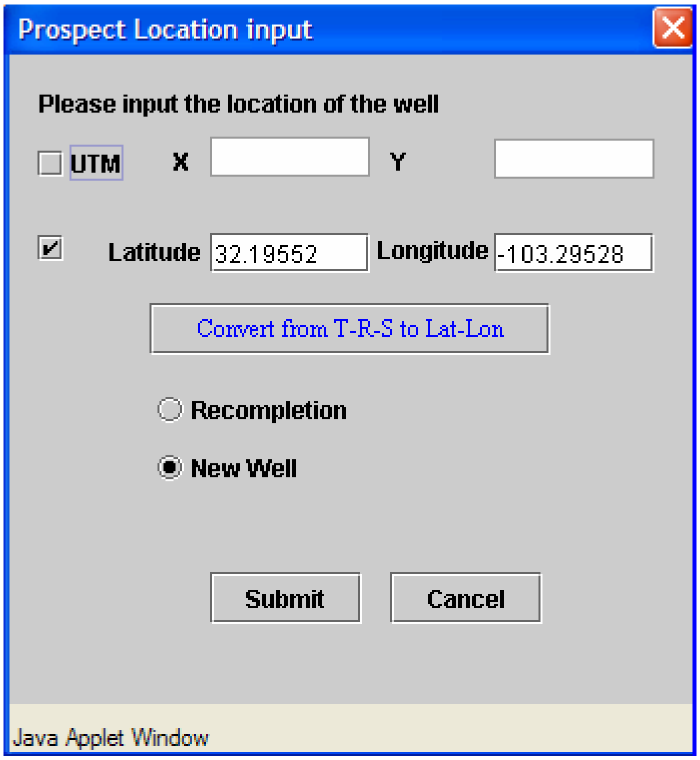

Fig. 14. Location input screen.

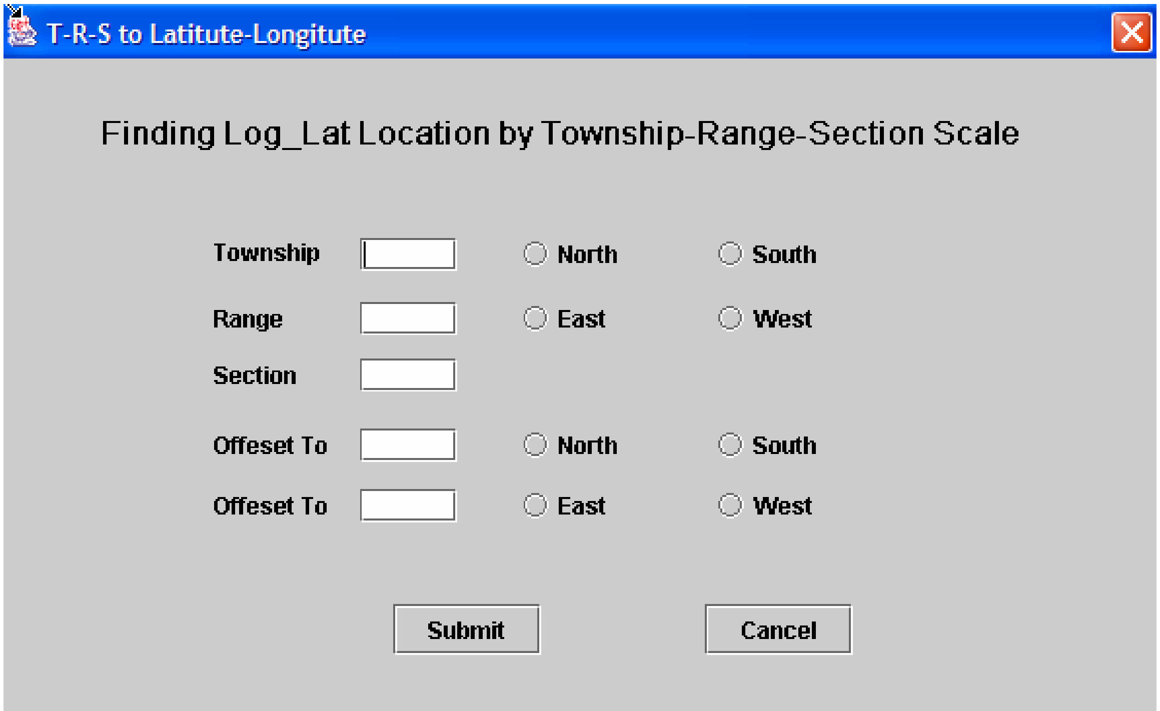

Fig. 15. T-R-S conversion.

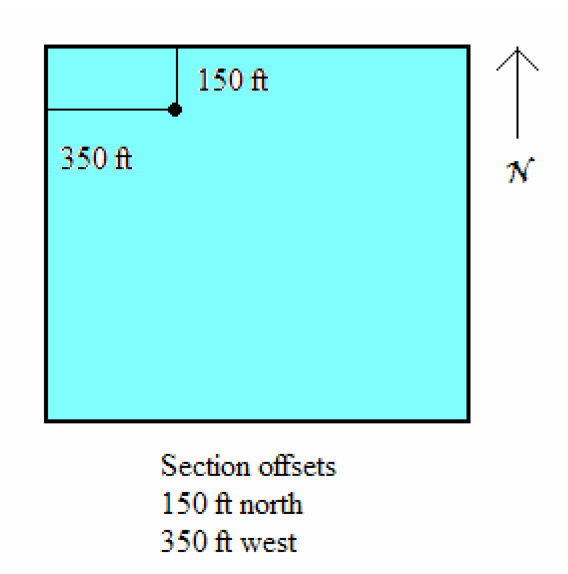

Fig. 16. T-R-S Offset example.

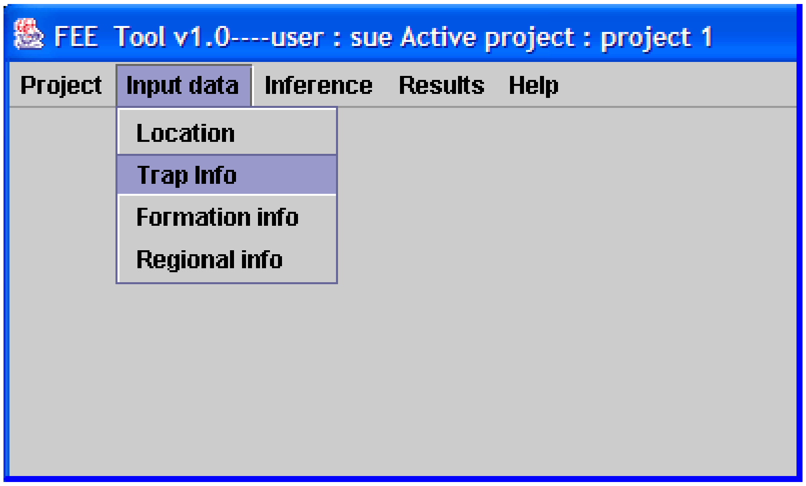

Fig. 17. Input data menu.

Fig. 18. Trap Step 1.

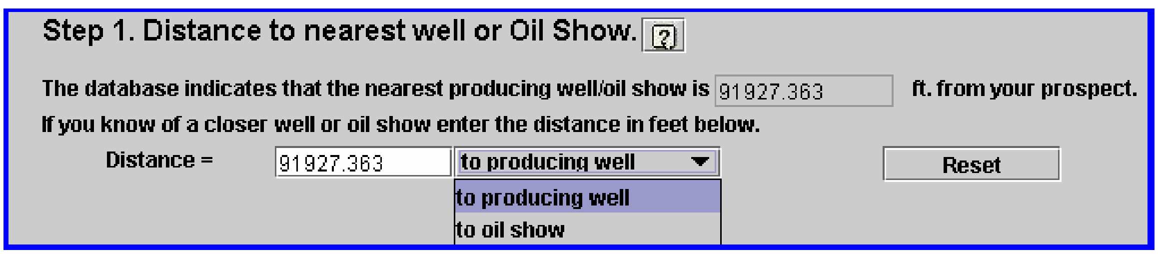

Fig. 19. Trap Step 1 pulldown menu.

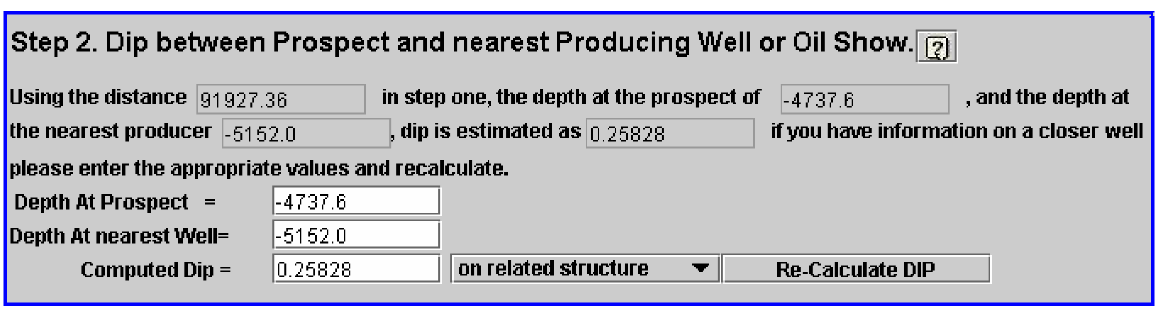

Fig. 20. Trap Step 2.

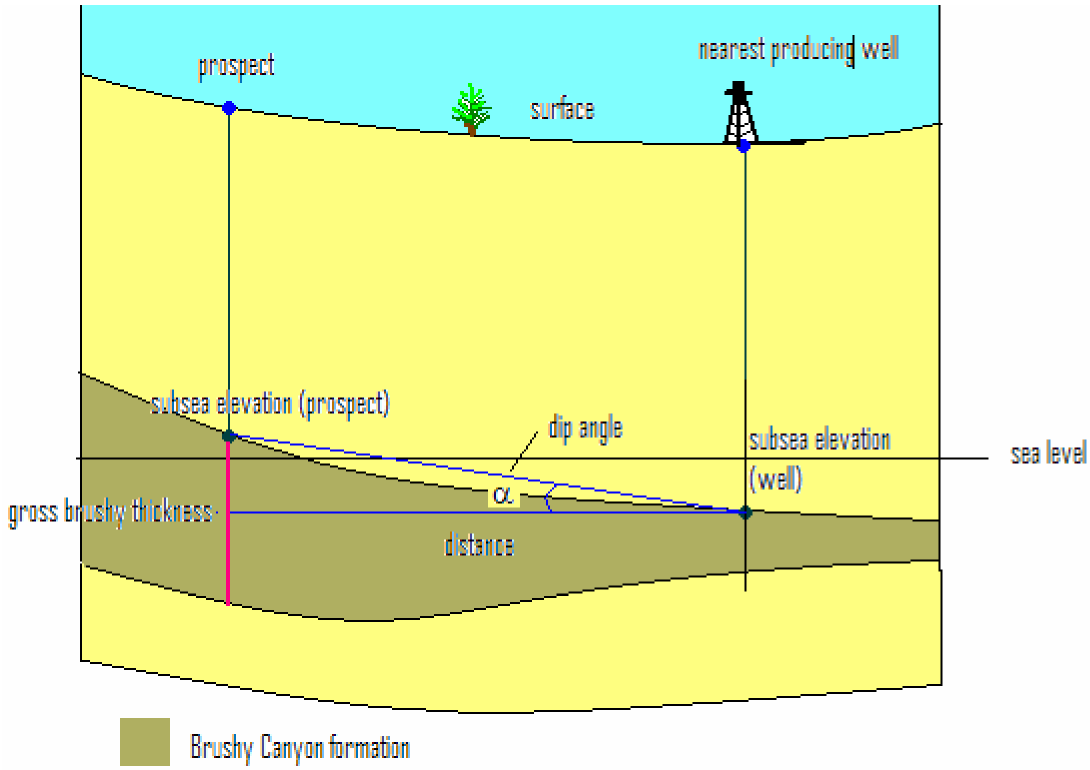

Fig. 21. Cutaway drawing of the lower Brushy Canyon formation illustration how the dip angle is computed.

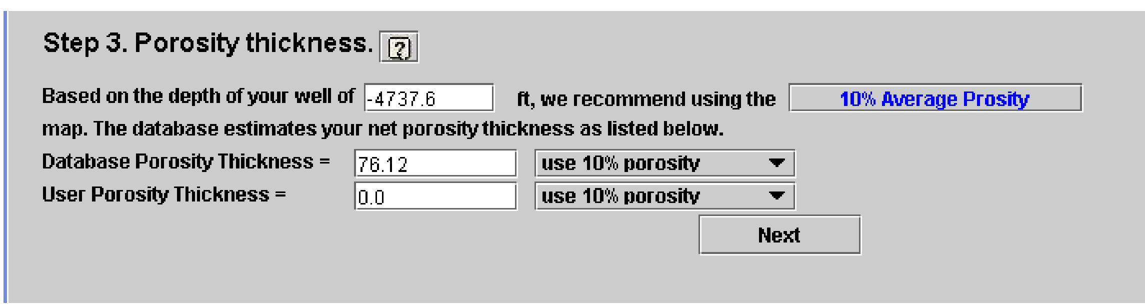

Fig. 22. Trap Step 3.

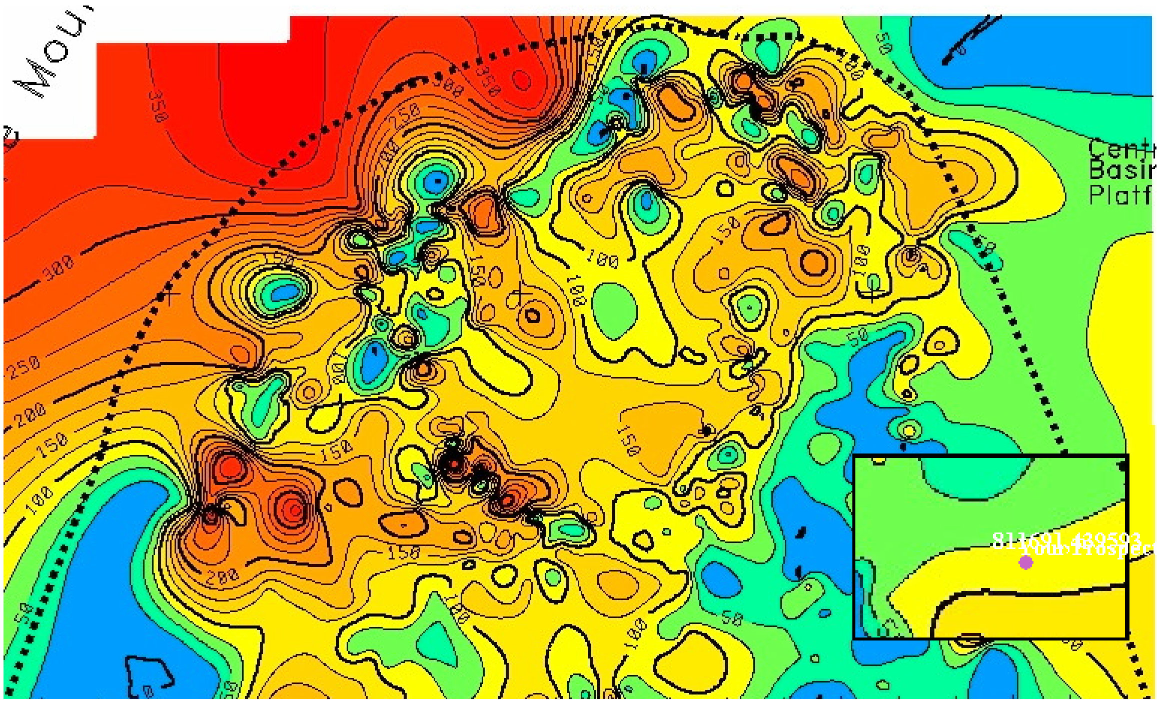

Fig. 23. 10% porosity thickness map.

Fig.. 24. Trap Step 3 pulldown map.

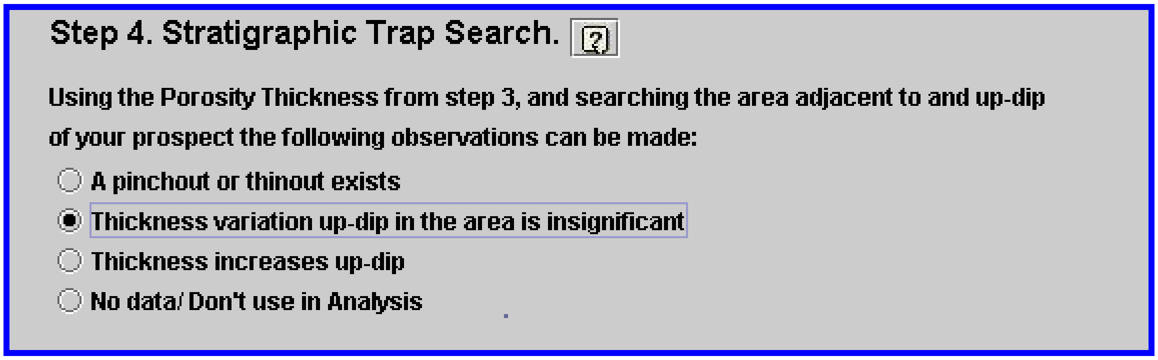

Fig. 25. Trap Step 4.

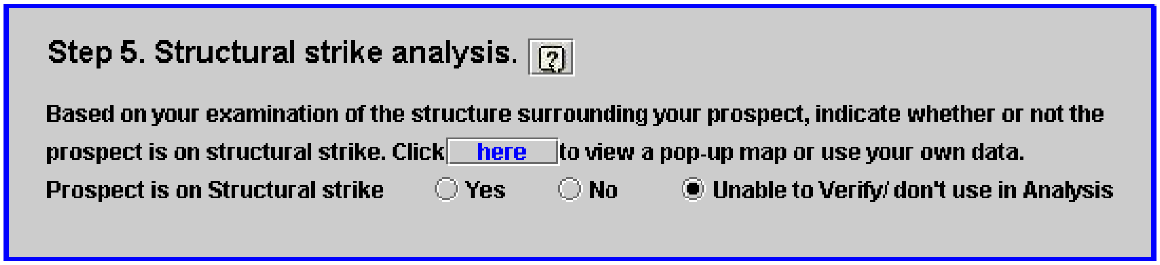

Fig. 26. Trap Step 5.

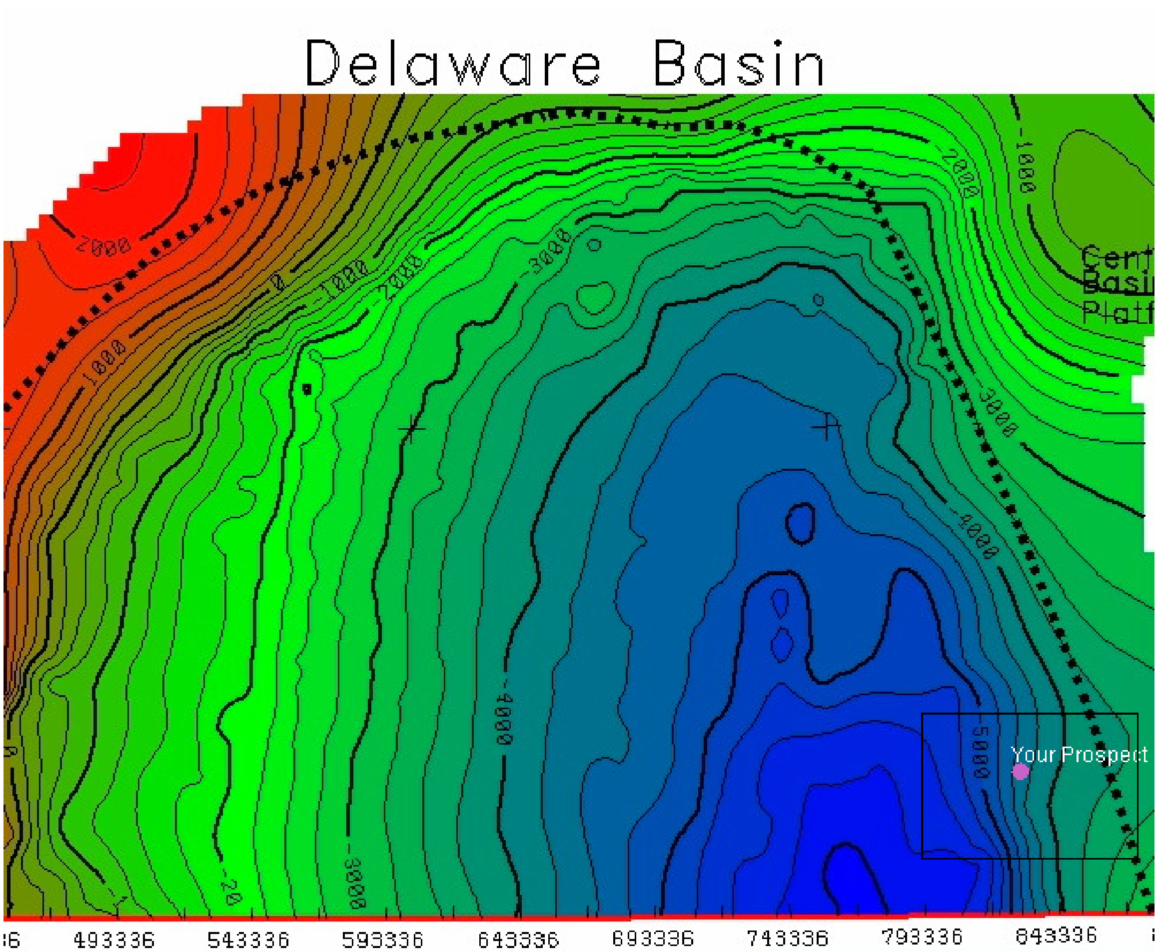

Fig. 27. Delaware Basin structure map.

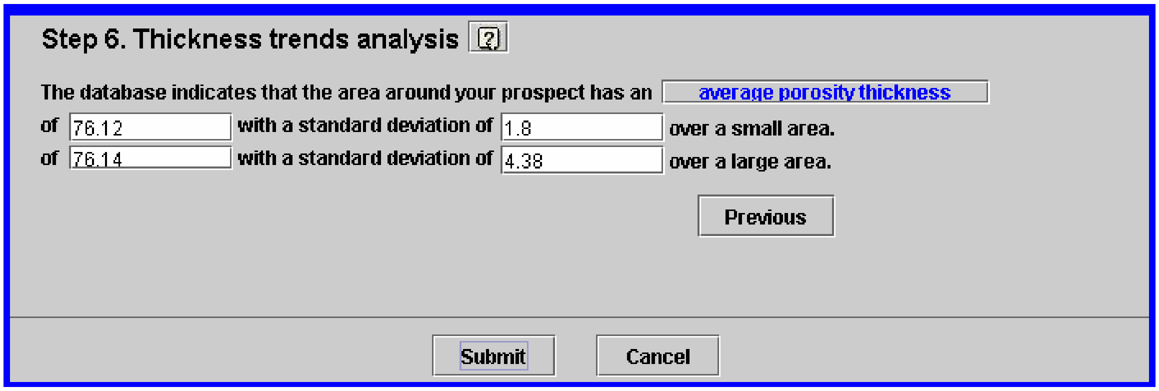

Fig. 28. Trap Step 6.

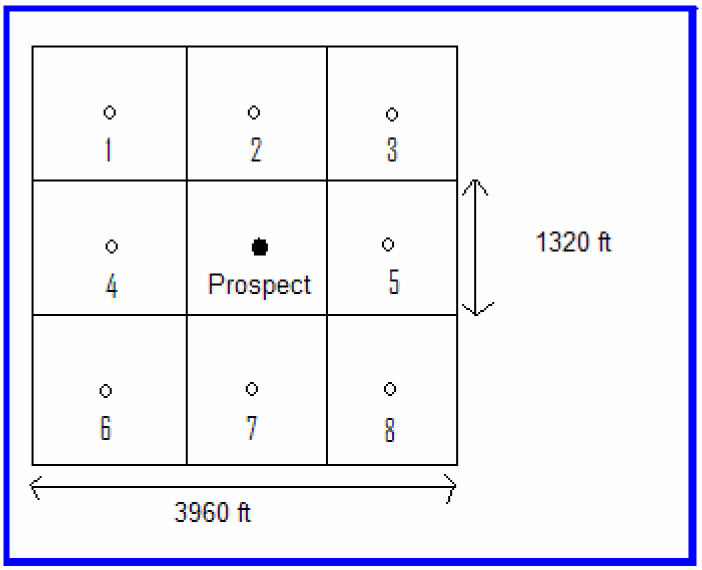

Fig. 29. Representation of ‘small area” used in consistency based steps.

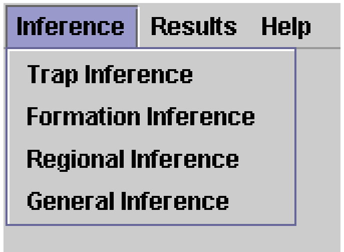

Fig. 30. Inference menu.

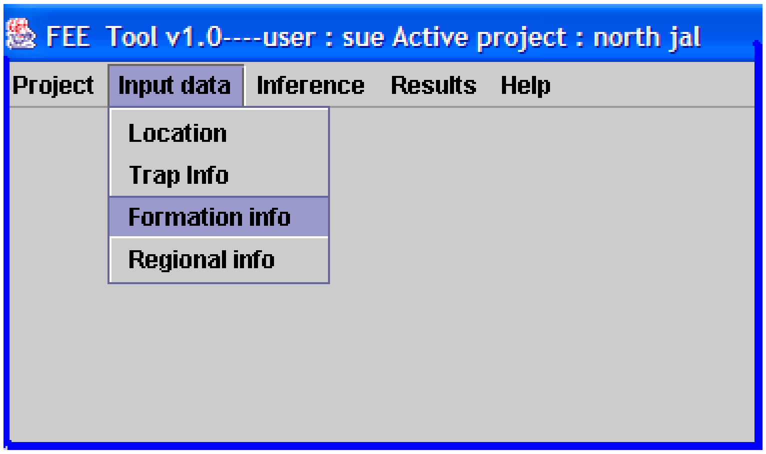

Fig. 31. Input data menu with **Formation Info** highlighted.

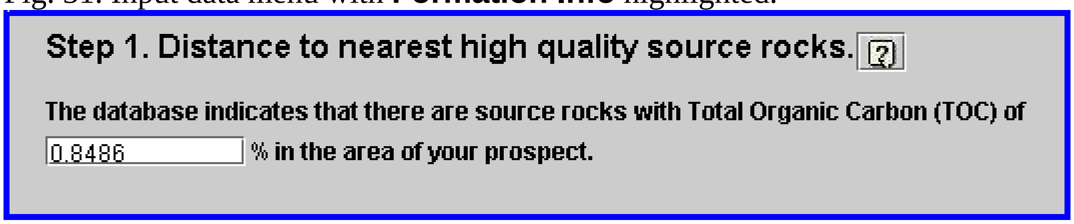

Fig. 32. Formation Step 1.

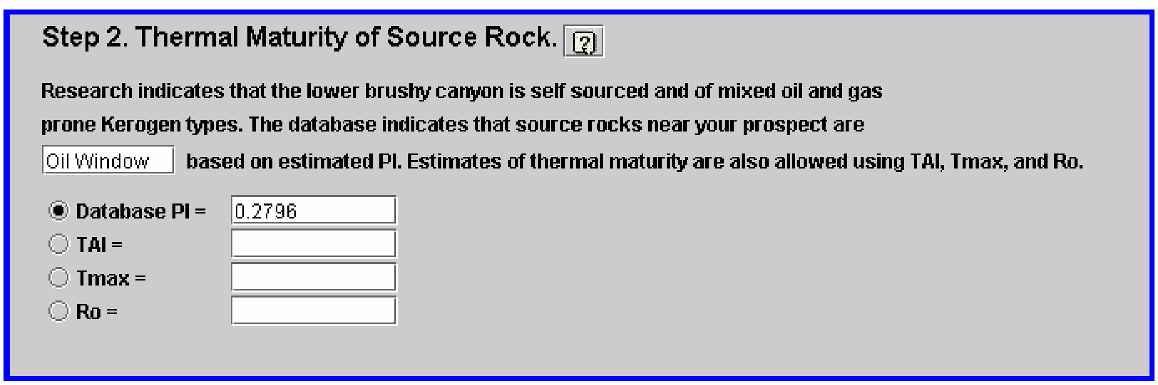

Fig. 33. Formation Step 2.

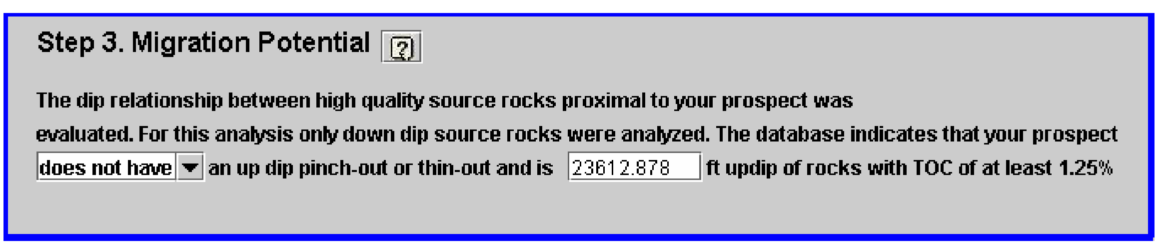

Fig. 34. Formation Step 3.

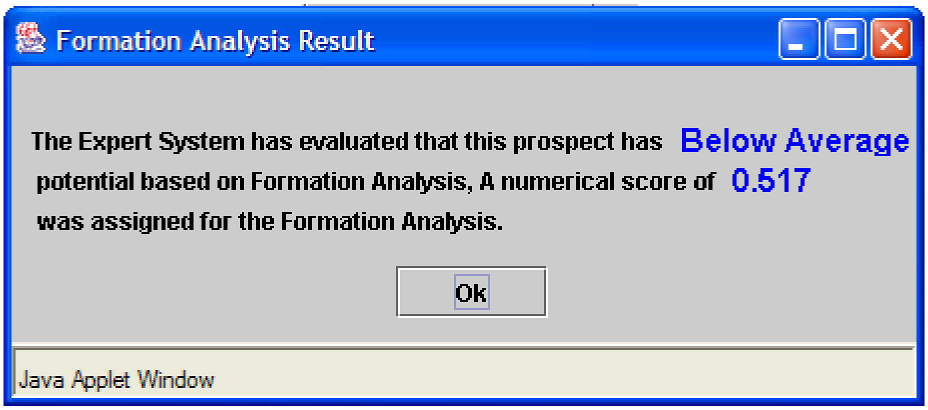

Fig. 35. Example of inference results for the formation analysis.

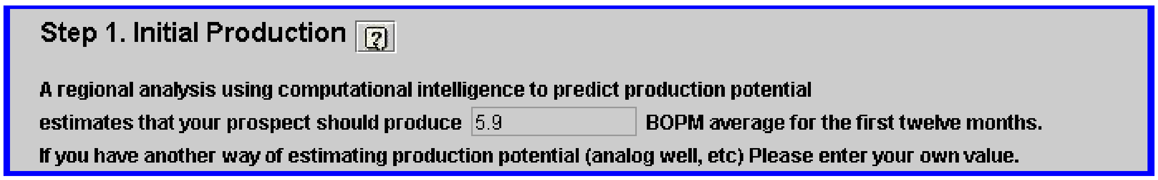

Fig. 36. Regional Step 1.

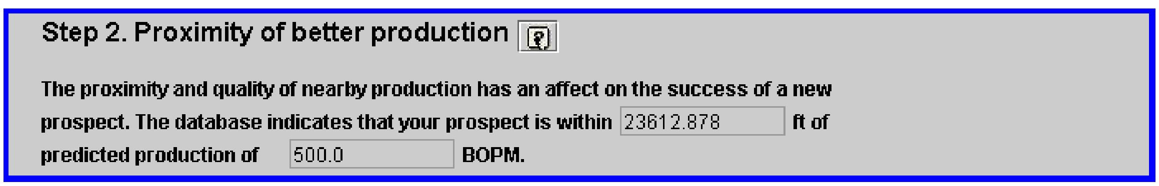

Fig. 37. Regional Step 2.

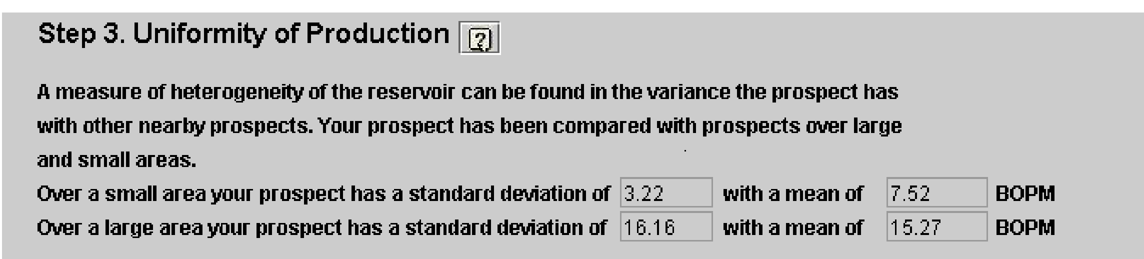

Fig. 38. Regional Step 3.

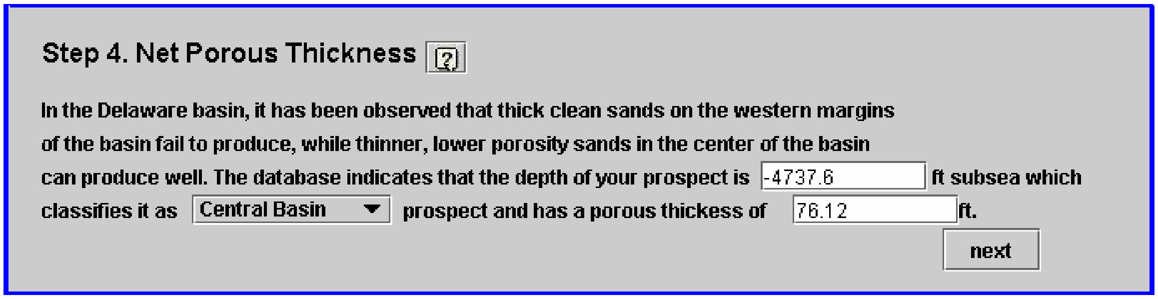

Fig. 39. Regional Step 4.

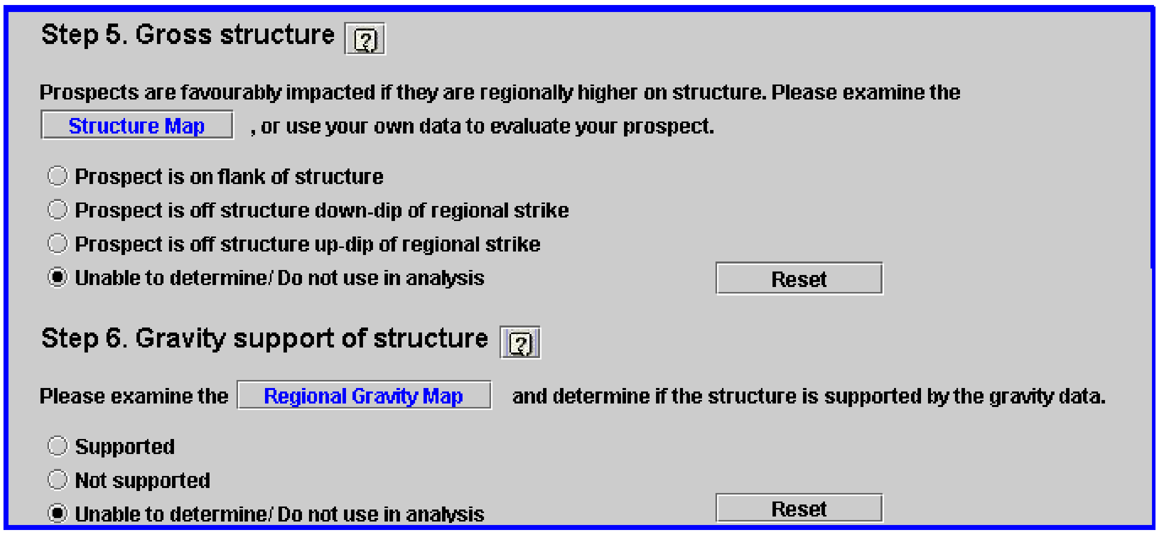

Fig. 40. Regional Step 5.

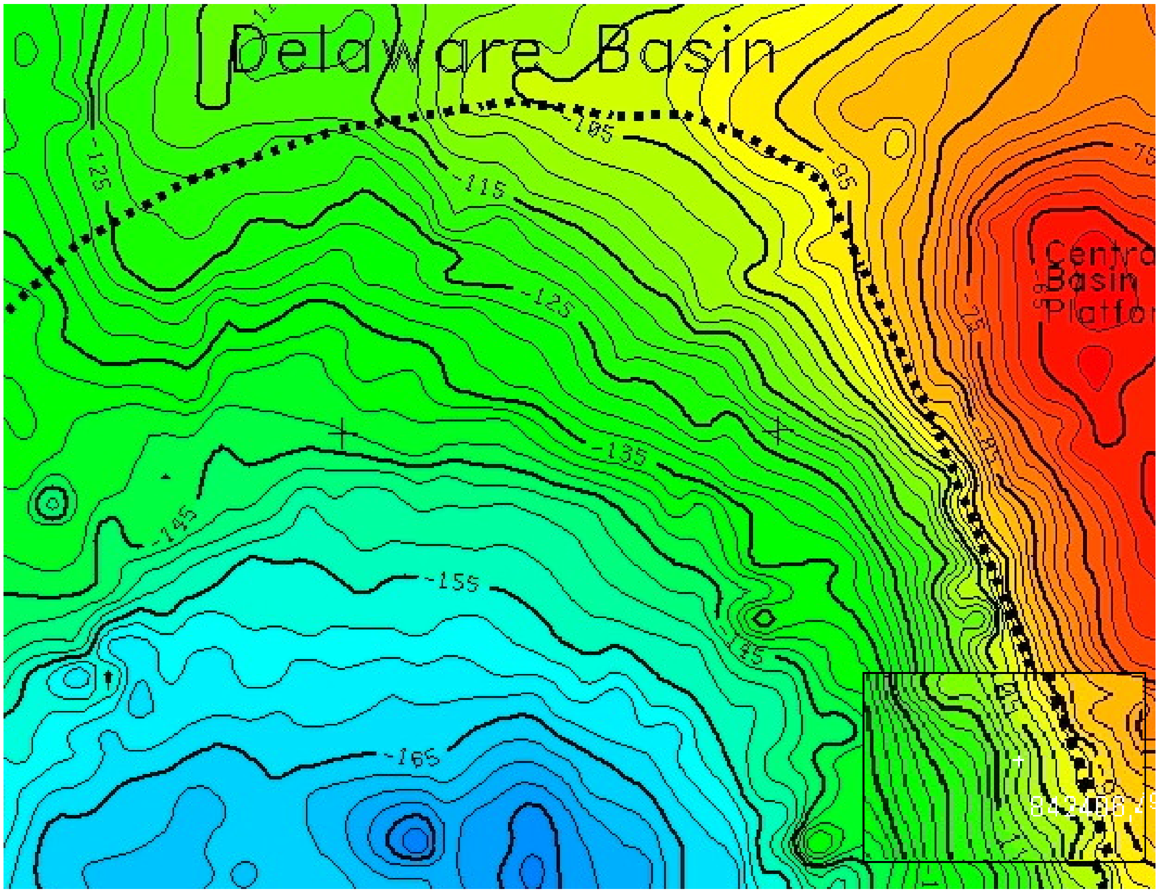

Fig. 41. Gravity map.

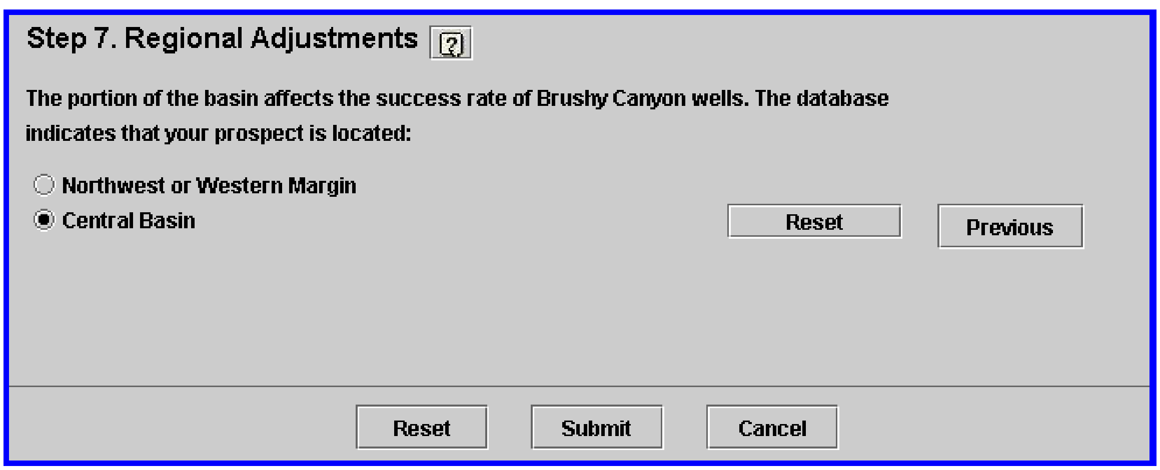

Fig. 42. Regional Step 7.

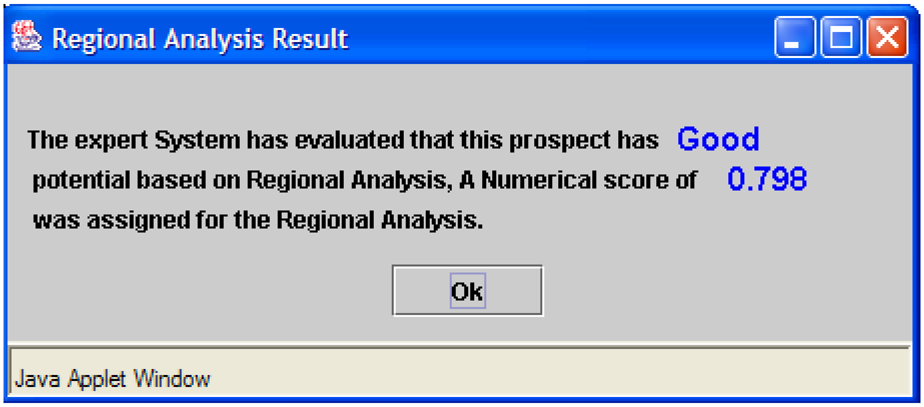

Fig. 43. Example of inference results for the regional analysis.

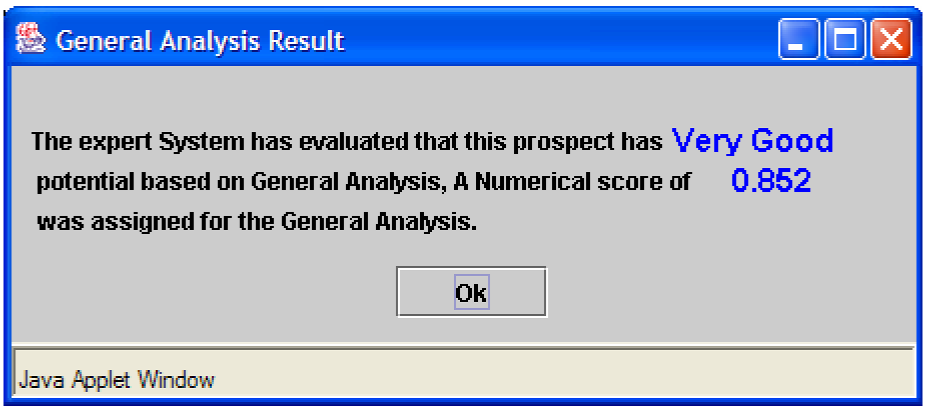

Fig. 44. Example of the general results.

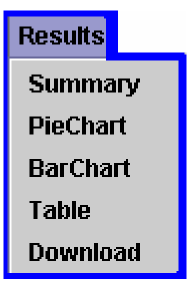

Fig. 45. Results menu.

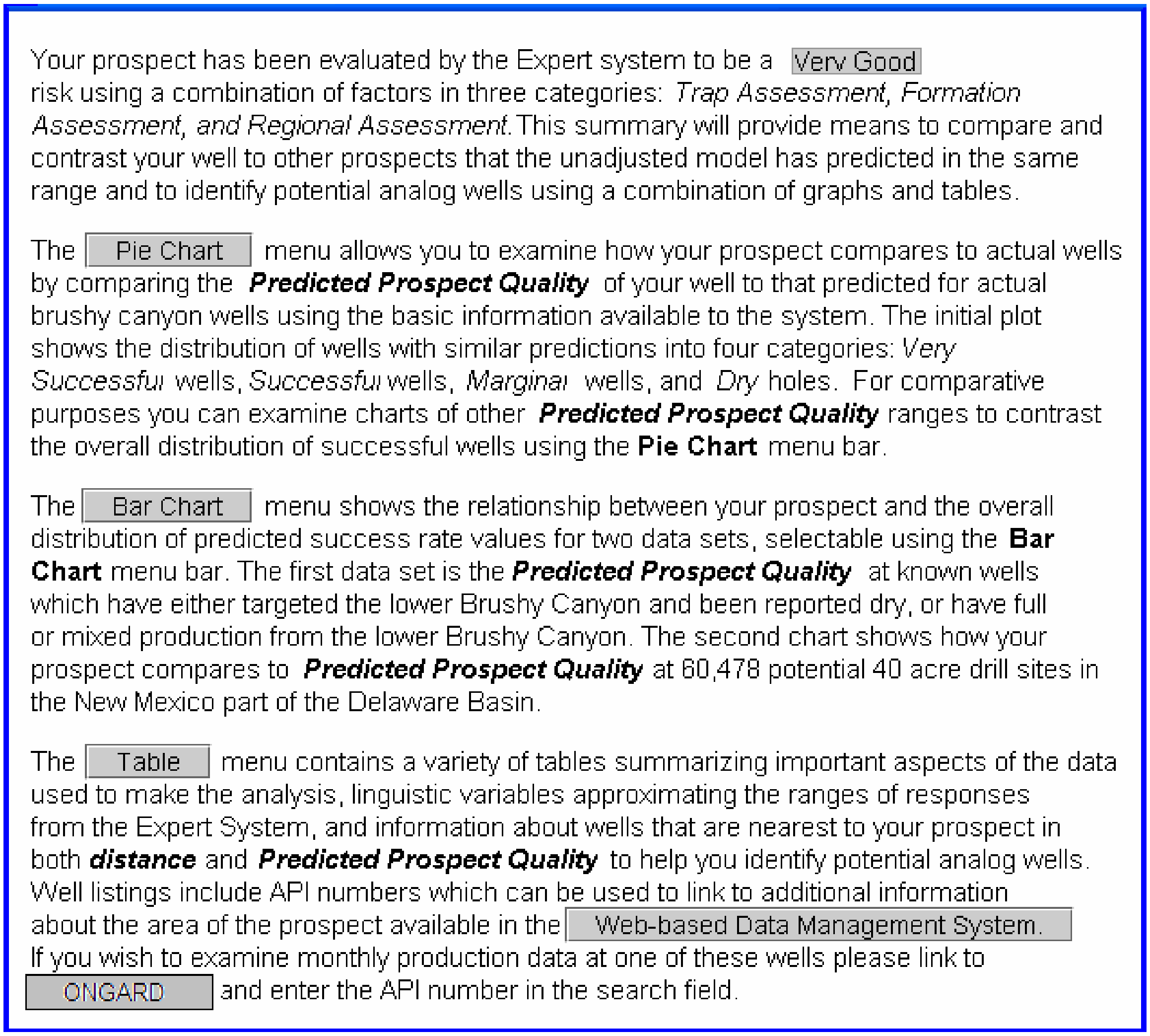

Fig. 46. Example of a summary sheet for a prospect.

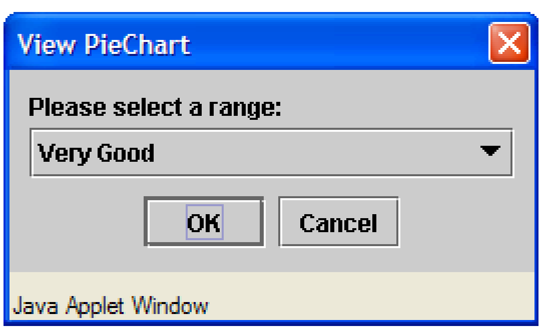

Fig. 47. Pie Chart menu.

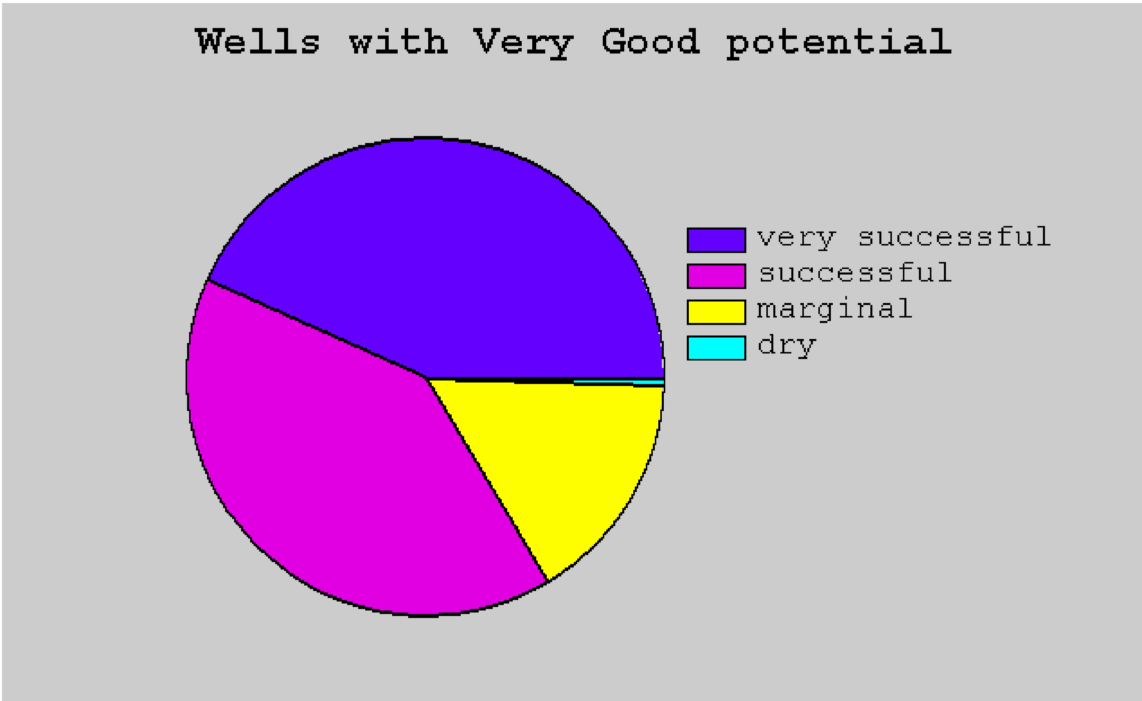

Fig. 48. Pie chart for locations with “Very Good” potential.

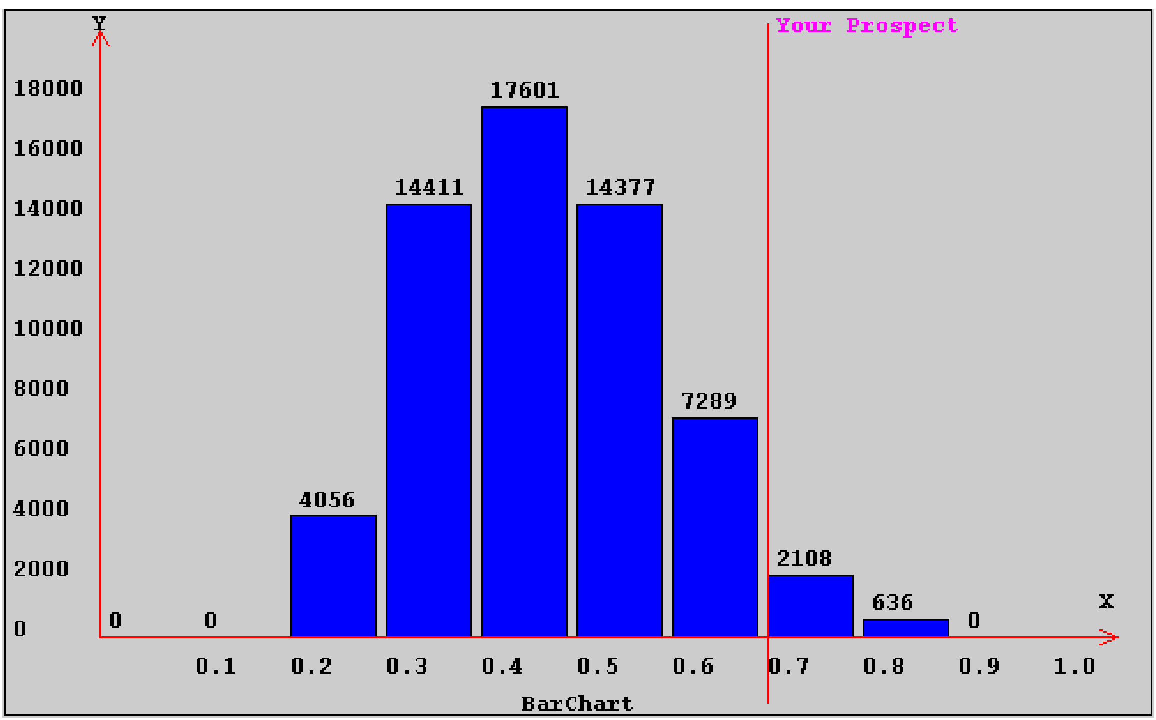

Fig. 49. Bar chart comparing your prospect to the entire system.

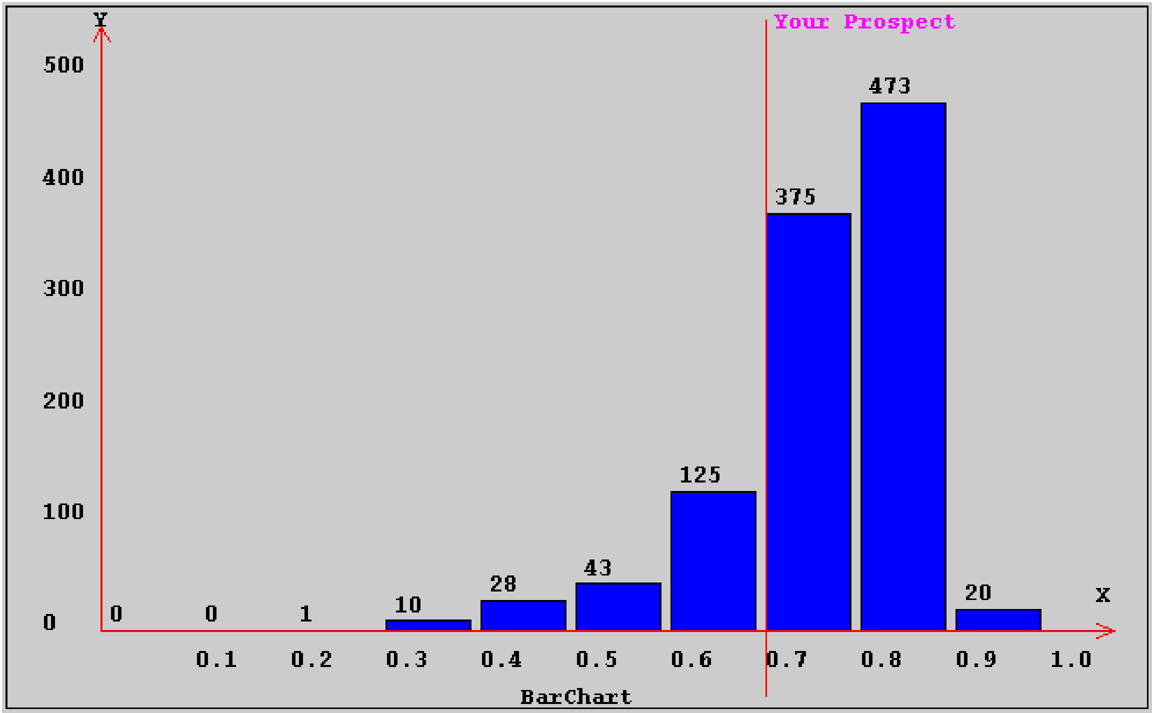

Fig. 50. Bar chart comparing your prospect to successful wells.

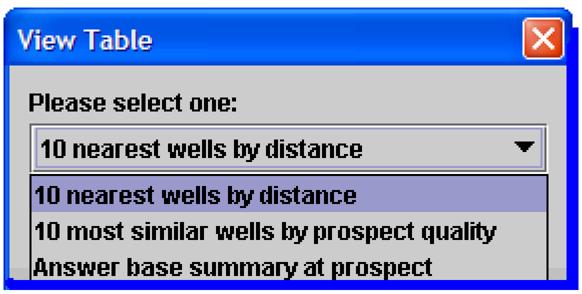

Fig. 51. Table menu.

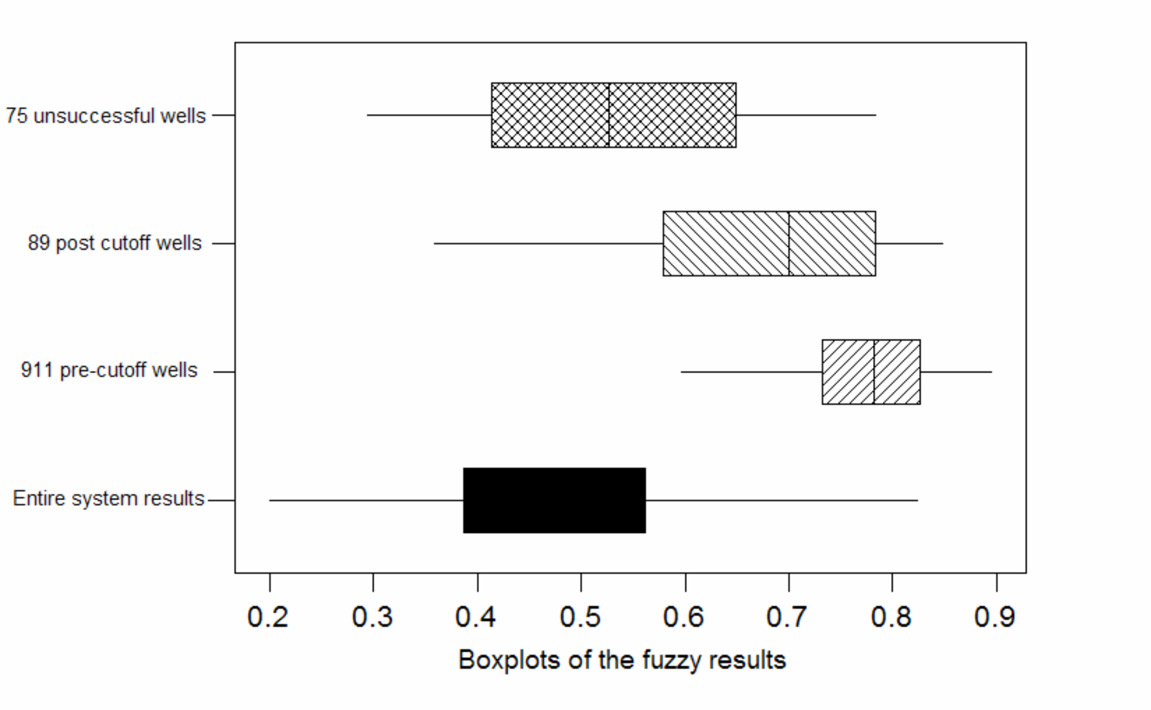

Fig. 52. Boxplots for the entire system and the three subsets.

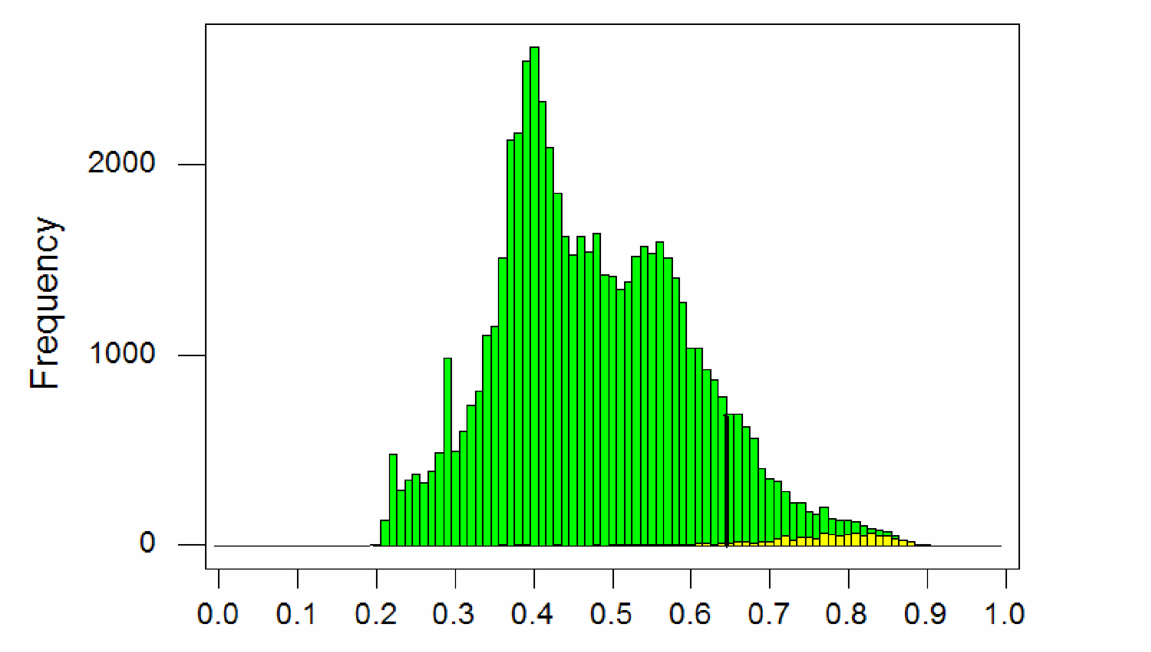

Fig. 53. Histogram of the estimates for the entire system (Green) and the estimates for the successful wells (yellow).

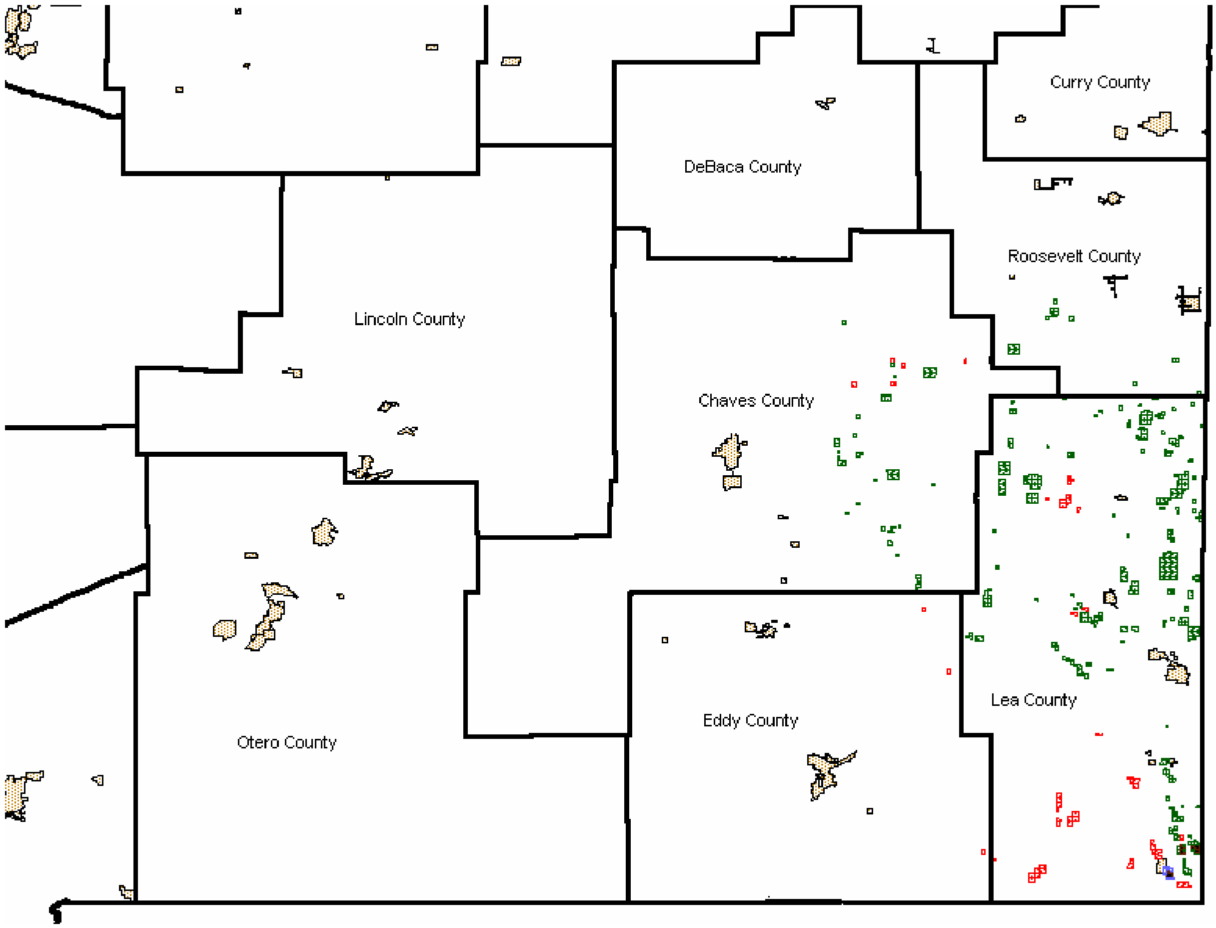

Fig. 54. Map of southeastern New Mexico showing county boundaries and oil reservoirs (green) and gas reservoirs (red) productive from Siluro-Devonian strata.

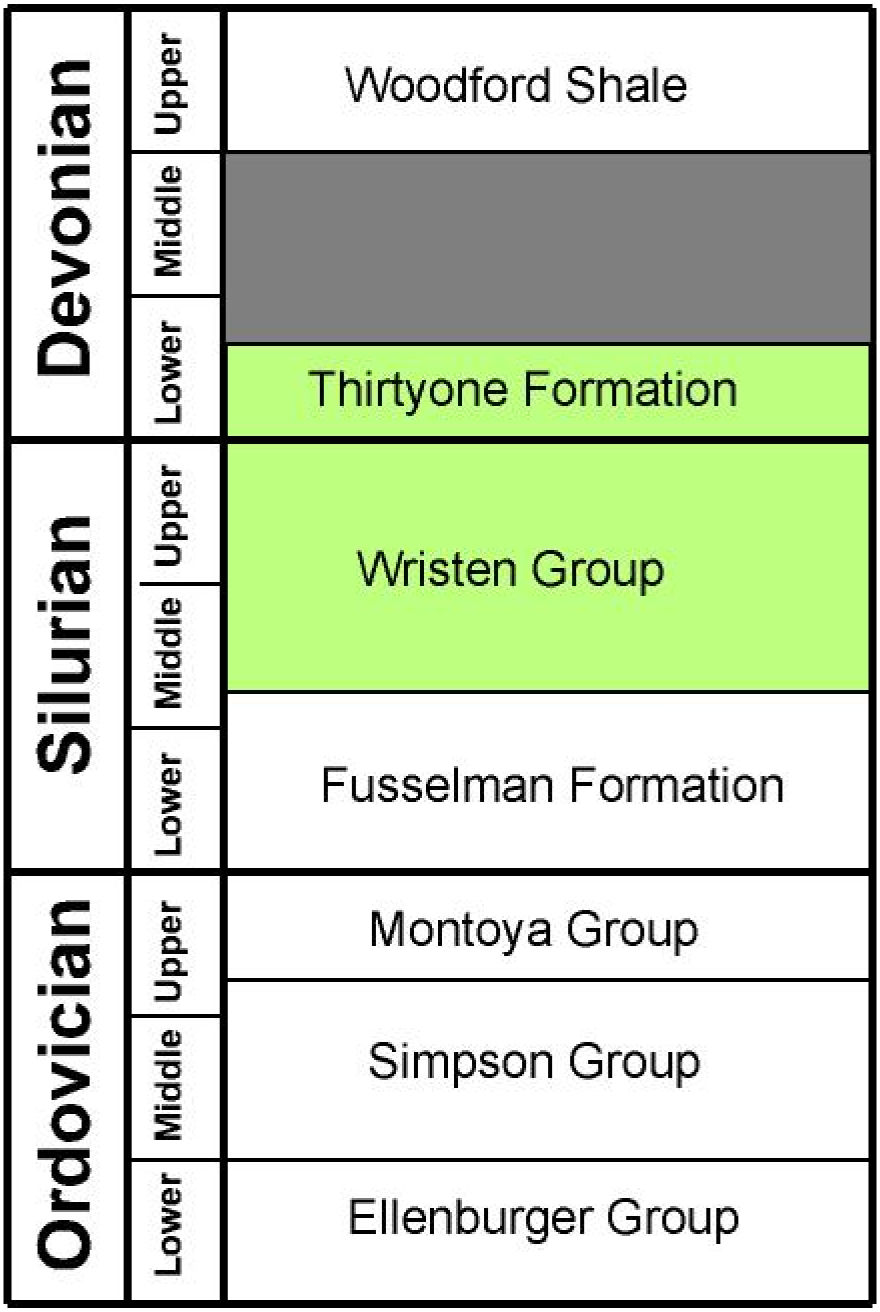

Fig. 55. Stratigraphic column of Lower Paleozoic rocks in southeastern New Mexico. Reservoirs in the Wristen Group and Thirtyone Formations are the subjects of current work.

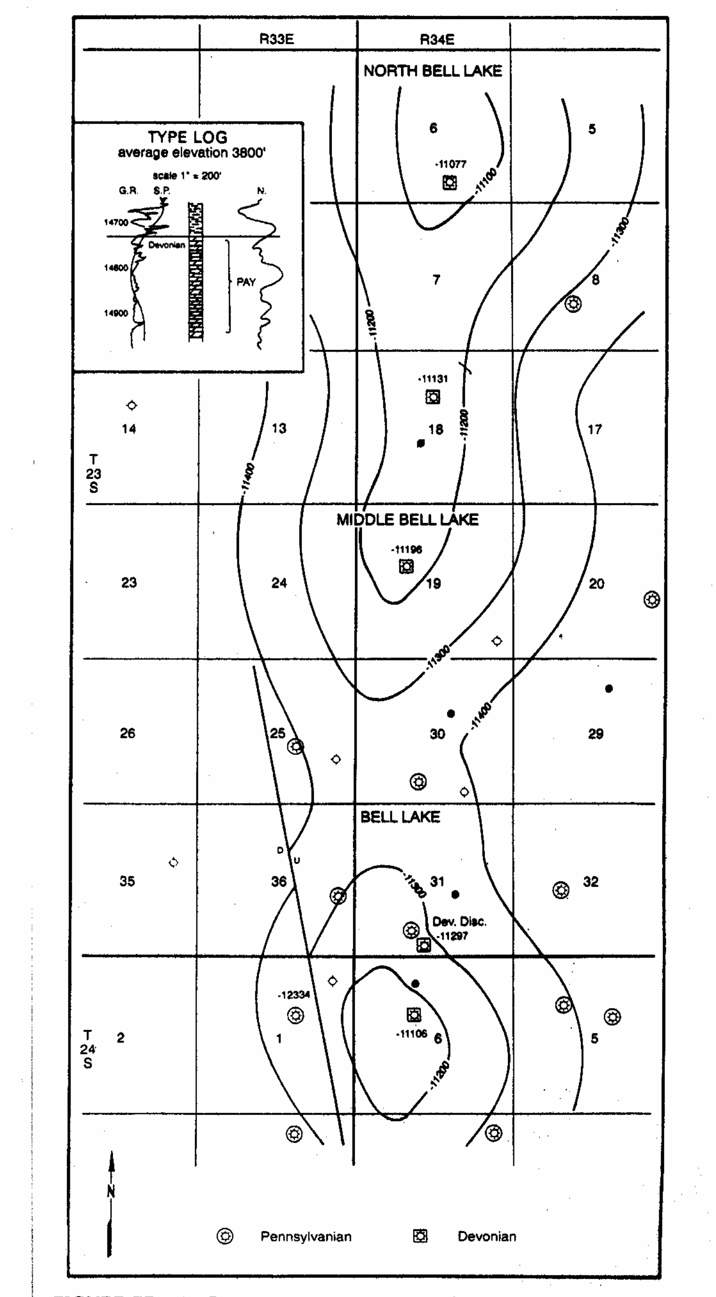

Fig. 56. Structure contours on top of Siluro-Devonian dolomite in the Bell Lake reservoir complex, Lea County, New Mexico. This deep Structural trends is representative of the type of structure and Trap in many Siluro-Devonian reservoirs. From Speer (1993) after Harvard (1967).

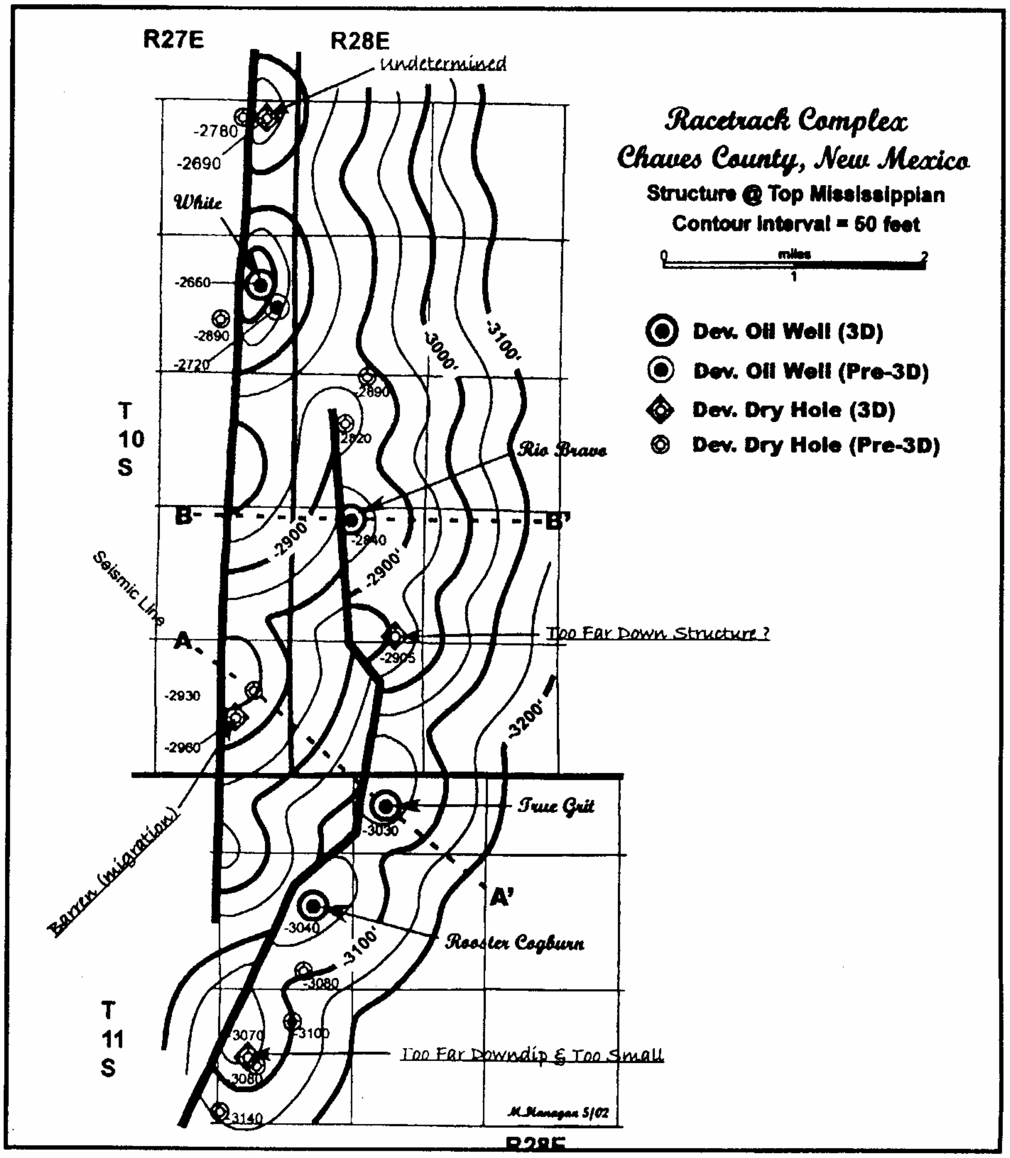

Fig. 57. Structure contours on top of the Mississippian limestones, Racetrack complex, Chaves County New Mexico. This structure is representative of productive structures that trap oil in Siluro-Devonian reservoirs.

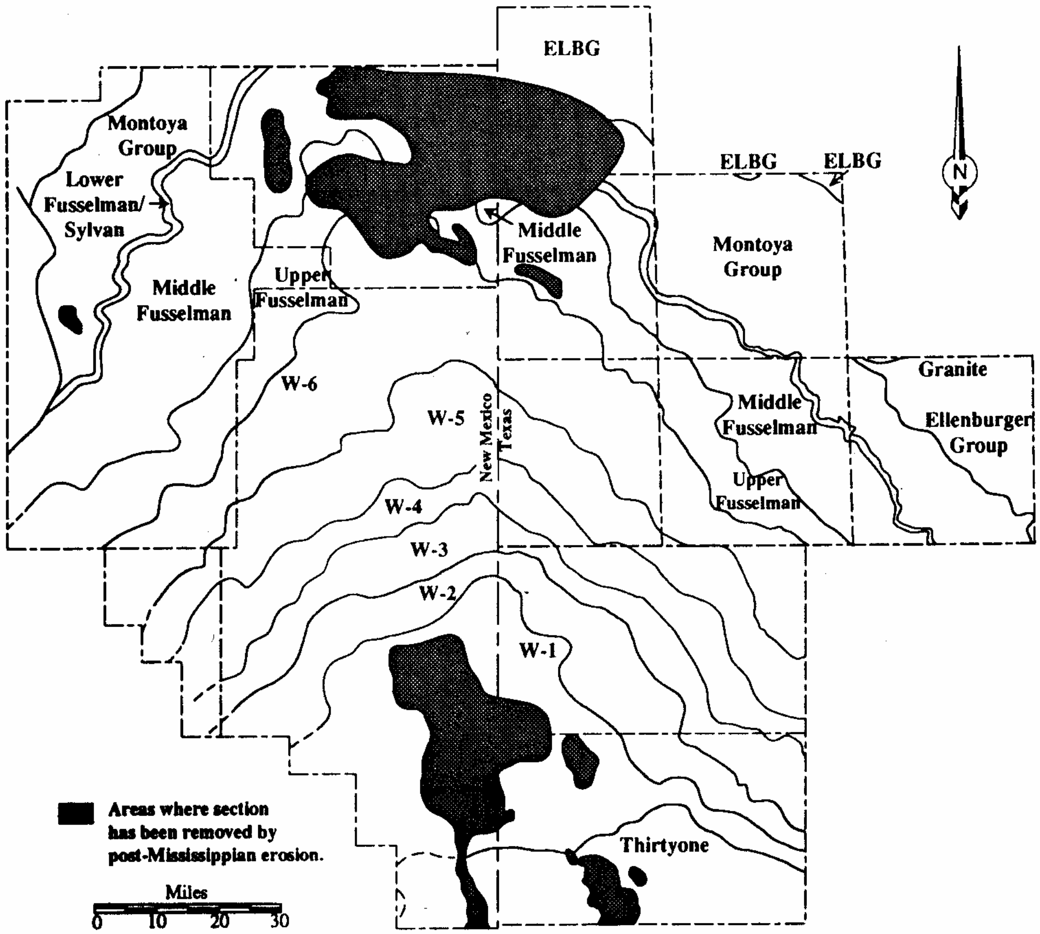

Fig. 58. Subcrop map of the pre-Woodford unconformity in southeastern New Mexico and west Texas showing how progressively older stratigraphic units underlie the Woodford to the north. From Canter et al. (1992).

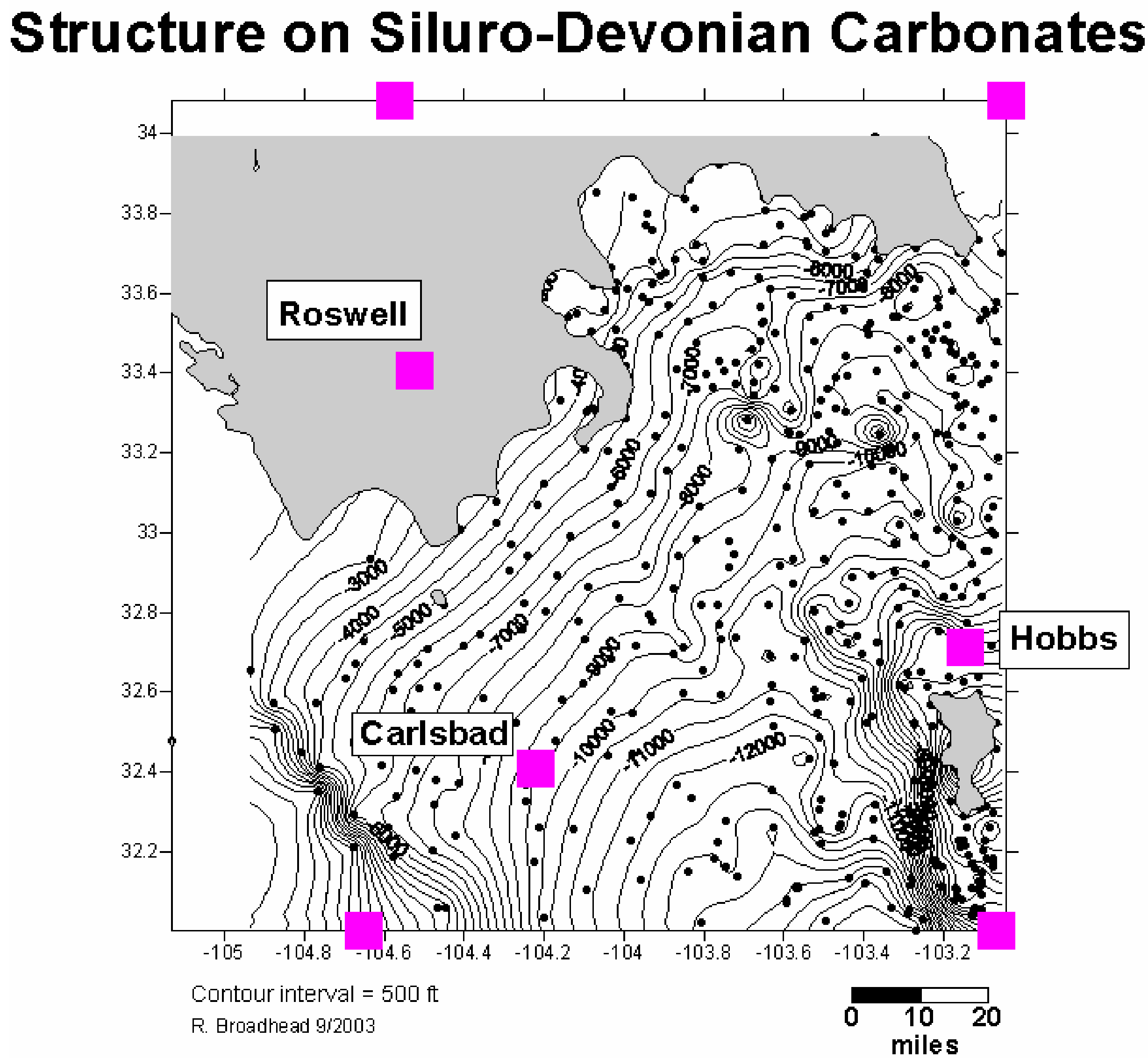

Fig. 59. Structure contour map of the top of the Siluro-Devonian carbonates in southeastern New Mexico. Dots are well control points developed in this project.

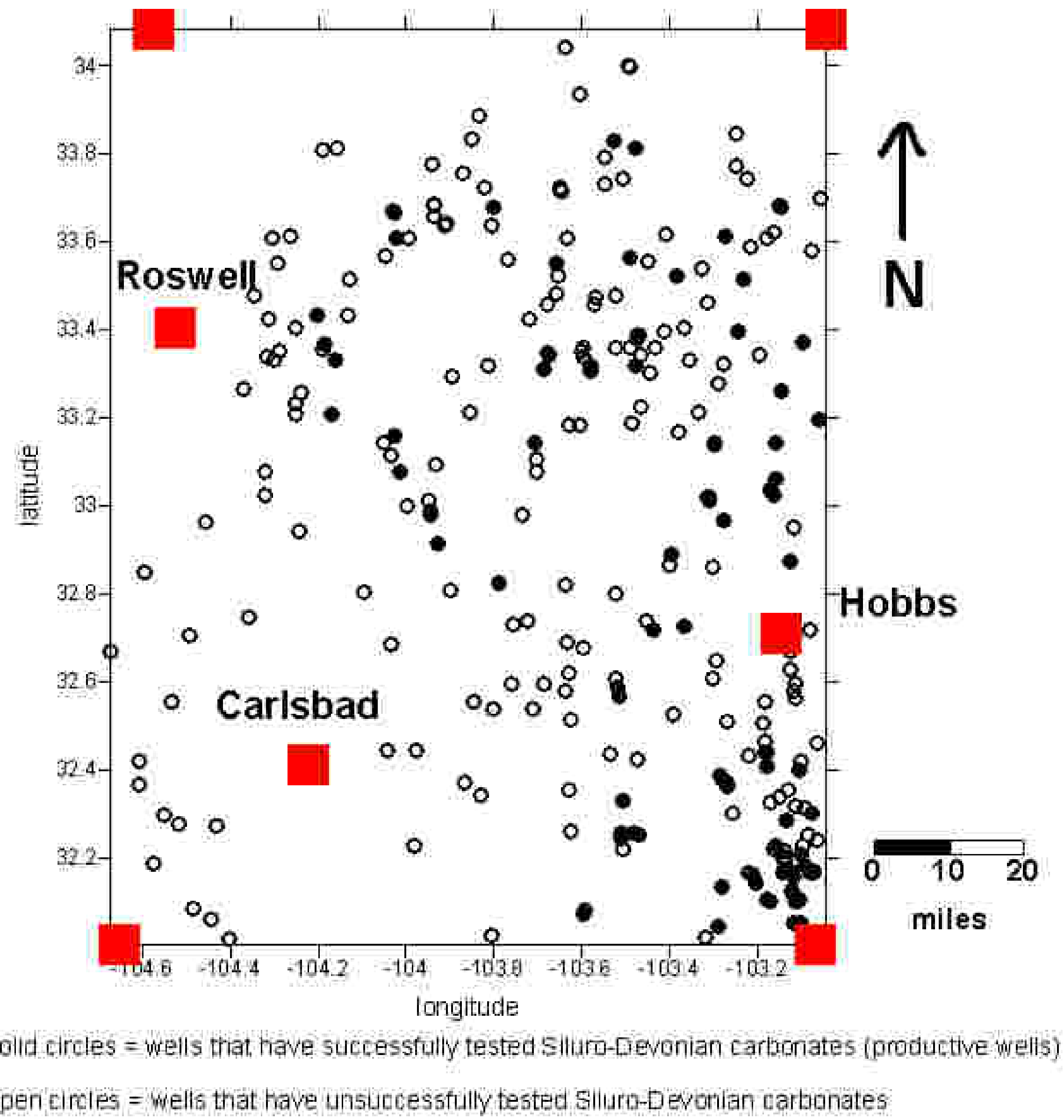

Fig. 60. Map showing database of wells that have successfully tested (solid circles) and unsuccessfully tested Siluro-Devonian carbonates in southeastern New Mexico.

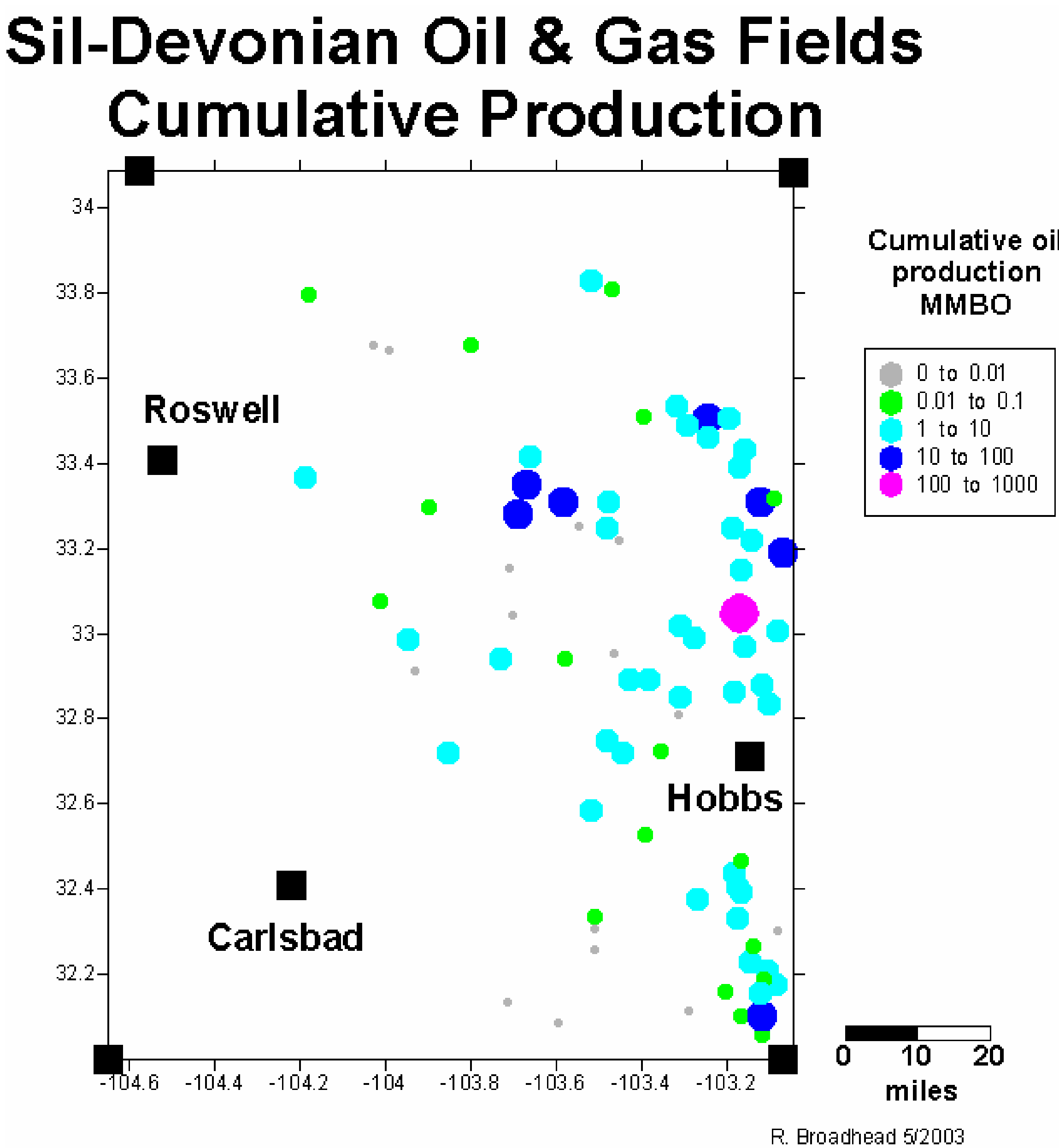

Fig. 61. Reservoirs productive from Siluro-Devonian carbonates in southeastern New Mexico, classified according to cumulative oil production.

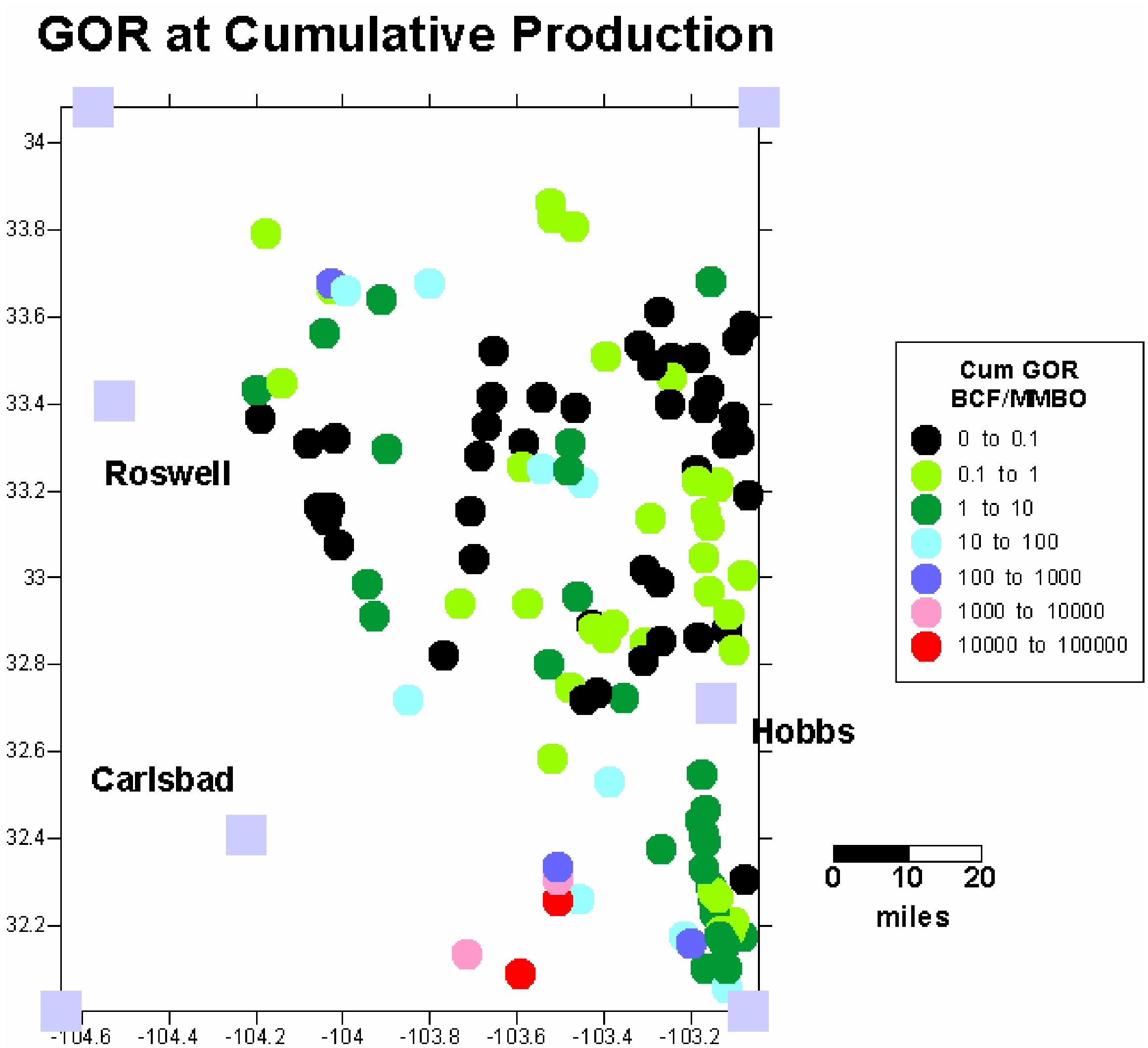

Fig. 62. Reservoirs productive from Siluro-Devonian carbonates in southeastern New Mexico, classed according to lifetime gas-oil-ratio.

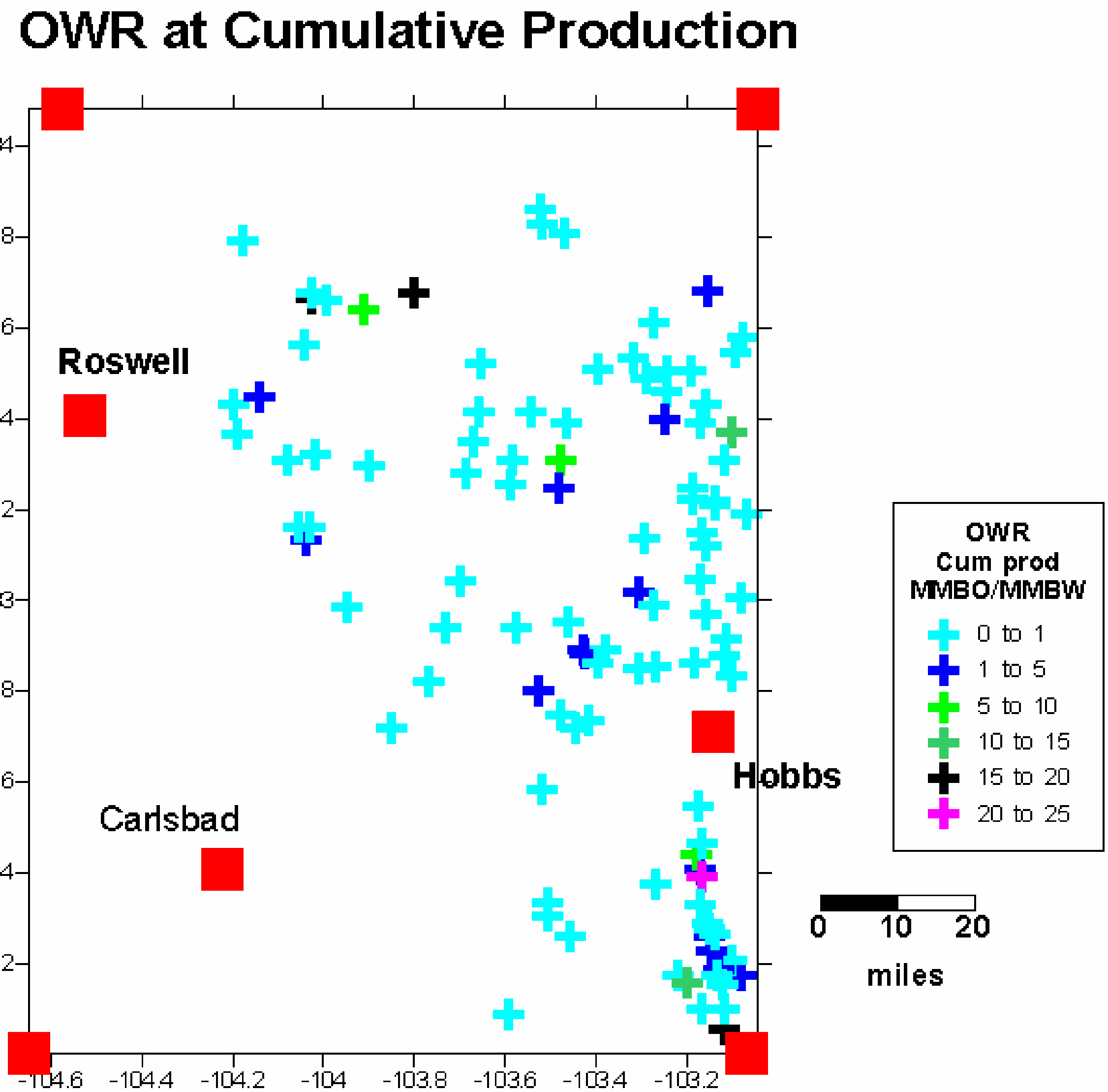

Fig. 63. Reservoirs productive from Siluro-Devonian carbonates in southeastern New Mexico, classed according to lifetime oil-water ratio.

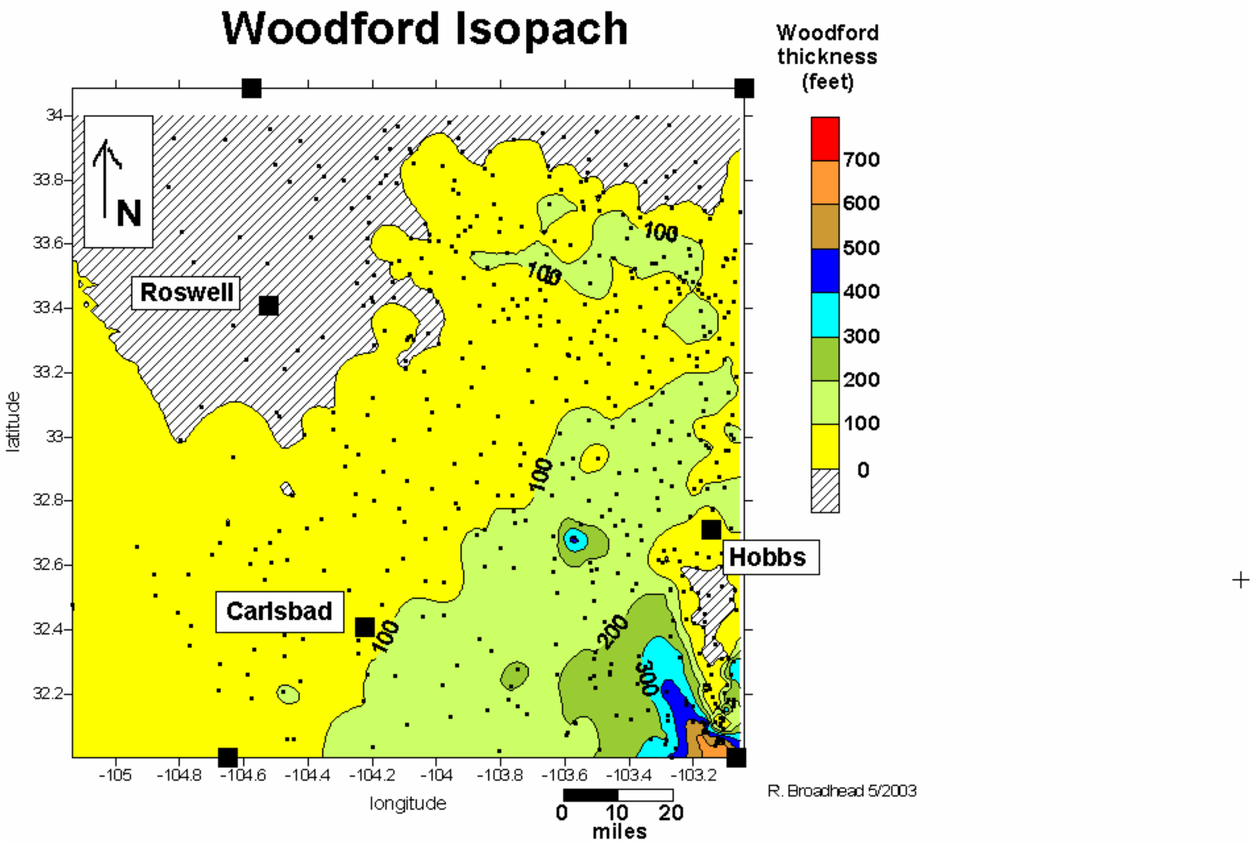

Fig. 64. Isopach map of Woodford Shale in southeastern New Mexico.

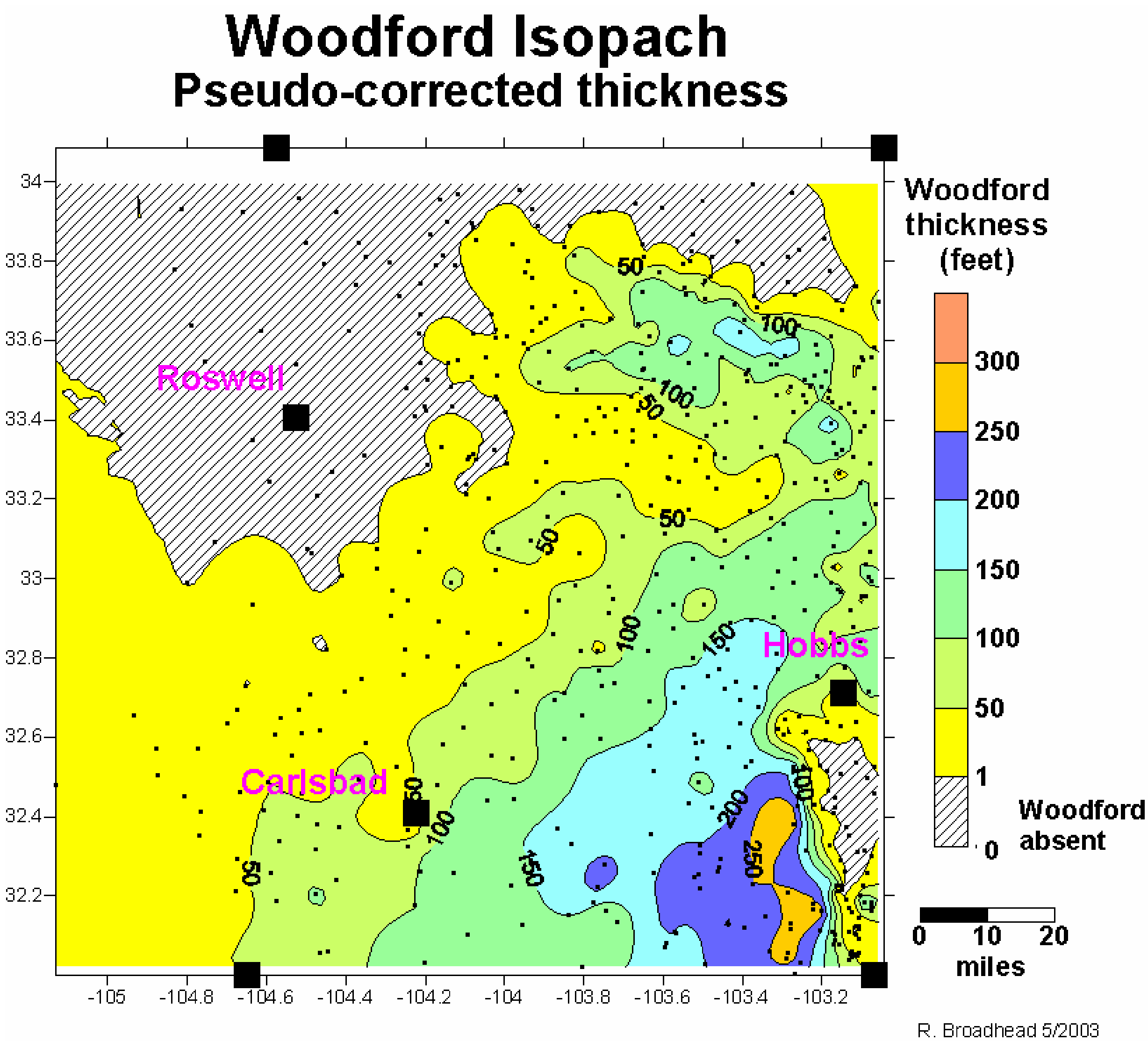

Fig. 65. Pseudo-corrected thickness map of Woodford Shale in southeastern New Mexico, constructed with same data used in Fig. 11 except that wells that encountered obvious steeply dipping Woodford were removed from database. This map more accurately portrays the true thickness of the Woodford than the map in Fig. 11.

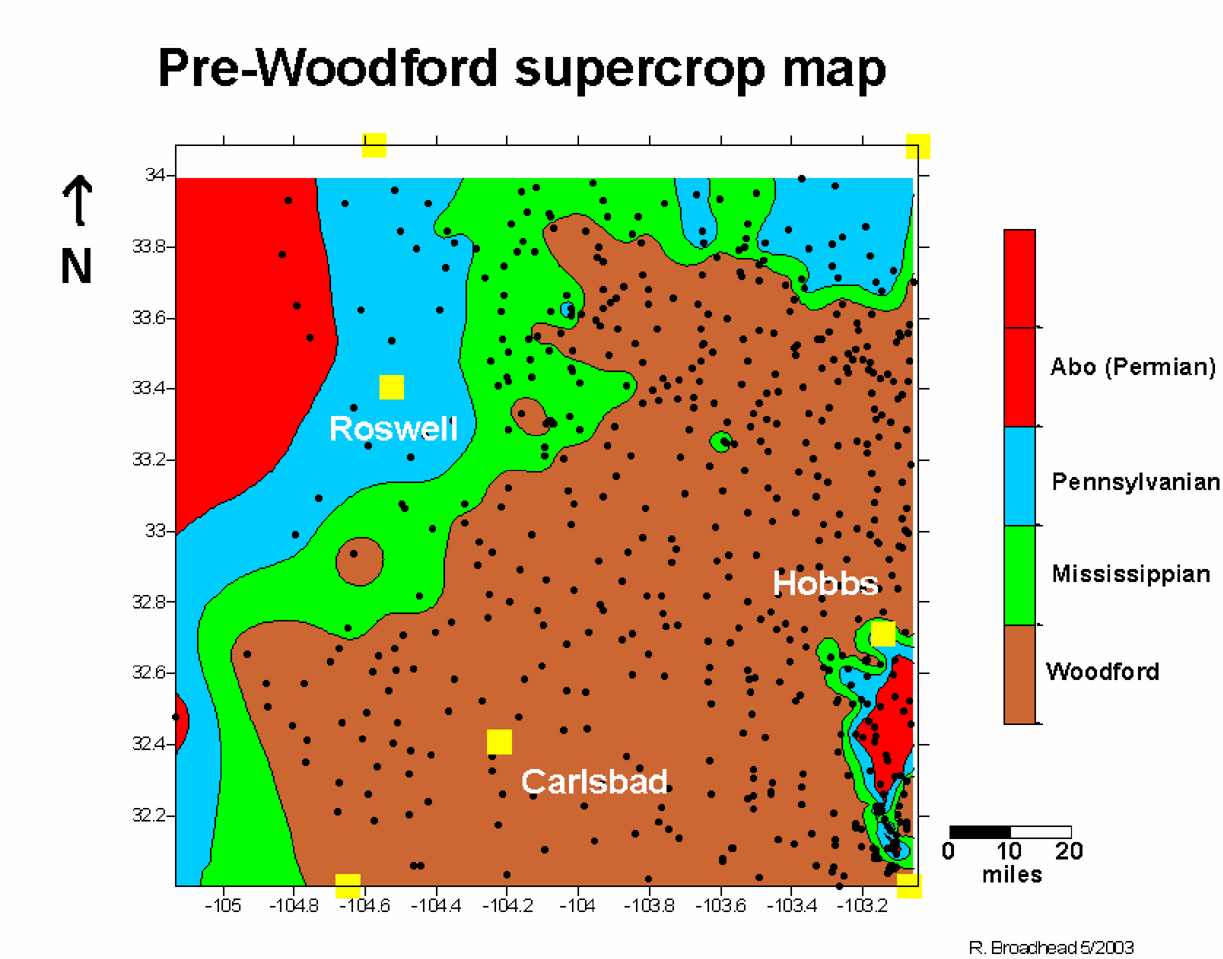

Fig. 66. Pre-Woodford supercrop map showing the stratal units that overlie the Siluro-Devonian carbonate section in southeastern New Mexico.

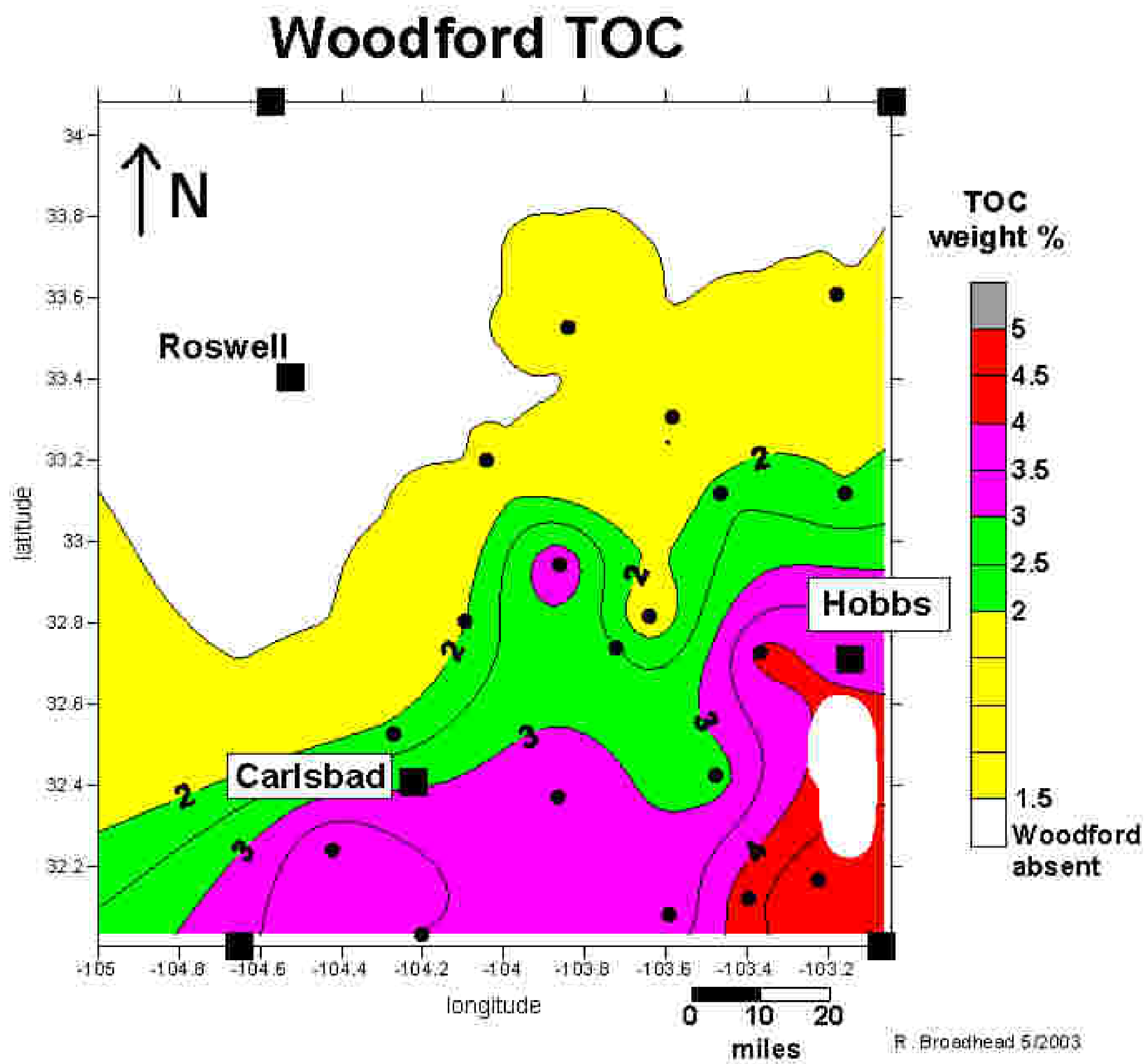

Fig. 67. Map of Total Organic Carbon (TOC) content of the Woodford Shale in southeastern New Mexico.

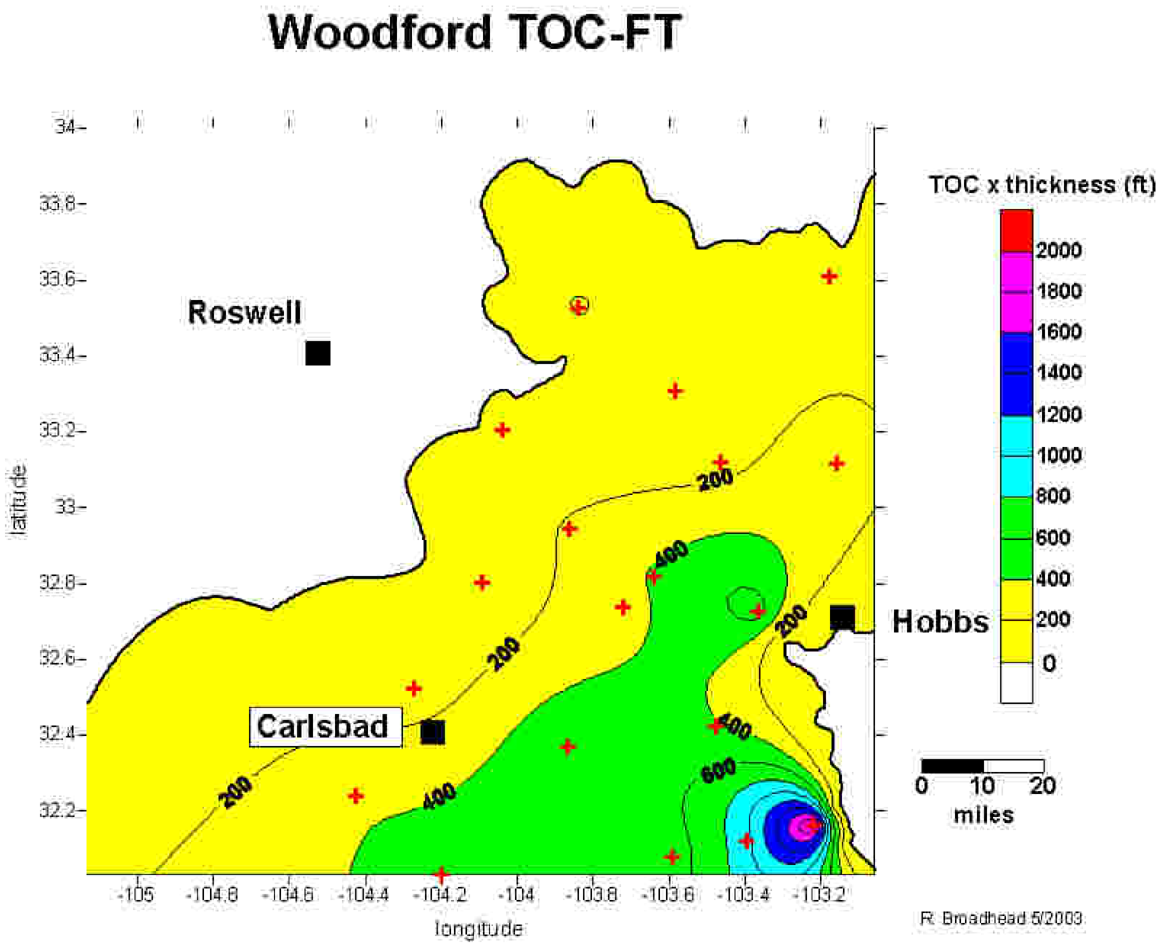

Fig. 68. Map of the product of Woodford thickness and TOC content of the Woodford in southeastern New Mexico.

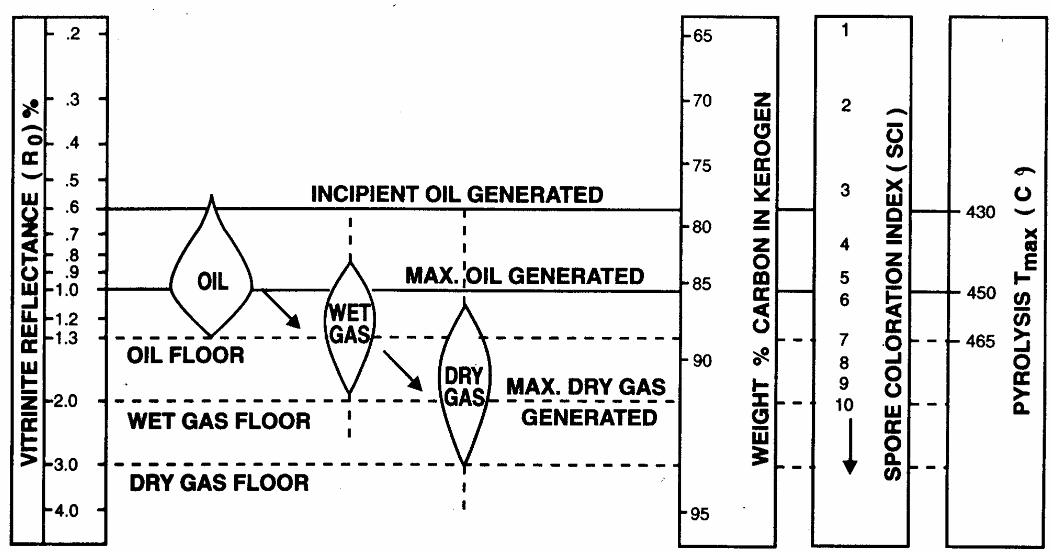

Fig. 69. Zones of petroleum generation and destruction and relationship to some commonly used maturation indicators. From Merrill (1991) after Dow (1978).

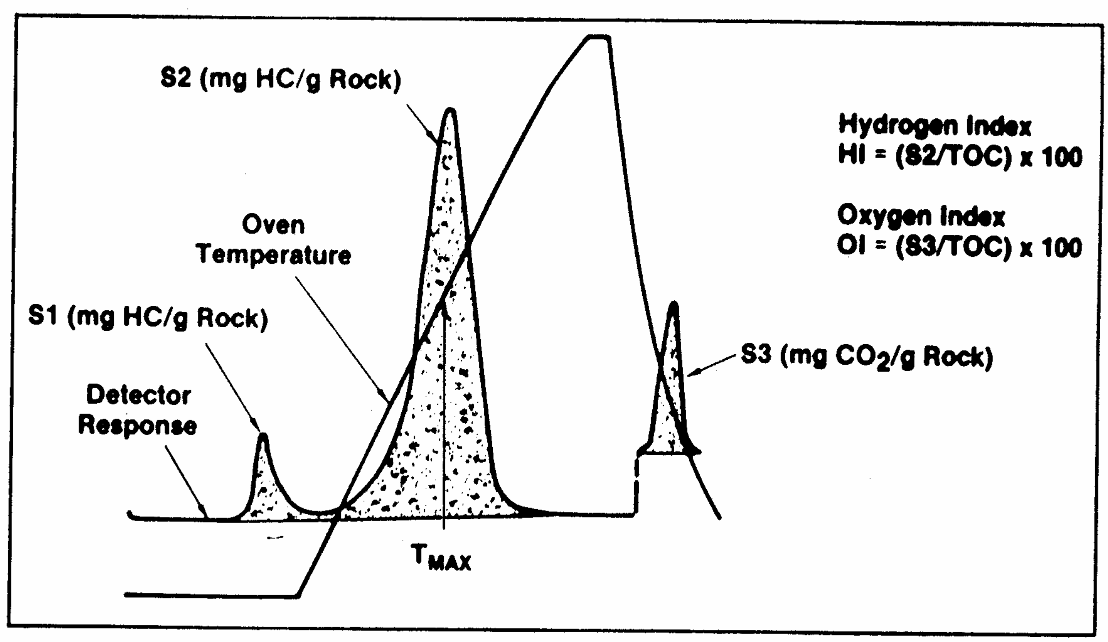

Fig. 70. Schematic of Rock-Eval pyrogram showing the evolution of organic compounds evolved from source rock during heating. Important parameters used for determination of thermal maturity are S_1, S_2, and TMAX. From Peters (1986).

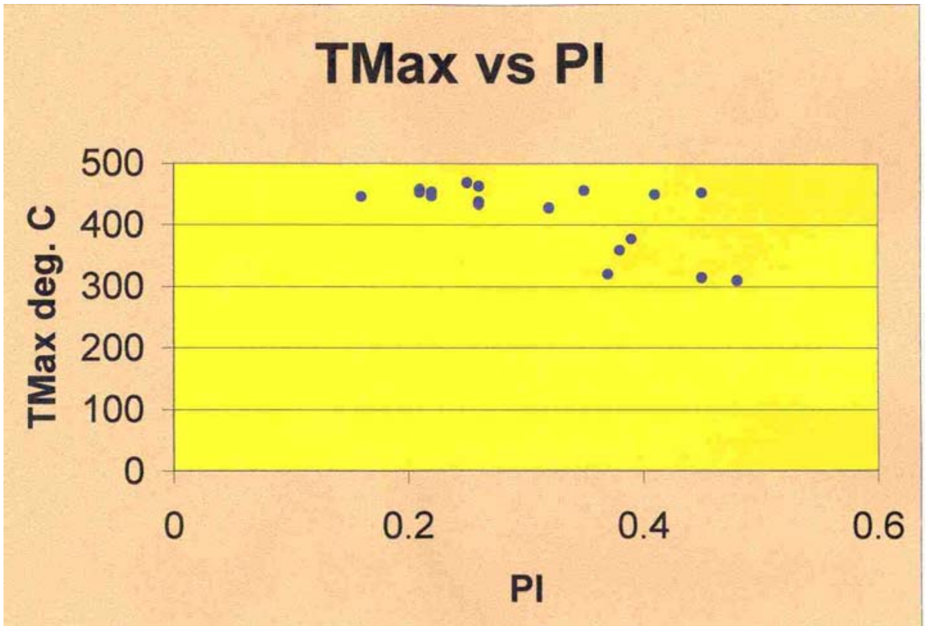

Fig. 71. Plot of Rock-Eval TMAX and Productivity Index (PI) values for Woodford Shale samples in southeastern New Mexico. Note that as PI increases, TMAX decreases, a trend opposite to what is expected as both parameters should increase as a function of increasing thermal maturity.

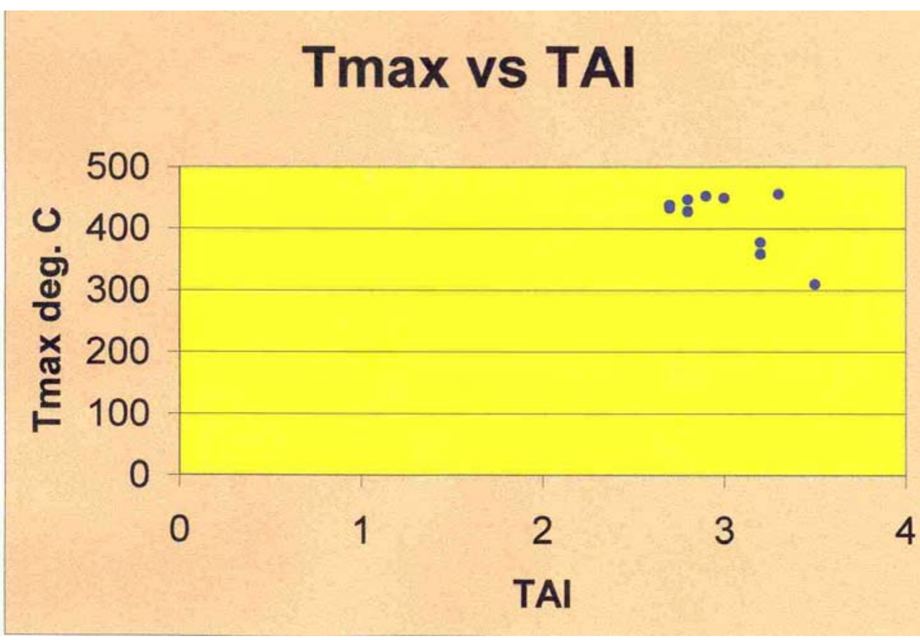

Fig. 72. Plot of Rock-Eval TMAX versus the Thermal Alteration Index (TAI) of kerogen for samples of the Woodford Shale in southeastern New Mexico. Note that as TAI increases, TMAX decreases, a trend opposite to what is expected as both parameters should increase as a function of increasing thermal maturity.

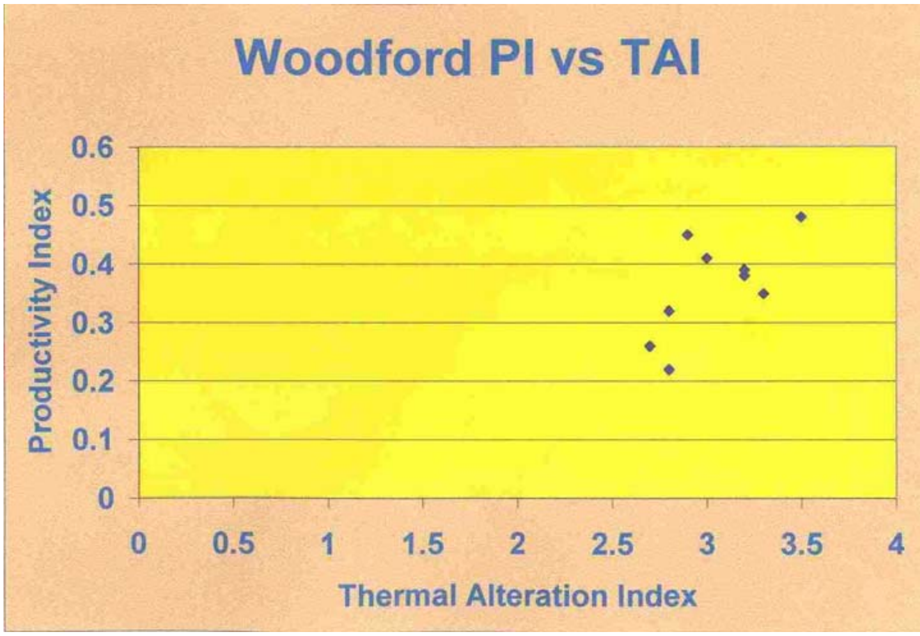

Fig. 73. Plot of Rock-Eval Productivity Index (PI) versus the Thermal Alteration Index (TAI) for samples of Woodford Shale in southeastern New Mexico. Note that as TAI increases, PI also increases, which is the trend expected because both parameters should increase as a function of thermal maturity.

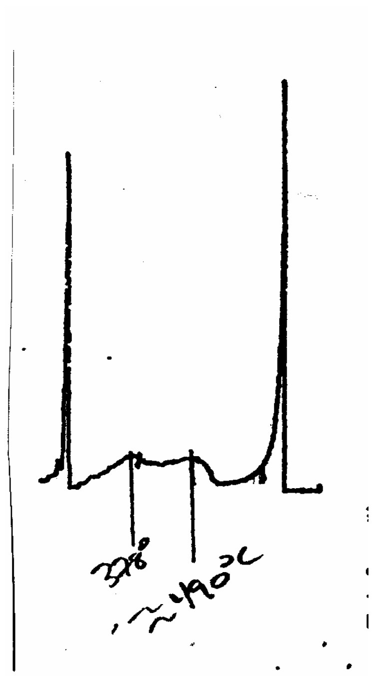

Fig. 74. Rock-Eval pyrogram for a sample of Woodford Shale, showing the bimodal S_2 peak which causes the instrument-derived TMAX values to be incorrect for the Woodford in this area.

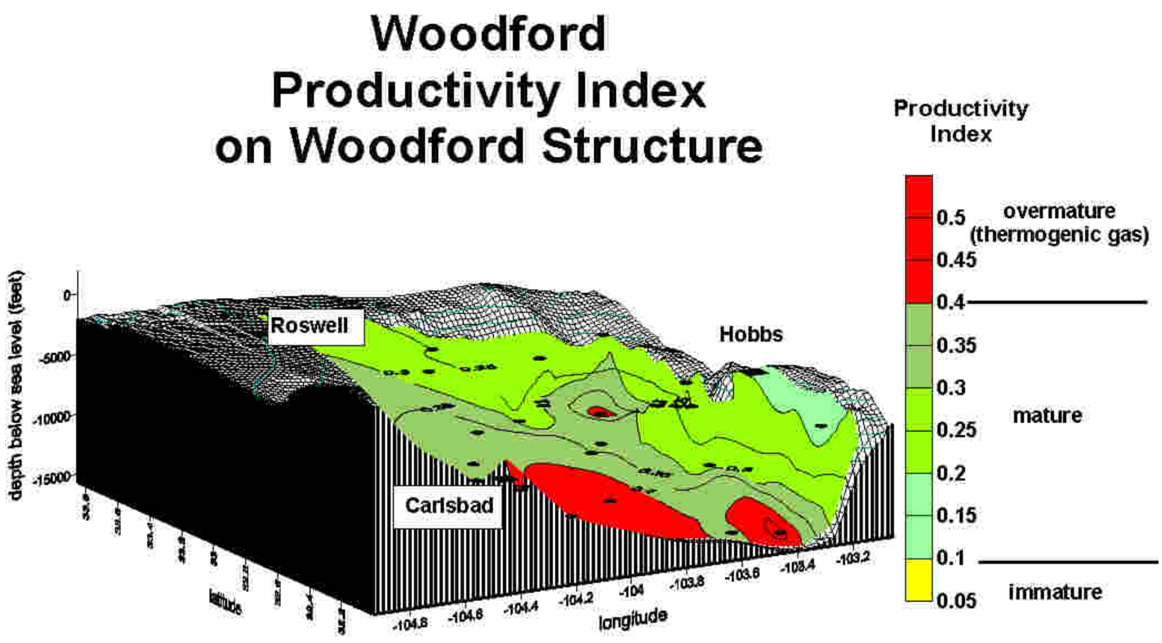

Fig. 75. Rock-Eval Productivity Index (PI) for the Woodford Shale, superimposed on a 3-D block diagram of Woodford structure.

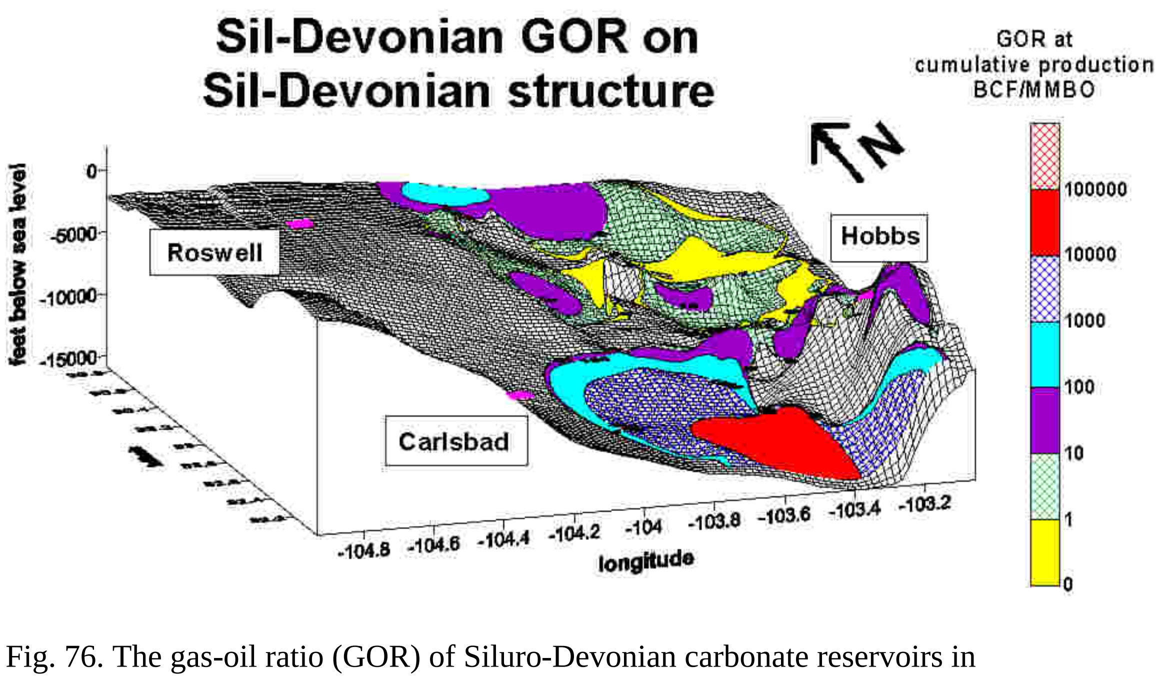

Fig. 76. The gas-oil ratio (GOR) of Siluro-Devonian carbonate reservoirs in southeastern New Mexico superimposed on a 3-D block diagram of structure of the upper surface of the Siluro-Devonian carbonates.