RISK REDUCTION WITH A FUZZY EXPERT EXPLORATION TOOL

Final Report

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Abstract

Incomplete or sparse data such as geologic or formation characteristics introduce 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 when working with sparse data. State-of-the-art expert exploration tools, relying on a database, and computer maps generated by neural networks and user inputs, have been developed through the use of "fuzzy" logic, a mathematical treatment of imprecise or non-explicit parameters and values. Oil prospecting risk has been reduced with the use of these properly verified and validated "Fuzzy Expert Exploration (FEE) Tools."

Through the course of this project, FEE Tools and supporting software were developed for two producing formations in southeast New Mexico. Tools of this type 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 today's oil industry environment, many smaller exploration companies lack the resources of a pool of expert exploration personnel. Downsizing, volatile oil prices, and scarcity of domestic 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 Tools benefit a diverse group in the U.S., allowing a more efficient use of scarce funds, and potentially reducing dependence on foreign oil and providing lower product prices for consumers.

Executive Summary

Expert systems are artificial intelligence tools that store and implement expert opinions and methods of analysis. The "Risk Reduction with a Fuzzy Expert Exploration Tool" project tested and proved the ability of expert systems to enhance the exploration process and to allow the rapid simultaneous evaluation of numerous prospects. The project resulted in two fuzzy expert exploration tools (FEE Tools), one developed for the Lower Brushy Canyon formation of the New Mexico portion of the Delaware Basin, and the second for the Siluro-Devonian carbonates of southeast New Mexico. Both systems were extensively tested and have been made available to the public in both online and a stand-alone versions.

The stratigraphic Brushy Canyon play of the Delaware Basin, SE New Mexico, was the initial target for the project. Analysis of 60,478 40 acre potential drilling sites by the expert system identified approximately 212 million barrels of new recoverable reserves in 4481 undrilled prospects. Reduced finding costs resulting from use of the system make the pool an enticing play for both new exploration and recompletions. The structurally complex Siluro-Devonian Carbonates of SE New Mexico was the second target. These deep, often prolific reservoirs typically require expensive 3D seismic data as a basis for exploration. The expert system has identified approximately 1500 sections, out of an area of more than 15,000 mi^2, with optimal production potential. The analysis can significantly reduce exploration costs and allow more focused surveys, therefore reducing wildcat risk.

To accomplish the development of these expert systems, massive databases of public domain information for both plays were compiled, and additional geological, engineering, and production data were generated during the course of the project, creating a knowledge base for both formations. Models employing human expert knowledge of each play were developed, along with intuitive graphical user interfaces and fuzzy

inference engines to process those expert rules, resulting in fast, multi-tiered systems, which can be customized for personal or corporate philosophies while maintaining the integrity of proprietary information. Both tools were designed using the Java programming language to allow easy use through a browser window over the Internet. Stand-alone versions were developed concurrently. Both systems were extensively tested using statistics and by exclusion of blind test data.

Both expert systems offer a very good simulation of expert human explorationists, reducing Brushy Canyon dry hole risk by 75% and potentially reducing the exploration area for the Siluro-Devonian in New Mexico by over 90%. The expert systems also provide a quick-look tool for prospect analysis, enabling a faster and more consistent exploration process and the ability to rapidly evaluate well re-completion opportunities.

Support software developed for this project includes: PredictOnline, an easily used neural network program; FuzzyRank, a program for selecting relevant variables using a fuzzy ranking algorithm: and WDMS, a Web-based Data Management System.

Experimental

No experiments are associated with this project.

Results and Discussion

1. Introduction

In the five years and nine months of the FEE Tool Project, an immense amount of data on the Delaware Basin and Devonian Carbonates has been accumulated, including data on geology, structure, production, regional information such as gravity, and local data, such as well logs. These data, organized and cataloged into several online databases, are available for both expert systems and users as needed and as appropriate in analyzing production potential. A map of production potential for the Lower Brushy Canyon formation of the Delaware Basin and the Devonian Carbonates has been generated and can now be modified by users by altering rules defined by human exploration experts in the target formations, and statistical rules defined by the database, using an interactive on-line expert system. A number of new and useful tools and technologies to support these efforts have been generated including: online useable interfaces for neural network analysis (PredictOnline); ranking of potential inputs using fuzzy logic (FuzzyRank); expert systems able to make prospect evaluations for the Lower Brushy Canyon and the Devonian Carbonates; and a web interface for accessing the databases and expert system software. The two expert systems, the Delaware FEE Tool and the Devonian FEE Tool are both available online and have been used by producers to evaluate prospects.

Though this on-line system is secured by 128-bit encryption, some users feel more comfortable working offline. In the final project year, stand-alone versions were produced for both tools, and user requested enhancements such as modifying the output formats, a batch mode, and providing downloadable data files were made.

Throughout the project, additional work has been done applying neural networks, fuzzy ranking algorithms and the fuzzy expert systems to diverse projects. These include using neural networks to correlate well logs and predict oil prices, and using the Delaware FEE Tool as a reserves estimating tool. These projects are also detailed in this report.

The report is organized as follows:

- Chapter 2 contains a discussion about the data used in the project. The major sections are **geology**, **geophysics** and **production data** sections.
- Chapter 3 covers the first of the two major tools developed through this project, the Delaware Fuzzy Expert Exploration Tool.
- Chapter 4 covers the second major tool, the Devonian FEE Tool.
- Chapter 5 contains information about the Java software developed for the two FEE Tools.
- Chapter 6 details the technology transfer that occurred throughout this project. This includes all papers, project reviews and training sessions.
- Chapter 7 is a collection of information about collateral project software and results, including the PredictOnline software, the FuzzyRank software and the WDMS software, as well as applications of the REACT software, including oil price forecasting, using neural networks to make predictions from well logs, and using the Delaware FEE Tool to estimate recoverable reserves.

2. Geology and Production Data

2.1 Geology

2.1.1 Lower Brushy Canyon Formation

The Brushy Canyon Formation of the Delaware Mountain Group (Permian: Guadalupian) consists of 550 to 1650 ft of interbedded fine-grained sandstones, siltstones, and minor detrital carbonates deposited in the deep-marine Delaware Basin (Fig. 2.1).

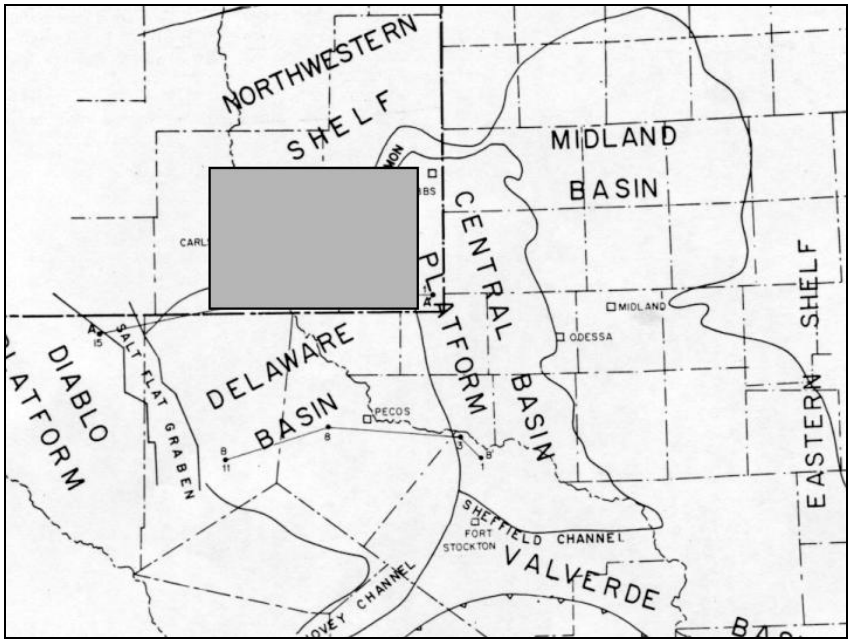

Fig. 2.1: Location of project area in relation to Delaware Basin and other geologic elements, Permian Basin area southeast New Mexico and west Texas. Geologic elements modified from Hills (1984).

The Brushy Canyon Formation unconformably overlies the Bone Spring Formation (Permian: Leonardian) or erosional remnants of the Cutoff Formation (Permian: Guadalupian) throughout much of the Delaware Basin (Fig. 2.2).

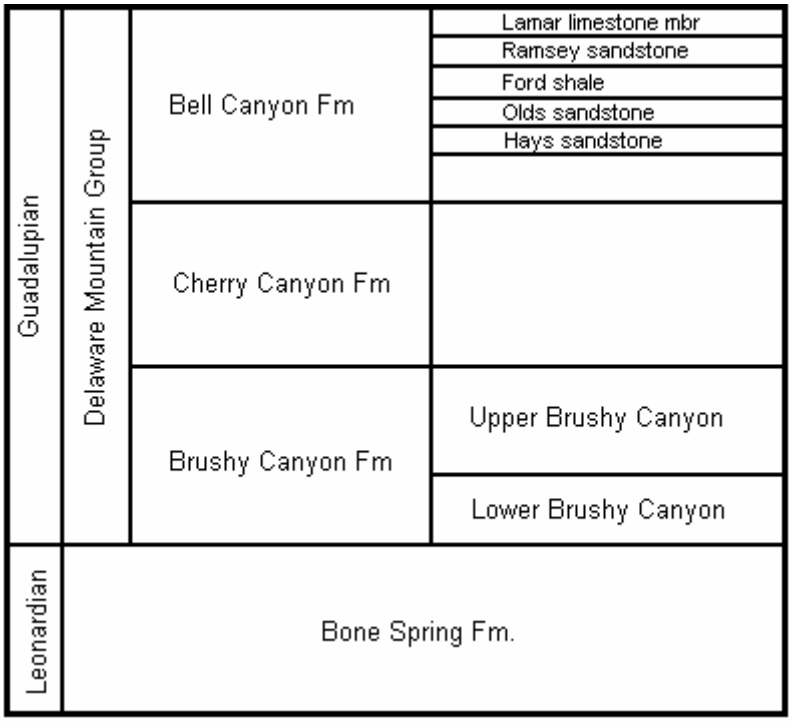

Fig. 2.2: Stratigraphic chart of Delaware Mountain Group. Compiled from Payne (1976), Grauten (1979), Harms and Williamson (1988), and Montgomery et al. (1999).

The Brushy Canyon is overlain by basinal sandstones and siltstones of the Cherry Canyon Formation (Permian: Guadalupian). In New Mexico, depth to the Brushy Canyon ranges from 1950 ft near the northern and western margins of the basin to 8600 ft in the deepest part of the basin in southwest Lea County.

The Brushy Canyon became a major exploration and development target in the middle to late 1980s. It had been drilled through and ignored for decades as producers concentrated on deeper targets, mainly gas-productive intervals in the Morrowan and Atokan (Lower Pennsylvanian) and also on shallower oil-productive sandstones of the Bell Canyon Formation of the Delaware Mountain Group (Permian: Guadalupian). The Brushy Canyon sandstones were not considered a viable exploration target for four reasons [Montgomery et al., 1999]. First, they are low-resistivity sandstones for which conventional log analysis indicates high water saturations. Second, they are less permeable than shallower oil-productive sandstones in the Bell Canyon. Third, the Brushy Canyon is a deeper target than the Bell Canyon, therefore making it seem less

economically viable. Fourth, few or no oil flows from Brushy Canyon sandstones are seen on drill-stem tests. Since the mid-1980s, however, the Brushy Canyon has been recognized as a major, economically viable target. More than 110 fields currently produce oil and associated gas from the Brushy Canyon in southeast New Mexico. The predominant trapping mechanism is stratigraphic [Montgomery et al., 1999].

The Brushy Canyon has been subdivided into three informal stratigraphic units by most workers, an upper unit, a middle unit, and a lower unit [Fig. 2.2; Montgomery et al., 1999]. Boundaries between the units are not well defined and generally vary from worker to worker. The upper Brushy Canyon produces significant volumes of oil and the middle Brushy Canyon produces relatively little oil. The lower unit has produced most of the oil obtained from the Brushy Canyon. This part of the project concentrated on the Lower Brushy Canyon.

Brushy Canyon fields have typically been discovered by reexamining and reentering old wells that have produced from deeper stratigraphic units such as the Morrow (Lower Pennsylvanian) but have been abandoned as the deeper production has declined to sub-economic levels. Recompletions are typically made in those wells that exhibited good mud log shows in the Brushy Canyon but were never tested or were tested with water recovery on a drill-stem test. A few operators have drilled new wells updip of older wells that have exhibited shows in the Brushy Canyon, but most discoveries have been made by reentering old wells. Most exploration, therefore, has been concentrated on wells that have been drilled to Lower Pennsylvanian targets. While this has proved to be a successful and economically viable strategy for many operators, it has largely limited exploration to areas where recently abandoned deep wells are available for reentry. Because many of the wells were originally drilled on structures that affect the Lower Pennsylvanian, most Brushy Canyon exploration has therefore been essentially structural in aspect and has largely ignored the dominant stratigraphic component of trapping for the play.

The initial portion of the project involved the acquisition, synthesis, and analysis of structural, stratigraphic, production, reservoir, and source-rock data. The data are collected from more than 720 wells basin-wide (Fig. 2.3).

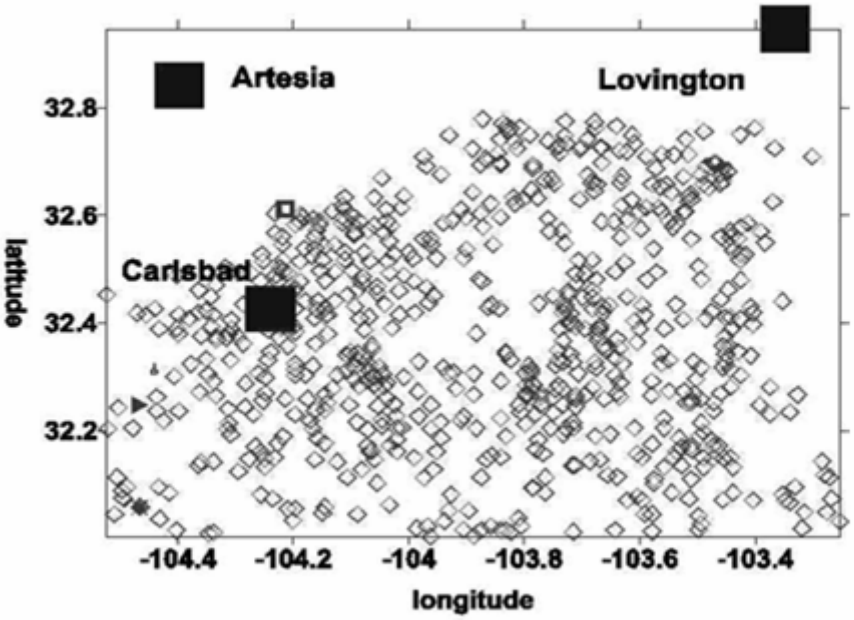

Fig. 2.3: Location of well data control points used in the Brushy Canyon part of this project. See Fig. 2.1 for map location.

Wherever possible, data were collected so that data from productive wells in Brushy Canyon pools were offset by nonproductive wells adjacent to those pools. In this way, geologic contrasts between productive areas and immediately adjacent nonproductive areas are reflected in the dataset and its derivative maps. Data synthesis and analysis performed as this part of the project have been used to help devise and structure the neural network system.

The structure on top of the Bone Spring Formation (Fig. 2.4) and Lower Brushy Canyon Formation (Fig. 2.5) indicate more than 7500 ft of structural relief between the shallower parts of the basin to the north and the deepest part of the basin to the southeast. The structure on the top of the Brushy Canyon Formation (Fig. 2.5) is very similar with a

relief of only 7200 ft, indicating a partial infilling of the basin during Brushy Canyon time.

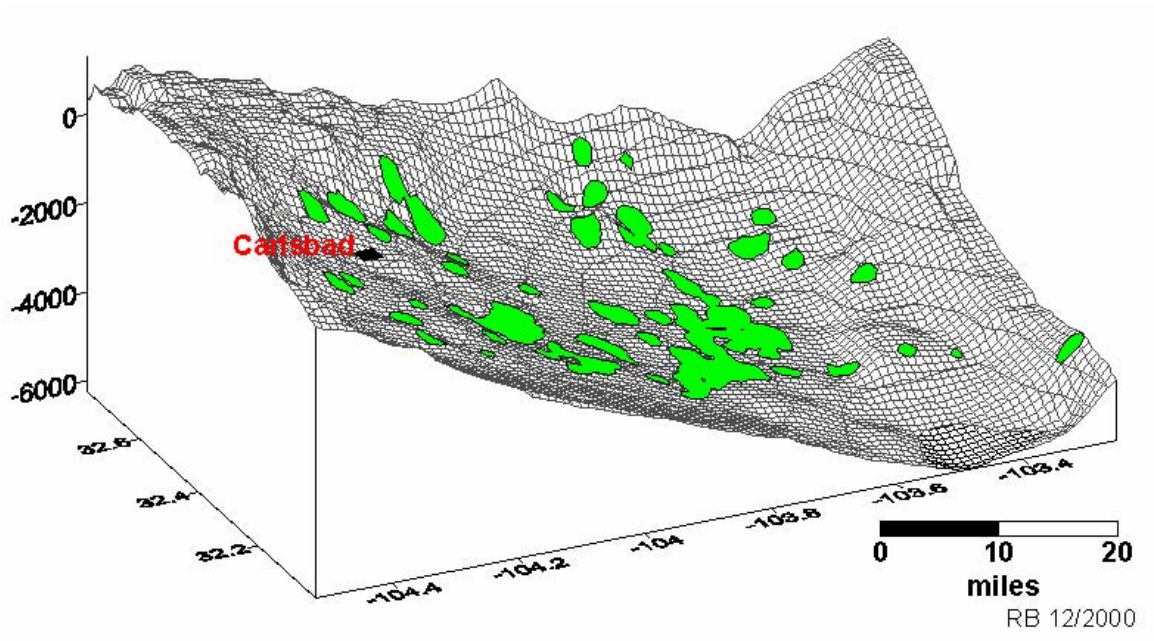

Fig. 2.4: Three-dimensional view of structure on Bone Spring Formation and location of oil pools (green) productive from the lower part of the Brushy Canyon Formation.

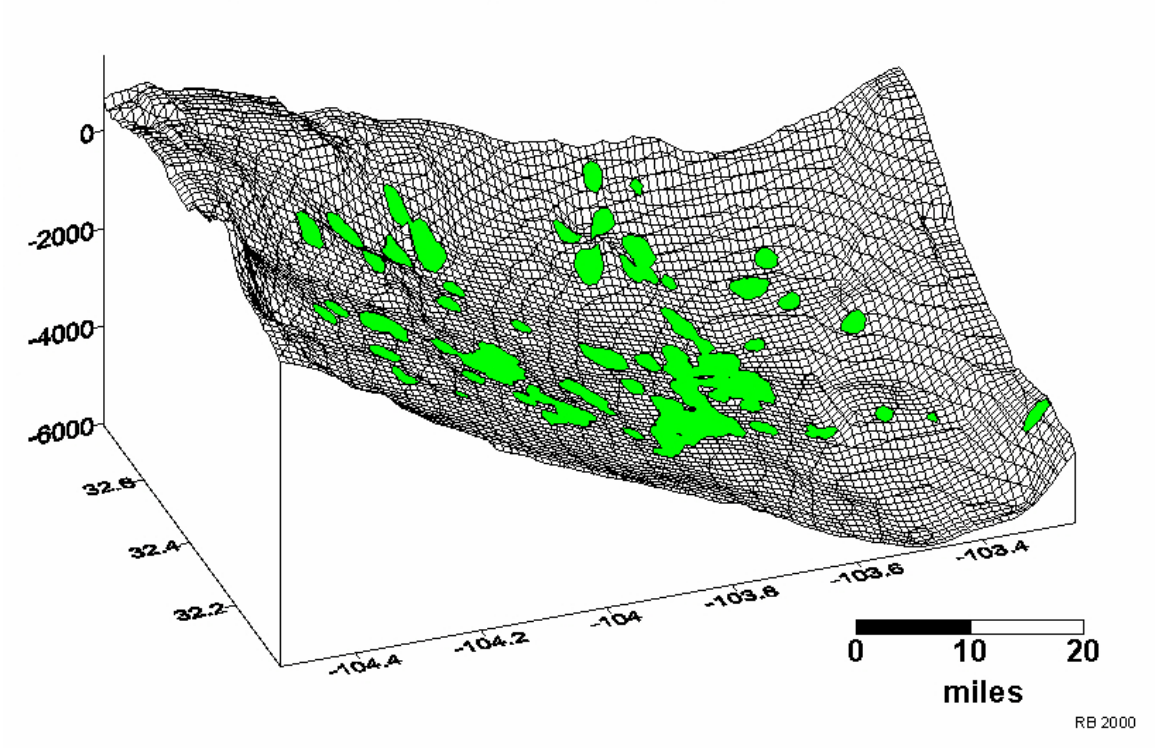

Fig. 2.5: Three-dimensional view of structure on Lower Brushy Canyon Formation and location of oil pools (green) productive from the lower part of the Brushy Canyon Formation.

The structure on the top of the Bone Spring Formation includes numerous local closures and structural noses that are superimposed on the regional descent of the Bone Spring into the Delaware Basin. Also present are several structural lows that extend into the basin from adjacent areas on the Northwest shelf. As discussed below, many of these local structures controlled sand distribution in the Lower Brushy Canyon and are therefore paleobathymetric elements that were in existence at the time of Brushy Canyon deposition. Many, but certainly not all, appear to be located over Pennsylvanian structures described by Montgomery et al. (1999). Pennsylvanian- and Permian-age structure has been overprinted by a southeast regional tilt of Laramide (Late Cretaceous Early Tertiary) age [Hills, 1963; Dickerson, 1985].

The lower part of the Brushy Canyon Formation is 60 to 500 ft thick within the project area in southeast New Mexico (Fig. 2.6). It consists of arkosic to subarkosic, fine-grained sandstones (reservoir facies), organic-rich siltstones (seal and source-rock facies), dolostones and limestones that are present mostly near the shelf margin, and black to dark-gray calcareous shales or marlstones [Montgomery et al., 1999].

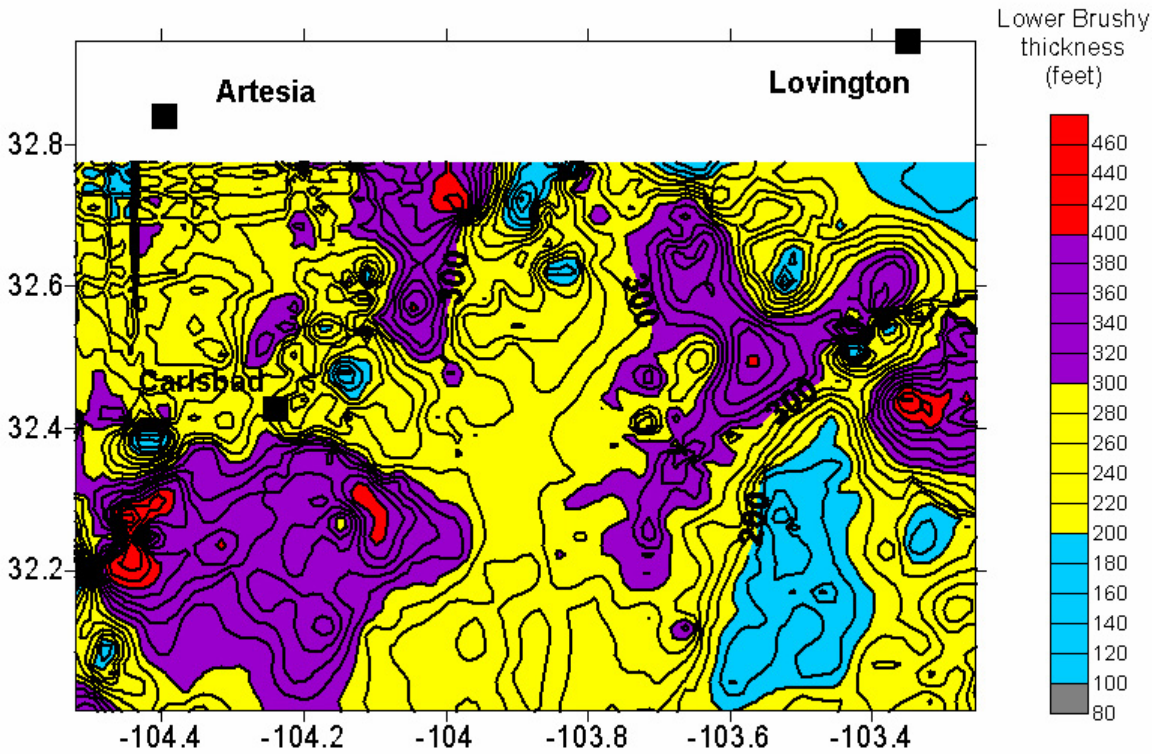

Fig. 2.6: Isopach map of the Lower Brushy Canyon Formation.

Brushy Canyon sandstones are allochthonous sediments that originated on surrounding shelf areas and were transported into the deep-marine Delaware Basin prior to deposition. The mechanism of transport is enigmatic and has been ascribed recently to various gravity-related flow processes including saline density currents [Harms, 1974; Harms and Williamson, 1988; Harms and Brady, 1996] and turbidity currents [Hull, 1957; Jacka et al., 1968]. Whatever the mechanism of transport, the conveying currents apparently flowed downslope and deposited the sands in submarine channels and on submarine fan and channel complexes [e.g. May, 1996; Thomerson and Catalano, 1996; Basham, 1996;

Broadhead et al., 1998]. Most depositional models hypothesize that Brushy Canyon sands were initially transported across the Northwest shelf during lowstands of sea level when the shelf was exposed. The sands were then remobilized and transported into the basin through submarine canyons incised into the shelf-edge carbonates.

Thicker areas of the Lower Brushy Canyon were deposited in structurally low depressions in the underlying Bone Spring Formation. Many of these depressions originate at the shelf edge and are elongate perpendicular to the shelf edge. This relationship between Lower Brushy Canyon thickness patterns and underlying Bone Spring morphology indicates that the structural depressions were depressions that acted as conduits for the transport of Brushy Canyon sands into the deep basin and as ponding areas where submarine fans were formed.

Similar patterns of thickness distribution can be seen on isolith maps of reservoir quality sandstone within the Lower Brushy Canyon. One map, derived from density porosity logs, show the net thickness of sandstone with at least 15 % porosity (Fig. 2.7). A map that shows thickness of sandstone with at least 10% porosity has similar patterns (Fig. 2.8). Both of these maps indicate the distribution of reservoir quality sandstones that are capable of sustained, economic levels of oil production, although the sandstones with a minimum of 10% porosity may be marginally productive. Reservoir quality sandstones in the Brushy Canyon that are oil-productive typically have porosity in the 12 to 22%

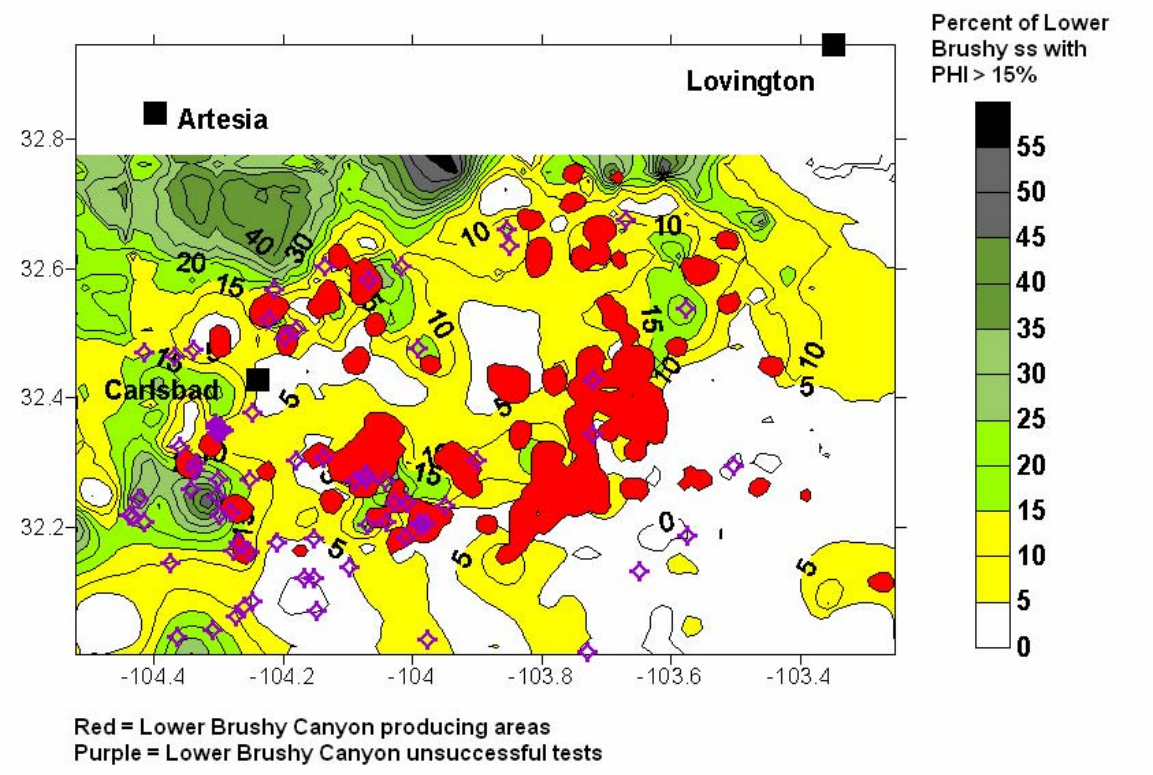

Fig. 2.7: Areas productive from Lower Brushy Canyon, net thickness of Lower Brushy Canyon sandstones with porosity > 15%, and wells that unsuccessfully tested the Lower Brushy Canyon.

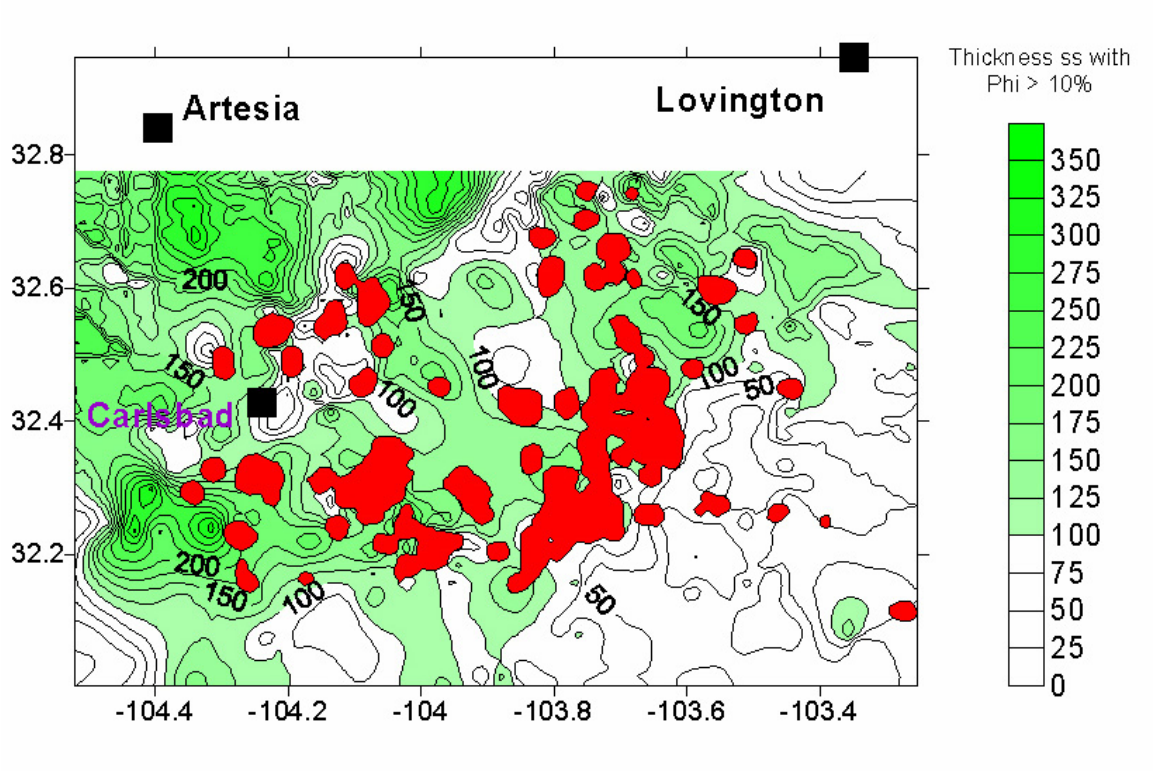

Fig. 2.8: Areas productive from Lower Brushy Canyon and net thickness of Lower Brushy Canyon sandstones with porosity > 10%.

range [Asquith et al., 1996; Gawloski, 1995; Hoose and Dillman, 1995; LeMar, 1995; May, 1996; Mitchell, 1995; Tittl, 1995; White, 1995; Worrall, 1995]. It is possible that some sandstones with more than 15% porosity will not be productive because of the dominance of micropores that that inhibit the migration and production of oil [Asquith et al., 1996].

Thicker areas of reservoir quality sandstones are located along the northern and western margins of the basin and are distributed along linear to lobate trends that extend from the basin margin into the deeper parts of the basin. Primary sources of reservoir quality sand were mostly located to the northwest and the west. The eastern part of the Northwest shelf contributed lesser, but still significant, volumes of sand. Only minor amounts of reservoir quality sand were derived from the central basin platform to the east. An overlay of the 15% porosity isolith map on the Bone Spring structure map indicates that

the reservoir sandstones are confined mostly to the structural depressions in the underlying Bone Spring or are present as lobe-shaped deposits (submarine fans) downslope of where the depressions terminate (Fig. 2.9). Deflection of transporting currents around structural closures and noses in the basin is evident in the map patterns.

Depositional sandstone units are separated by 5 ft to 20 ft thick layers of organic-rich siltstones. These siltstones are represented on logs as radioactive beds. Most exhibit much greater lateral continuity than the interbedded sandstones. Several of the siltstone beds can be correlated throughout the basin. They are thought to represent periods of basin starvation [Garber et al., 1989; Gardner, 1997]. The siltstones are use to internally subdivide the Brushy Canyon into its upper, middle, and lower units.

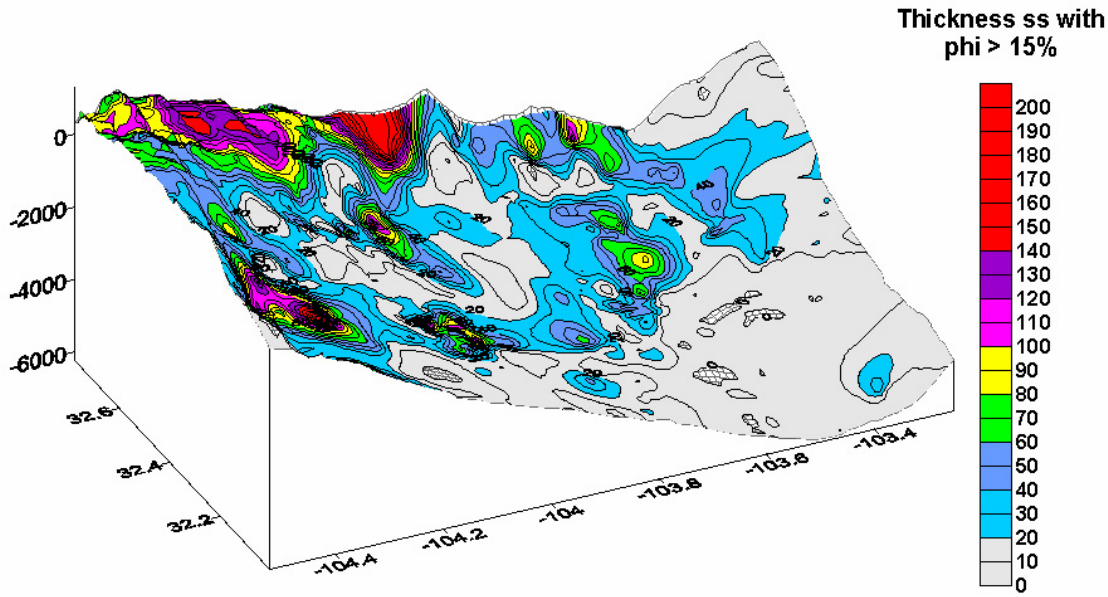

Fig. 2.9: Net thickness of Lower Brushy Canyon sandstones with porosity > 15% superimposed on 3-D diagram of Bone Spring structure.

When areas of established, discovered oil production from the Lower Brushy Canyon are compared with the structural configuration of the Lower Brushy Canyon (Fig. 2.5), it is evident that oil accumulations are not coincident with the larger scale structural closures

and noses. Productive areas are mostly coincident with structurally low areas in the Brushy Canyon. These low areas are inherited from paleobathymetric and paleostructural lows that characterize the upper surface of the underlying Bone Spring Formation. Areas of Lower Brushy Canyon production are coincident with reservoir fairways where net thickness of Lower Brushy Canyon sandstones with at least 15% porosity is 15 ft or more (Fig. 2.7). The map of net thickness of sandstones with porosity greater than 10% exhibits a somewhat less explicit correlation with production (Fig. 2.8). Structural closures may be significant where they are located downslope and acted to pond sediment flows and cause accumulation of thick reservoir quality sands, or where the structural configuration postdates sediment deposition and therefore had no affect on sediment transport routes.

A major question is raised by the maps that overlay productive areas on the reservoir sandstone trends. Why is production largely absent from areas in the westernmost and northwesternmost parts of the research area where reservoir sandstones occur in abundance? These areas typically have more than 100 ft of Lower Brushy Canyon sandstone with at least 15% porosity, yet these areas lack production. Although this may be due partially to incomplete testing and evaluation, it is likely those geological factors also play a role and that some parts of these sandstone-rich areas are truly barren of commercial hydrocarbons. Can this be explained by a paucity of seals? It may be that oil and gas have migrated updip out of the basin and have not been trapped in the Brushy Canyon for lack of adequate barriers to migration. Figure 2.7 shows that the larger oil accumulations within the Brushy Canyon coincide with areas of thick reservoir sandstones that thin or pinch out in an updip (northerly, northwesterly, or westerly) direction. The thin sands in the northernmost and westernmost parts of the basin appear to be continuously connected with the outcrop and therefore have not provided updip seals, at least along major sand trends.

Alternatively, eastward tilting during the Laramide may have led to flushing of the Brushy Canyon in this region by influent groundwaters [Lindsay, 2001]. Influent waters

may have moved downdip in an easterly direction until they encountered seals which also acted to trap hydrocarbons in stratigraphic traps to the east. Map that show salinity of produced Lower Brushy Canyon waters (Figs. 2.10, 2.11) were constructed for this project and indicates that salinity decreases toward the northern and western margins of the basin indicating recharge of fresh water along the Lower Brushy Canyon outcrop, and therefore supporting Lindsay's hypothesis.

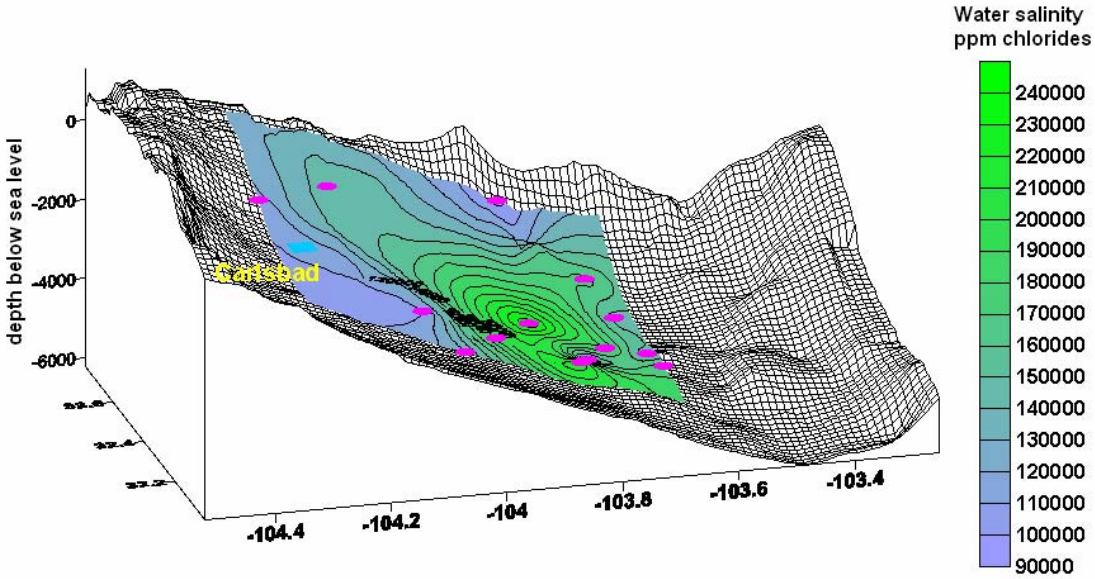

Fig. 2.10: Salinity of produced Brushy Canyon waters superimposed on 3-D diagram of Bone Spring structure.

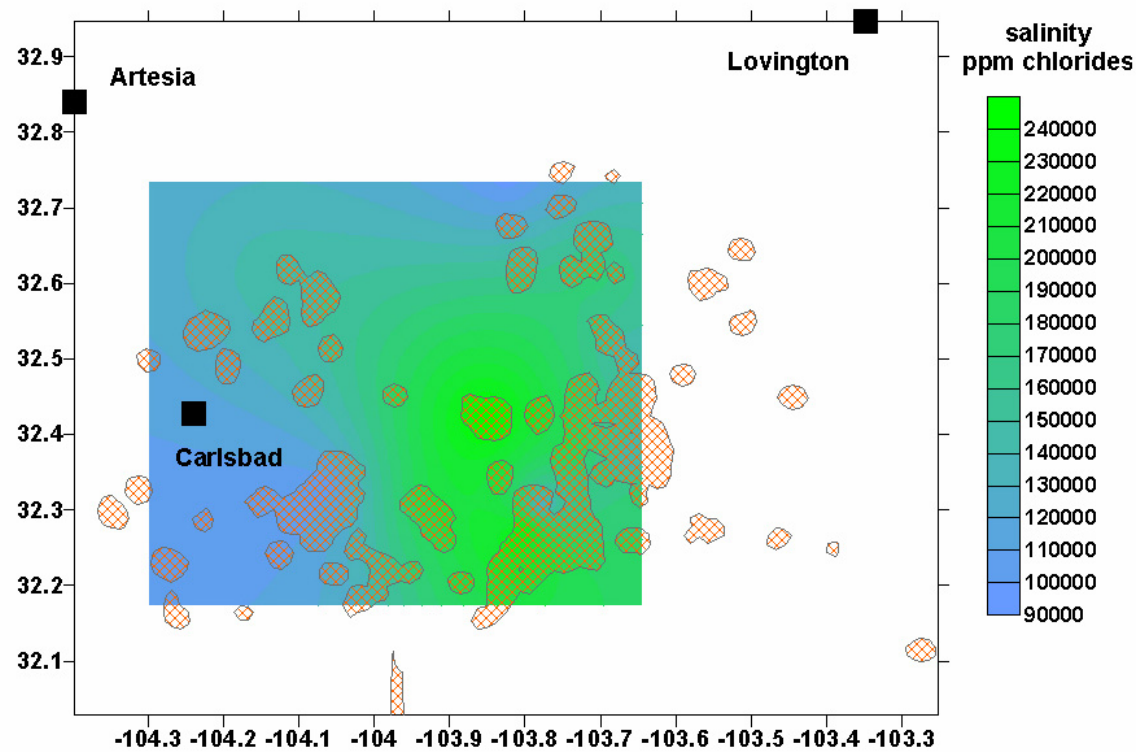

Fig. 2.11: Salinity of produced Lower Brushy Canyon waters and areas productive from the Lower Brushy Canyon.

Another possibility that may explain the sparse distribution of hydrocarbons in these areas is an absence or paucity of source rocks. It has been reasonably well established that, at least in places, oil accumulations within the Brushy Canyon are sourced by organic-rich siltstones within the Brushy Canyon [Hays and Tieh, 1992; Robinson, 1993]. The sandstone reservoirs are interbedded with their source rocks and the source strata also act as seals for the accumulations. Robinson [1993] concluded that the low permeabilities of Brushy Canyon reservoirs are indicative of short migration distances. If this is the case, then oil accumulations should be preferentially concentrated in areas where source rocks are mature, thick, and have relatively high contents of organic carbon. Data and maps relating to these hypotheses were collected and created as part of this project in order to provide the fuzzy expert tool information with which to evaluate the importance of source rocks. A map of total organic carbon (TOC) content of Lower Brushy canyon source rocks (Fig. 2.12) indicates that sufficient organic material is

present within the Lower Brushy Canyon to form adequate source facies throughout the Delaware Basin. Thermal maturity of Brushy Canyon source rocks, although adequate for oil generation throughout the research area, increases to the south in the deeper parts of the basin and also to the west with increasing proximity to the Rio Grande rift (Fig. 2.13). Oil gravity data collected and mapped for this project indicate a bimodal distribution of Lower Brushy Canyon oils (Fig. 2.14). Oils with higher API gravities (API > 40 degrees which are lighter and presumably more thermally mature) have been trapped along major sandstone fairways whereas somewhat heavier oils (API < 40 degrees) are present where sand bodies do not occur along major sandstone fairways. This distribution of oils suggests that lighter more mature Brushy Canyon oils may have been generated in deeper, more mature parts of the Delaware basin and migrated updip along sandstone fairways until they were trapped. The somewhat heavier oils had their origin in source beds close to the reservoirs in the shallower parts of the basin; the limited extent of sandstone bodies in these areas caused local hydrocarbon entrapment and prevented the oil from migrating longer distances. Thus, proximity to sandstone fairways plays a significant role in oil gravity and quality within the Lower Brushy Canyon.

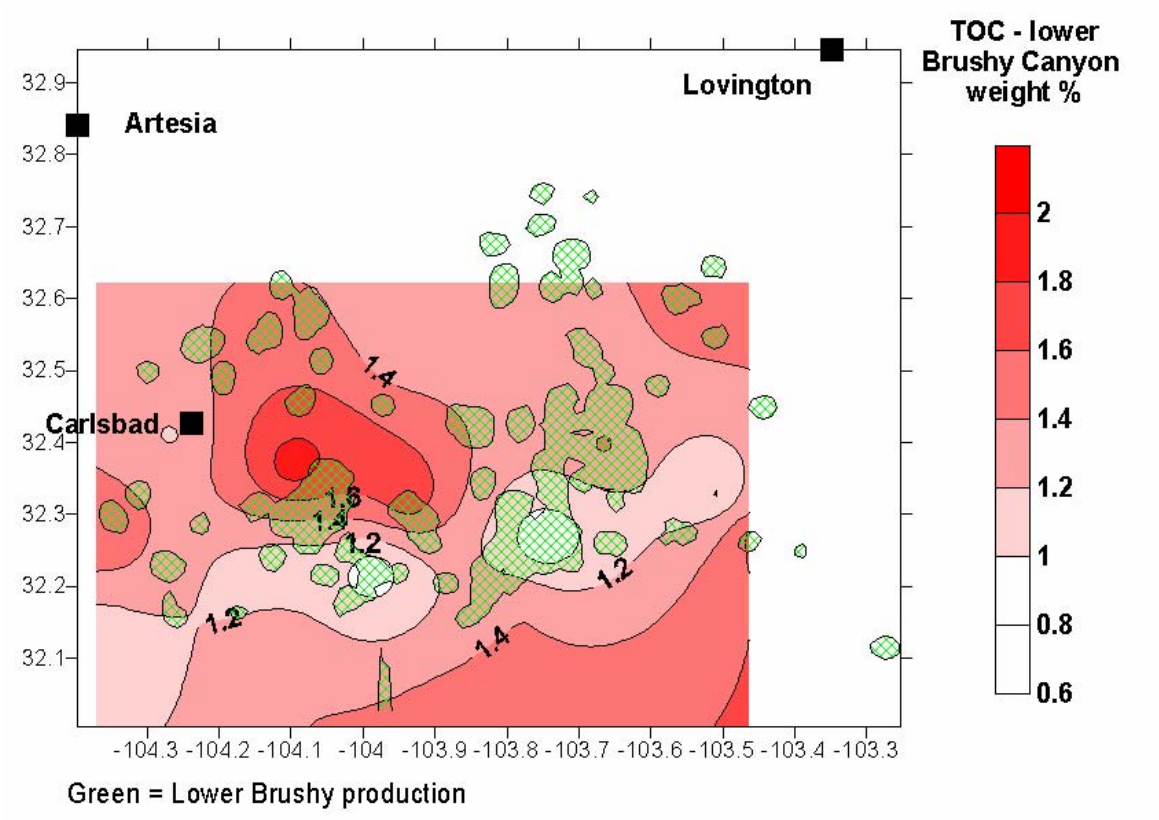

Fig. 2.12: Total organic carbon content, in weight percent, of Lower Brushy Canyon source rocks.

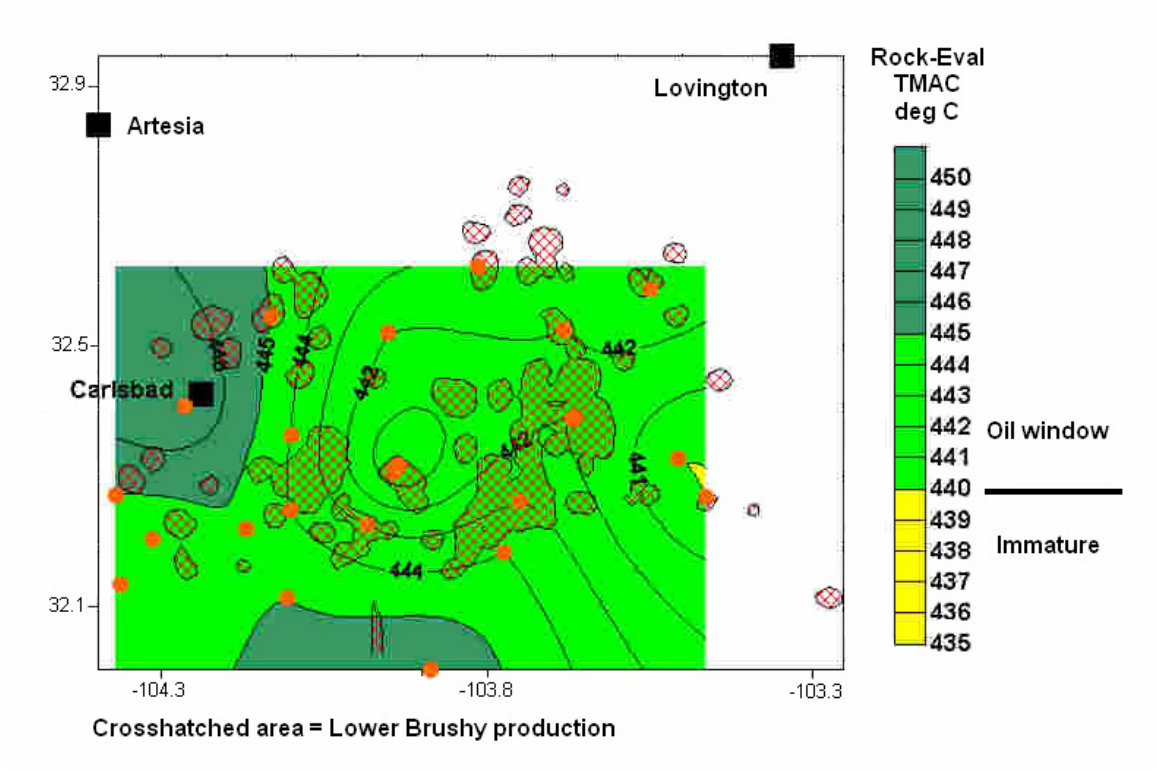

Fig. 2.13: Thermal maturity of Lower Brushy Canyon source rocks as determined by Rock-eval TMAX values and areas productive from Lower Brushy Canyon.

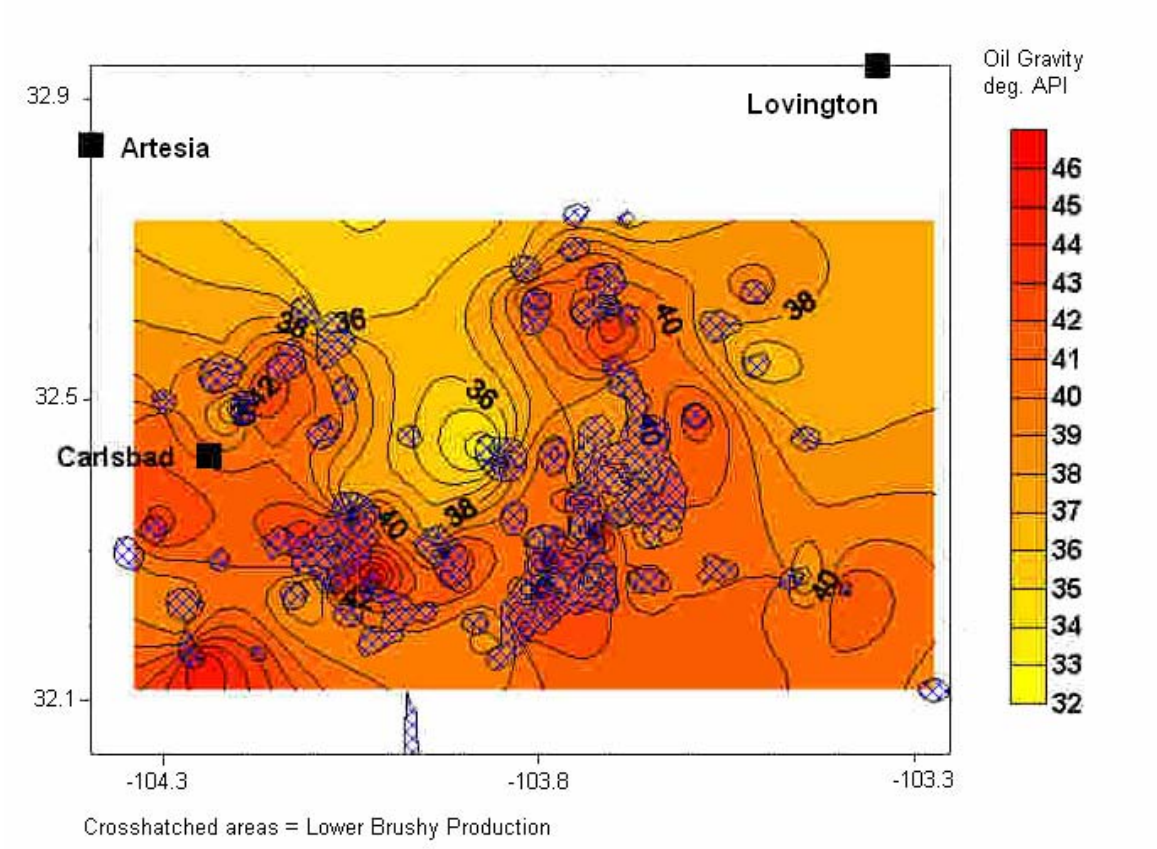

Fig. 2.14: API gravity of Lower Brushy Canyon oils.

2.1.2 Siluro-Devonian Formation

Devonian and Silurian carbonates produce oil and associated gas from numerous oil and gas fields in southeastern New Mexico.

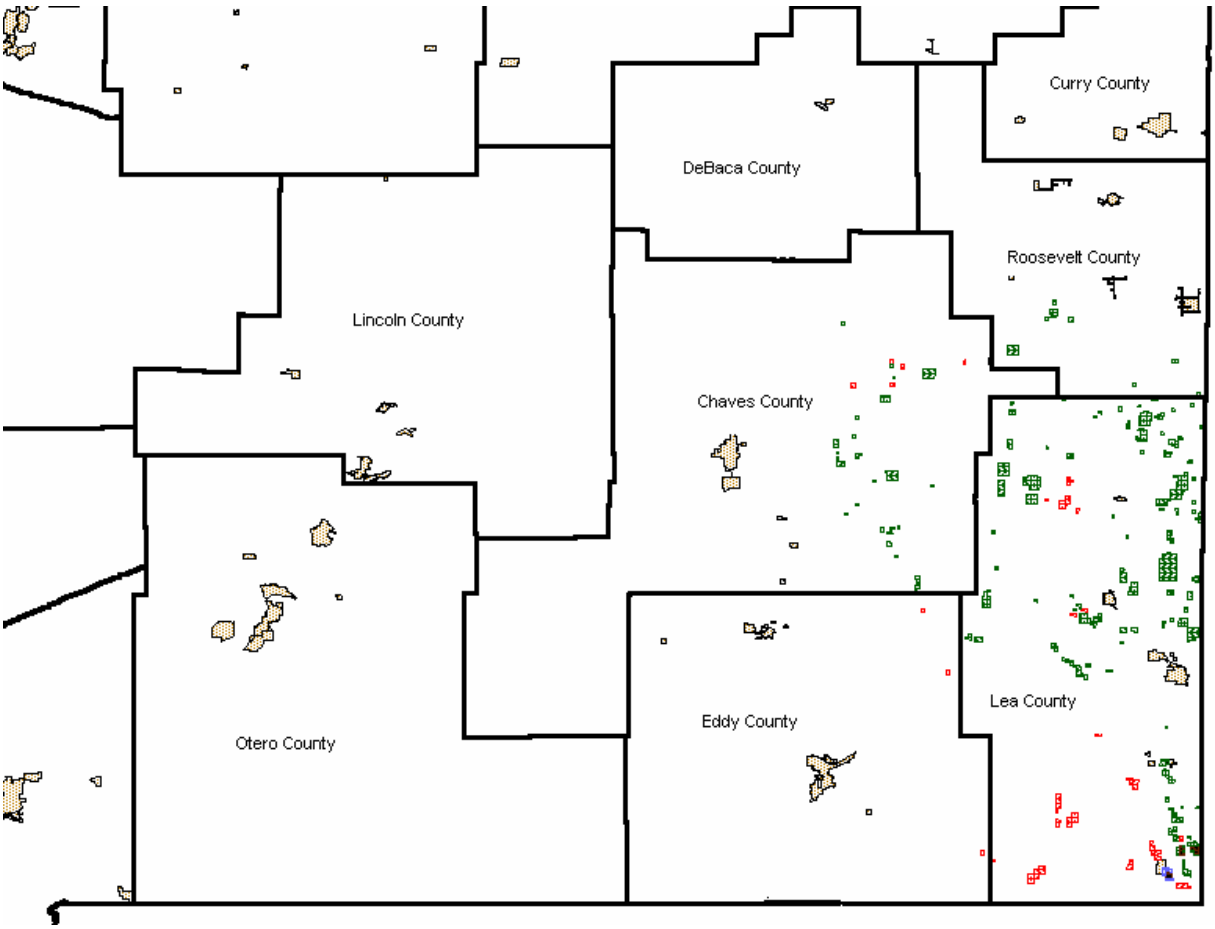

Fig. 2.15: Map of southeastern New Mexico showing county boundaries and oil reservoirs (green) and gas reservoirs (red) productive from Siluro-Devonian strata.

There are 122 productive Siluro-Devonian fields in southeastern New Mexico [Broadhead and Speer, 1995]. These had produced more than 440 million bbls oil by 2000, 10% of the oil produced from southeastern New Mexico part of the Permian Basin [Broadhead et al., 2004]. Production is from a number of zones within the Silurian and Devonian sections (Fig. 2.16). Although the reservoirs are colloquially referred to as "Devonian," most of the production is obtained from reservoirs of the Wristen Group of Silurian age, with lesser production from the Fusselman Formation and relatively

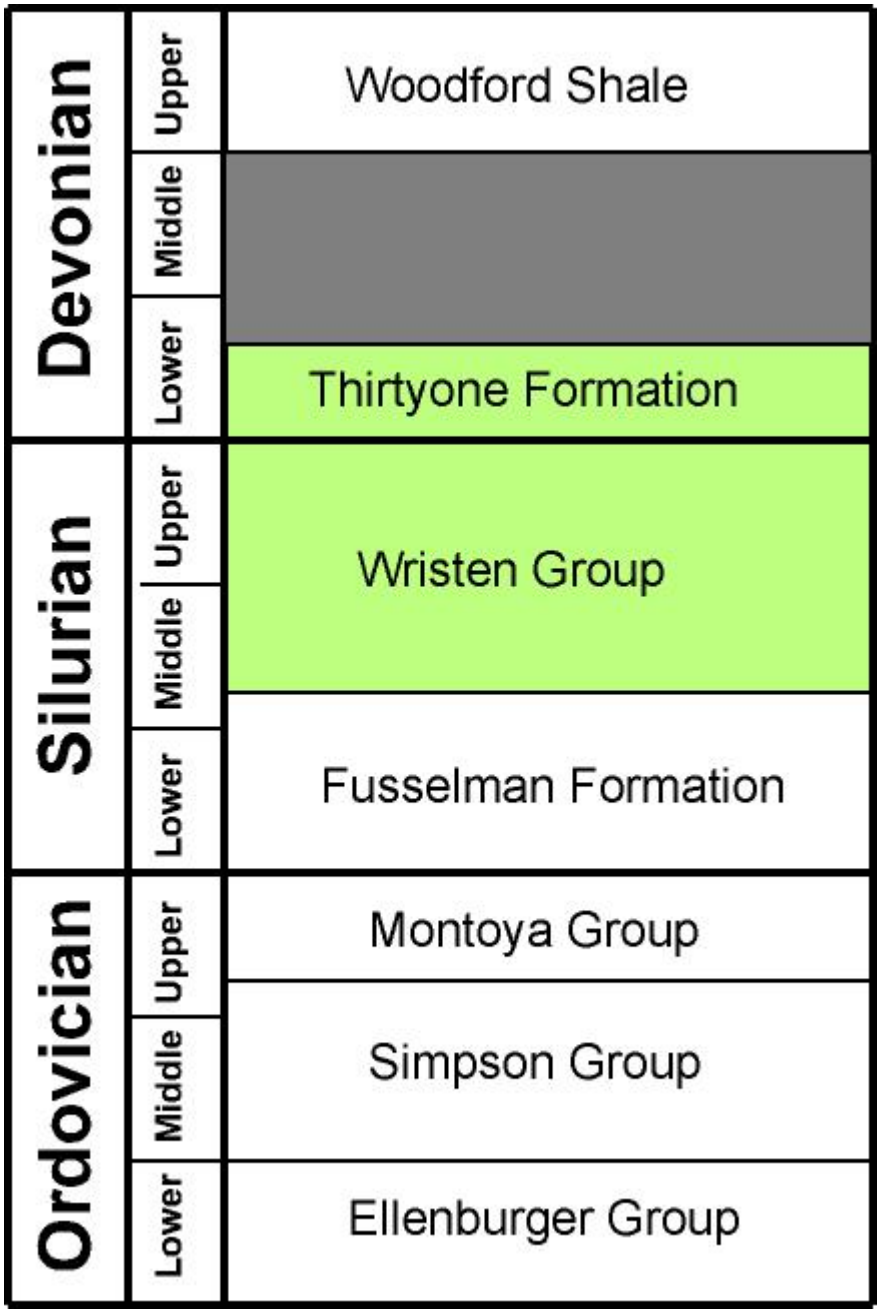

Fig. 2.16: Stratigraphic column of Lower Paleozoic rocks in southeastern New Mexico. Reservoirs in the Wristen Group and Thirtyone Formations are the subjects of this work.

minor production from the Thirtyone Formation in New Mexico. 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 carbonate strata of Devonian age are restricted to a relatively thin section of the Thirtyone Formation (less than 200 ft

thick) in southeastern Lea County [Barrick et al., 1993; Ruppel and Holtz, 1994]. Elsewhere, Devonian carbonates (Thirtyone equivalents) were removed during formation of a regional unconformity that preceded deposition of the Upper Devonian Woodford Shale. 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 date are present on structures (Figs. 2.17, 2.18) that can be identified with the help of seismic data [Fig. 2.19; Hanagan, 2002]. Not all drilled structures are filled with hydrocarbons, as some structures are filled with water. Risk factors include the sealing capacity of faults, the presence or absence of source rocks, migration pathways from source rocks to reservoirs, the presence or absence of adequate vertical seals ("caprocks") for the reservoirs, and the maturity of source rocks (which determines whether oil, condensate, or gas will be found in the trap). Many structures in Chaves County are only partially filled with hydrocarbons [Hanagan, 2002]. These factors suggest 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.

Identification of trap-forming structures in the Siluro-Devonian carbonates is best done by mapping of paleostructures. Paleostructures may be thought of as structures that formed during a single past tectonic event and are discreet from structures formed during other structural events. The structures that create traps in the Siluro-Devonian carbonates were formed during Middle Pennsylvanian to Early Permian tectonism that formed structural features associated with the formation of the Ancestral Rocky Mountains and the Ouachita orogenic belt. Isopach mapping of the stratigraphic interval between the top of the Abo Formation (Lower Permian) and the Mississippian limestones on a local basis has proven effective in locating trap-forming paleostructures [Fig. 2.19; Hanagan, 2002]. Local thin areas of the Abo-Mississippian interval delineate the paleostructures

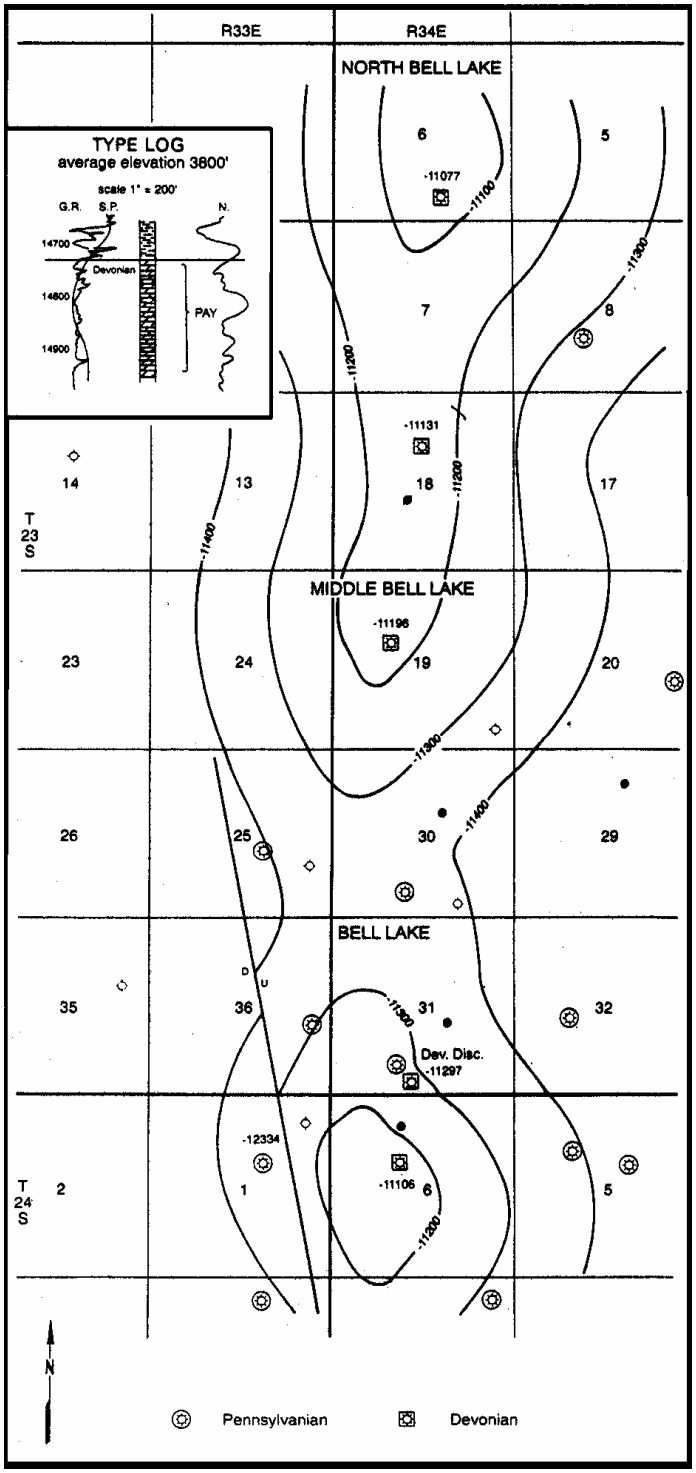

Fig. 2.17: Structure contours on top of Siluro-Devonian dolomite in the Bell Lake reservoir complex, Lea County, New Mexico. This deep structural trend is representative of the type of structure and trap in many Siluro-Devonian reservoirs. From Speer (1993) after Harvard (1967)

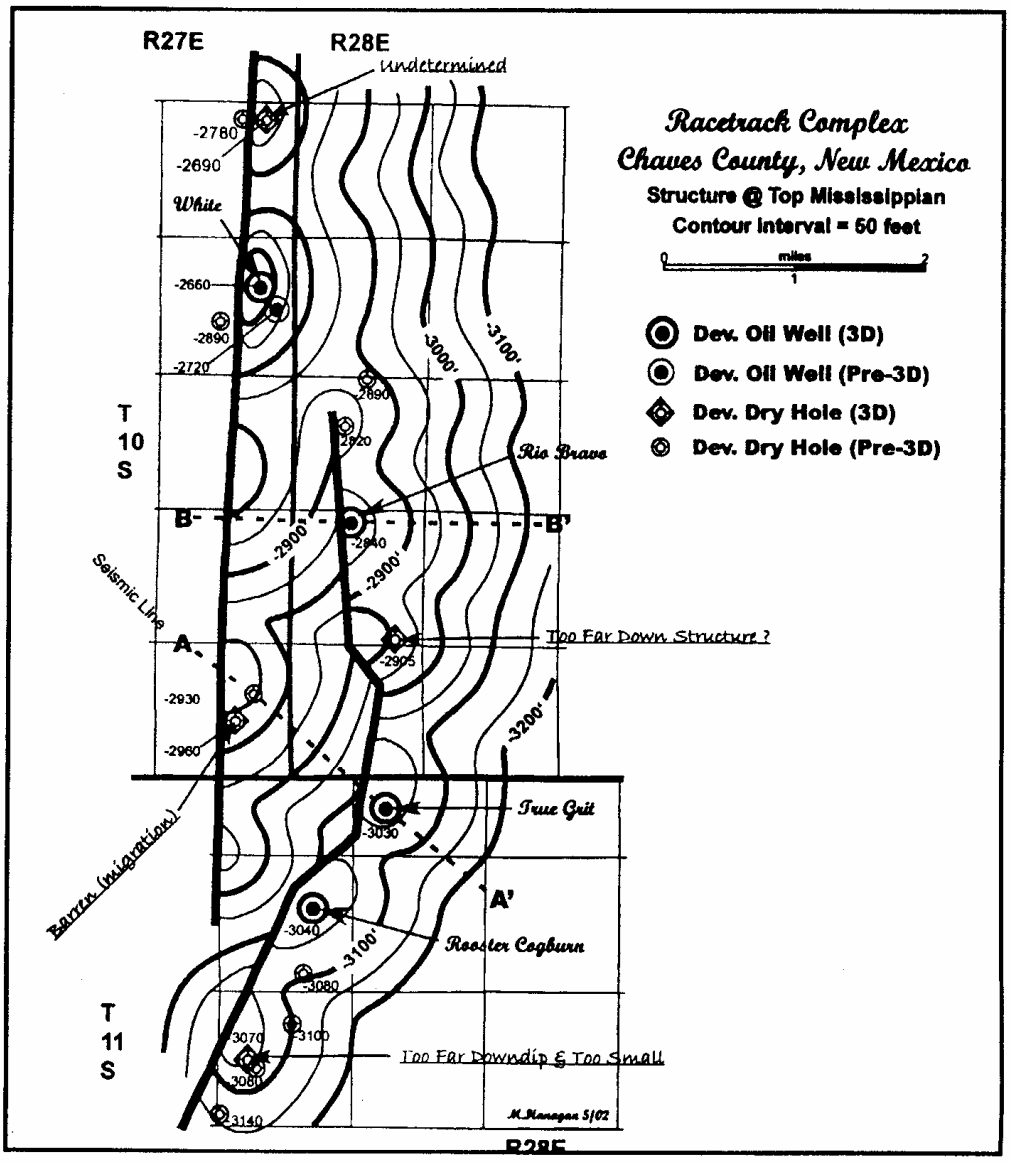

Fig. 2.18: Structure contours on top of the Mississippian limestones, Racetrack Complex, Chaves County New Mexico. This structure is representative of productive structures that trap oil in Siluro-Devonian reservoirs. From Hanagan (2002)

that form traps. For this project, paleostructure data acquisition and mapping was extended to regional coverage of southeastern New Mexico. A majority of the geologic effort has concentrated on acquiring Abo-Mississippian isopach data and producing an isopach/paleostructure map that delineates trap-forming paleostructures as well as trends of trap-forming paleostructures on the Northwest Shelf

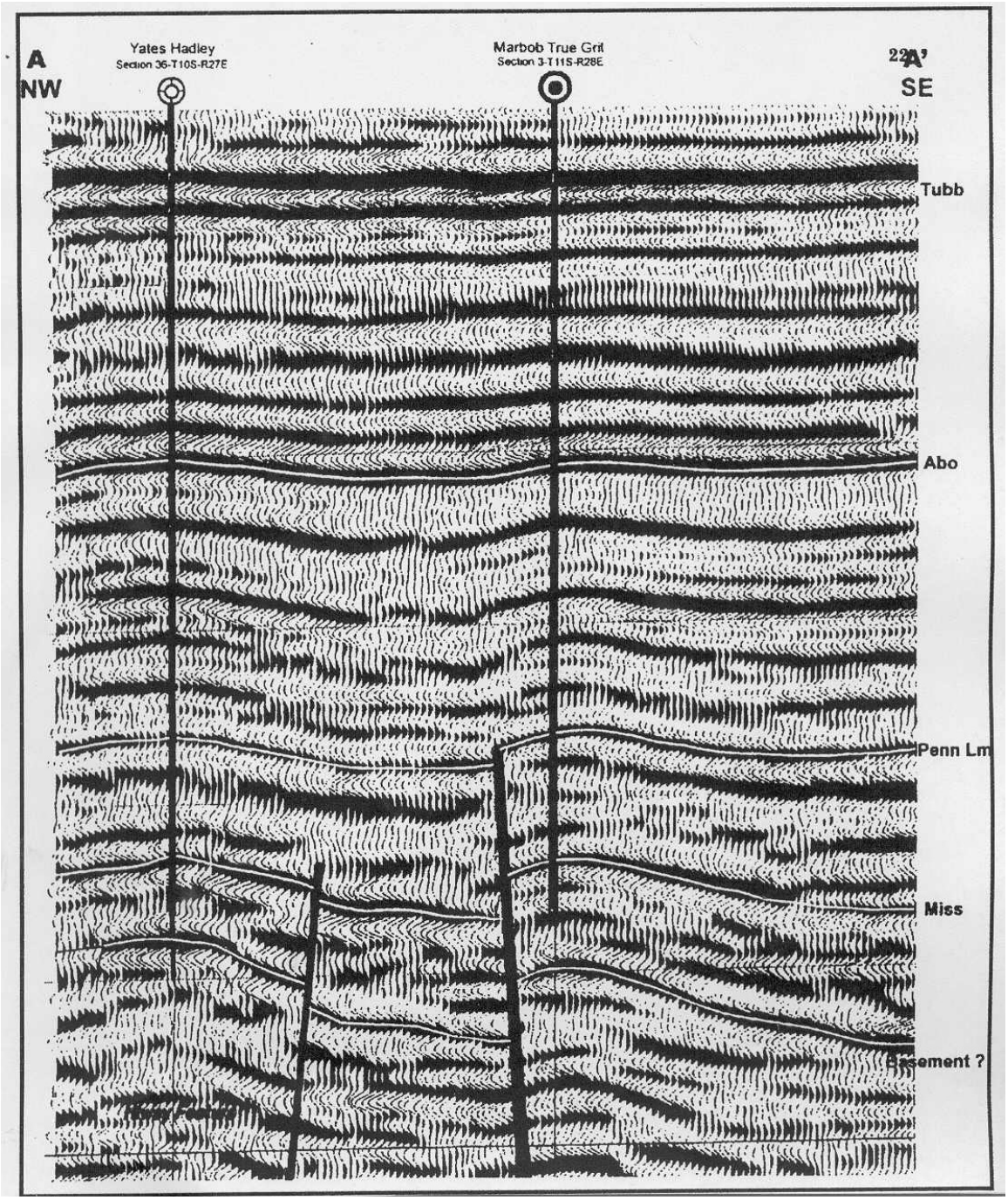

Fig. 2.19: Seismic line across Racetrack field showing thinning of stratigraphic interval between the top of the Abo Formation and the top of the Mississippian limestones over the productive structure. From Hanagan (2002)

of the Permian Basin (Fig. 2.20). Because the Abo Formation was not deposited to the south in the Delaware Basin, an Abo-Mississippian isopach map cannot be constructed to the south and this region appears without contours on Fig. 2.20.

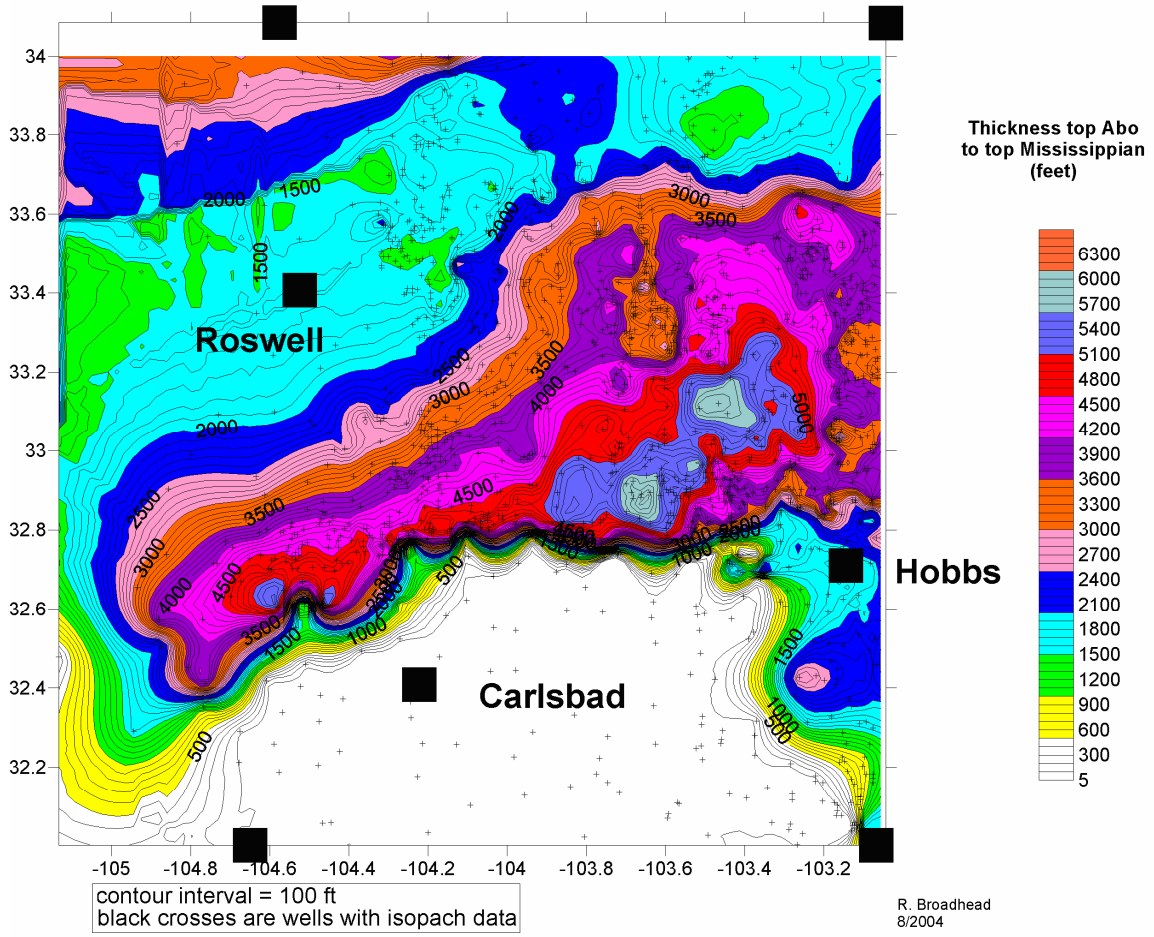

Fig. 2.20: Isopach map of stratigraphic interval between the top of the Abo Formation (Permian) and the top of the Mississippian limestones. Local thin areas delineate paleostructures developed on the Siluro-Devonian carbonates.

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 Shale is also the seal for most oil accumulations in the Siluro-Devonian carbonates. 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 the regional unconformity that truncates underlying strata in a northward direction [Canter et al., 1992; Fig. 2.21]. Productive porosity is primarily in leached intervals directly beneath the unconformity at the top of the Siluro-Devonian carbonates. Therefore, factors such as thickness and distribution of the Woodford seal (Fig. 2.22), organic richness of the Woodford (Fig. 2.23) and thermal maturity of the Woodford (Fig. 2.24), work performed in previous reporting periods, are important factors in constructing a fuzzy logic tool for risk reduction in petroleum exploration.

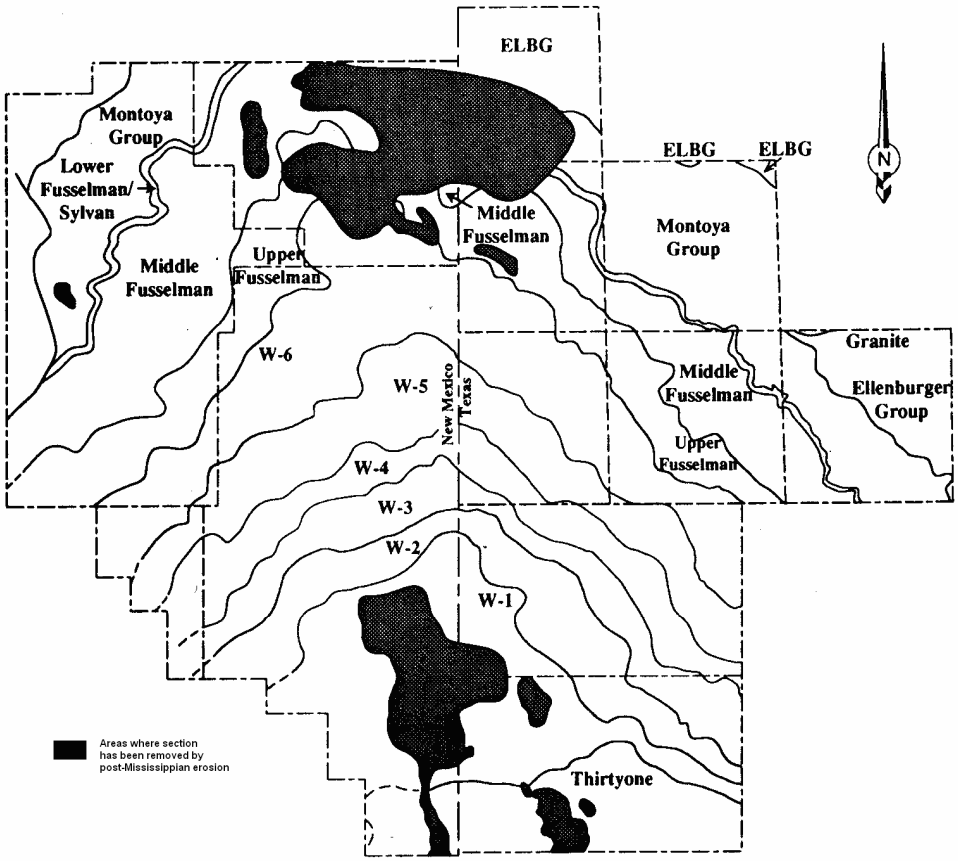

Fig. 2.21: Subcrop map of the pre-Woodford unconformity in southeastern New Mexico and west Texas showing how progressively older stratigraphic units underlie the Woodford to the north. From Canter et al. (1992)

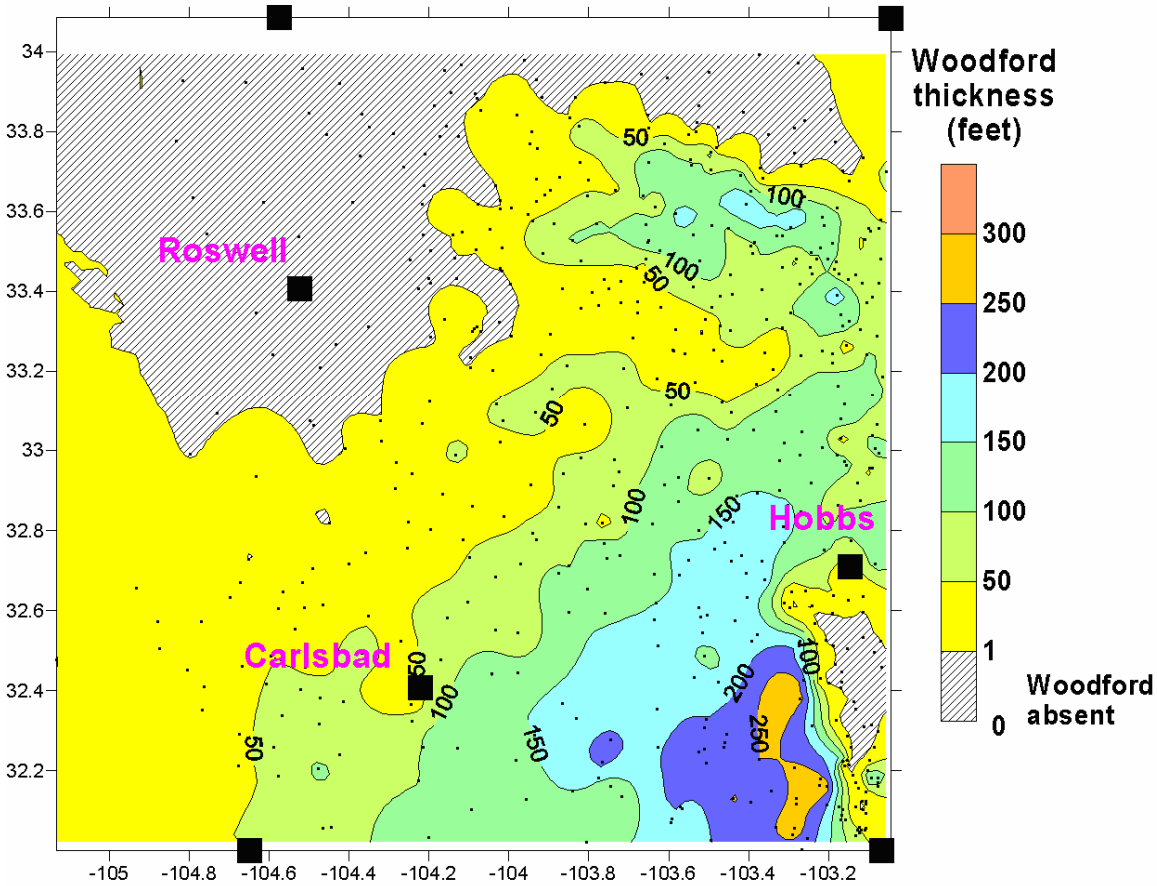

Fig. 2.22: Isopach of Woodford Formation, corrected for stratal dip in boreholes.

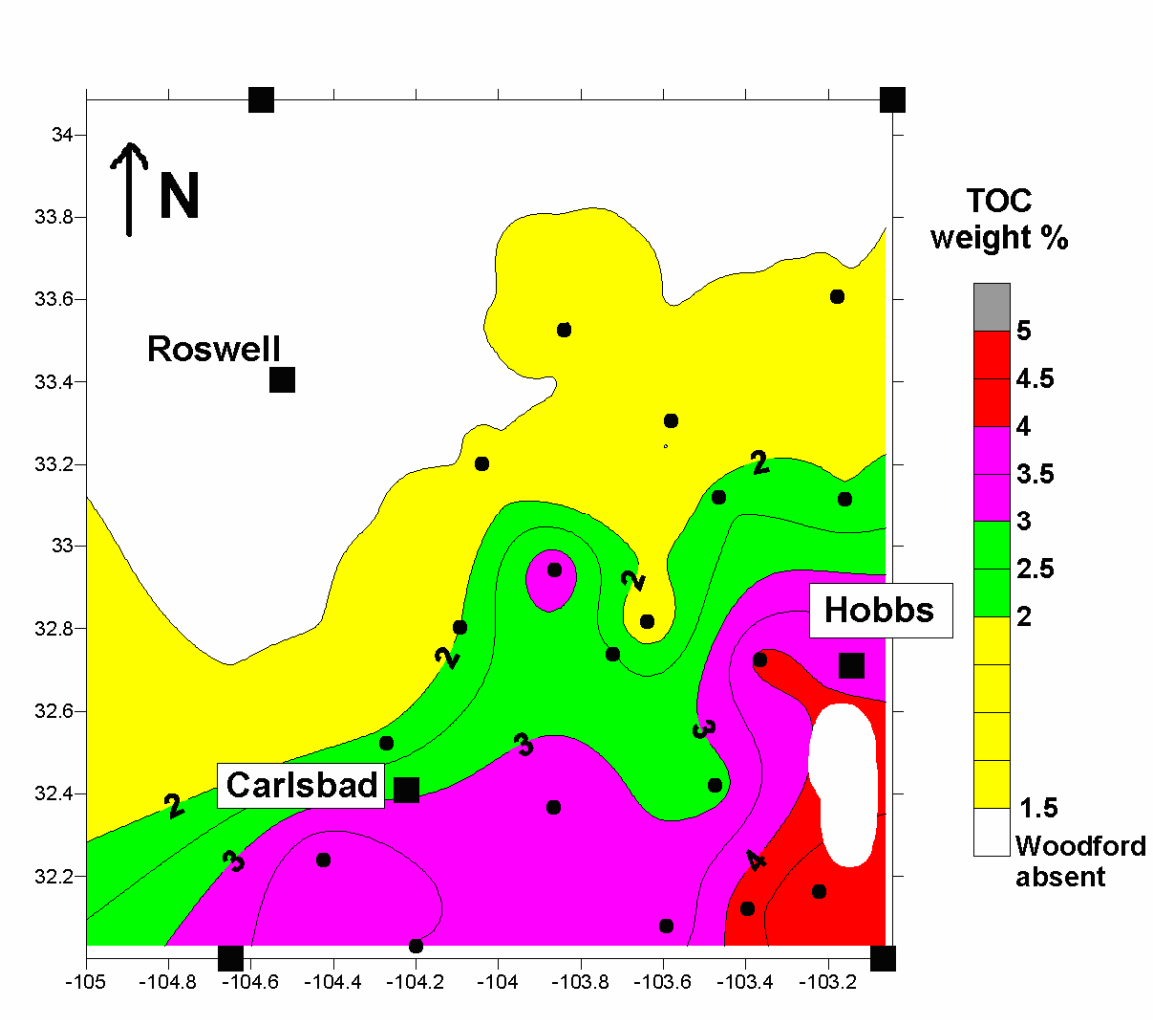

Fig. 2.23: Total organic carbon (TOC) content of Woodford shales, in weight percent.

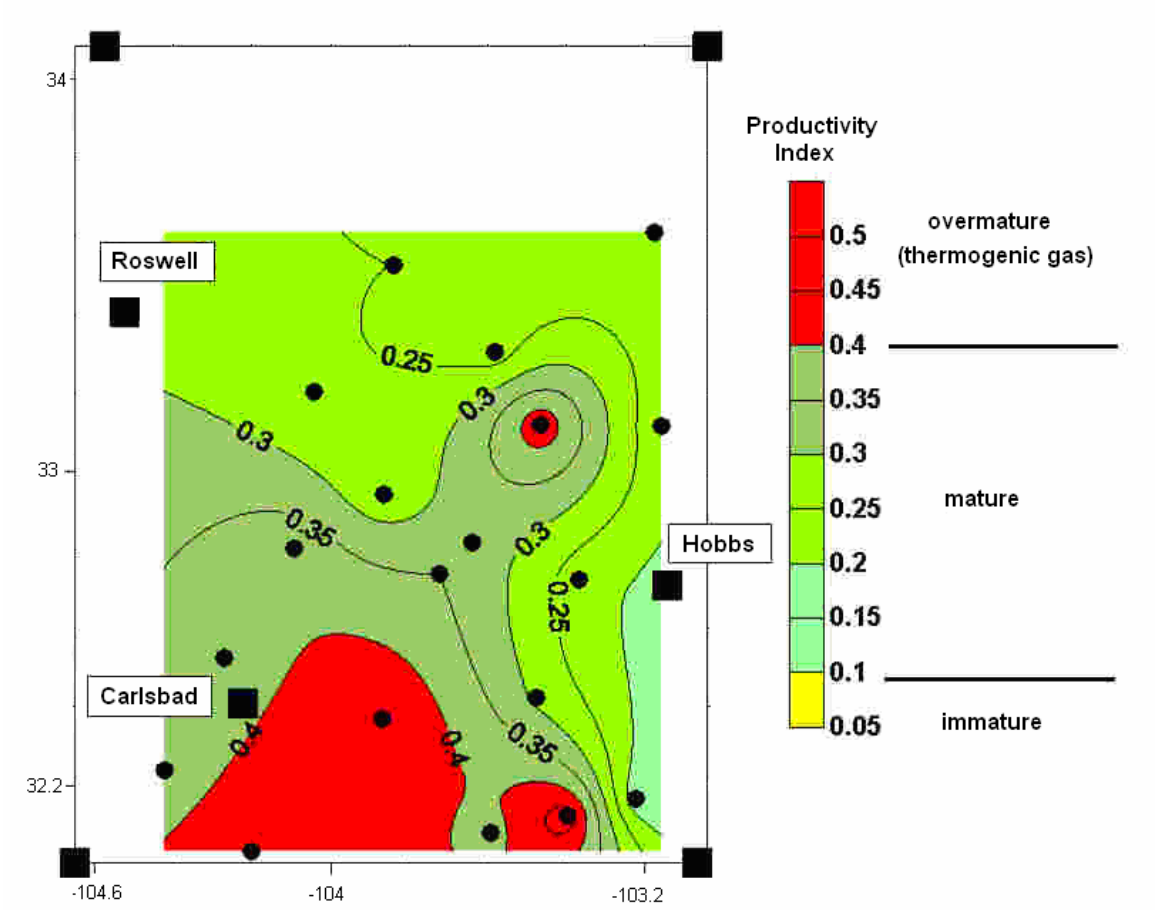

Fig. 2.24: Rock-Eval Productivity Index (PI) of Woodford Shale, indicating thermal maturity of Woodford with respect to stages of maturation in the oil and thermogenic gas windows.

Geologic data acquisition

A database of well information essential to the mapping of paleostructure was constructed, including the following information on 1481 wells:

1. operator, well name and well number;
2. location in terms of section, township and range;
3. location in terms of latitude and longitude (calculated via a digital land grid from section, township and range data);
4. depth to top of Abo Formation;
5. depth to top of Mississippian limestones;
6. thickness from the top of the Mississippian to the top of the Abo.

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. 2.25). 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. However, deformation during the Cretaceous to Early Tertiary has obscured the mapping of traps and the maps of present day structure will not accurately portray trends of trap-forming structures that developed during the Pennsylvanian and Early Permian.

A map was constructed during 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. 2.26). The data used in the construction of this map was essential in determining the presence or absence of oil at any single locality in the fuzzy logic system.

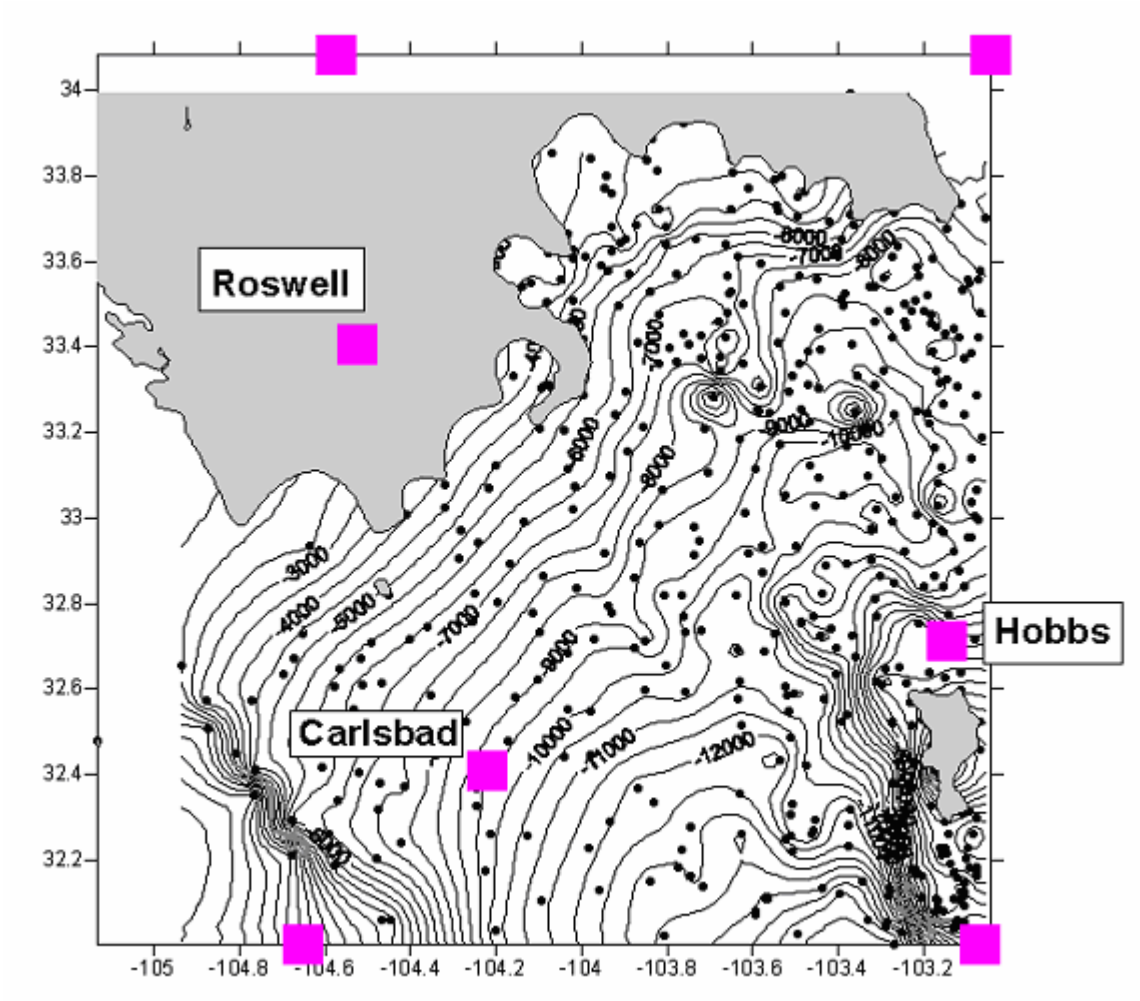

Fig. 2.25: Structure contour map of the top of the Siluro-Devonian carbonates in southeastern New Mexico. Dots are well control points developed in this project. Northern limit of contours coincides with northern pinchout of the Woodford Shale.

Perhaps most importantly, an isopach map of the interval between the top of the Abo Formation (Permian) and the top of the Mississippian limestones was constructed from the paleostructural database developed during the first part of the project (Fig. 2.20). As discussed above, local thin areas delineate paleostructures and trends of paleostructures that act to form traps in the Siluro-Devonian carbonates. When overlaid with the locations of productive wells (Fig. 2.27), it is apparent that local thin areas on this map generally coincide with production and that a great deal about the location of production can be explained by the paleostructural data.

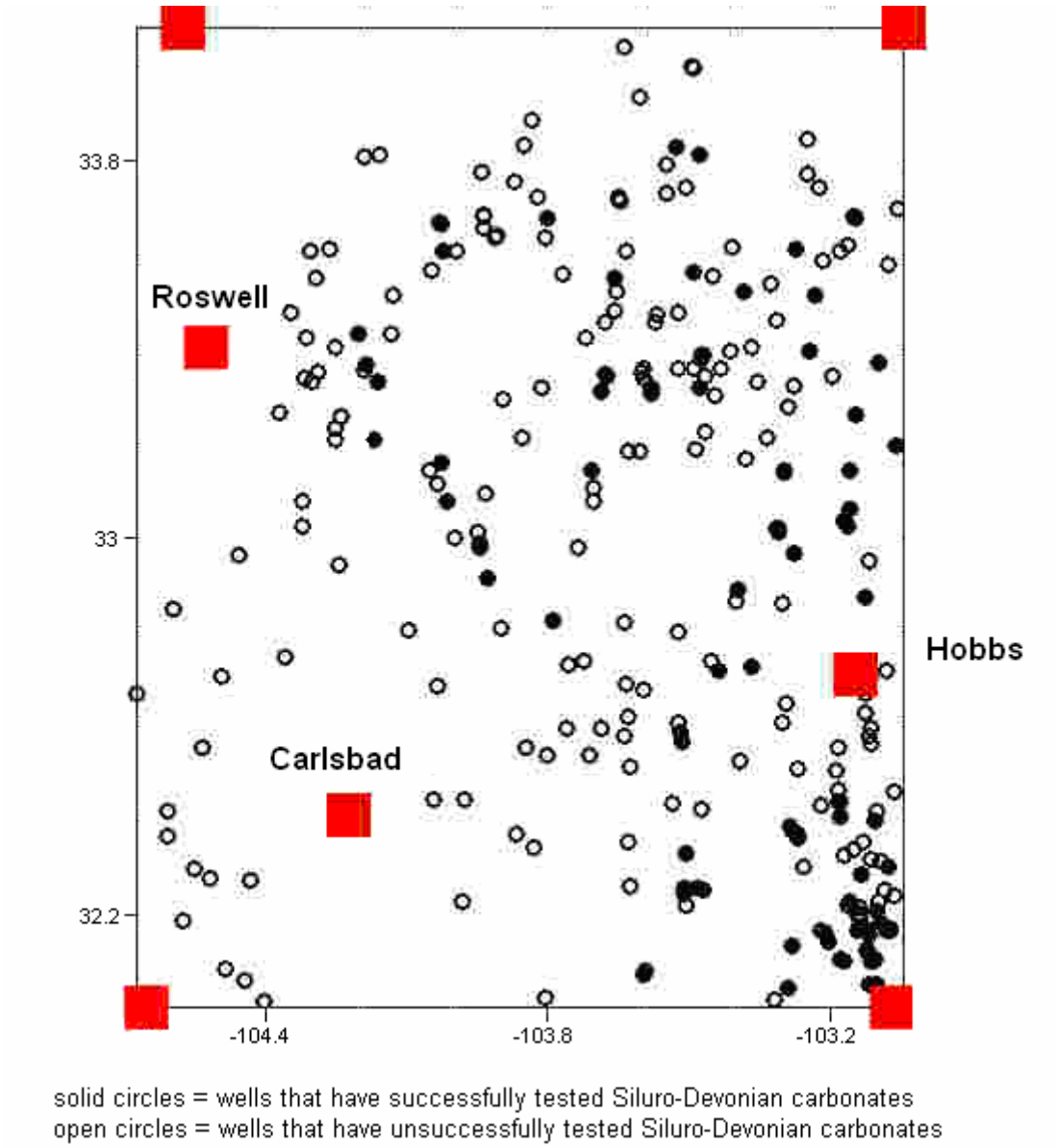

Fig. 2.26: Map showing database of wells that have successfully tested (solid circles) and unsuccessfully tested Siluro-Devonian carbonates in southeastern New Mexico.

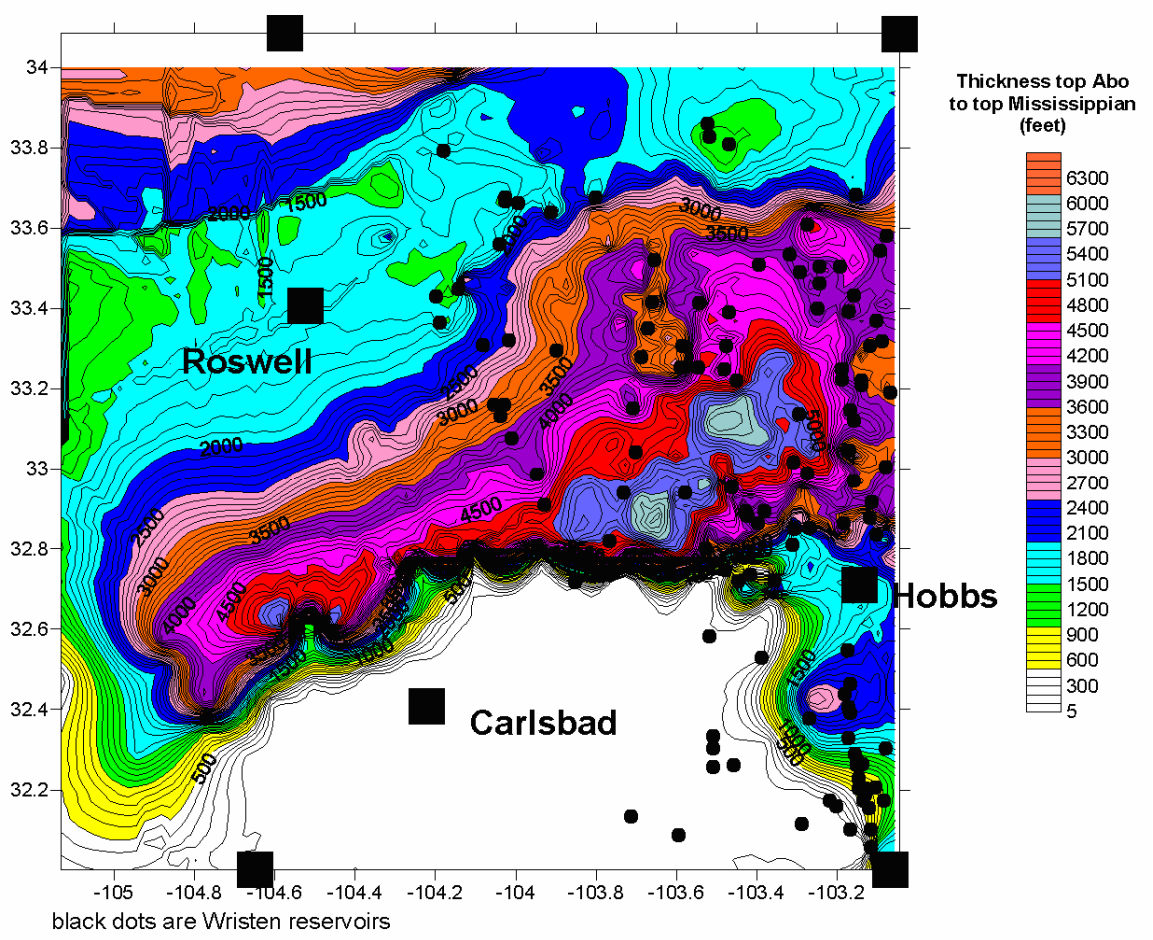

Fig. 2.27: Isopach map of stratigraphic interval between the top of the Abo Formation (Permian) and the top of the Mississippian limestones. Local thin areas delineate paleostructures developed on the Siluro-Devonian carbonates. The black dots are productive wells in major Wristen (Silurian) oil reservoirs.

2.2 Geophysics

Gravity and magnetic data were used to verify the extent of the Delaware Basin and to perform a preliminary analysis of regional structure for the Delaware FEE Tool. Both gravity (Fig. 2.28) and aeromagnetics (Fig. 2.29) clearly show the location of the basin in the regional data.

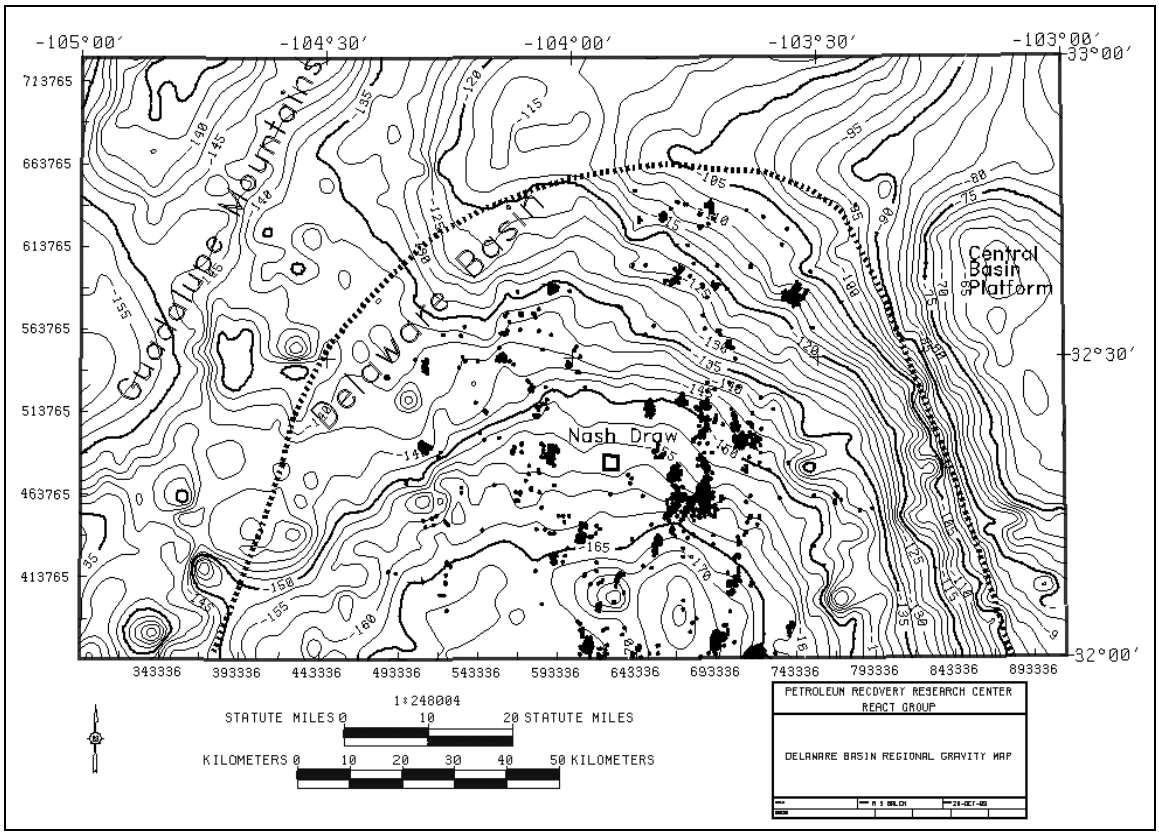

Fig. 2.28: Residual gravity anomaly for the Delaware Basin and surrounding regions and Delaware producing wells (dots). The gravity signature is quite strong.

Fine-scale studies used much more detailed local maps to compare production attributes to gravity and magnetic data. Figure 2.28 shows the regional gravity structure for the New Mexico portion of the Delaware Basin. A strong negative Bouger anomaly clearly defines the deeper parts of the basin, while the Central Basin Platform and Guadalupe Mountains exhibit the smallest Bouger anomalies in the region. Black dots represent the 1395 wells that were operating in the beginning of 1999, or plugged and abandoned after 1992. Additionally, 700 wells plugged and abandoned in the 1970–1980 time period are included in the production database, and accurate positions are being computed for display on maps. The figure supports the need for the FEE Tool, as large areas of the Basin remain unexploited.

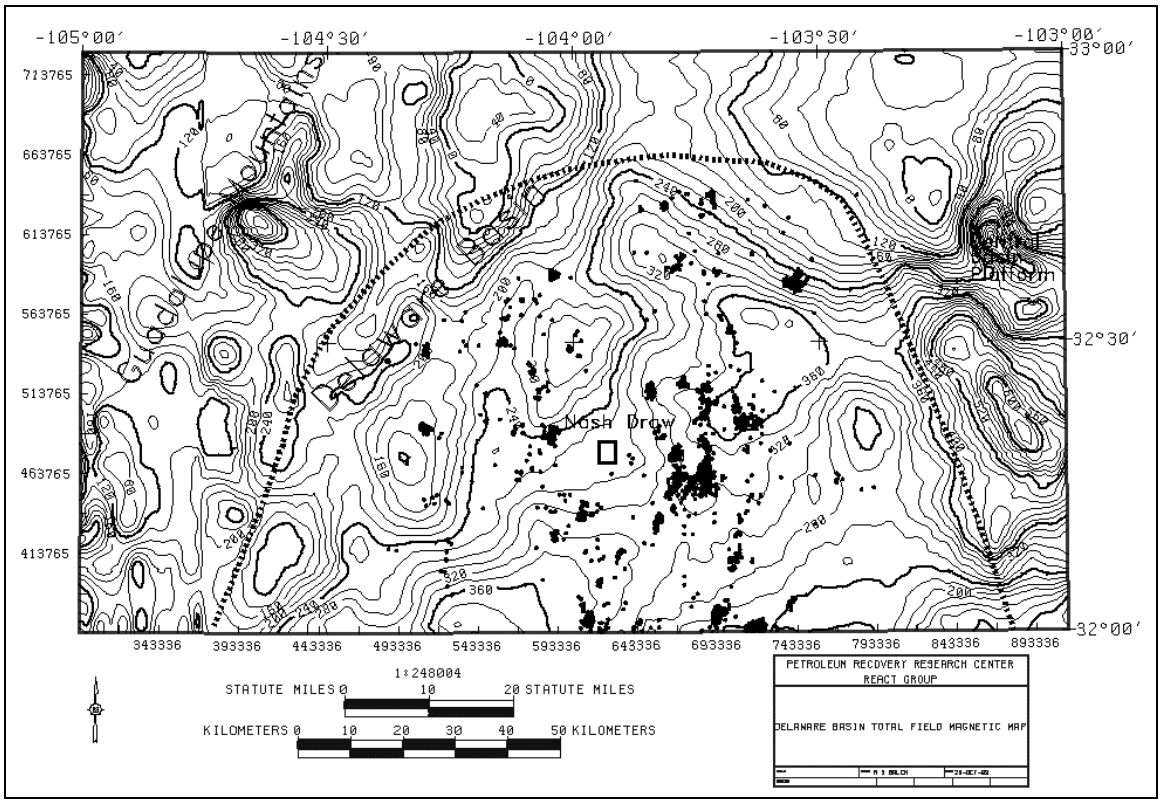

Fig. 2.29: Total field magnetic map for the Delaware Basin and surrounding regions. The basin can be seen encompassed by low magnetic values. Delaware producing wells (dots) are concentrated along the flanks of magnetic highs.

Second derivative maps in both the X and Y directions were studied to search for regional scale anomalies such as faults in the Brushy Canyon by removing the effects of basement features from the gravity map. No such features were apparent on this scale, but future analysis at finer resolutions may reveal field-sized anomalies in the upper crust. Rigorous and systematic studies of the data using fuzzy ranking and neural networks may help reveal subtle features that are difficult to interpret visually.

The magnetic data included in the FEE Tool database were collected through an airborne survey flown at a constant elevation of 1000 feet with flight lines spaced one mile apart. This profiled line data was then gridded into equally spaced data points of 0.296 miles longitude and 0.346 miles latitude. An airborne magnetic survey provides data that are "smoother" than data collected on the ground. The airborne survey is similar to the upward continuation modeling problem, which acts like a low pass filter taking out the

high frequency components of the signal, i.e. surface effects. Because of the great depths to basement, known from drilling, airborne magnetic data were preferred for this investigation. The airborne magnetometer used to collect these data is known to have collected data to an accuracy of ±2.0 gamma. The applied diurnal correction, loop-based method allowed for a reliability of the reading within the same order of magnitude as the accuracy [Telford, 1990].

Aeromagnetic data are generally used to determine the depth to and structure of the basement. "Basement" is used here to define the local igneous intrusive structure responsible for measured signal. The goal was to process the aeromagnetic data further to isolate the effects associated with the Delaware Mountain group. This processing included band-pass filtering to target the Delaware Mountain group source depth and calculation of directional derivatives to indicate possible trends related to fault sets within the Delaware Mountain group.

Attributes were generated from the regional gravity and aeromagnetic maps. Dip azimuth, magnitude, and first and second order derivative maps were also completed for gravity and aeromagnetic data for the Delaware Basin and the surrounding region. Second derivative maps of gravity are widely interpreted [Hart, 2000] to represent removal of basement features, leaving a regional residual for rocks above the basement. Figure 2.30 shows a second derivative gravity, residual map in the X direction. Notice that alignment of fields (clusters of producing wells) seems to occur in the Y direction.

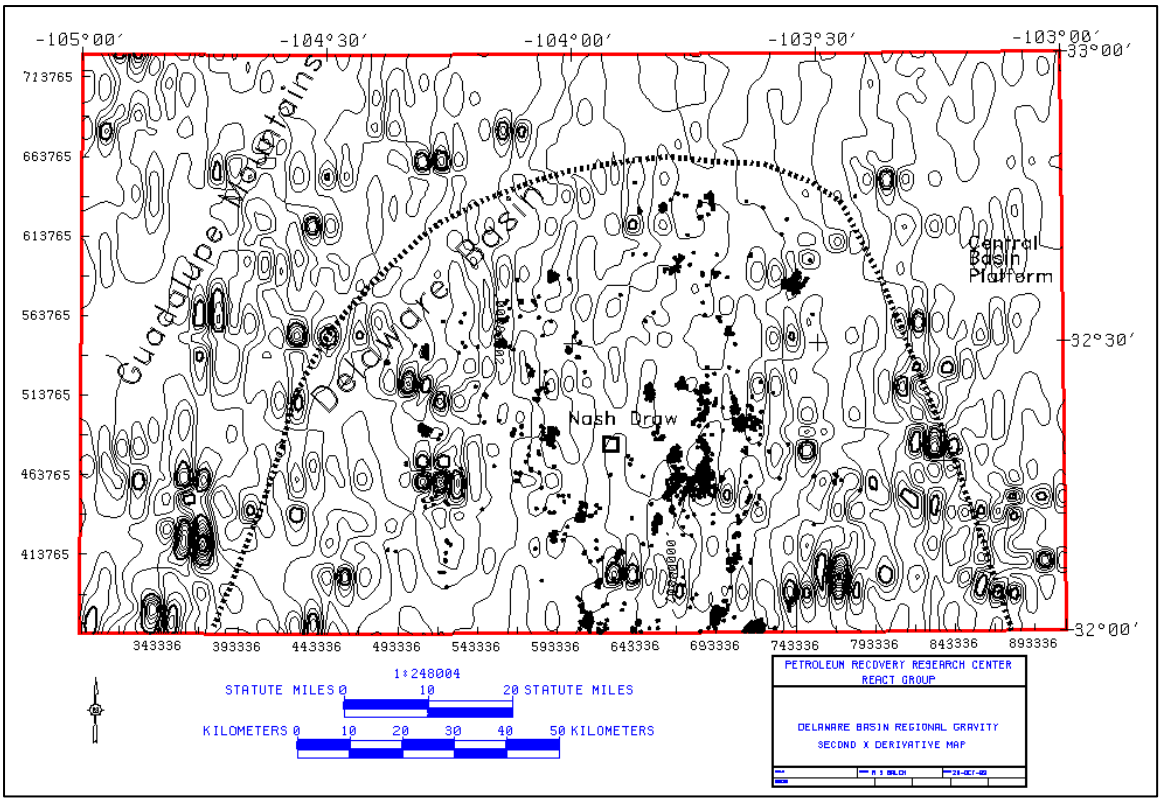

Fig. 2.30: Second derivative gravity map (x direction). The second derivative map acts as a high pass filter and tends to remove larger scale features such as those caused by basement features.

Figure 2.31 is a dip azimuth map for the aeromagnetic data in Fig. 2.29. The amplitude of the whole-field aeromagnetic anomaly is very dependent on the strength of the magnetic susceptibility contrasts in the basin. The largest contrasts in susceptibility represent offset basement blocks or lateral differences in basement intrusions. These features have many closely spaced lines in the dip azimuth map and may represent boundaries of individual basement blocks. Production seems to be related to margins of these “blocks” and may be due to faults propagating up-section into the Brushy Canyon, or local and regional structural highs built on uplifted blocks down-section of the Brushy Canyon. The boundary of the potash reserve follows the basement feature in a manner similar to the oilfields.

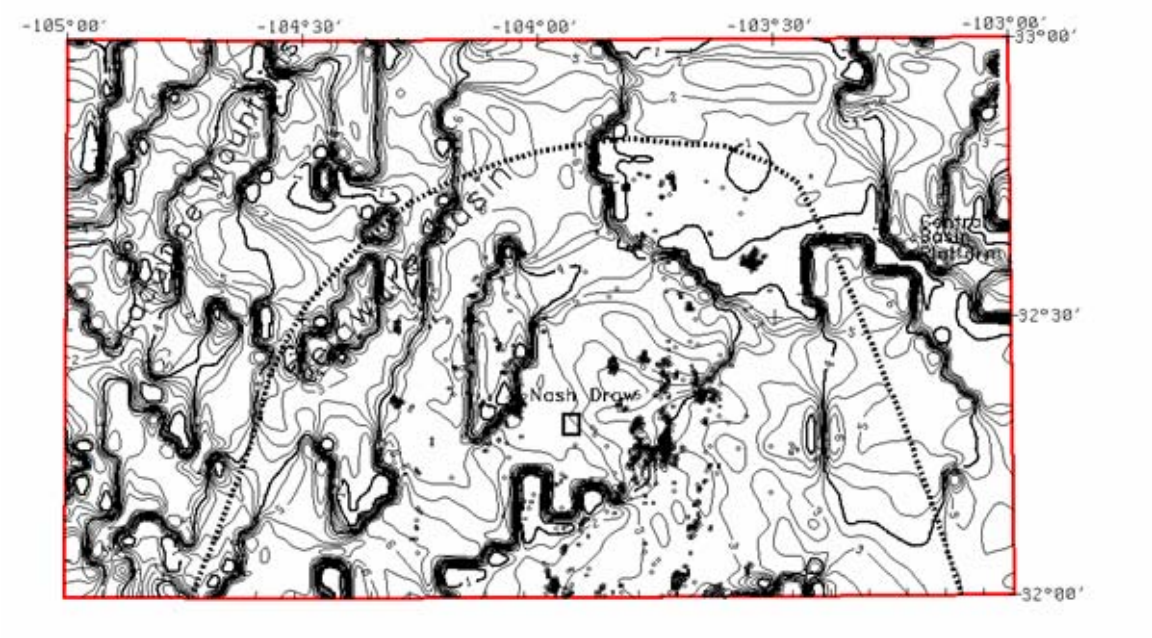

Fig. 2.31: Magnetic dip azimuth map. Areas with large numbers of close contours represent areas of large-scale magnetic susceptibility, which typically occur in basement blocks or intrusions.

A total of 27 maps were generated for the regional structure, gravity, and aeromagnetic data. Table 2.1 lists the existing geophysical maps.

Table 2.1: Existing Geophysical Maps for the Lower Brushy Canyon

SOURCE	*MAP*	*EXPLANATION OR USE*
Structure	Brushy Canyon Subsea	Structural traps in Brushy Canyon
Structure	Dip Azimuth	data trends – faults - anticlines
Structure	Dip Magnitude	Steepness or scale of data trends
Structure	Curvature Azimuth	Rate of change in dip – flexure
Structure	Curvature Magnitude	Scale of curvature changes – fracture indicator
Structure	X-Derivative	X directional derivative - data trends of slope
Structure	Y-Derivative	Y directional derivative - data trends of slope
Structure	2nd X-Derivative	X directional derivative - rate of slope change
Structure	2nd Y-Derivative	Y directional derivative - rate of slope change
Gravity	Bouger Anomalies	Variations in regional densities incl. basement
Gravity	X-Derivative	X direction rate of change in gravity
Gravity	Y-Derivative	Y direction rate of change in gravity
Gravity	2nd X-Derivative	Removes basement features–sedimentary gravity
Gravity	2nd Y-Derivative	Removes basement features–sedimentary gravity
Gravity	Dip Azimuth	Data trends
Gravity	Dip Magnitude	Data trends
Gravity	Curvature Azimuth	Data trends
Gravity	Curvature Magnitude	Data trends
Aeromag	Aeromagnetic anomalies	Variations in magnetic susceptibility
Aeromag	Dip Azimuth	Differentiation of basement blocks?
Aeromag	Dip Magnitude	Data trends – scale of susceptibilities
Aeromag	Curvature Azimuth	Data trends
Aeromag	Curvature Magnitude	Data Trends
Aeromag	X-Derivative	Data Trends
Aeromag	Y-Derivative	Data Trends
Aeromag	Second X-Derivative	Sedimentary section aeromagnetics
Aeromag	Second Y-Derivative	Sedimentary section aeromagnetics

Time Depth Conversion Using Seismic Attributes

A new technique [Hart, 2000] for time-to-depth conversion of seismic horizons was generated for this project and tested at the Nash Draw field for the Brushy Canyon interval. The Brushy Canyon has been interpreted as being deposited through slope to basin turbidity or saline density currents [Montgomery, 1999]. This complex depositional process limits an interpretation of depth structure constructed strictly using the commonly-used method of geostatistical extrapolation of well control points. The geologic model is fairly complex, so a sophisticated pattern recognition tool was used to

determine an empirical relationship between well and seismic data. Neural networks are such tools, and for this study they were used to predict a velocity model. Thus a robust computed depth map using seismic attributes to control velocity calculations in bins away from well control was obtained when the velocity and time pick maps were combined.

Several aspects of reservoir development require an accurate understanding of depth structure to adequately evaluate a play. Reservoir volume calculations, trapping mechanism analysis, and drilling are all depth-dependent, so an accurate depth structure map is an invaluable resource. The accuracy of the traditional techniques (TDQ and Zmap by Landmark Graphics) in predicting depth away from the central part of the Nash Draw field (Table 2.2) needed to be improved. An artificial intelligence approach, a multilayer perceptron neural network, (MLP) was used to evaluate the dataset. Training and prediction cross-correlations were well above 95%. Figure 2.32 shows the TDQ map, which poorly predicted the three offset points, and Fig. 2.33 shows the MLP depth map, which accurately and blindly predicted the same points.

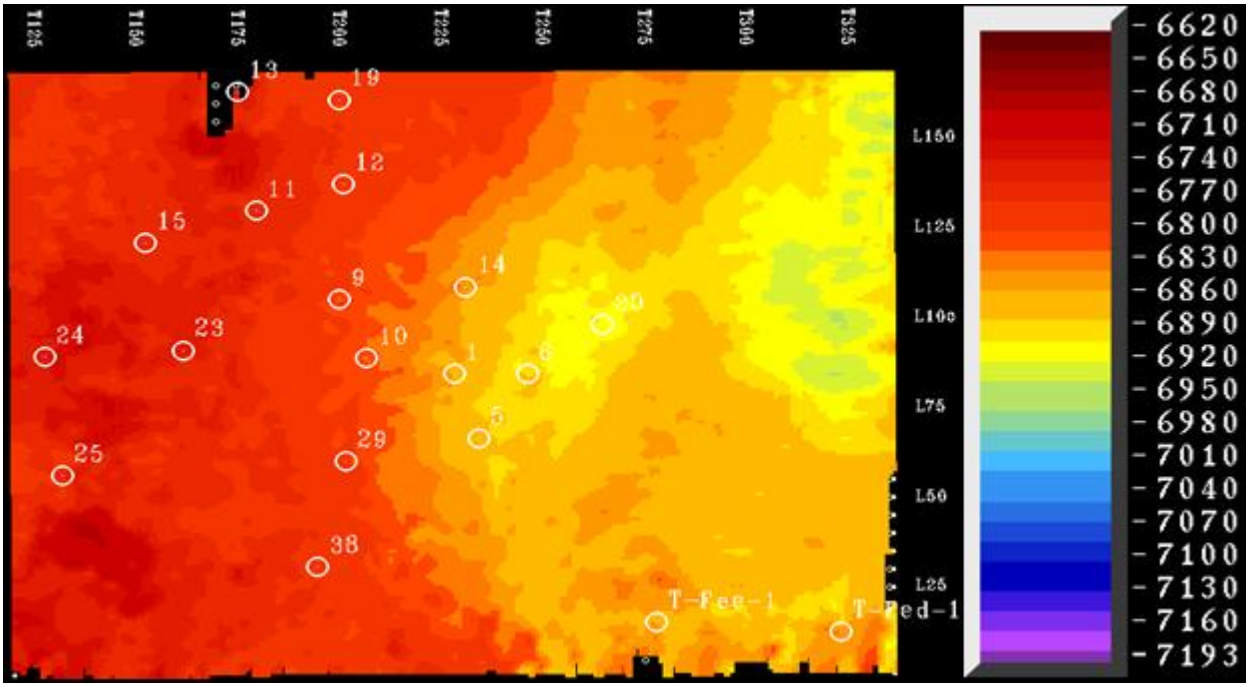

Fig. 2.32: This depth map is the result of using TDQ, a time-to-depth conversion program, with a simple one-layer velocity model based on well control points. This program honors the data points exactly, and uses a weighted linear interpolation to convert the time horizon to depth. Test points are poorly predicted (T-Fee-1 and T-Fed-1). Scale is in feet.

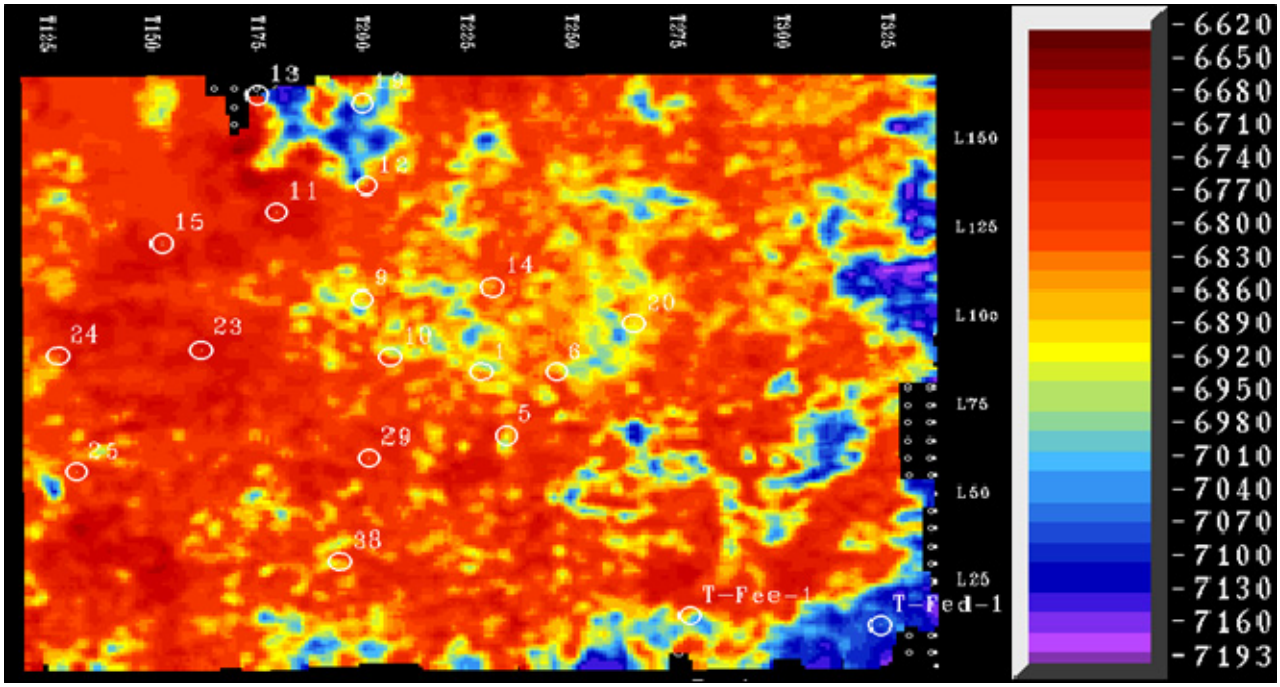

Fig. 2.33: This is the depth map predicted using the MLP with a network architecture of 3-3-3-2-1, and training to CC=0.9895. This map was filtered lightly to highlight trends. The filter was based on a 3x3-bin size, equally weighted low pass filter. Test wells T-Fee-1 and T-Fed-1 were accurately predicted. Scale in feet.

Table 2.2: Relative Errors at Each Control Point for Three Time-to-Depth Conversion Tools

Well	Depth	MLP Dep	MLP-Err	TDQ Dep	TDQ Err	Zmap Dep	Z,map Err
T-Fed	7081.5	7073.9	7.62	6852.11	*229.39*	6976.84	*104.66*
T-Fee	6994.0	6950.3	43.66	6864.6	*129.4*	6946.35	*47.65*
38	6800.0	6816.5	-16.53	6787.65	*12.35*	6795.89	*4.11*
25	6764.0	6763.9	0.06	6764.0	0	6762.86	1.14
29	6803.0	6807.0	-4.02	6803.0	0	6803.48	-0.48
5	6882.0	6876.9	5.1	6882.0	0	6880.50	1.50
1	6862.0	6866.5	-4.47	6862.0	0	6860.96	1.04
6	6891.5	6891.4	0.12	6891.5	0	6889.74	1.76
10	6824.0	6807.1	16.9	6824.0	0	6823.66	0.34
24	6746.0	6747.3	-1.31	6746.0	0	6746.51	-0.51
23	6753.5	6749.5	4.02	6753.5	0	6754.01	-0.51
20	6912.0	6913.6	-1.61	6912.0	0	6912.20	-0.20
9	6807.5	6822.7	-15.18	6807.5	0	6808.40	-0.90
14	6850.0	6846.2	3.78	6850.0	0	6850.20	-0.20
15	6771.5	6767.9	3.62	6771.5	0	6770.92	0.58
11	6773.0	6775.7	-2.74	6773.0	0	6773.32	-0.32
12	6794.0	6799.4	-5.44	6794.0	0	6793.72	0.28
19	6787.5	6787.7	-0.22	6787.5	0	6787.51	-0.01

2.3 Production Data

Production data was used in the development of the FEE Tool in a number of ways. Both FEE Tools use predicted production data developed by training neural networks with actual production data. Production data was also used to compute inputs such as distance to nearest producing well, dip angles, etc. Finally, producing wells were held out from the development to be used as testing well sets. Unsuccessful wells were also used as testing well sets.

2.3.1 Lower Brushy Canyon Formation

Producing well data for the Lower Brushy Canyon formation was developed by first using the ONGARD [PTTC, 2004] website and other sources to create a list of over 2200 wells producing from the Delaware Mountain group. This group contains the Lower Brushy Canyon, the Upper Brushy Canyon and the Cherry Canyon formation. To separate out the wells producing primarily from the Lower Brushy Canyon formation, formation tops and bottoms were interpolated from core data. Completion cards for each

of the Delaware Mountain group wells were located at the New Mexico Tech Petroleum Library, and the producing depths from the cards were compared to the formation top and bottom. Wells were divided into three categories: wells with no significant Lower Brushy Canyon production, wells with mixed production including a significant production interval in the Lower Brushy Canyon, and wells with all production from the Lower Brushy Canyon. The latter two sets were used in the development process of the Delaware FEE Tool, creating a 1000-well set of producing wells. This was further separated into a development set of all wells in the 1000-well set completed prior to March of 2000, and another group of remaining, more recent wells, held aside for blind testing. The development set contained 911 wells and the testing set contained 89 wells. A third set of 75 unsuccessful wells from the formation was collected as another testing set [Broadhead, 2001].

2.3.2 Siluro-Devonian Formation

The well data used for the development and testing of the Devonian FEE Tool originated from a database of approximately 280 oil and 45 gas wells [Broadhead, 2004]. These wells were then entered into the ONGARD database and the New Mexico production data books to verify the producing formation and determine the amount of production. Oil and gas production were combined using the formula 6 mcf = 1 BOE (barrel of oil equivalent). Wells that could not be verified as producing from the formation, and wells without available production data were removed from the set, and the final set of wells was then subdivided into training and testing sets as follows:

- A set of 67 producing wells spread throughout the region, used as a training set to train a neural network to predict production for the region,
- A set of 105 unsuccessful wells (dry holes), used as a training set for the neural network and as a testing set to test performance of the Devonian FEE Tool,
- A set of 25 producing wells used to test the neural network performance,

- A set of 35 recent producing wells (not included in other sets) used as a testing set to test performance of the Devonian FEE Tool.

3. Delaware Basin FEE Tool

3.1 Development

3.1.1 Knowledge Base

The expert system was built on the guidelines of a knowledge base developed for the Lower Brushy Canyon formation of the Delaware Basin. Rules in the knowledge base 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 type of thought process in a series of rules.

The knowledge base is divided into three sections, the *Trap*, *Formation* and *Regional* assessments. Each section begins with a rule for developing an initial estimate, followed by a series of modification rules that enhance or degrade the initial estimate. The *Trap* assessment begins with an estimate based on the step function defined in Fig. 2.1, the *Formation* assessment begins with an estimate based on the percentage of total organic carbon (TOC) at the prospect and the *Regional* assessment begins with an estimate from a similar step function using predicted production as an input.

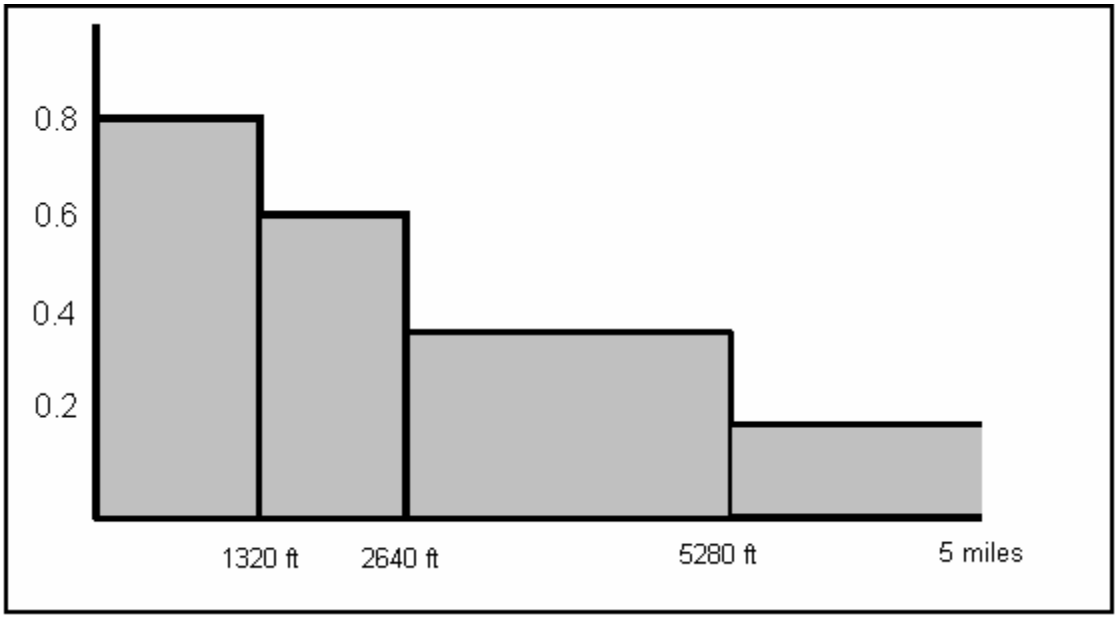

Fig. 3.1: Step function for determining initial trap assessment value. This value is based on distance between the prospect and the nearest producing well. The crisp version of the rule is shown in this diagram; fuzzifying the rule has the effect of smoothing the graph.

In each assessment there are rules for modifying the initial estimate. For the trap assessment, modifications include rules based on dip, thickness of the porous sand, structure and existence of sand pinchouts. An example of a set of rules to modify the initial estimate is given below. These rules use the dip angle as an input, and the output is a "flag" a number that indicates whether to increase or reduce an estimate and the magnitude of the modification.

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

For the formation assessment, modifications are based on production index or other measures of thermal maturity and distance to high quality downdip source rock; for the regional assessment, modifications include rules based on distance to higher predicted production, consistency of predicted production and thickness of porous sands. The knowledge base, used for the crisp expert system, is given in the appendices. An example of how the rules are 'fuzzified" for use in the FEE Tool is provided in Chapter 5.2

3.1.2 Answer Base

The answer base stores the specific data required as inputs for the knowledge base rules. For example, the first set of rules in the trap assessment requires the distance from the prospect to the nearest producing well. First, the nearest gridpoint to each producing well is located. Then the distance from the gridpoint to each of 911 wells producing from the Lower Brushy Canyon formation is computed, and the minimum is selected. The answer base contains a column with these distances for each gridpoint. A second column, termed relevant thickness, is either the 10% or the 15% porosity thickness based on whether the gridpoint is in the central basin or the northwest margin. Other columns involve values that were computed to provide the necessary input. These values include dip angle, sand pinchout, distance to high quality downdip source rock, and distance to higher predicted production. A representative section of the answer base is shown in the appendices.

Development of the software used to compute these columns is discussed in the following chapters, and sample codes are included in the appendices. All of the columns in the answer base provide input required by the knowledge base to evaluate the rules. Table 3.1 lists the variables in the answer base, the section of the knowledge base that uses the variable, and a brief description of how the variables were developed.

3.1.3 Crisp Model Development

The crisp model of the expert system was developed to aid in the development of the FEE Tool in a number of ways. Through developing the crisp model expert system, the numerical approach for evaluating rules and modifications was created, improved codes were written to calculate values stored in the answer base, and various weighing schemes to combine the three assessments were evaluated to help select a final weighing scheme for both systems. The crisp models were also used as verification tools and the final crisp expert system model has served to verify the expert system. As a validation tool, the crisp model results were applied to test well sets throughout the process to determine if the models were able to predict, at statistically significant levels, the locations of recent producing wells. As a verification tool, the final crisp model results were compared to the final results of the FEE tool to uncover possible discrepancies or errors in coding.

Nine models were developed in the process leading to the final crisp model expert system. The first model of the expert system was constructed using rules and answer base values that related to the trap assessment. It consisted of the initial trap assessment estimate (Fig. 3.1) subject to three modifications rules based on dip, gross brushy thickness and existence of a sand pinchout. The final crisp model expert system used all the rules as written in the final knowledge base. Throughout the process of developing the model expert systems, rules were refined and improvements were made in the coding used to develop the answer base. The well sets used for developing the trap assessment and for testing were also refined to include only hand-verified wells producing from the Lower Brushy Canyon formation of the Delaware Basin. This development process, and the improvements generated by the process are discussed in detail in Chapter 5; a brief outline of each of the models is provided below.

<u>Version 1</u>

- Trap assessment only.
- Initial estimate and three modifications: dip, thickness and sand pinchout.
- Initial estimate based on distance to nearest producing well, using a 2257-well set of all Delaware Basin wells drilled before cutoff date (3/2000).

- Access™ queries used to search for sand pinchout.

Version 2

- Trap, Formation and Regional assessment.
- First version of the model expert system to include a computation representing each of the rules in the knowledge base except the consistency rules.
- Gross thickness, used in the first model, was replaced by either 10% or 15% porosity thickness based on the location in the basin (deep or margin).
- Dip measured as a slope was replaced by dip angle and a new set of cutoff values for each rule was developed.
- Weighing scheme: 60%, 10%, 30%.

Version 3

- Used new sand pinchout results based on new code using Matlab instead of Access queries.
- Added rules for consistency (standard deviation in a large and small area vs. mean standard deviation for the entire system) in both the trap and regional assessment
- Weighing scheme: 1/3 for each branch.

Version 4

- Improved method of searching for downdip source rock, verifying in each step that the location of the high TOC percentage was downdip of the prospect in question.
- Weighing scheme: 60% T, 5% F, 35% R.

Version 5

- Changed trap assessment to use a set of 516 wells reported as producing from only the Lower Brushy Canyon.

Version 6

- Used a set of 609 wells that were hand verified by reviewing completion cards to be producing from the Lower Brushy Canyon only.

Version 7

- Used a set of 911 wells that were either producing from the Lower Brushy Canyon only, or producing from a mix of formations, including significant production from the Lower Brushy Canyon.
- Used a new method of searching for nearest high predicted production that matched knowledge base.
- Weighing scheme: 60% T, 10% F, 30% R.

Version 8

- In this version multiple weighing schemes were compared.

- Final weighing schemes are 35% T, 30% F and 35% R; 50% T, 25% F and 25%R, split off to make Version 9.

Version 9

- Weighing scheme is 50% T, 25% F, 25% R.
- Made two corrections to the model to better match the rules, assigning the flags for standard deviation for thickness differently if the prospect is deep or on the margin, and changing the lowest starting estimate in the Formation assessment to match the rules.

Mathematical Methods

In order to generate a numerical final output for each of the 60,479 gridpoints using the crisp expert system, an initial estimate was generated in the set {0, 1} for each of the three branches: trap, formation and regional. The first rule in each branch of the knowledge base provided this estimate and the subsequent rules modified these initial estimates.

The basic modification method used in this and all versions of the model expert systems is called a *roots and powers method*. The initial estimates are numbers between zero and one; to enhance them a root is taken, and to reduce them a power is taken. For example, if the goal is to slightly enhance an estimate (flag = 1), the square root is taken, while if the goal is to strongly enhance an estimate (flag = 2), the cube root is taken. Similarly, to slightly reduce an estimate (flag = -1), it would be squared, while to strongly reduce it (flag = -2), it would be cubed. The flags are not restricted to integers, so the method is generalized. For a positive flag, s, indicating an enhancement, the estimate would be raised to the 1/(s+1) power, and for a negative flag, the estimate would be raised to the |s| + 1 power.

For the first few models of the expert system, a sequential method was used to make the modifications. In this method, the initial estimate was modified using the roots and

powers approach for each flag. For the later crisp models and the FEE Tool, a new method was developed in which the flags are summed, and this sum was used to modify the initial estimate according to the following approach. This new "sum of flags" method removes the dependency on the order that the rules are presented in.

Let the sum of flags = s
Let the initial estimate to be modified = t

If s > 0, then $t_{new} = \sqrt[s+1]{t}$
If s = 0 then $t_{new} = t$
If s<0, then $t_{new} = t^{|s|+1}$

For illustration, consider a gridpoint for a location of interest with an initial trap estimate of 0.6, indicating the nearest producing well is between 1320 and 2640 feet away. Suppose the set of modification flags associated with this gridpoint is {0,2, -1,0}.

Sequential Approach

$$t_0 = 0.6,$$
$$s_1 = 0, \quad t_1 = 0.6$$
$$s_2 = 2, \quad t_2 = \sqrt[2+1]{0.6} = 0.84343$$
$$s_3 = -1, \quad t_3 = (0.84343)^{|-1|+1} = 0.7114$$
$$s_4 = 0, \quad t_4 = 0.7114 \approx 0.71$$

Sum of Flags Approach

$$s = 0 + 2 + (-1) + 0 = 1$$
$$t_{new} = \sqrt[1+1]{0.6} = 0.7746 \approx 0.77$$

Finally, the estimates from the three branches were combined to form a final estimate. This was done using a weighted average. The values of the weights were determined by expert opinion and studying models where the weights were varied.

$$final_estimate = \sum w_1 t + w_2 f + w_3 r$$

$$\sum w_1 + w_2 + w_3 = 1$$

w_i = weight
t = trap estimate
f = formation estimate
r = regional estimate

Tools Used in the Development of the Crisp Model

The process of developing the crisp model expert system required the use of a variety of software packages. As described in Chapter 2, much of the original data was the result of interpolating values from core testing, well logs, or other measurements, across the region in question. This interpolation was done using the Landmark Z-Map® software. The Z-Map® software was also used to generate maps of the final estimate during the process of developing the crisp models [Balch, 2003], [Hart, 2000]. These maps helped refine the model system, the knowledge base and the FEE Tool.

The data was interpolated using a kriging technique. Kriging is a popular gridding method that often helps identify trends in the data. [Golden Software Inc., 2002] One concern with the kriging method is that it can cause small negative values to appear in data that is expected to be positive. In the gridding applications in this project, these negative values were replaced with zeros.

The codes required for computing many of the variables in the answer base were written in the Matlab®6 programming language. These codes included algorithms to find the distance between each gridpoint and the nearest producing well, as well as more complex codes that looked for the existence of a sand pinchout updip of the gridpoint or measured the consistency of a variable in a small or large neighborhood surrounding the gridpoint.

Table 3.1 lists the values that were computed and the branch of the knowledge base where they were used.

Table 3.1: Answerbase Variables

Variable	Used by:	Developed by:
Distance to Nearest Producing Well	Trap	Matlab 6 code
Relevant Thickness	Trap and Regional	Interpolated with Landmark
Dip	Trap	Computed in Excel
Sand Pinchout	Trap and Formation	Matlab 6 code
Thickness Consistency	Trap	Matlab 6 code
Location of prospect in basin	Trap and Regional	Computed in Excel
Total Organic Carbon	Formation	Interpolated with Landmark
Production Index	Formation	Interpolated with Landmark
Predicted Production	Regional	Neural network
Distance to Downdip Source Rock	Formation	Matlab 6 code
Distance to Higher Predicted Production	Regional	Matlab 6 code
Predicted Production Consistency	Regional	Matlab 6 code

The spreadsheet program MS Excel™ was used to store the data and perform many of the required computations. These computations included finding the input for the dip angle rule, applying the if-then rules in the knowledge base, performing the estimate modifications using the *sum of flags* and *roots and powers* approach, and computing the weighted average to produce the final estimate. The major database tables were also imported into the database management program, MS Access™. This software was used for a variety of queries both for development of the answer base and for reporting results. The major tables created to store data or for computational purposes are described below.

1. Delgrav: The spreadsheet "Delgrav" contains the gridded geological data used in many aspects of this project, including the data used as inputs by the neural network, gridpoint location in both UTM and latitude-longitude coordinates, subsea elevation of the formation top, and gross formation thickness. Calculations

of dip between the gridpoint and the nearest producing well and sand pinchout computations were done using the values in this database.

2. First Year Production: This database contains the first year production of wells listed as producing from the Delaware Sands formations. First year production was used to calculate average monthly production over the first year. These production values were used in developing the neural network and in testing the expert systems.

3. LBC Wells: This database contains the set of wells that have production from the Lower Brushy Canyon formation of the Delaware Basin. To determine which wells from the previous set fit in this category, data from the completion cards were hand-checked against the formation top and formation bottom values at each well location, determined from the "Delgrav" database. These wells were further divided into pre-cutoff and post-cutoff wells, and were used for developing and testing the crisp model and the FEE Tool.

4. FEE Tool Answer Base: This database contains the values for the variables listed in Table 3.1, along with location information given in UTM and latitude-longitude coordinates.

5. Trap Assessment, Formation Assessment and Regional Assessment: These three databases contain the initial estimates and flags that were computed. Each of the three contains the values from the answer base that are relevant to the assessment, and use Excel functions to compute the flags and initial estimates according to the crisp versions of the knowledge base rules.

6. System Model Trap Analysis, System Model Formation Analysis, and System Model Regional Analysis: These databases contain the initial estimates and flags from their respective assessments. Using these values, and the *sum of flags* and *roots and powers* methods, the final estimate for each branch was calculated with Excel functions.

7. Results from 3 Branches: In this database, the final results were imported from the "system model" databases and combined using the selected weighing scheme. Using this database, various weighing schemes could be quickly evaluated.

8. Results Entire Grid: The final results from the crisp model are stored in this database, along with the gridnumber and location data. A second final results database contains the results from applying the FEE Tool to all 60,479 databases in a batch run. These databases were used to test each expert system and to compare the results of the crisp and fuzzy models.

3.2 Results

3.2.1 Statistical Methods Used in Validating and Verifying the Crisp Model Expert System and the FEE Tool

Verification and validation are two different types of testing done on any program or system. Verification can be defined as determining whether "each level of specification and the deliverable code are traceable to a superior specification; that is, the specification or code fully and exclusively implements the requirements of the superior specification." [Gupta, 1990]

Validation, however, is concerned with whether or not "the deliverable code correctly implements the original user requirements." [Gupta, 1990] A simplistic explanation of validation and verification as they relate to this project is that verification is the debugging of the codes and processes used in the development of the expert systems, while validation is the evaluation of the performance of the completed expert systems.

Both validation and verification testing were performed throughout the development of the model expert system and for the FEE Tool.

Verification work discussed in this study included the use of the final crisp model results with the results of the FEE Tool. This type of comparison provided a method of searching for coding errors in both the crisp and fuzzy expert systems.

Validation work involved measuring the performance of the expert systems. This was done in part by looking at the recommendations provided by the expert system at locations where recent wells were drilled. This helped determine if the expert systems were able to recognize low risk drilling locations.

The majority of the statistical computation used in the development and the testing were done using the Minitab™ statistical package. This software was used to find the

parameters of numerical data, create statistical graphs, conduct hypothesis tests, test for normality, create histograms and perform linear correlation and cubic regression studies. Excel spreadsheet functions were used to find percentiles. A breakdown of the statistical work is given below.

Mean: A measure of the central tendency of the data, found by summing the values and dividing by the sample size.

Standard deviation: A measure of the variance of the data, found for a population by the following formula:

$$\sigma = \sqrt{\frac{\sum (x-\mu)^2}{N}}$$

A small value of standard deviation indicates that the data is fairly consistent. If the data is normally distributed, at least 68% of the data falls within one standard deviation of the mean, and even if the data is not normally distributed, at least 75% of the data falls within two standard deviations of the mean.

Percentiles and the five-number summary: A percentile is a value that separates the bottom k percent of the data from the top (1-k) percent. For instance the 90th percentile (or the 9th *decile*) separates the top 10% of the data from the bottom 90%. The 50th percentile is also called the *median*, and the 25th and 75th percentile are also called the first and third *quartile*. The five-number summary consists of the minimum, the first quartile, the median, the third quartile and the maximum.

Statistical graphs: There were a number of statistical graphs used to evaluate the results of this project, including *histograms*, *boxplots*, and *scatter plots*. Histograms are constructed by first sorting the data into classes, and then finding the frequency of each class. The frequency is plotted on the vertical axis, and the class boundaries are plotted on the horizontal axis. The shape of the histogram is a good first indication of the normality of the distribution.

The boxplot is drawn using the five-number summary. It consists of a number line drawn from the minimum to the maximum, with a box on the number line from the first to the third quartile, with the median indicated as a vertical line in the box.

A scatter plot is a plot that shows the relationship between two sets of data. The closer the plot is to a straight line, the stronger the linear relationship between the data. Examples of the three types of graphs are given in Figs. 3.2 through 3.4 below. For these sample graphs, the data used are a selection of pressure gradients and permeabilities from wells drilled into the Devonian carbonate formation.

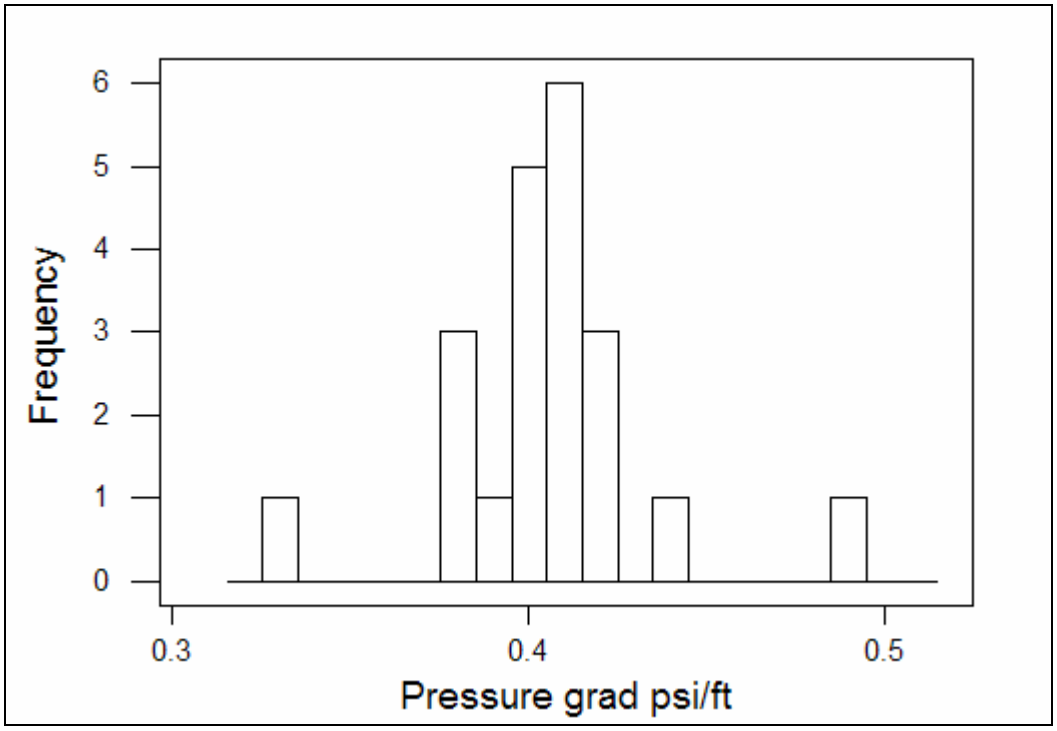

Fig. 3.2: Sample histogram of pressure gradient data.

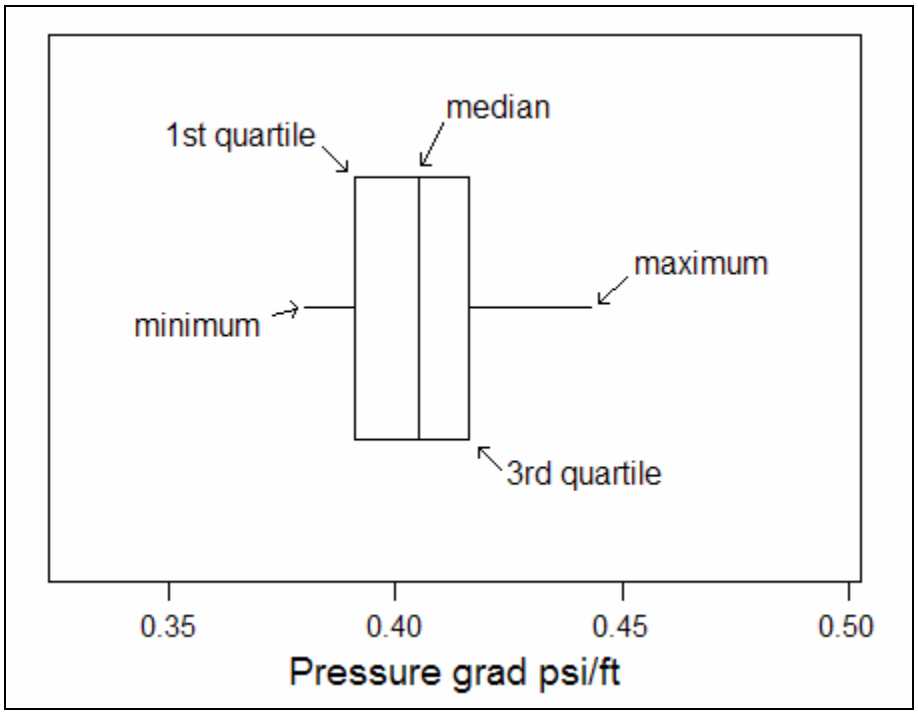

Fig. 3.3: Boxplot of pressure gradient with the five-number summary values labeled.

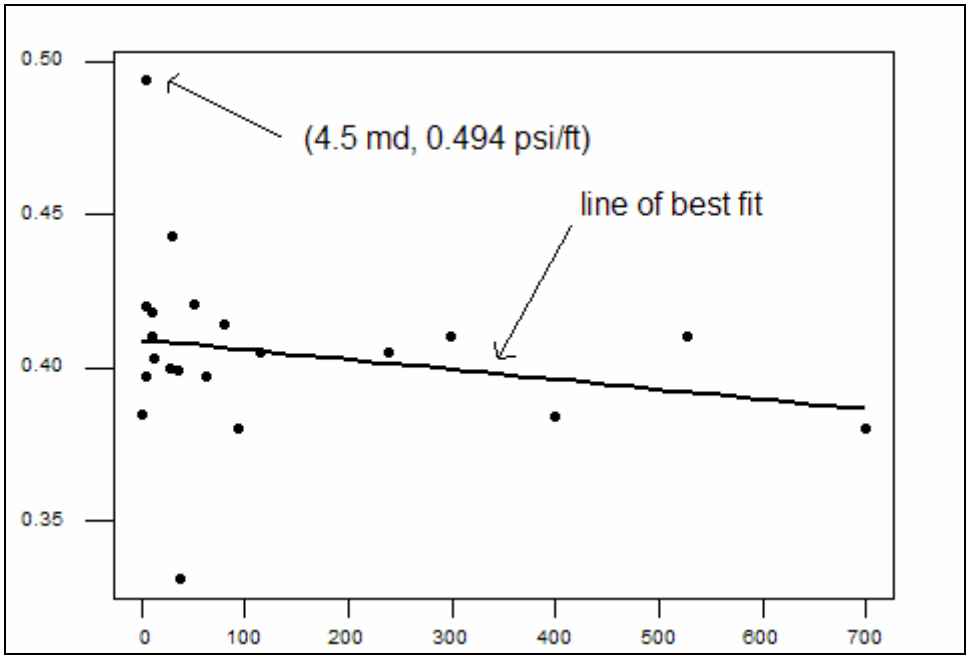

Fig. 3.4: Scatter plot of permeability vs. pressure gradient showing a poor correlation.

Hypothesis test on a mean: A hypothesis test on a mean is a method of determining whether or not there is a significant difference between a sample and a population mean. In this project, the hypothesis test is used to see if there is a significant difference between estimates at well sets (the sample) and the estimates for the entire system (the population).

Linear and cubic regression: Regression involves finding the curve that best describes the relationship between two sets of data. Linear regression finds the best straight line as shown in Fig. 3.4, and cubic regression fits the data with a third degree polynomial. The goodness of fit of the curve is given by a correlation coefficient, R^2. The closer this value is to one, the better the fit.

These statistical techniques were used in a variety of ways in both the testing and development work of the project, including the fine-tuning of the rules in the knowledge base. For example, an expert might provide a rule stating that if the porous sand thickness is significantly high, the potential prospect is enhanced. Statistical parameters were used to determine a numerical value for "significantly high." For instance, significantly high might be defined as greater than the mean plus one standard deviation.

3.2.2 Results of the Crisp Model Expert System

Early Versions

For each of the 60478 gridpoints, a final estimate between 0 and 1 was calculated using the first version of the crisp expert system. This version, detailed in Chapter 5.1, consisted of an initial estimate based on distance to the nearest producing well, and three enhancements, based on dip, gross formation thickness and sand pinchout. The mean of these estimates was found to be 0.28. These results were not tested extensively; however, final estimates from this model were found for locations in the Delaware Sands area where recent producing wells were located. The mean final estimate for these locations was found to be 0.70, a significantly higher value.

Testing on the second model is worth mentioning here as well, as the second version is the first one where all three branches were included. The other versions, versions three through eight, were tested extensively as well.

For the second version, the mean estimate for the 60478 gridpoints was found to be 0.385. The mean estimate for the subset of gridpoints where the recent wells were located was found to be 0.61. This is a significant difference, as verified by a hypothesis test. Histograms (Figs. 3.5 and 3.6) for the entire system estimates and the estimates for the recent well locations also show this improvement.

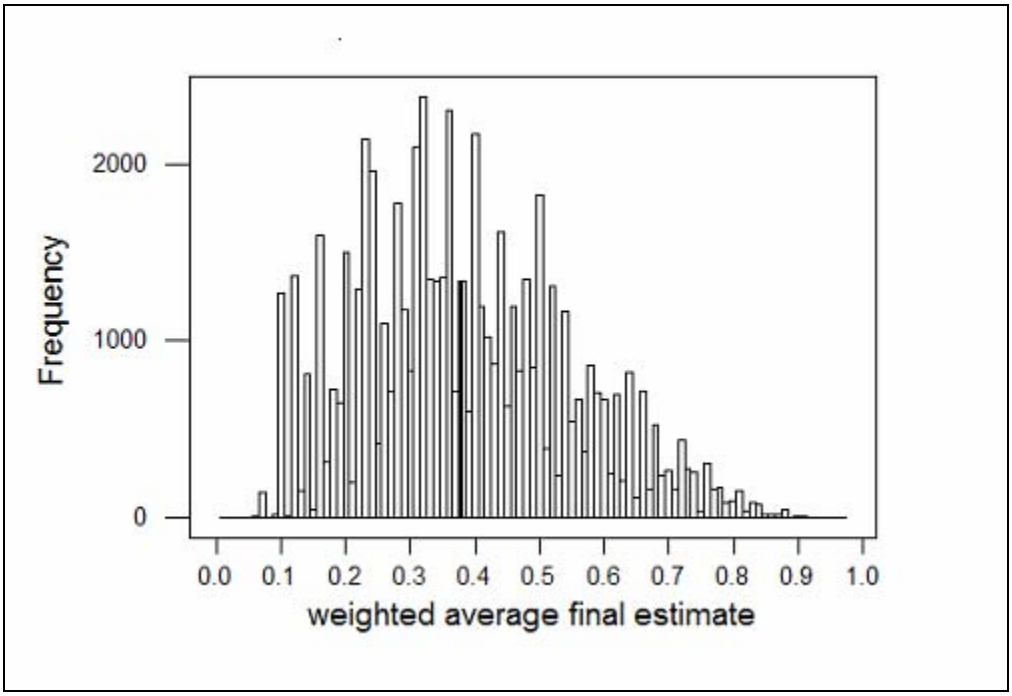

Fig. 3.5: Histogram of the final estimates for all gridpoints with mean.

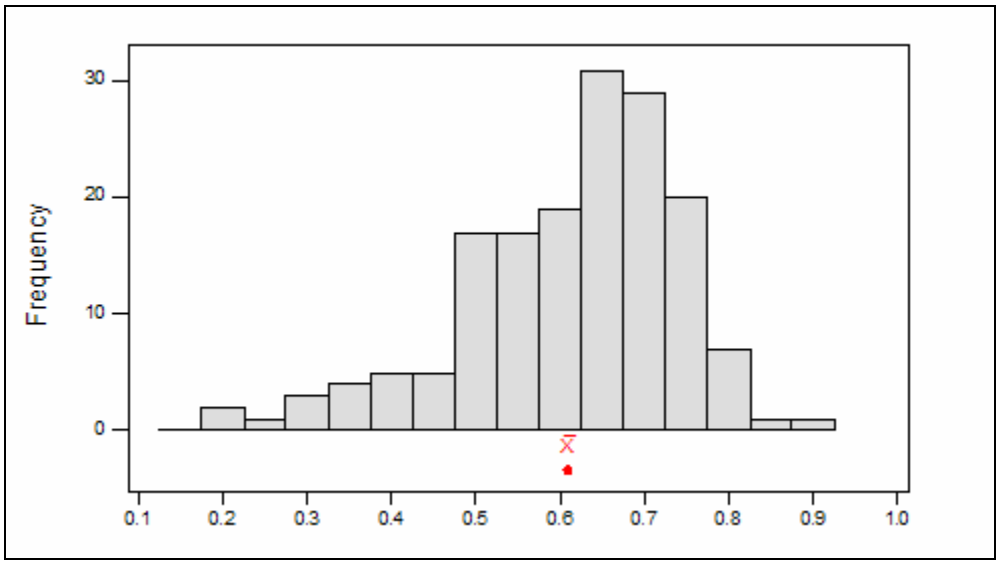

Fig. 3.6: Histogram of the final estimates at the set of recent wells. This graph, using the second version of the crisp model, shows a mean estimate greater than 0.6.

Parameters of the Final Crisp Model

The parameters of the crisp model for all 60,478 gridpoints are given in Table 3.2 below. Figure 3.7 shows a histogram of the data, with a normal distribution curve imposed on the graph to give an idea of the skewedness of the distribution.

Table 3.2: Parameters of the Final Crisp Model Expert System

Mean	0.48
Standard Deviation	0.13
Minimum	0.17
Q1	0.39
Median	0.47
Q3	0.57
Maximum	0.93

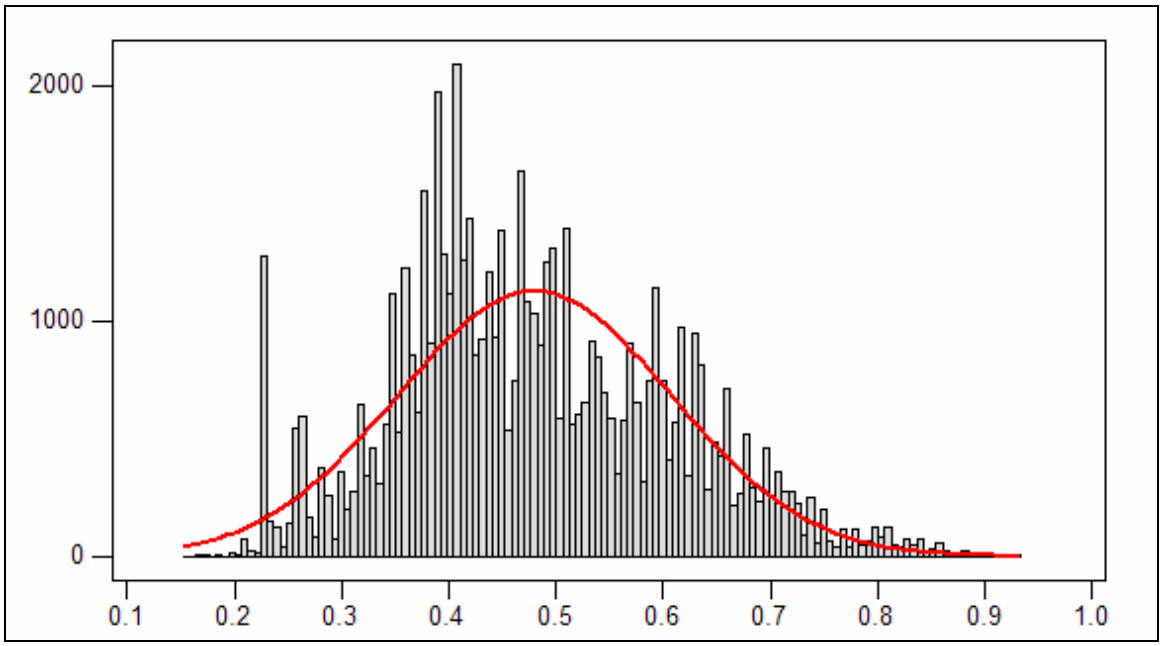

Fig. 3.7: Histogram of the final crisp model for all gridpoints with normal curve.

Results of the Final Crisp Model Expert System

The model expert system was applied to the testing well sets described previously (the 89 post-cutoff wells, 911 pre-cutoff wells and 75 dry holes), as well as the combined set of 1000 successful wells, consisting of the 911- and 89-well sets. Table 3.3 gives the mean of the estimates for each of these sets.

Table 3.3: Mean Estimates for Testing Well Sets

Well set	Mean
89 post-cutoff	0.66
75 dry hole	0.55
911 pre-cutoff	0.79
1000 successful	0.78

Figure 3.8 shows a boxplot of the estimates for the first three well sets and the estimates for the entire system. The boxplot gives a representation of the five-number summary of the data. The five-number summary consists of the minimum and maximum indicated by

the endpoints of the line, the first and third quartiles indicated by the endpoints of the box and the median, or second quartile shown by the line visible in the box. Figure 3.9 is the histogram of the entire system, similar to Fig. 3.7. In this figure, the histogram of the estimates for the 1000 successful wells is overlaid on the entire system histogram, with the successful wells shown as solid.

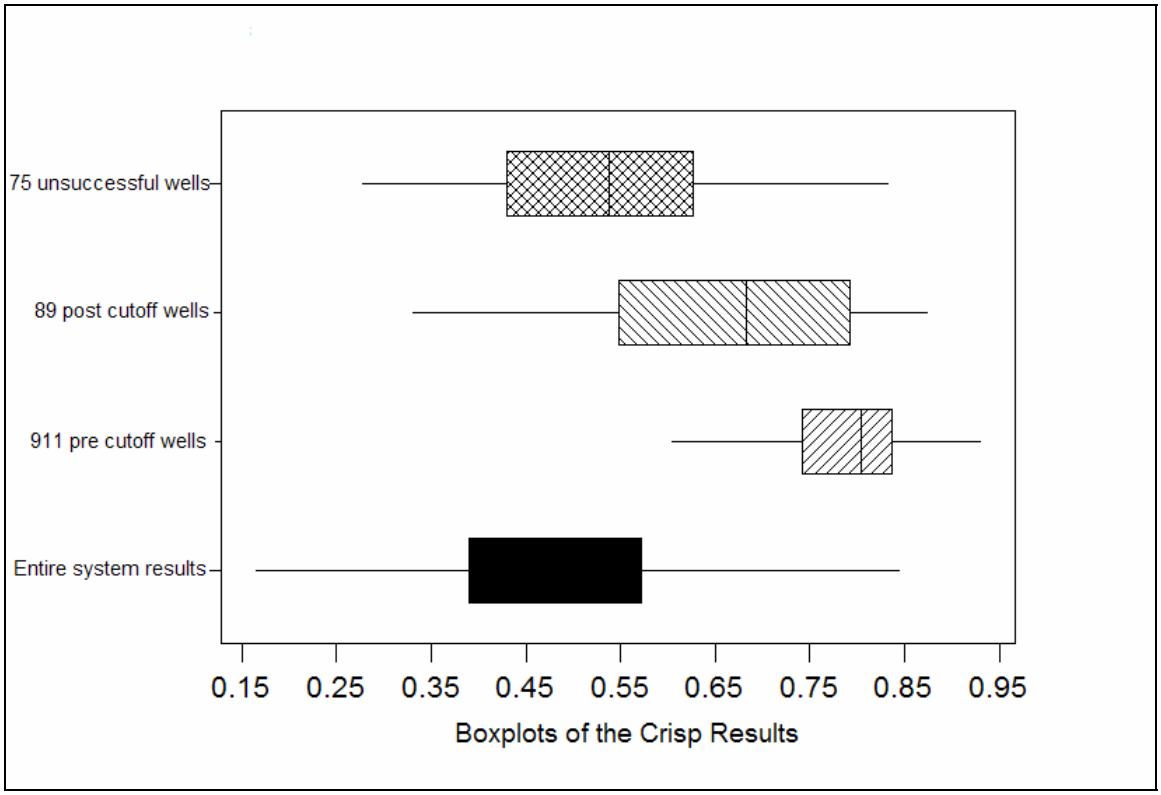

Fig. 3.8: Boxplots for the final crisp model expert system.

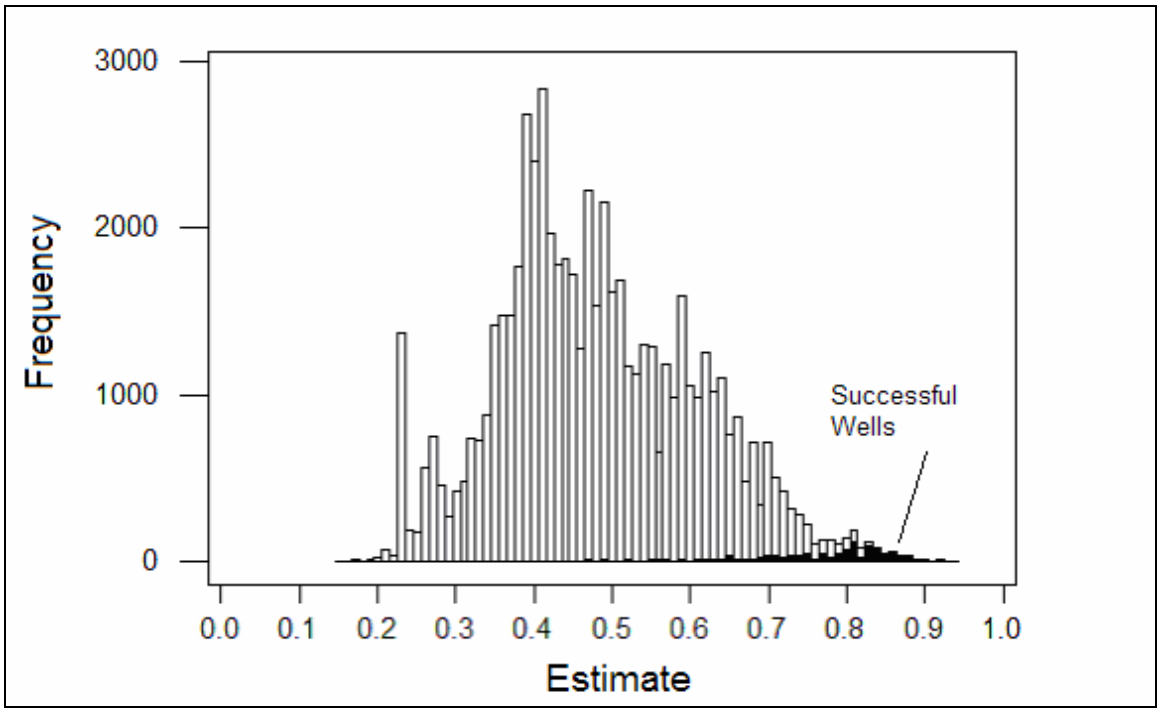

Fig. 3.9: Histogram for the entire system and the successful wells.

From the parameters and graphs, three characteristics can be noted:

1. The mean estimates for the three well sets are significantly higher than the mean estimate for the entire system.
2. The mean estimate for the 911 pre-cutoff well set is higher than the mean estimate for the 89 post-cutoff well set.
3. The mean estimate for the 89 post-cutoff well set is higher than the mean estimate for the 75 unsuccessful wells.

Hypothesis tests (z-tests) verify that these differences are significant. It is expected that the 911 pre-cutoff well set should have a higher estimate than the 89 post-cutoff well set, as the 911 set was used in developing the system, and therefore these locations have the highest possible initial trap estimate. The fact that the mean estimate for the 89 post-

cutoff well set is significantly higher than the system mean estimate provides validation that the model expert system recognizes the locations of successful wells. Finally, the fact that the expert system scores the 75 unsuccessful wells' mean estimate higher than the overall mean estimate but lower than the 89 post-cutoff well set estimate shows reasonable performance in modeling expert thought by recognizing these locations, while not recommending them at the level of the successful wells.

3.2.3 Parameters and Validation of the FEE Tool

In order to evaluate the parameters of the FEE Tool, as well as to evaluate its results, the 60,478 gridpoints were run as a batch. In other words, the final estimates are based on only the inputs in the answer base, without user input.

One of the reasons for developing the crisp model expert system was to provide a way of validating the FEE Tool. This was done by comparing the estimates generated by the crisp model with the FEE tool batch estimates. Figure 3.10 shows a scatter plot of the crisp and fuzzy estimates. While a reasonable correlation coefficient was obtained, the grouping of points to the right of the regression line indicates an error. To narrow down the search for the error, similar plots were generated comparing the crisp and fuzzy estimates for each branch. These plots indicated that the problem might be located in the regional assessment branch. The scatter plot of the regional assessment crisp and fuzzy estimates is given in Fig. 3.11.

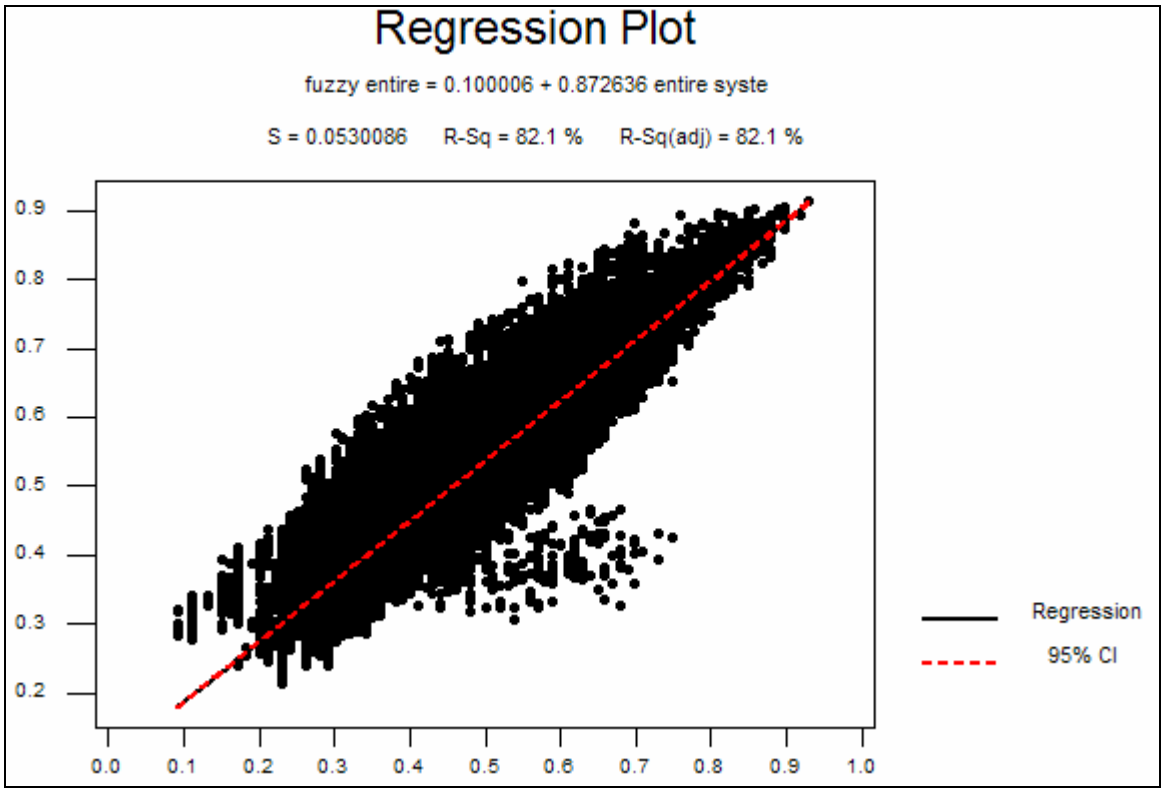

Fig. 3.10: The first scatter plot correlating crisp and fuzzy estimates indicating a possible error to the right of the line.

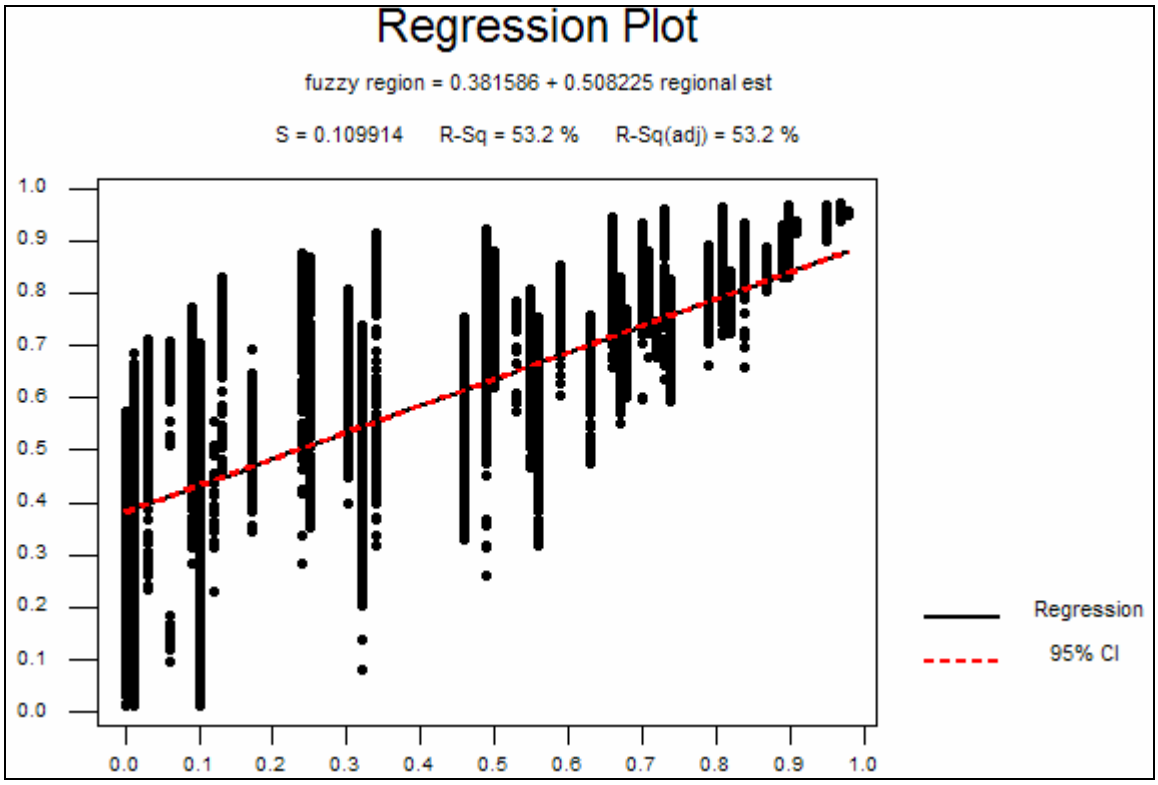

Fig. 3.11: Scatter plot of regional estimates indicating the possible error.

Of the three scatter plots; the plot for the regional branch had the lowest correlation coefficient. Further review of the codes used in this branch in both the FEE tool and the crisp model led to the correction of the problem. (The error was in regional step 3b in knowledge base: the variable "thickness" was called by the FEE Tool instead of "PBOPM.")

Figure 3.12 shows the final scatter plot comparing the fuzzy and the crisp final estimates after all corrections have been made.

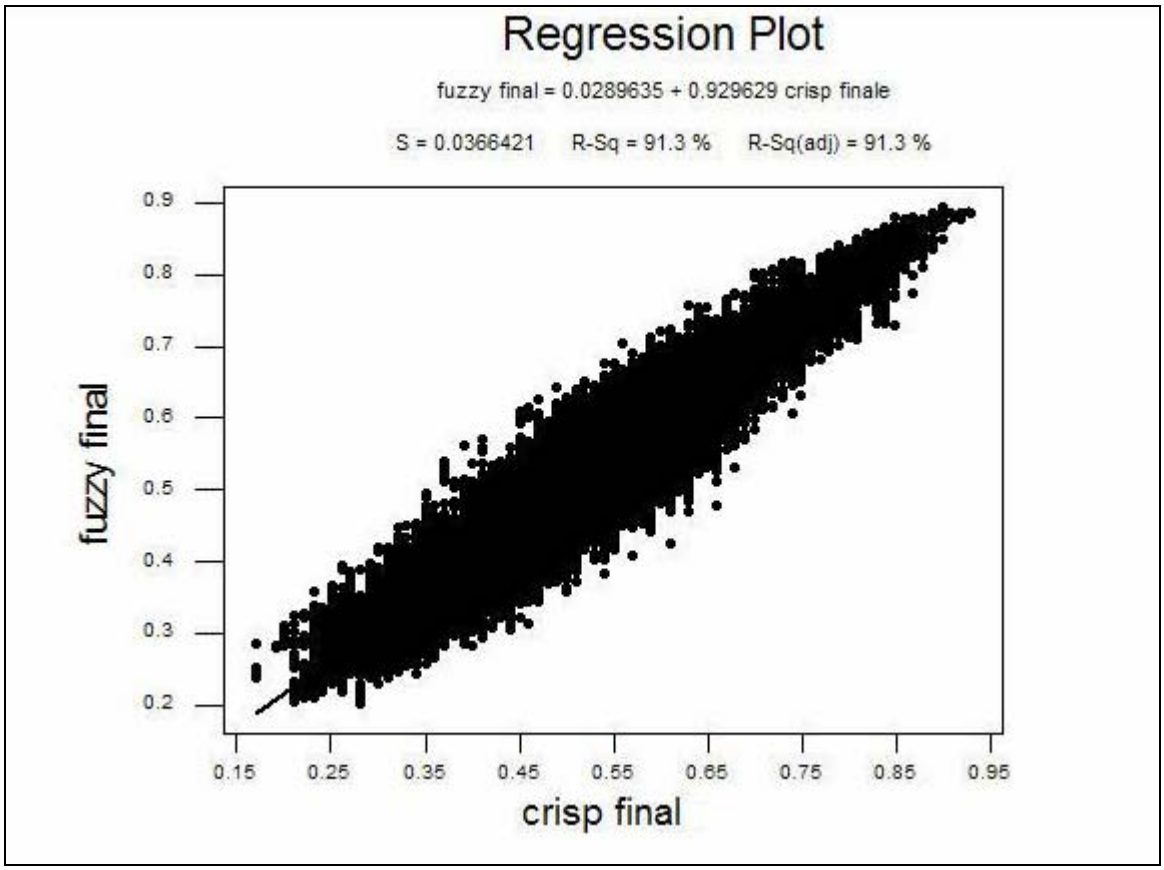

Fig. 3.12: Final scatter plot comparing crisp and fuzzy outputs.

Figure 3.12 shows the desired correlation between the two systems, and provides a good visual representation of how the FEE Tool "fuzzified" the outputs. The next graph is a similar scatter plot; however, instead of comparing the estimates at all 60,478 grid points, this graph gives the relationship between estimates from both systems for the 89 post-cutoff well test set.

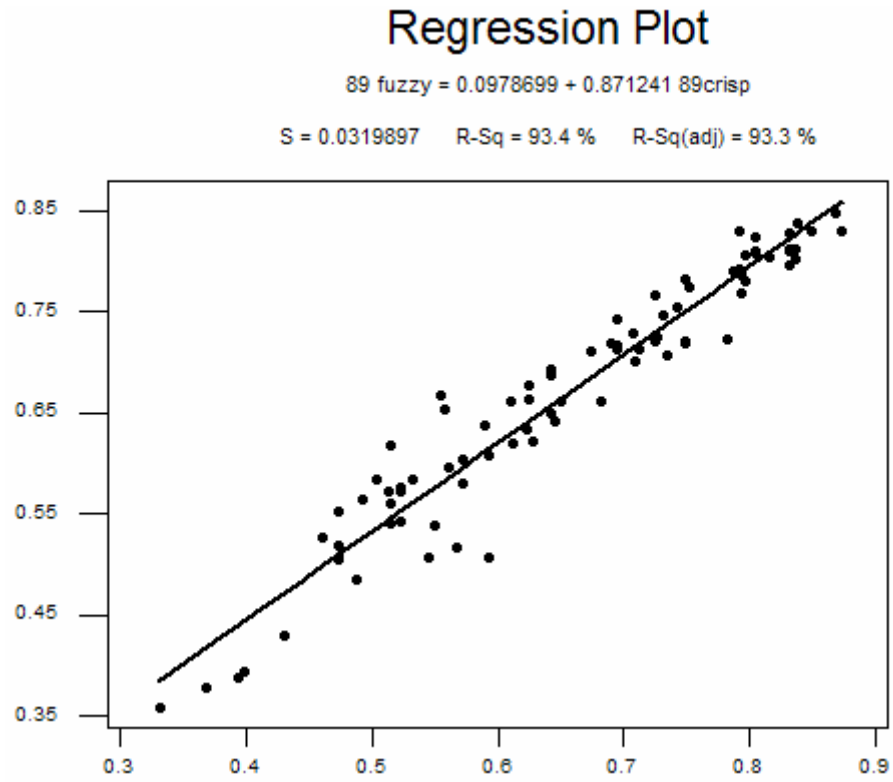

Fig. 3.13: Scatter plot comparing crisp and fuzzy estimates at the 89 wells.

The batch estimates from the fuzzy expert system are examined in more detail than the set of final estimates for the crisp model. One reason for this is to begin the search for natural "break-points" and to determine how many good locations remain undrilled.

The parameters included in Table 3.4 are the mean, the trimmed mean (TrMean), calculated by finding the mean of the data with the top and bottom 5% removed, the standard deviation and the variance.

The mean and the trimmed mean give an indication of the center of the data, and the standard deviation is the most common measure of variance.

Table 3.4: Parameters of the Full Set of FEE Tool Estimates

Parameters	
Mean	0.476
TrMean	0.473
Standard Deviation	0.124
Variance	0.015

The five-number summary is given in Table 3.5, and contains the minimum, first quartile, median or second quartile, third quartile and maximum. Table 3.6 gives the deciles for the fuzzy estimates.

Table 3.5: 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

Table 3.6: Deciles for the Full Set of FEE Tool Estimates

Deciles	
D1	0.330
D2	0.373
D3	0.398
D4	0.425
D5	0.461
D6	0.501
D7	0.543
D8	0.583
D9	0.643

Finally, the full set of estimates was checked to see how close the estimate distribution was to a normal distribution curve. Three methods of considering normality were done with this data. The first was just to inspect a histogram with a normal distribution curve superimposed. This is shown in Fig. 3.14. The second consideration is the skewness and kurtosis values for the data. The skewness, which describes asymmetry, is 0.387, which indicates that the data is somewhat skewed to the right, or that the right tail is "heavier" than the left tail. The kurtosis is a measure of how the histogram of the data differs from a normal distribution. The kurtosis value is –0.15, with the negative sign indicating that the data has a flatter peak and thinner tails than the expected normal distribution. Finally, an Anderson-Darling test was run, with the results shown in Fig. 3.15. The P-value of 0 shown in Fig. 3.15 indicates that there is evidence to assume that the distribution is not normal. Visually, the closer the points are to the straight line, the more "normal" the distribution. If the distribution is a normal distribution, traditional parametric methods of statistics can be used. This includes applying the normal or Gaussian distribution in the process of hypothesis testing, regardless of the sample size.

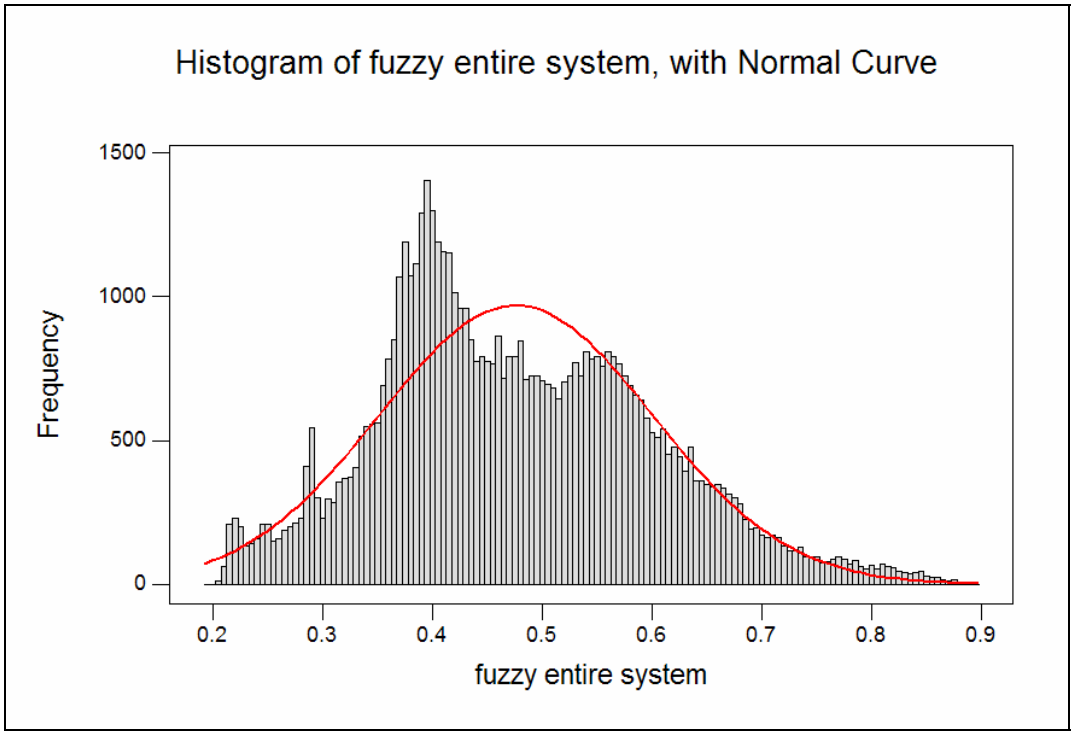

Fig. 3.14: Histogram and normal curve for the estimates for the entire system.

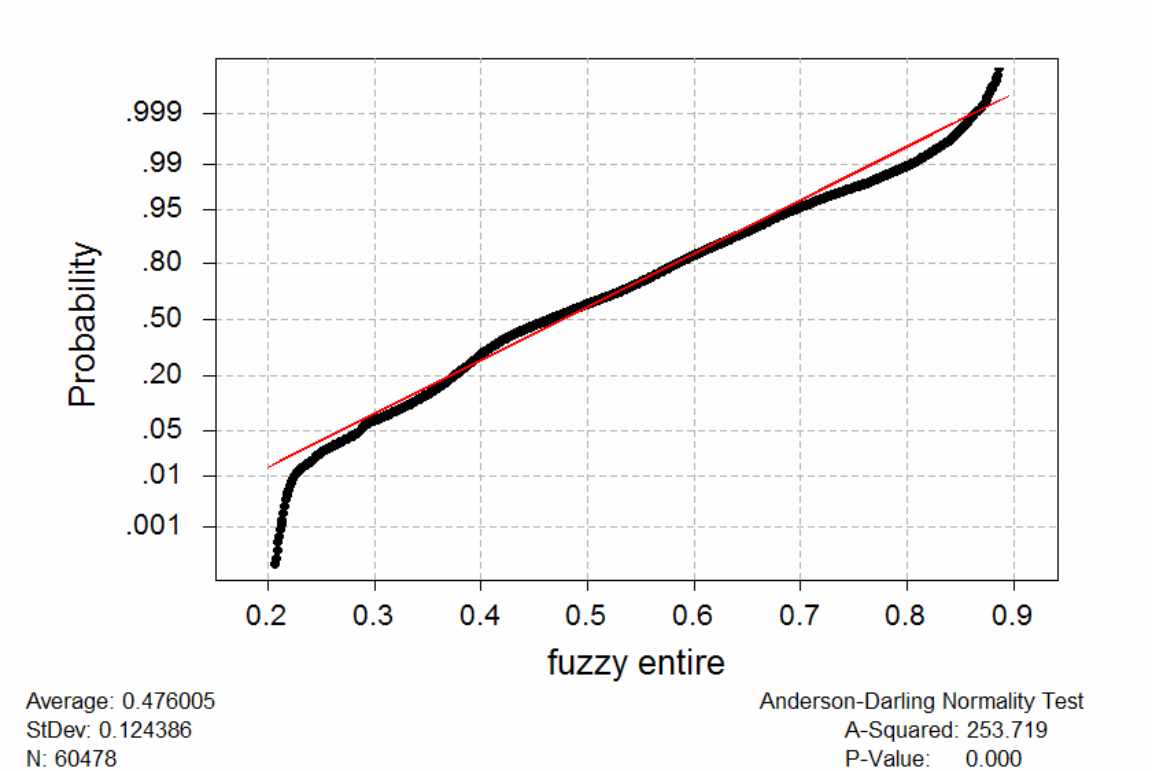

Fig. 3.15: Anderson-Darling normality test graph and results.

3.2.4 Results of the Delaware FEE Tool

The FEE Tool was applied to the test well sets to determine if it was successful in locating good drilling locations. Throughout this testing, a cutoff value was also sought that would separate locations recommended by the FEE Tool from locations that were not recommended.

Table 3.7 gives the mean FEE Tool estimate for each of the testing well sets. It is interesting to note that the mean FEE Tool estimate of the 89-well set is slightly larger than the crisp estimate mean of the same set, although the crisp estimates are slightly larger in the pre-cutoff wells. Also, the mean of the FEE Tool estimates for the 75 unsuccessful wells is lower than the mean of the crisp estimates. Although a Z-test shows that there is not enough evidence to consider these differences to be significant, it does indicate that fuzzifying the rules in the knowledge base is a move in the right direction.

Table 3.7: Mean Fuzzy Estimates for the Testing Well Sets

Well set	Mean
89 post-cutoff	0.67
75 dry hole	0.54
911 pre-cutoff	0.78
1000 successful	0.77

Figures 3.16 and 3.17 show the boxplot and the histograms using the FEE Tool estimates.

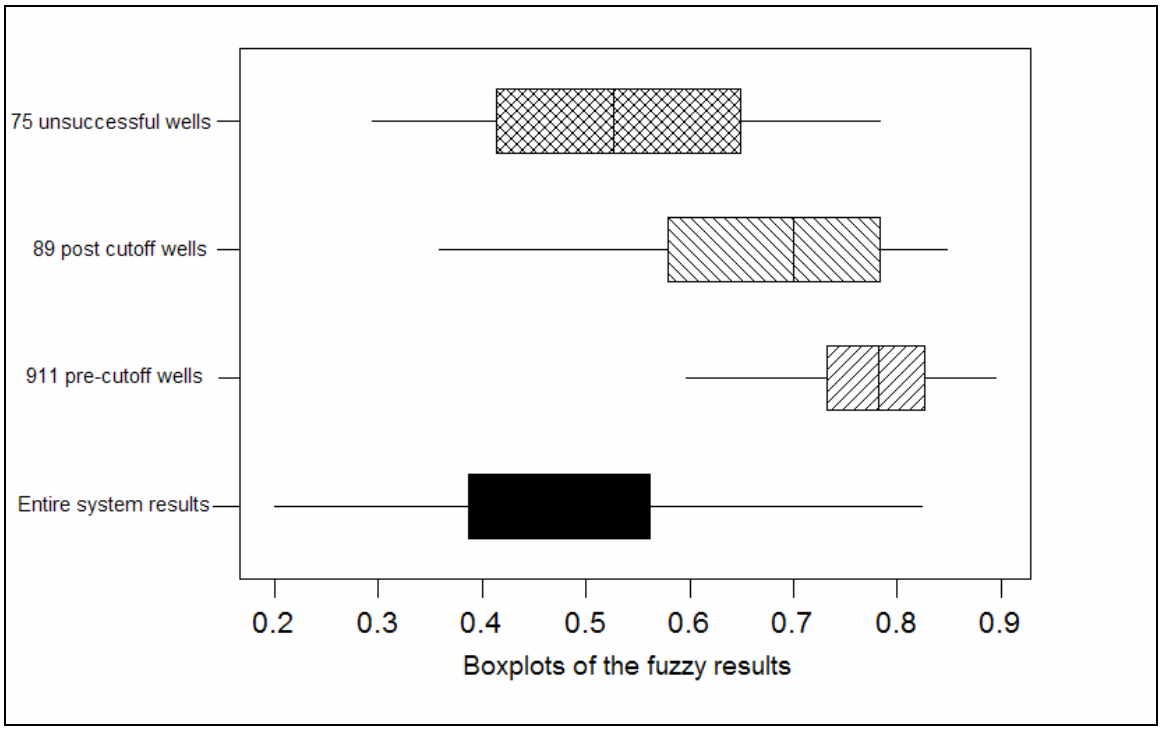

Fig. 3.16: Boxplots for the fuzzy estimates of the entire system and the test wells.

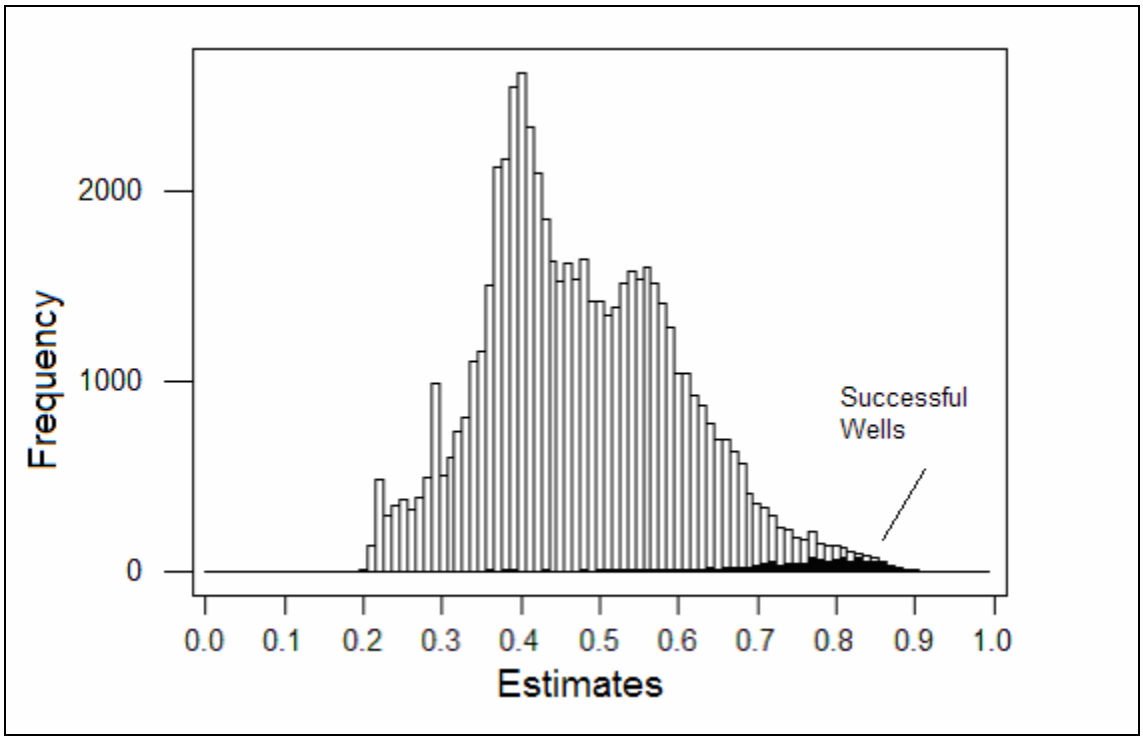

Fig. 3.17: Histogram of the FEE Tool system and successful well estimates. As with the previous histogram, the dark values are the estimates at the successful wells.

From these graphs, and a review of the deciles and other percentiles, a natural cutoff value of 0.65 was selected as the value that separates recommended locations from non-recommended locations. Using the deciles given in Table 3.6, fewer than 10% of the 60478 locations would have an estimate of 0.65 or higher. Adding this value as a marker to Figs. 3.16 and 3.17 also shows that this is a reasonable cutoff value. In Fig. 3.18, the boxplot of Fig. 3.16 is shown with a line indicating the 0.65 cutoff value. The boxplot indicates that using this cutoff value would help avoid recommending potential unsuccessful wells. Figure 3.19 shows the histogram of Fig. 3.17, with this marker added.

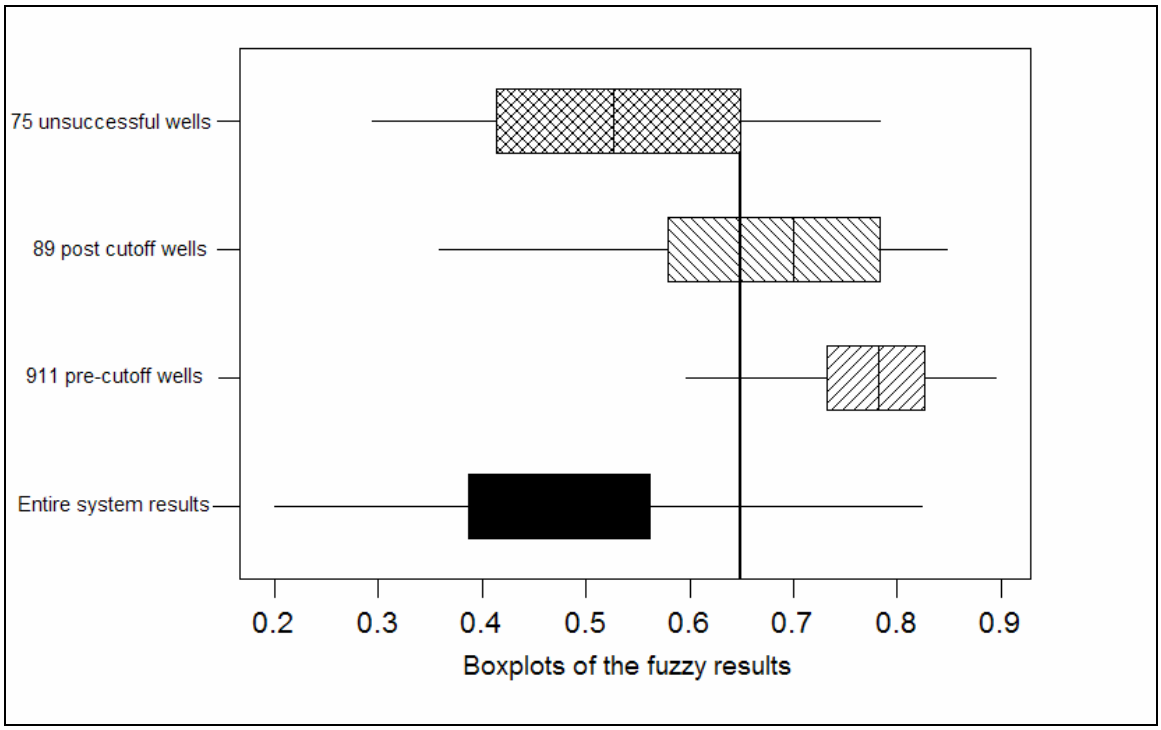

Fig. 3.18: Boxplot of the fuzzy results with the cutoff line indicated.

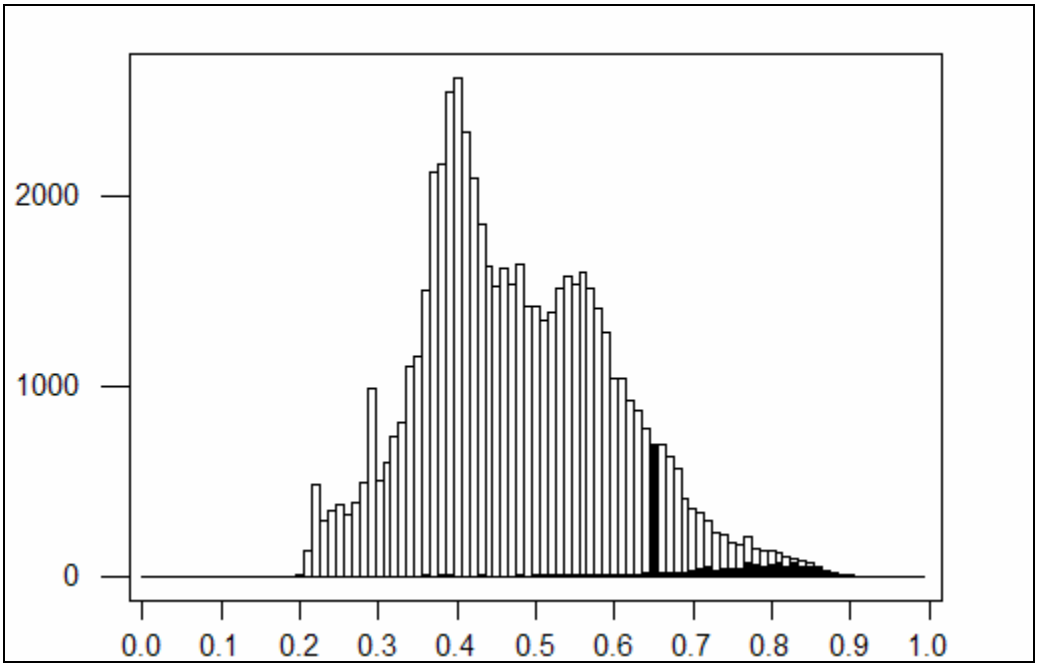

Fig. 3.19: Histograms with the 0.65 cutoff line added.

Using the 0.65 value, it is possible to compute the actual number of undrilled locations that the FEE Tool recommends. First, the number of locations with an estimate of 0.65 or higher was found to be 5556. The number of completed wells was subtracted from that number, indicating that there are 4481 undrilled locations that the FEE Tool recommends based on the values in the answerbase.

To find these locations, the FEE Tool estimates were used to create a map. This map, generated using the Surfer™ mapping software, used different colors to represent different estimates, with yellow, red and orange indicating high estimates. A map of the completed wells in the region was overlaid on this contour map, providing a good indication of where the recommended drilling locations can be found, is given in Fig. 3.20.

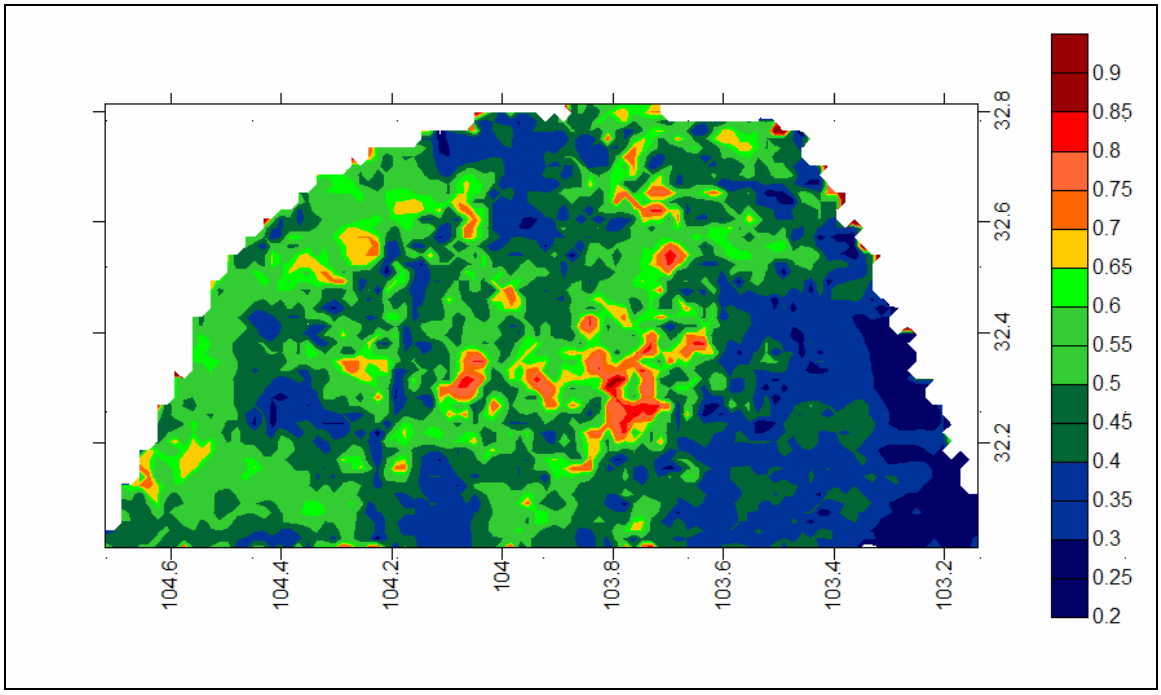

Fig. 3.20: Map of the FEE Tool estimates generated by the Surfer™ software

Finally, the amount of production was again considered in relation to the FEE Tool output. This was done by creating pie charts, similar to those that are available to the users of the online FEE Tool. Wells are divided into four categories based on production: dry, marginal (<500 BOPM), successful (500 – 1500 BOPM) and very successful (>1500 BOPM). Figure 3.21 shows the pie chart for the wells with estimates greater than or equal to 0.65 and is based on 940 wells. Fig. 3.22 shows the pie chart for the wells with estimates less than 0.65, and is based on 135 wells.

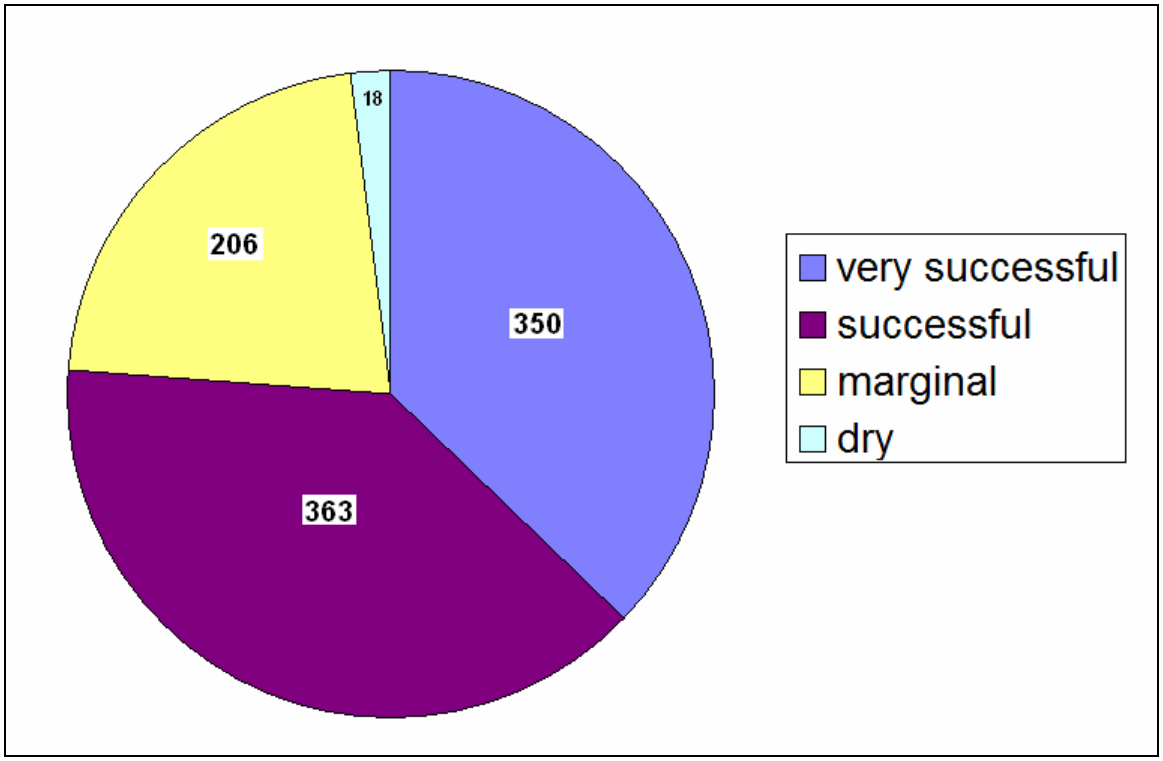

Fig. 3.21: Pie chart of wells with FEE Tool estimates greater than 0.65.

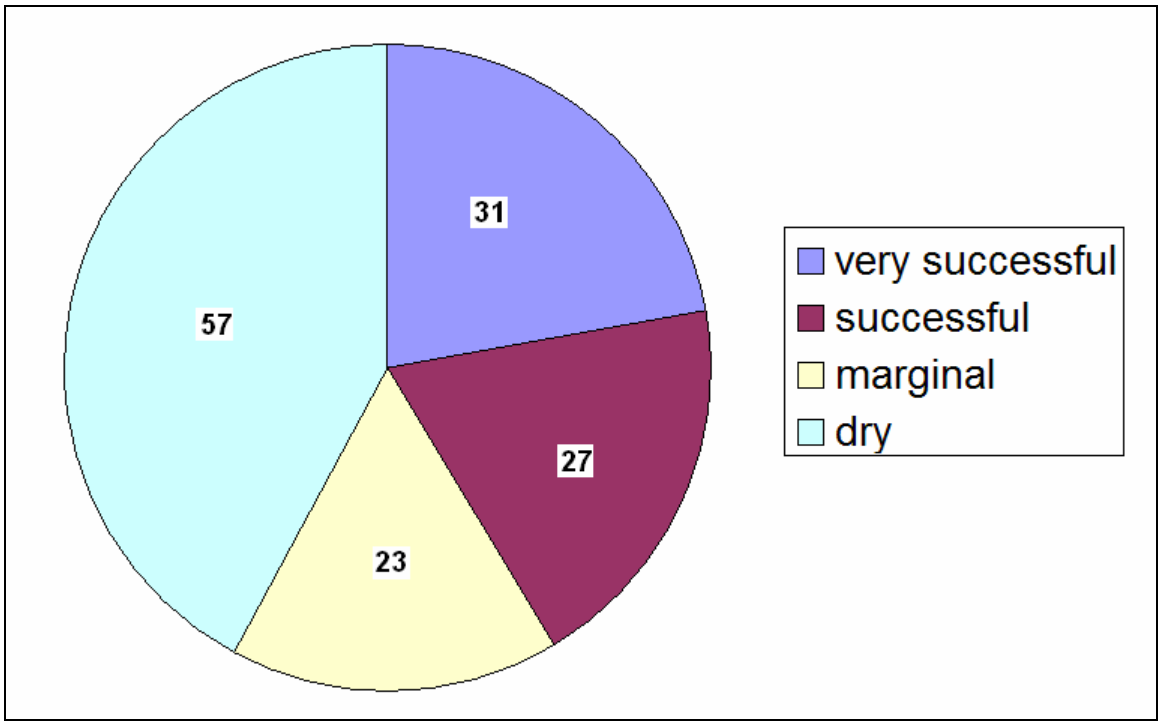

Fig. 3.22: Pie chart of wells with FEE Tool estimates less than 0.65.

The pie charts represent the wells in each category as a percentage of the total number of wells. The first pie chart, which only included wells with an estimate of 0.65 or higher, indicates that the majority of wells are in the “very successful” or “successful” categories, with a very small fraction in the dry category. The second pie chart, with wells with an estimate of less than 0.65, indicates that the majority of the wells are in the “dry” or “marginal” categories.

3.3 User Interface

The Delaware FEE Tool is available to users both online and through a stand-alone version. Both versions have an extensive user interface that allows users to create and manage projects, input locations of interest, review and modify answerbase data and view results in a variety of formats. There is also a batch mode, where the user can input a larger area and modify the data in tabular format. Examples of the FEE Tool user interface are found in the "User's Guide" in the appendices and a discussion of the coding involved in the interface is in Section 5.3.1.

4. Devonian FEE Tool

4.1 Development

The Devonian FEE Tool was developed using an approach similar to the one used for developing the Delaware FEE Tool. The first step was to develop a knowledge base through interviews with experts. Then, the answerbase was generated, containing the variables used as inputs for the knowledge base rules. This process included using a neural network to generate predicted production values for the region. The knowledge base and answerbase were used to create a crisp model of the expert system for testing and debugging. When this was performed satisfactorily, the interactive fuzzy expert system was considered complete.

4.1.1 Knowledge Base

The expert system is built on the guidelines of a knowledge base developed for the Devonian carbonate formation. Interviews with knowledgeable experts suggested four categories important to Devonian production, *Trap, Formation, Structure and Regional* analyses. Each of these corresponds to a branch in the knowledge base. The first set of rules in each branch provides an initial guess scaled between 0 and 1. After the initial value is assigned, the remaining rules in the branch are applied, and for each rule that "fires" an appropriate flag value is computed and stored. At the end of each section of questions the overall evaluation for that section is calculated by applying the sum of the flags to the initial estimate using the same sum of flags approach as used to calculate the final Delaware estimate. The *Trap* branch includes rules about the thickness of the Woodford shale, the amount of closure on structure, fracture induced porosity, stratigraphic porosity and the potential for other porosity. The *Formation* branch includes rules involving the quality of the source rock, with total organic carbon and production index among the inputs. The *Structure* branch rules begin with a series of rules regarding early or paleo structure, and also include rules relating to structural relief, fault bounding and seismic data. The *Regional* branch includes rules related to predicted production. Predicted production is estimated using the neural network software PredictOnline and is

discussed in further detail in the answer base section. The complete Devonian knowledge base is included in the appendices.

4.1.2 Answerbase Development

Both the Devonian FEE Tool and the model crisp system use a grid to divide the region into 64347 units measuring 160 acres. The coarser grid is due to the large size of the region and Devonian prospects. Each of these units is represented by its center point (gridpoint), the coordinates of which are provided in latitude and longitude. Each well or prospect location is then related to the closest gridpoint is located. The necessary inputs for the knowledge base rules are computed for each of these gridpoints and stored in the answerbase.

Columns in the answerbase include the thickness and elevation of the Woodford Shale, total organic carbon, production index, closure, structure, flexure and predicted production (computed using the neural network software, PredictOnline). All of the columns in the answerbase were gridded over the region with a kriging method using the Surfer 8™ software. A representative section of the answerbase is included in the appendices.

Construction of the answerbase variable "predicted production"

One of the variables in the answerbase is termed "predicted production." This variable is used as an input to the first set of rules in the regional branch of the knowledge base, but could also be considered as a stand-alone variable. It was constructed with the help of two in-house software packages, PredictOnline and FuzzyRank, discussed in Chapter 7. The process of developing this variable is described below:

1. A list of possible input variable for the neural network was compiled. This included Woodford subsea elevation, Woodford TOC, Rock-Eval production index, permeability, generative potential, structural relief, closure, structure, flexure, and paleo structure. The

values for these variables, along with the amount of production (first year averaged production measured in BOEPM – barrels of oil equivalent per month), were collected for a set of 67 wells known to produce out of the Devonian formation.

2. A file containing the possible inputs and the production for the 67 wells was uploaded to the FuzzyRank software. The software selected the two "best" variables based on the fuzzy ranking algorithm (Chapter 7). Two more variables were selected based on their Pearson correlation coefficient when compared to the production. The four input variables were Woodford thickness, TOC, generative potential and permeability.

3. A training file that consisted of the values of the four input variables and the production (output variable) for the 67 wells was uploaded to PredictOnline. A variety of neural networks were trained with these inputs and the performance of each architecture was rated based on its R and R^2 values (a value close to one indicating good performance). When an architecture showed consistently good performance, it was re-run multiple times to verify its performance. The final architecture selected was 4 – 6 – 1 and the R and R^2 values were .91 and .84 respectively.

4. A file containing the four input variables at all 64,347 gridpoints was then uploaded to PredictOnline and the neural network (4 – 6 – 1) was used to predict production for the entire region.

5. The predicted values were then mapped using Surfer 8™, and it was apparent that it would be a good idea to filter the outputs at locations where the Woodford shale was not present.

6. Once filtered, the final values were imported into Minitab™ a statistical package, where the descriptive statistics were found, a histogram of predicted production for the entire region was drawn and the Pearson correlation coefficient between the predicted production and the actual production at the producing wells was found. The correlation was r = 0.79, a strong positive correlation, which provided another way of measuring the

success of the neural network production. Figure 4.1 shows the histogram of the predicted production values.

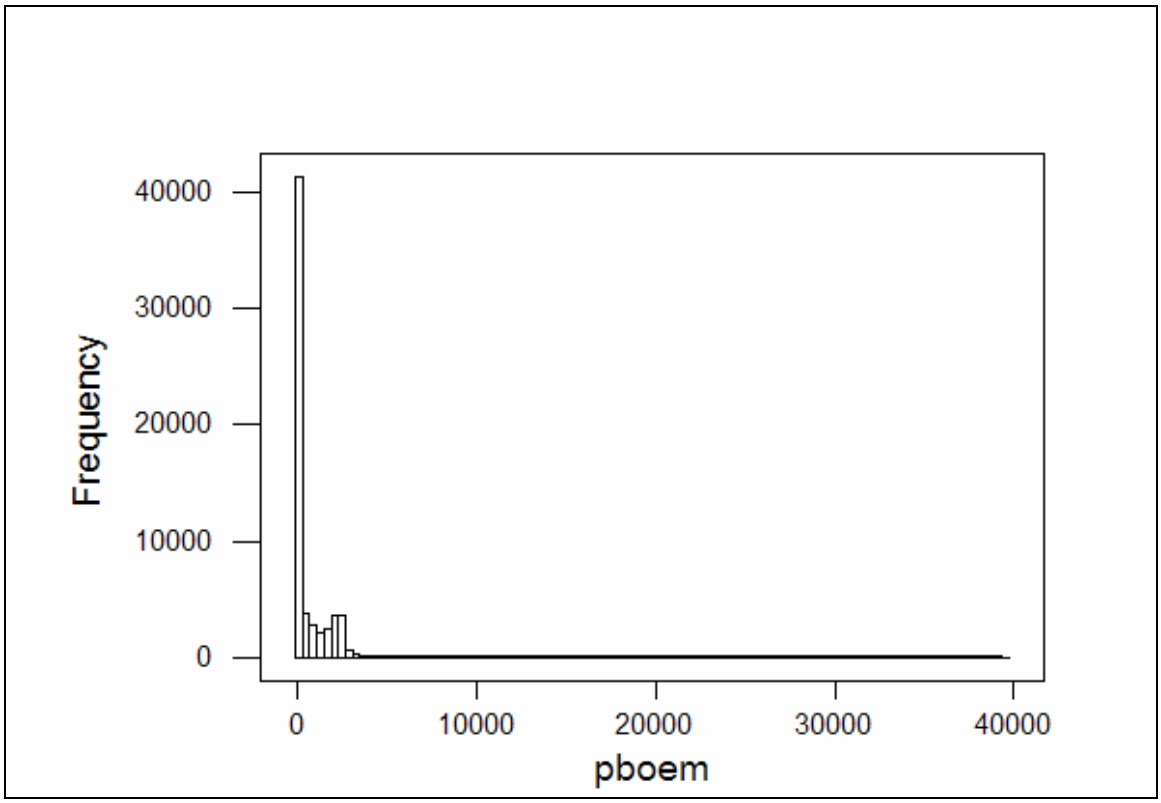

Fig. 4.1 Histogram of predicted production values in units of PBOEPM (predicted barrels of oil equivalent per month) for the entire region.

4.2 Statistics and Results

4.2.1 Data

The FEE tool was used to generate a set of estimates for all 64347 points in the Devonian region. Relevant subsets were also identified and their estimates were evaluated. These subsets include locations with answerbase wells (wells used in the computations to develop answerbase values), test wells and unsuccessful wells.

4.2.2 FEE Tool Summary Statistics

The following tables show the descriptive statistics for the estimates generated for the entire region using the Devonian FEE Tool. Table 1 gives the parameters, and Table 2 provides the five-number summary used to generate the boxplot shown in Fig. 4.2.

Table 4.1: Parameters of the Full Set of Devonian FEE Tool Estimates

Parameters	
Mean	0.282
TrMean	0.271
Standard Deviation	0.192
Variance	0.037

Table 4.2: Five-Number Summary of the Full Set of FEE Tool Estimates

Five-number summary	
Min	0.05
Q1	0.06
Median	0.28
Q3	0.43
Max	0.85

4.2.3 Devonian FEE Tool Results

The three subsets described above were used for testing 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 0.28. For the answerbase well set, the mean estimate was 0.523. For the test well set, the mean was 0.61, which is significantly higher than the system mean, indicating success at locating potential well sites. Finally, the mean estimate for the set of unsuccessful wells was 0.364. 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 for reducing the number of dry holes. A boxplot of the entire system and the three subsets is shown in Fig. 4.2. The graph also includes the total set of producing

wells, and indicates the estimate value of 0.55, a preliminary cutoff estimate. Figure 4.3 shows a histogram of the estimates for the entire system and the producing well estimates, also indicating the 0.55 value. Figure 4.4 is a map of the region, showing the estimates at or above the recommended level.

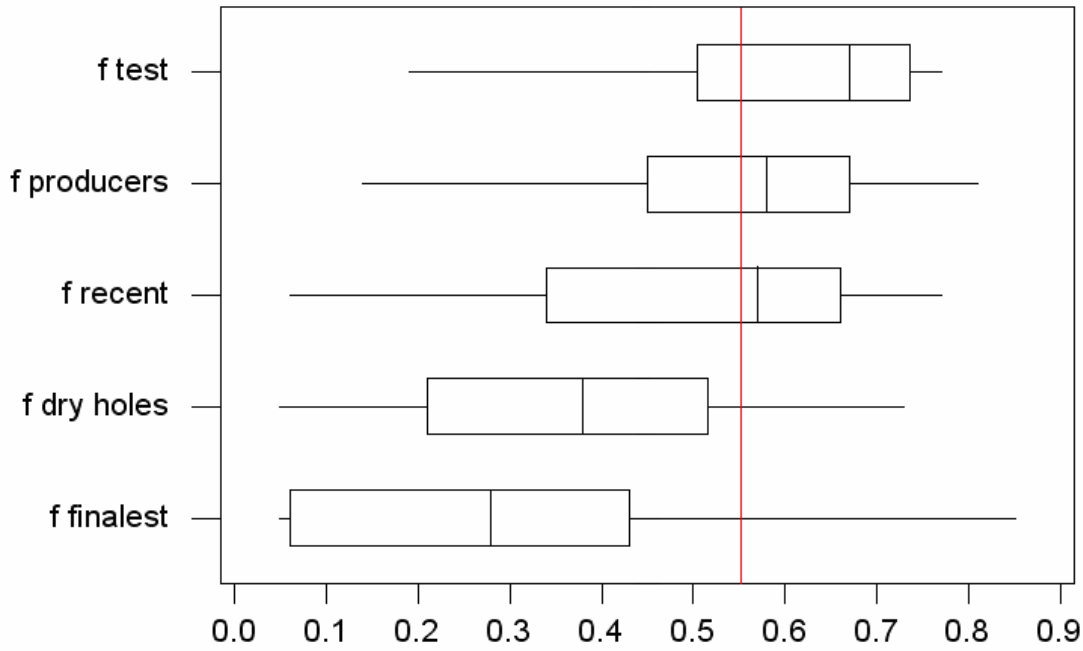

Fig. 4.2: Boxplot of the estimates from the Devonian FEE Tool for the entire system (finalest), the producing wells (producers), a set of recent wells (recent), the test wells (test) and the dry holes.

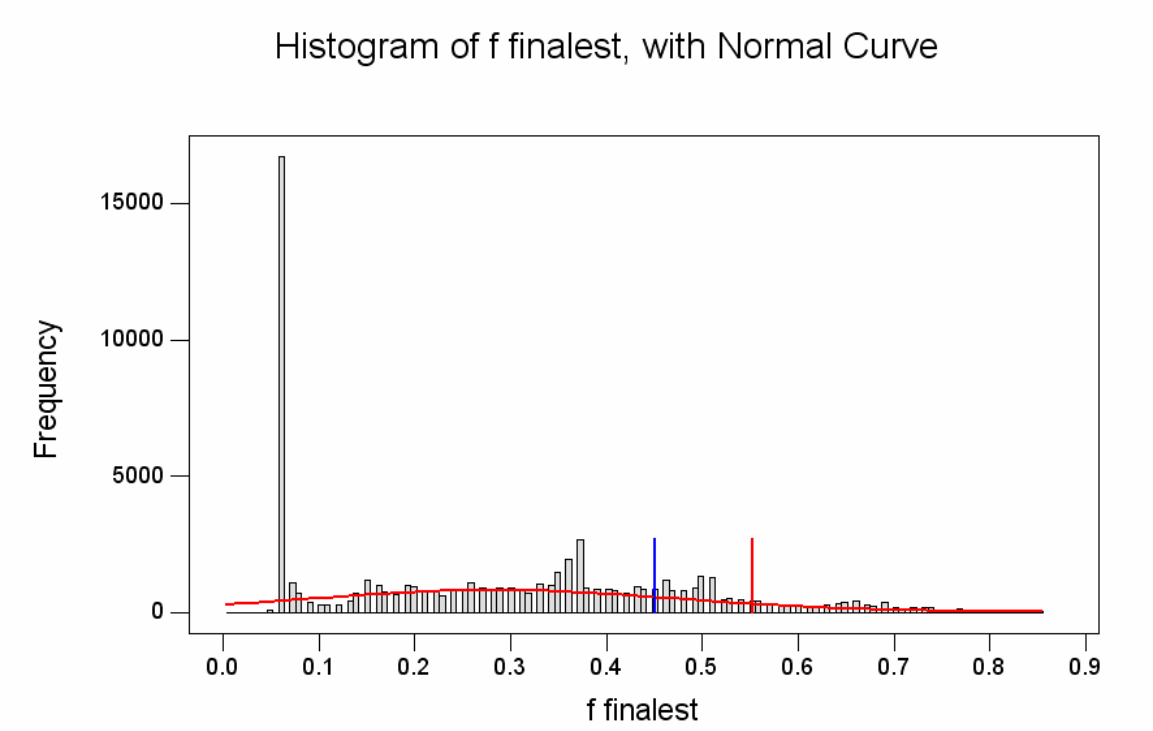

Fig. 4.3: Histogram of the final estimates from the Devonian FEE Tool, indicating a recommended cutoff value of 0.55 (red)

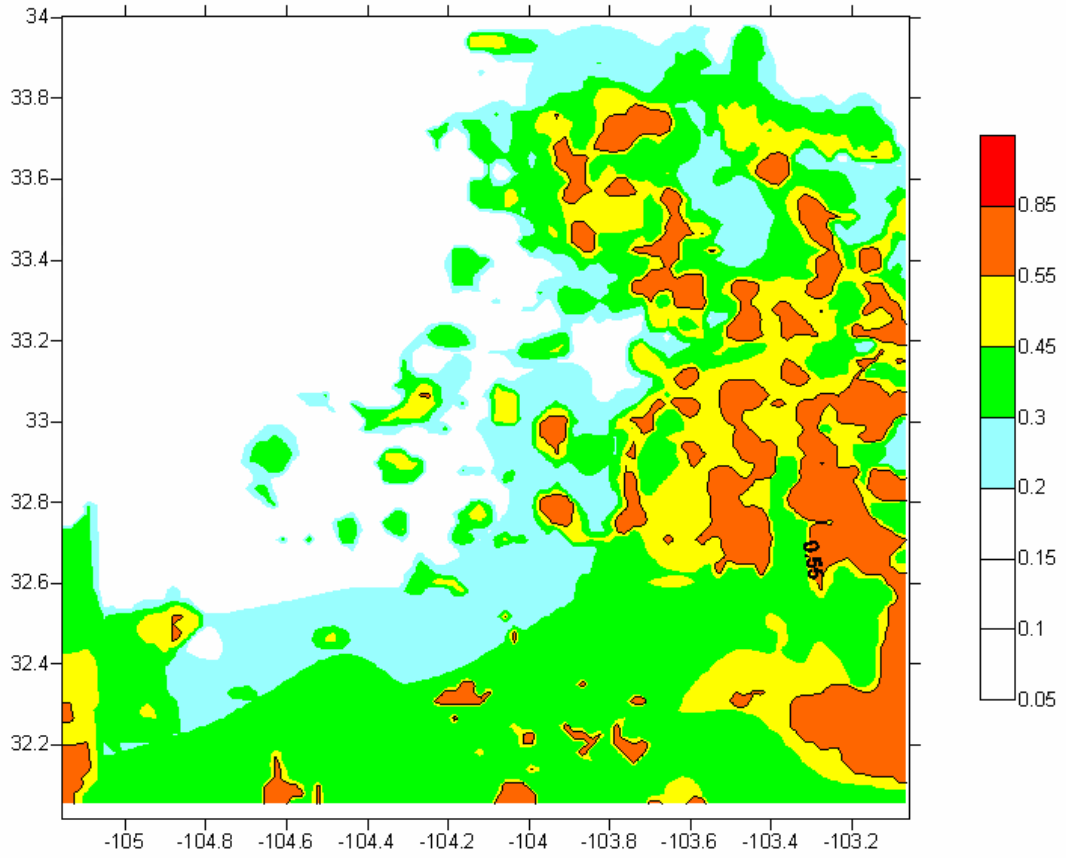

Fig. 4.4: Map of the quality estimates from the Devonian FEE Tool.

4.3 User Interface

The Devonian FEE Tool was written using Java, and runs as a web page, accessible over the Internet using a variety of browsers. As with the Delaware FEE Tool, the Devonian FEE Tool requires the installation of the latest version of the Java plug-in. Users are prompted to install this plug-in, if it is not already on their systems. Once logged into the Devonian FEE Tool, users are able to create a project, enter a prospect location, review the answerbase data for that location, update or modify the data, and view the results of the inference. The user interface is very similar to the Delaware FEE Tool interface, and details of the use of the online FEE Tool are given in the appendix in the "User's Guide."

A batch mode has been added to the Devonian FEE Tool, and a similar tool has been developed for the Delaware FEE Tool. With this mode, users can enter multiple locations at once, instead of going through the process of entering a single location, reviewing and modifying answerbase values, and getting the results.

The first screen of the process allows users to enter the location of each location, either in Township-Range-Section notation or using Latitude and Longitude. Figure 4.5 shows the input screen and Fig. 4.6 shows the converter.

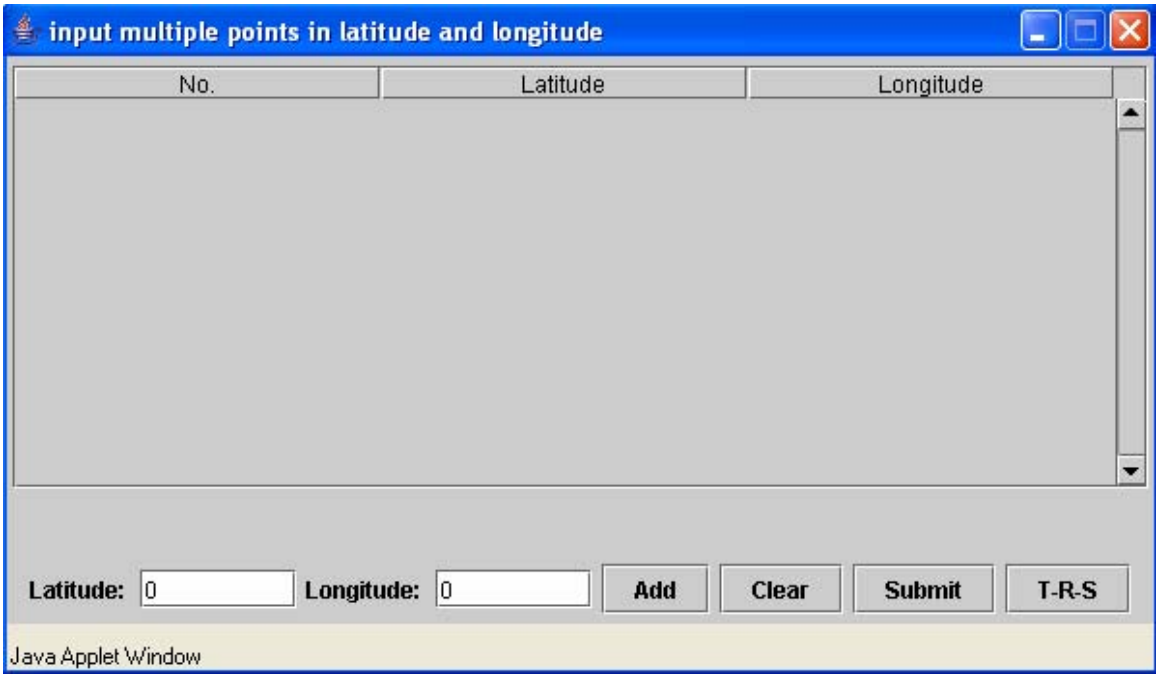

Fig. 4.5: Input screen for Devonian FEE Tool batch mode.

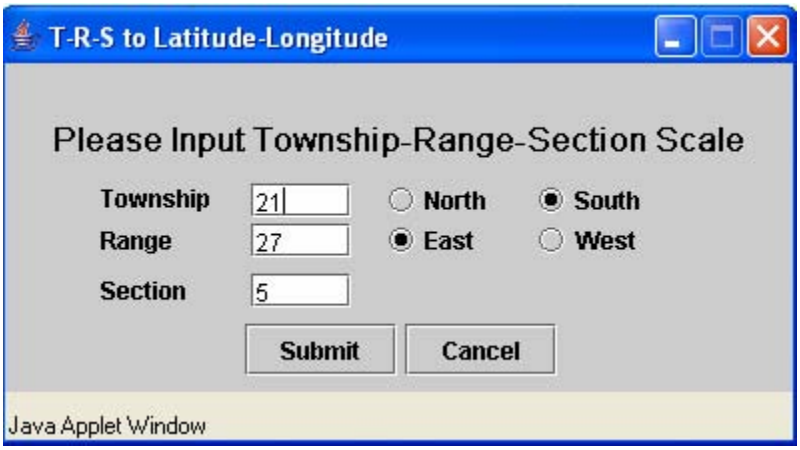

Fig. 4.6: T-R-S to Latitude-Longitude converter.

Users can add more points with the **Add** button, and, when finished, use the **Submit** button. A table then appears with all of the answerbase values (Fig. 4.7). By scrolling through the table, users may view and modify all of the answerbase data for each of their prospects. When completed, they may then use the submit button to view the inference results (Fig. 4.8).

Data at prospects

No	lat	lon	woodThickness	woodTOC	oilOrGasWindow	PI	generativePotential
0	32.511	-104.22	89.413	2.368	Oil Window	0.373	78.958
0	32.511	-104.211	91.103	2.387	Oil Window	0.375	81.507
0	32.518	-104.22	87.168	2.338	Oil Window	0.372	75.881
0	32.518	-104.211	88.834	2.358	Oil Window	0.374	78.387
0	32.504	-104.22	91.664	2.4	Oil Window	0.374	82.213
0	32.504	-104.211	93.377	2.418	Oil Window	0.376	84.79
0	32.511	-104.22	89.413	2.368	Oil Window	0.373	78.958
0	32.511	-104.211	91.103	2.387	Oil Window	0.375	81.507
0	32.518	-104.22	87.168	2.338	Oil Window	0.372	75.881
0	32.518	-104.211	88.834	2.358	Oil Window	0.374	78.387
0	32.504	-104.22	91.664	2.4	Oil Window	0.374	82.213
0	32.504	-104.211	93.377	2.418	Oil Window	0.376	84.79
0	32.511	-104.22	89.413	2.368	Oil Window	0.373	78.958
0	32.511	-104.211	91.103	2.387	Oil Window	0.375	81.507
0	32.518	-104.22	87.168	2.338	Oil Window	0.372	75.881
0	32.518	-104.211	88.834	2.358	Oil Window	0.374	78.387

Submit

Java Applet Window

Fig. 4.7: Section of the answerbase screen.

Estimations at prospects

Lat	Lon	Structure Inferen...	Regional Infere...	Trap Inference	Formation Infere...	General Inference
32.510826	-104.219566	0.1	0.031	0.331	0.611	0.252
32.510841	-104.210999	0.1	0.031	0.337	0.614	0.253
32.518086	-104.219583	0.1	0.031	0.323	0.606	0.249
32.5181	-104.211016	0.1	0.031	0.329	0.609	0.251
32.503567	-104.219548	0.1	0.031	0.338	0.616	0.254
32.503582	-104.210982	0.1	0.031	0.344	0.619	0.256
32.510826	-104.219566	0.1	0.031	0.331	0.611	0.252
32.510841	-104.210999	0.1	0.031	0.337	0.614	0.253
32.518086	-104.219583	0.1	0.031	0.323	0.606	0.249
32.5181	-104.211016	0.1	0.031	0.329	0.609	0.251
32.503567	-104.219548	0.1	0.031	0.338	0.616	0.254
32.503582	-104.210982	0.1	0.031	0.344	0.619	0.256
32.510826	-104.219566	0.1	0.031	0.331	0.611	0.252
32.510841	-104.210999	0.1	0.031	0.337	0.614	0.253
32.518086	-104.219583	0.1	0.031	0.323	0.606	0.249
32.5181	-104.211016	0.1	0.031	0.329	0.609	0.251

Close

Java Applet Window

Fig. 4.8: Inference results table for the batch mode.

5: Development of the FEE Tool Software

5.1 Introduction

Applications of the FEE Tool project (Delaware FEE Tool, Devonian FEE Tool and auxiliary software such as PredictOnline) were developed using Java™ technology based on a three-tiered model. The main applications have two versions:

1. Web-based version

   For the web-based version, all codes and data are stored on the project server, which hosts the web server, application server and database server. Users running the application need a Java capable Internet browser to open the related link. The interface codes are downloaded into the user's computer and run in the browser. Users login to the software with an account name and password.

2. Standalone version

   This version is suitable for users without an Internet connection. Users need to download the compiled binary code and data into a computer upon which Java Virtual Machine has been installed (recommend JDK 1.4 or later).

5.1.1 Client-Server Architecture

As computer networks develop, more applications utilize a Client-Server Architecture in which:

- The computational work can be distributed among different machines.
- Clients can access the server's functionality from a distance .
- The client and server can be designed separately, so they can both be simpler than a program that does everything.
- All the data can be kept centrally at the server, thus making it easier to assure its reliability.

- Conversely, distributing data among many different geographically-distributed clients or servers can mean that if a disaster occurs in one place, the loss of data is minimized .
- The server can be accessed simultaneously by many clients .
- Competing clients can be written to communicate with the same server and vice-versa.

The web-based applications of the FEE Tool project were developed based on a Client – Server model. A high performance server at the PRRC was used.

5.1.2 Three-Tiered Model of Client-Server Architecture

The expansion of the use of web browsers and the increasing demand for supplying interactive and dynamic information through the Internet makes a three-tiered application popular as well as practical. Normally, an application consists of three layers:

1. Presentation layer
2. Business layer
3. Data layer

A three-tiered application separates the three layers into separate components. In the three-tiered model, a server communicates with both the presentation layer and the data layer. Applications (web-based version and standalone version) of the FEE Tool project were based on this model.

In the web-based versions, the communication between the presentation layer and business layer is a communication between Java Applets and Java Servlets using a set of defined application protocols over HTTP protocol.

To create the standalone versions, the communication between the presentation layer and business layer was changed from communication between Java Applets and Java Servlets to communication between an interface class and a business logic class by changing Java

Applets and Java Servlets (getting rid of applets and servlets attributes) into normal classes of Java application using the same application protocols.

5.1.3 Java Technology

Since 1995, Java technology has made great progress and is used for academic and industry applications. Java was developed to run on Java Virtual Machine (JVM). Every computer can execute Java code with the support of JVM. Java codes have the ability to run on the client side (web-browsers such as Internet Explorer, Netscape, etc.) and to run on the server side on web application servers (Tomcat and Weblogic etc). When Java codes run in a browser with Java Virtual Machine (JVM) installed, they are called Java Applets. When Java Codes run on the server side they are called Java Servlets. Applets have the ability to use advanced JFC/Swing Components and the full graphical and user interface capability of Java applications. Java Servlets handle web requests, returning data or HTML programmatically. They can access databases, perform calculations, and communicate with other components (JavaBeans, etc). Servlets are persistent; once they are instantiated, they continually handle requests for the life of the web server. Servlets run on an application server with JVM and are not burdened with security restrictions. Since Servlets run entirely on the server, they can run with all the capabilities that the operating system allows. To the client, requests that go to Servlets look no different from any other web request. The client contacts a URL and gets the results. Virtually any kind of data can be sent and received via the HTTP protocol [Darby, 1998].

5.1.4 Developing the Tool

Due to the characteristics of Java's platform independence and its ability to run on client-side and server-side, application codes for the FEE Tool project were implemented in Pure Java Technology (both client- and server-side codes are written in Java). Using one computer language for both sides reduced the development and maintenance time and cost [Balch, 2003]. JavaScript and HTML were used to develop home pages.

5.1.5 Platform

The server *ford.nmt.edu* is a DELL PowerEdge with the following specifications and features:

- 4600 2x2.2GZ CPU
- 2GB RAM
- 480GB HD
- Window 2000 Server
- MS SQL Server 2000
- MS IIS
- Tomcat 3.3
- MS Data Source v3.5
- Tomcat with built-in JSP and Servlets engine to work with Web Server software.

5.2. Communication between Applet and Servlet

Communication between front-end and back-end (Applets-Servlets communication) is a key part of the web-based (online version) FEE Tool Application Software. Java provides two ways to exchange data for Applet –Servlet communication via HTTP: stream of text and Java objects.

The simplest way for an Applet to exchange information with a Servlet is through an HTTP text stream. Java's URL and URL Connection classes make it easy to read data from a URL without having to worry about sockets and other complex issues of network programming. The only requirement is a server-side component that can deliver information via a URL [Darby, 1998].

HTTP text streams are relatively straightforward and easy to use. The Applet establishes a connection to a Servlet back on its originating server, reads the information, and interprets it appropriately. Using simple text streams to exchange data has one major weakness, however: the need for the Applet to not only know the format of the data but

also perform parsing and conversion of the data into a useful form. For a simple data set, it is not too hard to convert the strings to numbers, but the conversion chore could quickly escalate when dealing with more complex data and objects. An easier way of exchanging complex data is an HTTP Object Stream. An HTTP connection can be used to transfer binary data as well as textual data. This can be combined with something called object serialization to pass complete Java objects from a Servlet to an Applet or from an Applet to a Servlet. Complex data can be passed very easily this way with no need for parsing and interpretation [Darby, 1998]

Data exchange for the FEE Tool over the Internet between tier 1 and tier 2 is a communication between Java Applets running in the users' browsers on the client-side and Java Servlets running on the server-side supported by the application server, Tomcat. For efficient development, a set of application protocols was designed and implemented to unite the communication between tier 1 and tier 2. Using these specifically designed protocols for the FEE Tool, only a few objects are needed to exchange between Applets and Servlets. Data of other classes are packed into the object on sender-side and extracted from the object and cast into its original class on receiver-side, which reduces the time needed to pass the extra non-data parts of the classes.

Following is the frame of application protocols:

- Request package

  Field 1: key word—a string, tells Servlets what kind of request this is.

  Field 2: userID—a string, tells Servlet which user is requesting.

  Field 3: projectName—a string, tells Servlets which project for this user.

  Field 4: Command—a string, tells Servlets what the Applets are requested to do.

  Field 5: Parameters/data—a string or vector, parameters needed to execute the command that will be defined based on different key words and commands.

- Response package

  Field 1: Executing Result: 1— "Success"; 0— "failed";

  Field 2: key word—a string, tells Applets what kind of request to respond to.

Field 3: User ID—a string

Field 4: Project name—a string

Field 5: Command—a string, tells Applets what the Servlets have done.

Field 6: if "Success" message/contents—a string or vector that will be defined based on different key words and commands.

Following is a specific protocol for project data:

- Request format:

  Field 1: key word - "data"

  Field 2: userID - string

  Field 3: projectName - string

  Field 4: Command - "read" or "write"

  Field 5: Parameter - a vector contains writing data for "write" or a vector contains parameters for "read."

- Response format:

  Field 1: Executing result - 1— "success"; 0— "failed"

  Field 2: keyWord - "data"

  Field 3: userID - string

  Field 4: projectName - string

  Field 5: Command - "read" or "write"

  Field 6: if success - a vector contains requested data for "read," null for "write;" if failed - a vector contains error information - "Cannot read the data" (or "write").

A pair of classes, AppletComm and ServletComm, was designed to exchange a specific object, DataObject. The DataObject was defined as follows:

```
class DataObject extends Object implements Serializable
{//indicate what kind data and what protocol will be used
String keyWord;
// indicate which user and which project data will be accessed
String userID;
String projectName;
// Command indicate what kind of job
String command;
//dataVector
Vector dataVector;
```

…… }

All data members of other objects (data for Project, Prospect and Location, etc.) are packaged into the vector, DataObject at the client-side (or server-side) and passed to server-side (or client-side) between AppletComm and ServletComm classes over the Internet. The recipient can extract the vector from DataObject and cast it into the original Object (Project, Prospect or Location, etc). Figure 5.1 shows the structure of client-server communication.

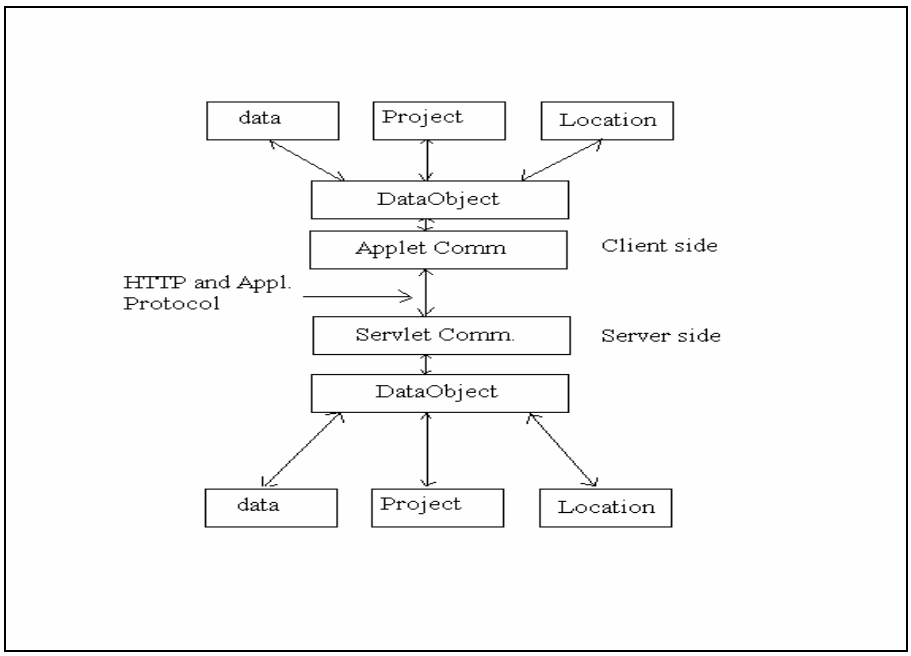

Fig. 5.1: Communication between the interface and server.

5.3 Fuzzy Expert Exploration Tool (FEE Tool)

The FEE Tool was developed as a three-tier web-based application, with components running in parallel on both the user's computer and the server. Fig. 5.2 shows the architecture of the Delaware FEE Tool (Brushy Canyon formation). The architecture is 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 users to seamlessly consider only the data types they feel

are most influential, and are 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.

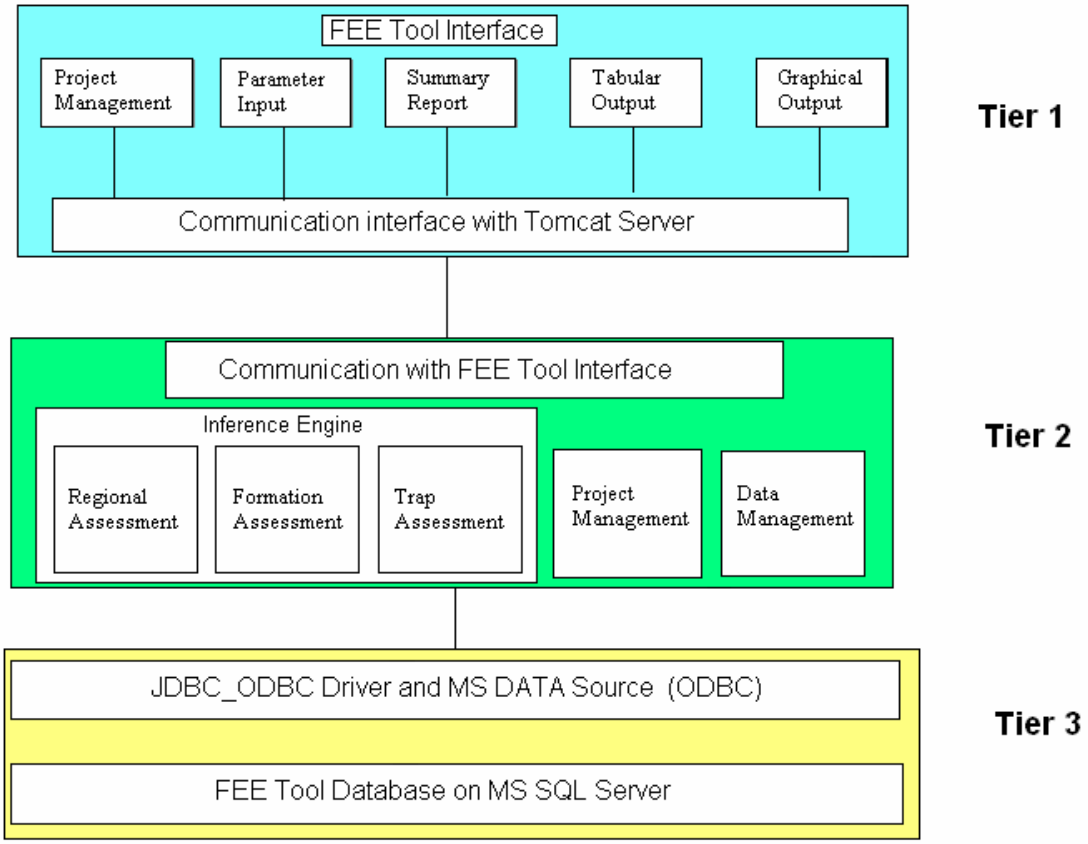

Fig. 5.2: Architecture of the Delaware FEE Tool.

Tier 1, the presentation tier of the FEE Tool, is an interactive interface (written as Java Applets) running on JVM (Java Virtual Machine) embedded in the user's browser. It 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. Results are given as a summary report, or in tabular and chart form.

In Tier 2, there are three branches of the expert system that can be applied based on the user's wishes. These address Regional Assessment, Trap Assessment, and Formation Assessment. Operations of project management and data management are implemented in this tier as well. All the codes of this tier are written as Java Servlets.

Tier 3 is the data layer that represents the FEE Tool databases on the MS SQL Server. Java Servlets access all data through JDBC (Java Database Connectivity) and ODBC (Open Database Connectivity).

5.3.1 Interactive Interface

For the FEE Tool, an interactive interface was a necessary component. The interface provides a convenient way for the user to use the FEE Tool. Due to the rich GUI capability of JFC/Java Swing and the requirement of system consistency, the FEE Tool interface was implemented in Java Applets.

All of the windows have the same style. The interface of the FEE Tool was designed with the following functions: (The main menu consists of five items, with each item having two to five sub-menu items.)

1. Project management
   - Create a new project
   - Open an existing project
   - Close an opened project
   - Delete an existing project
2. Data Input
   - Location input
     a. X-Y coordinates
     b. Latitude-Longitude
     c. Township-Range-Section
   - Data
     a. Trap data
     b. Formation data
     c. Regional data
3. Evaluation
   - Trap evaluation
   - Formation evaluation
   - Regional evaluation
   - General evaluation
4. Output result
   - Tabular
   - Chart
   - Summary report

5. Help and instruction
   - Provide user with version information.
   - FEE Tool usage

Fig. 5.3 shows a screen shot of the Delaware FEE Tool Interface.

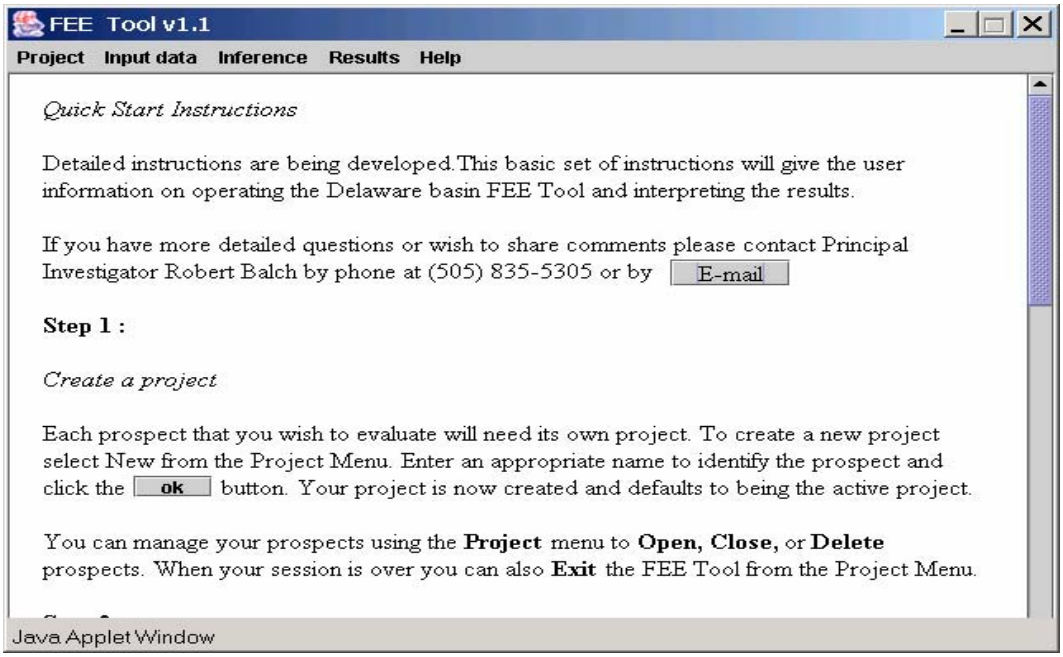

Fig. 5.3: Sample screen shot of the FEE Tool interface.

5.3.2 Inference Engine

The inference engine is the key part of FEE Tool. Two kinds of rules, crisp and fuzzy rules, were used to inference the results based on user input or default input values from the answerbase. A new fuzzy inference method was used in the inference engines of both the Delaware FEE Tool and Devonian FEE Tool.

Fuzzy Reasoning Method

Each major section, *Trap*, *Formation,* or *Regional* starts with an initial evaluation value scaled between 0 and 1. After the initial value is assigned, a series of rules are 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.

Example:

An initial estimate is evaluated by using a fuzzy reasoning method based on the first step of each section.

Trap Step 1: rules for the initial estimate using distance between the prospect and the nearest producing well:

- If distance to nearest producing well (d) is very far , then trap starting estimate (x)=very poor
- If d is far then x = poor
- If d is middle far then x = middle
- If d is close then x = good
- If d is very close then x = very good

Fuzzy sets for "distance to producing well" are defined in Fig. 5.4.

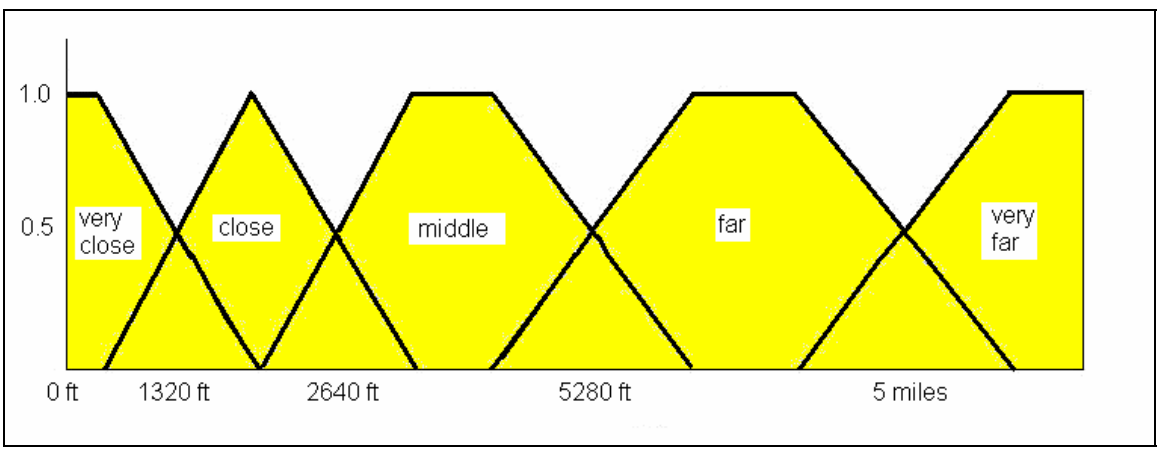

Fig. 5.4: Membership sets for distance to the nearest producing well.

The initial estimate fuzzy sets are defined in Fig. 5.5.

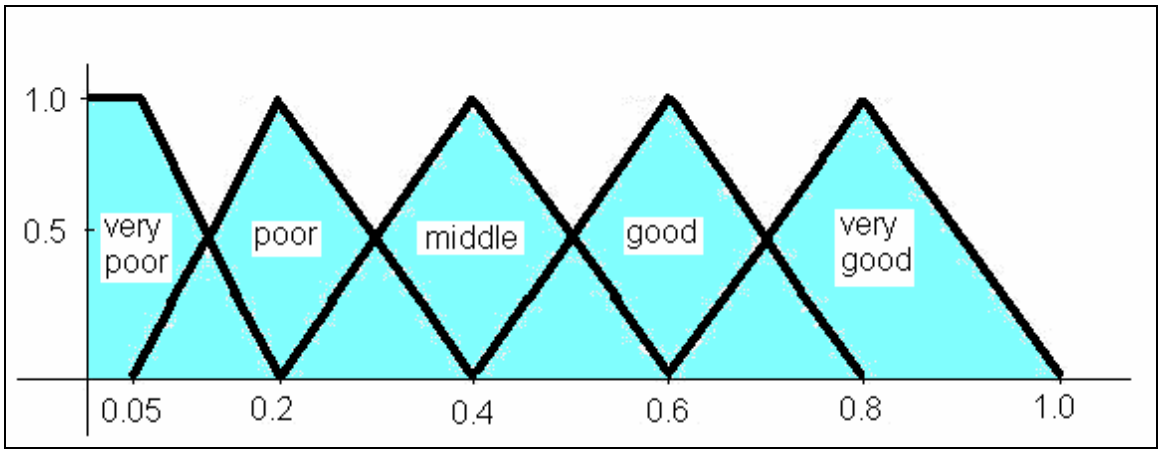

Fig. 5.5: Membership for trap initial estimate.

The trap initial estimate is computed by following process:

1. fuzzify d (distance to nearest producing well) and get the fuzzy set(s)
2. use relevant rules (Trap Step 1) to get the initial estimate fuzzy set(s)
3. defuzzify the fuzzy set(s) of result and get the initial estimate using following formula:

$$InitialValue = \frac{\sum c(x_i) * u_i(d)}{\sum u_i(d)}$$

The variable $c(x_i)$ is the center value of initial estimate fuzzy sets relevant to ith rule and $u_i(d)$ is the membership value of d belonging to ith fuzzy set.

The remaining rules of each section generate flags. The generated flags are used to enhance or degrade the initial estimate to get the final evaluation for each branch.

For the trap example, after getting the initial estimate, other are executed using the same type of fuzzy inference process. The difference between the first step (initial evaluation) and the other rules is that these other rules will generate a flag value instead of initial estimate. If a flag value is positive then it enhances the initial estimate. If the flag is negative, then it degrades the initial estimate. Figure 5.6 shows the definition of a flag.

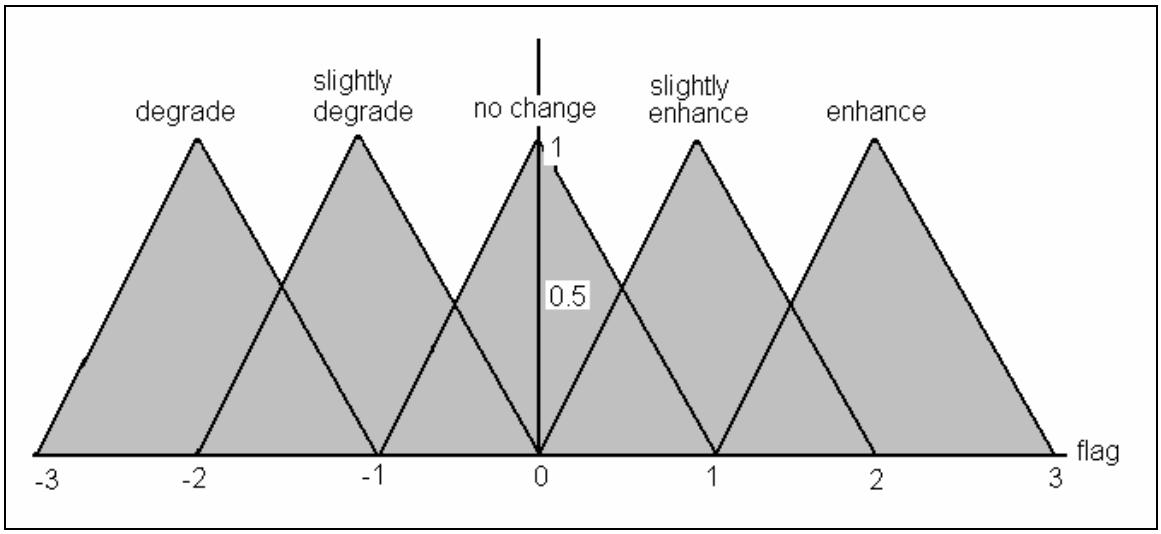

Fig. 5.6: Membership sets for a flag.

A key component to the project is to take the identified rules, and in some manner grade them, so that they have a weight 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. Mathematically, a value between zero and one is used to for the initial estimate. This initial estimate is enhanced or degraded based on the flag values while remaining between 0 and 1. The method used to do this is the "sum of flags" method discussed in section 3.1.3.

5.3.3 Databases

Since all data is stored at a MS SQL Server, ODBC and JDBC are needed for Java Servlets to access the data. JDBC is a collection of database access middleware drivers that provide Java programs with a call-level SQL API. Java Applets and applications can use the drivers' API to connect to database, store and retrieve database content and execute stored procedures, thus making JDBC a Java-enabled delivery mechanism for SQL. When a JDBC-based Applet starts, it downlinks JDBC classes and drivers from the web server. The size of the class files, JDBC driver manager and JDBC driver will affect the performance at load time [Network Computing, 2004]. To avoid this weakness, the

FEE Tool is designed to let Applets communicates with Servlets, which locates web servers and accesses databases via JDBC and ODBC. All SQL statements are sent to MS SQL Server by Java Servlets via JDBC and ODBC, and SQL servers operate the table and return the results to Java Servlet (Fig. 5.1).

5.3.4 Devonian FEE Tool

Implementation of the Devonian FEE Tool is similar to that of the Delaware FEE Tool. The main differences are:

1. The Devonian FEE Tool contains four branches instead of three. The branches are Regional, Formation, Structure and Trap.
2. There is no UTM (X-Y) coordinate option for location.

5.3.5 Standalone Versions

Standalone versions of both FEE Tools were developed, meaning the software can run on the user's computer without requiring an Internet connection.

Three major changes were made:

1. The Applets and Servlets were combined into Java applications by getting rid of the communication codes over the Internet and making a direct call to the Business tier classes.
2. All tables stored in the MS SQL server in the online version were changed into binary files and Java classes for access. These files were developed to implement the Data tier.

3. The transformation of Township-Range-Section to Latitude –Longitude was coded using Java. In the online version, this was implemented by using an SQL statement of SQL server and Java class.

5.3.6 Translation of Township-Ranch-Section Coordinates to Latitude-Longitude Coordinates

This translation was implemented based on the Digital Land Grid-New Mexico Longitude -Latitude Coordinates, a data file containing the corners' Longitude – Latitude coordinates for all sections of New Mexico. The accuracy of corner boundaries is +/- 40 ft.

The code accepts a user's prospect location in the format of Township-Range-Section and offsets from the closest borders to the prospect location. The code first searches for the Latitude-Longitude coordinates of the Township-Range-Section in the data file, then calculates the prospect location's Latitude-Longitude coordinates by using the following formulas:

- To calculate latitude:
  - Latitude of prospect = latitude of the closest section corner +/- Δ.
  - Δ = offset from the border of the section/101.1/3600.
  - Every second corresponds to 101.1 ft.
  - Divide by 3600 to transform from seconds to degrees.
  - Add Δ if the offset is from the south border of the section.
  - Subtract Δ if the offset is from the north border of the section.

- To calculate longitude of the prospect:
  - Calculate the distance to which the second corresponds (in meters).
    - This can be obtained with the following formula:
      - Unit_w_e=(p1*Math.cos(deg2rad(lat)) + p2*Math.cos(3*deg2rad(lat)) +p3*Math.cos(5*deg2rad(lat)))/3600; where
        - lat is the latitude of the closest section,
        - p1 = 111412.84,
        - p2 = –93.5,
        - p3= 0.118, and
        - deg2rad is a function that transforms from degrees to radians and is defined as follows:
          - deg*(2.0*3.14159265)/360.0.
  - Then use the following formula to transform meters to feet:
    - Distance in feet = (distance in meter /12)*39.370079.

  - Calculate the number of degrees to which the offset of the prospect corresponds:
    - Offset degrees= offset/unit_w_e/3600, where

        - Offset is the distance to the closest (east or west) and this value is given by the user.
        - Unit_w_e is as calculated above.

- Finally the longitude of the prospect=lon+/-offset_degrees, where:

    - Lon is the longitude of the closest section corner, and
    - Offset_degrees are as calculated earlier.
    - It should be positive if offset is from the west border of the section.
    - It should be negative if the offset if from the east border of the section.

For the online version of the FEE Tools, a SQL select statement is used to query the table that holds the data file. For the standalone version of FEE Tools, the binary-search method is used to search the data file sorted on Township-Range-Section.

6. Technology Transfer

The following papers, posters and abstracts were prepared and presented during the course of this project:

1. Balch, R. S., Ruan, T., and Schrader, S: "Fuzzy Expert Systems in Oil Exploration", SIAM Conference on Computational Science and Engineering, Orlando, FL, Feb. 12-15, 2005.
2. Balch, R. S.: "Risk Reduction with a Fuzzy Expert Exploration Tool," West Texas Geological Society Lunch Talk, Midland, September 9, 2003.
3. Balch, R. S.: Project update at the NPTO office, Tulsa Oklahoma to a mixed group of DOE project managers and members of the Tulsa Geological Society, August 7, 2003.
4. Balch, R.S., Hart, D.M., and Weiss, W. W.: "Regional Data Analysis to Better Predict Drilling Success: Brushy Canyon Formation, Delaware Basin New Mexico," paper SPE 75145 presented at the 2002 Symposium on Improved Oil Recovery, Tulsa, April 13–17.
5. Balch, R.S., Hart, D.M., Weiss, W.W., and Broadhead, R.F.: "Using Artificial Intelligence to Predict Drilling Success Using Regional Data, Brushy Canyon Formation, Delaware Basin, New Mexico," Transactions, Southwest Section A.A.P.G Convention, Ruidoso, June 6–8, 2002.
6. Balch, R.S., Ruan, T., and Schrader, S. M.: "Automating Basic Exploration Processes Using an Expert System: Applications to the Delaware Basin", presented at the 2003 West Texas Geological Society Fall Symposium, Midland, October 8–10.
7. Balch, R. S., Ruan, T., and Schrader, S. M.: "Drilling Risk Reduction with a Fuzzy Expert Exploration Tool" presented at the 2004 American Association of Petroleum Geologists, Southwest Section Annual Meeting, El Paso, March 8–9.
8. Balch, R. S., Ruan, T., Weiss, W. W., and Schrader, S.M.: "Simulated Expert Interpretation of Regional Data to Predict Drilling Risk," paper SPE 84067 presented at the 2003 SPE Annual Technical Conference and Exhibit, Denver, October 4–8.
9. Balch, R.S., Stubbs, B.S., and Weiss, W.W., and Wo, S.: "Using Artificial Intelligence to Correlate Multiple Seismic Attributes to Reservoir Properties," paper SPE 56733 presented at the 1999 SPE Annual Technical Conference and Exhibit, Houston, October 3–6.
10. Balch, R.S., Weiss, W.W., and Ruan, T.: "Simulated Expert Interpretation of Data to Predict Drilling Risk on a Regional Scale, Case Study—Brushy Canyon Formation, Delaware Basin, New Mexico," In: *The Permian Basin: Preserving our Past – Securing our Future*: West Texas Geological Society, Publication **No. 02-111**, 55.
11. Balch, R.S., Weiss, W.W., and Wo, S.: "Core Porosity Prediction Using Wire-Line Logs, Case Study: Dagger Draw Field, New Mexico," paper presented at the AAPG 2000 Rocky Mountain Meeting, Albuquerque, New Mexico, September 17-20.

12. Balch, R.S., Weiss, W.W., Wo, S., and Hart, D.M.: "Regional Data Analysis to Determine Production Trends Using a Fuzzy Expert Exploration Tool," West Texas Geological Society, Fall Symposium Publication **No. 00-109**, (2000) 195.
13. Balch, R.S., Weiss, W.W., and Wo, S. and Welch, D.M.: "Predicting Core Porosity Using Wireline Logs at Dagger Draw Field, Southeast New Mexico," paper SPE 59554 presented at the 2000 SPE Permian Basin Oil & Gas Recovery Conference, Midland, March 21–23.
14. Baldonado, D., and Broadhead, R.: "Preliminary Investigation of the Regional Stratigraphy of Siluro-Devonian Carbonates, Tobosa Basin, New Mexico," In: *The Permian Basin: Preserving Our Past –Securing Our Future:* West Texas Geological Society, **No. 02-111** (2002) 55.
15. Baldonado, D., and Broadhead, R.: "Preliminary Investigation of the Regional Stratigraphy of Siluro-Devonian Carbonates, Tobosa Basin, New Mexico," (abstract) Transactions Southwest Section AAPG Convention, Fort Worth, 2003.
16. Broadhead, R.F., and Hall, A.: "Regional Aspects of the Wristen Petroleum System, Southeast New Mexico," (abstract), In: *Banking on the Permian Basin: Plays, Field Studies and Techniques:* West Texas Geological Society, **No. 04-112**, (2004) 107.
17. Broadhead, R.F., and Justman, H.A.: "Regional Controls on Oil Accumulations, Lower Brushy Canyon Formation, Southeast, New Mexico," In: *The Permian Basin: Proving Ground for Tomorrow's Technologies*: West Texas Geological Society, **No. 00-109** (October 2000) 9.
18. Broadhead, R.F., and Justman, H.A.: 2002, "Regional Controls on Oil Accumulations and Regional Sand Trends, Lower Brushy Canyon Formation, Southeast New Mexico," presented to the Roswell Geological Society, February 11, 2002.
19. Choudhari, G.: "Contributions towards the Development and Design of the Delaware Basin FEE Tool and the Devonian Carbonate FEE Tool," M.S. Independent Study, New Mexico Institute of Mining and Technology, April 2004.
20. Du, Y.: "Optimization of Artificial Neural Network Design through Synthetic Datasets Analysis," M.S. Thesis, New Mexico Institute of Mining and Technology, May 2002.
21. Gottumkkala, V.: "A New Method of Calibrating Wireline Logs with Carbonate Core Measurements to Recognize Pay Zones," M.S. Thesis, New Mexico Institute of Mining and Technology, August 2002.
22. Hart, D. M.: "Evaluation of a Multi Layer Perceptron Neural Network for the Time-to-Depth Conversion of the Nash Draw "L" Seismic Horizon using Seismic Attributes," M.S. Thesis, New Mexico Institute of Mining and Technology, May 2001.
23. Hart, D. M.: "Tikhonov Linear Inversion of Gravity Data to Determine 3-D Differential Density Distribution – Case Study of Southeast New Mexico and West Texas," West Texas Geological Society, Fall Symposium Publication **No. 00-109**, (October, 2000) 195.
24. Hart, D.M., Balch, R.S., Tobin, H.J., and Weiss, W.W.: "Time-to-Depth Conversion of Nash Draw "L" Seismic Horizon Using Seismic Attributes and Neural Networks," paper SPE 59555 presented at the 2000 SPE Permian Basin

Oil and Gas Recovery Conference, Midland, March 21–23.
25. Hart, D.M., Balch, R.S., Weiss, W.W., and Wo, S.: "Time-to-Depth Conversion of Nash Draw "L" Seismic Horizon Using Seismic Attributes and Neural Networks," paper presented at the AAPG 2000 Rocky Mountain Meeting, Albuquerque, September 17-20, 2000.
26. Huang, X.: "Graphical Representations of the Results of the FEE Tool and Fuzzy Variable Definition System," M.S. Independent Study, New Mexico Institute of Mining and Technology, December 2004.
27. Justman, H. A.: "Petroleum Source Rocks in the Brushy Canyon Formation (Permian), Delaware Basin, Southeastern New Mexico," M.S. Thesis, New Mexico Institute of Mining and Technology, May 2001.
28. Justman, H. A., and Broadhead, R.: "An Evaluation of the Source Rock, Reservoir Rock, and Sequence Stratigraphy for the Brushy Canyon Formation's Hydrocarbon Accumulations of the Delaware Basin, Southeastern New Mexico," (abstract) presented to the Rocky Mountain Section of the APG, Albuquerque, September 2000.
29. Justman, H. A., and Broadhead, R.: "An Evaluation of the Source Rock, Reservoir Rock, and Sequence Stratigraphy for the Brushy Canyon Formation's Hydrocarbon Accumulations of the Delaware Basin, Southeastern New Mexico," (abstract) presented to the Roswell Geological Society, Roswell, December 2000.
30. Justman, H.A., and Broadhead, R.F.: "Source Rock Analysis for the Brushy Canyon Formation, Delaware Basin, Southeastern New Mexico," The Permian Basin: Proving Ground for Tomorrow's Technologies: West Texas Geological Society, Publication **No. 00-109**, (October 2000) 211.
31. Koganti, M.K.: "Contributions to the Fuzzy Expert Exploration Tool, M.S. Independent Study," New Mexico Institute of Mining and Technology, November 2003.
32. Lennane, J.: "Controls on the Accumulation of Hydrocarbons in the Lower Brushy Canyon Formation, Southeastern New Mexico," M.S. Thesis, New Mexico Institute of Mining and Technology, May 2002.
33. Lennane, J., and Broadhead, R.F.: "The Hydrocarbon Producing Rocks of the Lower Brushy Canyon," (abstract), *Transactions,* Southwest Section AAPG Convention: Roswell Geological Society, (2002) 91.
34. Liang, B.: "Cherry Canyon Well Logging Interpretation by Artificial Neural Network," M.S. Thesis, New Mexico Institute of Mining and Technology, May 2002.
35. Ruan, T., Balch, R.S., and Hart, D.M.: "A Web-Based Fuzzy Ranking System and Application," 9th World Multiconference on Systemics, Cybernetics and Informatics, Orlando, July 10-13, 2005.
36. Ruan, T., Balch, R.S., and Schrader, S.M.: "The Fuzzy Expert Exploration Tool," Sixth IASTED International Conference on Intelligent Systems and Control, Honolulu, August 23-25, 2004.
37. Ruan, T., Balch, R.S., and Schrader, S.M.: "A Web-Based Database Management System," IASTED International Conference on Communications, Internet and Information Technology, St. Thomas, November 22-24, 2004.

38. Schrader, S.M.: “Development, Testing and Application of an Expert System for Petroleum Exploration,” Ph.D. Dissertation, New Mexico Institute of Mining and Technology, May 2004.
39. Schrader, S.M.: “A New Method of Recoverable Reserves Estimation Using an Expert System”, presented at the 2004 SPE Annual Technical Conference International Student Paper Contest, Houston, September 26.
40. Schrader, S.M., Balch, R.S., Ruan, T.: “Preserving and Applying Expert Knowledge: A Case Study for the Brushy Canyon Formation of the Delaware Basin,” presented at the 2003 West Texas Geological Society Fall Symposium, Midland, TX, October 8-10.
41. Subramaniam, V.: “Evaluation of Well Completion Opportunities in the Lower Brushy Canyon Using Neural Networks,” M.S. Thesis, New Mexico Institute of Mining and Technology, December 2002.
42. Subramaniam, V., and Weiss, W.W.: “Evaluation of Well Completion Opportunities in the Lower Brushy Canyon Using Neural Networks,” *Transactions*, Southwest Section A.A.P.G Convention, Ruidoso, June 6–8, 2002.
43. Weiss, W. W.: “Advanced Oil Recovery Technologies for Improved Recovery from Slope Basin Clastic Reservoirs,” paper presented at the 1999 Oil & Gas Conference, DOE Office of Fossil Energy, Dallas, June 28–30.
44. Weiss, W.: “Mining Regulatory Files with Artificial Intelligence to Predict Waterflood Recovery,” presented to the New Mexico Landman’s Association, Roswell, March 29, 2001.
45. Weiss, W.: “Mining Regulatory Files with Artificial Intelligence to Predict Waterflood Recovery,” presented to the City Different Petroleum Club, Santa Fe, May 3, 2001.
46. Weiss, W.: “Risk Reduction with a Fuzzy Expert Exploration Tool,” SPE 70054, presented at the 2000 SPE Permian Basin Oil & Gas Recovery Conference, Midland, May 14–17.
47. Weiss, W.W.: “Neural Networks and Geostatistics Used to Characterize a Reservoir in a Coastal Dune Environment,” Short Course presented at the Annual Petroleum Engineering Summer School, Workshop No. 8, “Geomodeling In Exploration and Production of Oil and Gas,” Dubrovnik, Croatia, June 4–8, 2001.
48. Weiss, W.W.: "Reducing the Risk of Installing a Waterflood," presented at the Annual Petroleum Engineering Summer School, Workshop No. 11, “Risk Minimization and Probabilistic Application in the Petroleum Industry,” Dubrovnik, Croatia, June 10–14, 2002.
49. Weiss, W. W., Balch, R.S., and Stubbs, B.A.: “How Artificial Intelligence Methods Can Forecast Oil Production,” paper SPE 75143 presented at the 2002 Symposium on Improved Oil Recovery, Tulsa, April 13–17.
50. Weiss, W. W., Gottumukkala, V., and Balch, R.S.: “A New Method of Calibrating Wireline Logs With Carbonate Core Measurements to Recognize Pay Zones,” paper 77330 presented at the 2002 SPE Annual Technical Conference and Exhibit, San Antonio, September 29.
51. Weiss, W. W., Stubbs, B.A., and Balch, R.S.: “Estimating Bulk Volume Oil in Thin-Bedded Turbidites,” paper SPE 70041 presented at the 2001 SPE Permian Basin Oil & Gas Recovery Conference, Midland, May 14-17.

52. Weiss, W.W., Sung, A.H., and Broadhead, R.: "Risk Reduction with a Fuzzy Expert Exploration Tool," poster SPE 62810 presented at the 2000 SPE Permian Basin Oil and Gas Recovery Conference, Midland, March 21–23.
53. Weiss, W.W., Sung, A.H., and Broadhead, R.: "Risk Reduction with a Fuzzy Expert Exploration Tool," poster presented at the AAPG 2000 Rocky Mountain Meeting, Albuquerque, September 17-20.
54. Weiss, W.W., Wo, S., and Balch, R.S.: "Integrating Core Porosity and Sw Measurements with Log Values," paper SPE 55642 presented at the 1999 SPE Rocky Mountain Regional Meeting, Gillette, May 15–18.
55. Weiss, W.W., Wo, S., Balch, R.S., Scott, L., and Kendall, R.P.: "Assessing the Potential Redevelopment of a 1960's Vintage Oil Field," paper SPE 59297 presented at the 2000 SPE/DOE Improved Oil Recovery Symposium, Tulsa, April 3–5.
56. Weiss, W. W., Wo, S., Weiss, J.: "Data Mining at a Regulatory Agency to Forecast Waterflood Recovery," paper SPE 71057 presented at the 1999 SPE Rocky Mountain Technical Conference, Keystone, May 21-23.
57. Wo, S., Weiss, W.W., Balch, R.S., Scott, L., and Kendall, R.P.: "New Technique to Determine Porosity and Deep Resistivity from Old Gamma Ray and Neutron Count Logs," paper SPE 59553 presented at the 2000 SPE Permian Basin Oil and Gas Recovery Conference, Midland, March 21–23.
58. Wo, S., Weiss, W.W., Balch, R.S., Scott, L., Roe, J., and Kendall, R.: "Producing GOR Used to Predict Permeability Distribution in a Tight Heterogeneous Reservoir," paper SPE 56505 presented at the 1999 SPE Annual Technical Conference, Houston, October 3–6.

Additional presentations were made at PTTC seminars in Jackson MS, Evansville IN, Washington PA, and Tyler TX demonstrating the application of fuzzy ranking and neural networks to solve oilfield problems.

The following project review meetings and training sessions were held by the REACT group during the project period:

Project Reviews:
First: Albuquerque, New Mexico, Wyndham Hotel, Sept. 9-10, 1999
Second: Hobbs, New Mexico, NMJC, Nov. 2, 2000
Third: Midland, Texas, Petroleum Club, Oct. 24, 2001
Fourth: Roswell, New Mexico, ENMU-R, Sept. 17, 2002
Fifth: Albuquerque, New Mexico, Wyndham Hotel, Oct. 29-30, 2003

Training Sessions:

Delaware FEE Tool: Roswell, New Mexico, ENMU-R Aug. 27, 2003
Devonian FEE Tool: Roswell, New Mexico, ENMU-R, Dec. 1, 2004

7. Additional Projects

7.1 Predict Online

A neural network program was developed to aid in developing the knowledge base. This software, PredictOnline, was successfully tested in-house and generated correlations equal to or superior to the first generation MLP (multilayer perceptron) developed several years ago.

The Java-sourced program is available online along with the two FEE Tools. The following documentation describes the utility of the software.

PredictOnline is a web-based neural network application. More precisely, it is a web-based interface to SNNS—Stuttgart Neural Network Simulator developed at the University of Stuttgart and the University of Tübingen. [Stuttgart, 2004] SNNS is a comprehensive neural network package featuring a full GUI. It can also be used without GUI, using a special SNNS program called Batchman. This program is the engine of *PredictOnline*. A Java Servlet calls the Batchman file of SNNS, which configures the SNNS to execute a Scaled Conjugate Gradient (SCG) algorithm, to train the given data sets according to users' set-up ANN architecture.

"Web-based" means that end users can run the program through their web browsers on local computers connected to the Internet. The computation is then performed remotely on the server machine. Thus, the users are not limited by the speed of their local computers, as neural network training can be computationally demanding.

The second goal of *PredictOnline* is to create a simple user interface with the minimum number of user-settable parameters. The current version uses Swing for its user interface -- a state-of-the-art Java GUI package.

Neural networks

Neural networks are useful for correlating more than two variables. They can be viewed as an inverse problem solver where a system of non-linear equations is developed to yield a known value. The variables in the equations are the input parameters. The constants in the equations are called weights. During the training of a neural network, the weights are adjusted to yield the known output value.

A non-linear, feed forward, back propagation, neural network with a fast matrix solver is used to correlate the input parameters with the known independent variable. Fully connected neural network architectures are evaluated for speed and efficiency. As an example, two different neural network architectures (4-4-2-1 and 4-3-2-1) are seen in Fig. 7.1. A1, A2, A3, and A4 are the input variables; any number of inputs can be used. The tie lines are the weights and circles are the non-linear functions. Maintaining a satisfactory ratio of training data to weights (coefficients of the regression equation) is desired.

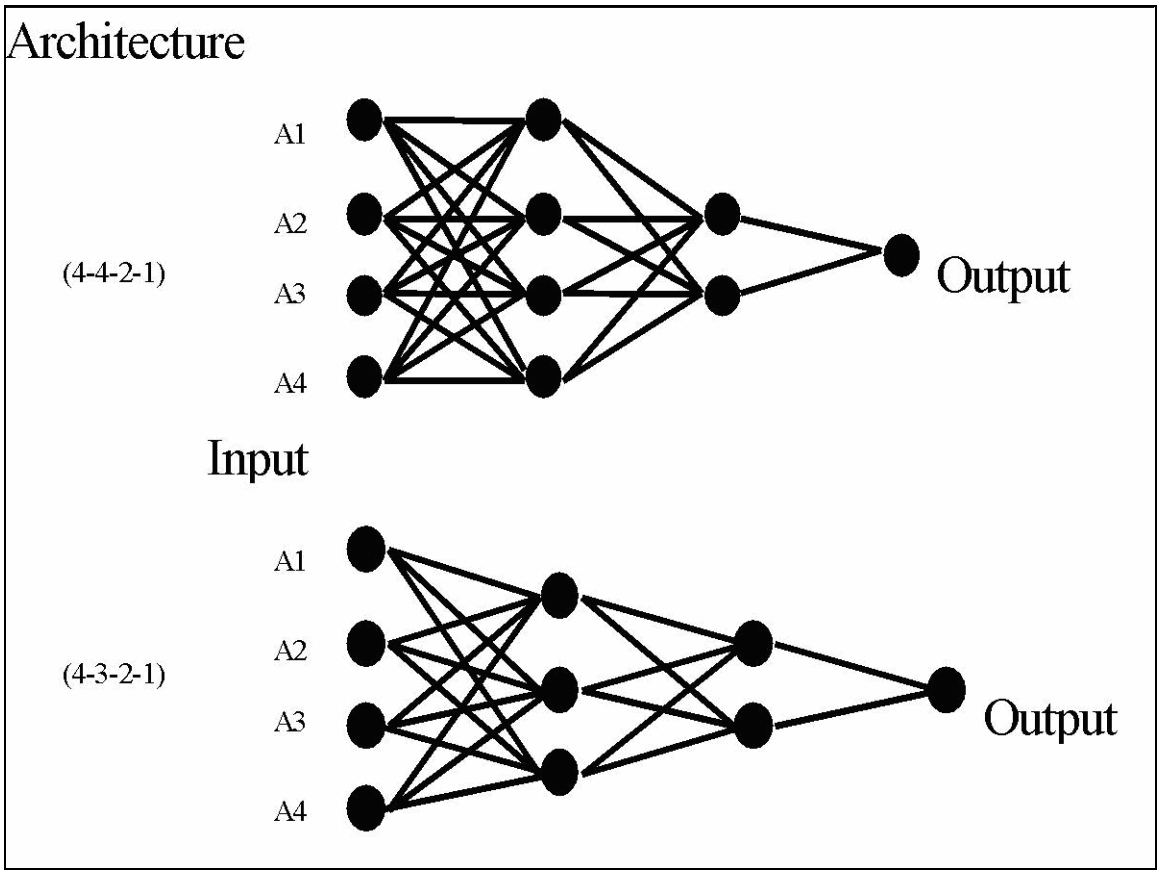

Fig. 7.1: Example of neural network architectures.

Neural networks are trained to yield an output value. The goodness of the training is expressed as a correlation coefficient, with 100% being perfect. In reality, networks trained to about 80% are suitable for forecasting. Once a network is trained it can be used to predict unknown output values given the input parameters. The accuracy of the predictions can be judged with exclusion testing.

Input files

PredictOnline accepts files in ASCII text format. There are two types of input files:

- *Data files*—a single data file is used by *PredictOnline* for network training and testing. This is the file with all known patterns. Each line in that file defines a single pattern. For example a simple data file may look like this:

10.0 0.7 5.81 3.1

11.0 1.5 4.21 2.19

12.0 0.9 3.1 2.1

For instance, the first pattern (i.e., the first line) is: "for input vector [10.0, 0.7, 5.81] the output value is 3.1."

Each line in the data file must contain the same number of values (in the example each line has 4 values).

The network will be trained and tested using all patterns (i.e., all lines in the data set). The data file will be split into two portions, training and testing, according to the value of perc for testing. Each line (i.e., each pattern) from the data file has the perc for testing probability of ending up in the testing file. Therefore, if one wants to train the network using the entire data file, one should set perc for testing to 0, etc.

- *Predict files*—when the network is trained, one can use it to make predictions. A predict file contains input vectors with no output. Output will be predicted by the trained network. So, for the network trained using the above data file, a simple predict file may look like this:

10.5 0.8 5.3

11.0 1.0 4.9

In this file the last column (output) is missing. Each line in the predict file must contain the same number of values (which is the number of columns in the data file minus 1).

Output

- *Training/testing output*

This is the trained network with its performance, i.e., how precisely it can predict the output. The trained network is not shown on the screen. The performance is measured with the following two parameters:

$$r^2 = 1 - \frac{\sum_i (x_i - y_i)^2}{\sum_i (x_i - \overline{Y})^2} \quad \text{and,} \quad \text{if } r^2 \geq 0, \; r = \sqrt{r^2},$$

where n is the number of patterns, x_i is the desired output for pattern i, y_i is the neural network output for pattern i, and $\overline{Y} = \sum_i y_i / n$.

These two parameters (r^2 and r) are computed for both training and testing portion of the data file.

- *Predict output*

The predict output is simply the vector of neural network outputs $Y = [y_1 \ldots y_m]$, where m is the number of patterns in predict file. When predicting, the desired output is not available and, of course, the performance of the prediction cannot be measured. The predict output file looks just like the input file, except that it has an additional column—the output obtained from the trained neural network.

Usage

PredictOnline is just a network-based interface to SNNS's batchman. Therefore, all computation is performed on the server machine. Figure 7.2 shows the architecture of *PredictOnline* (see Fig. 7.3 for additional detail).

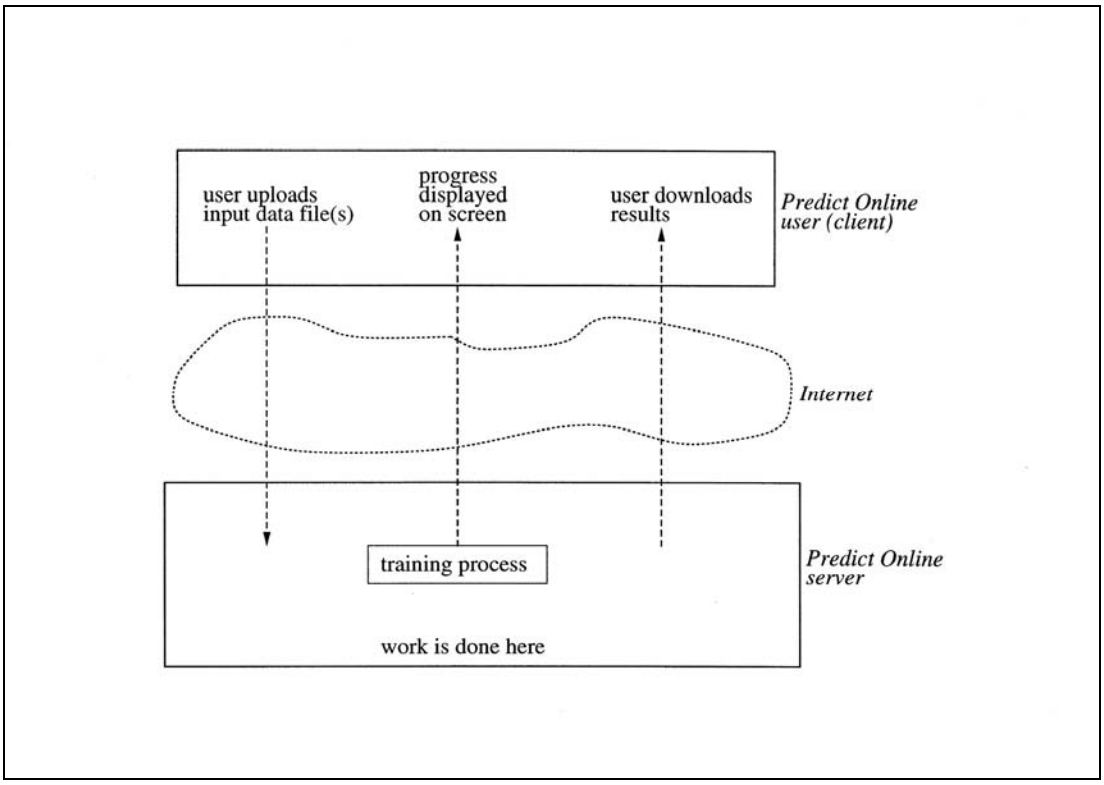

Fig. 7.2: General architecture of *PredictOnline*.

The most important consequence of the web-based nature of the system is that the *PredictOnline* engine (i.e., batchman) has no direct access to the input files, which reside at the client side. The input files have to be transferred by some means to the server side and the output transferred back to the client (see Fig. 7.3). In previous versions FTP was used for file transmission; however, the current release of *PredictOnline* takes care of file transmission as well.

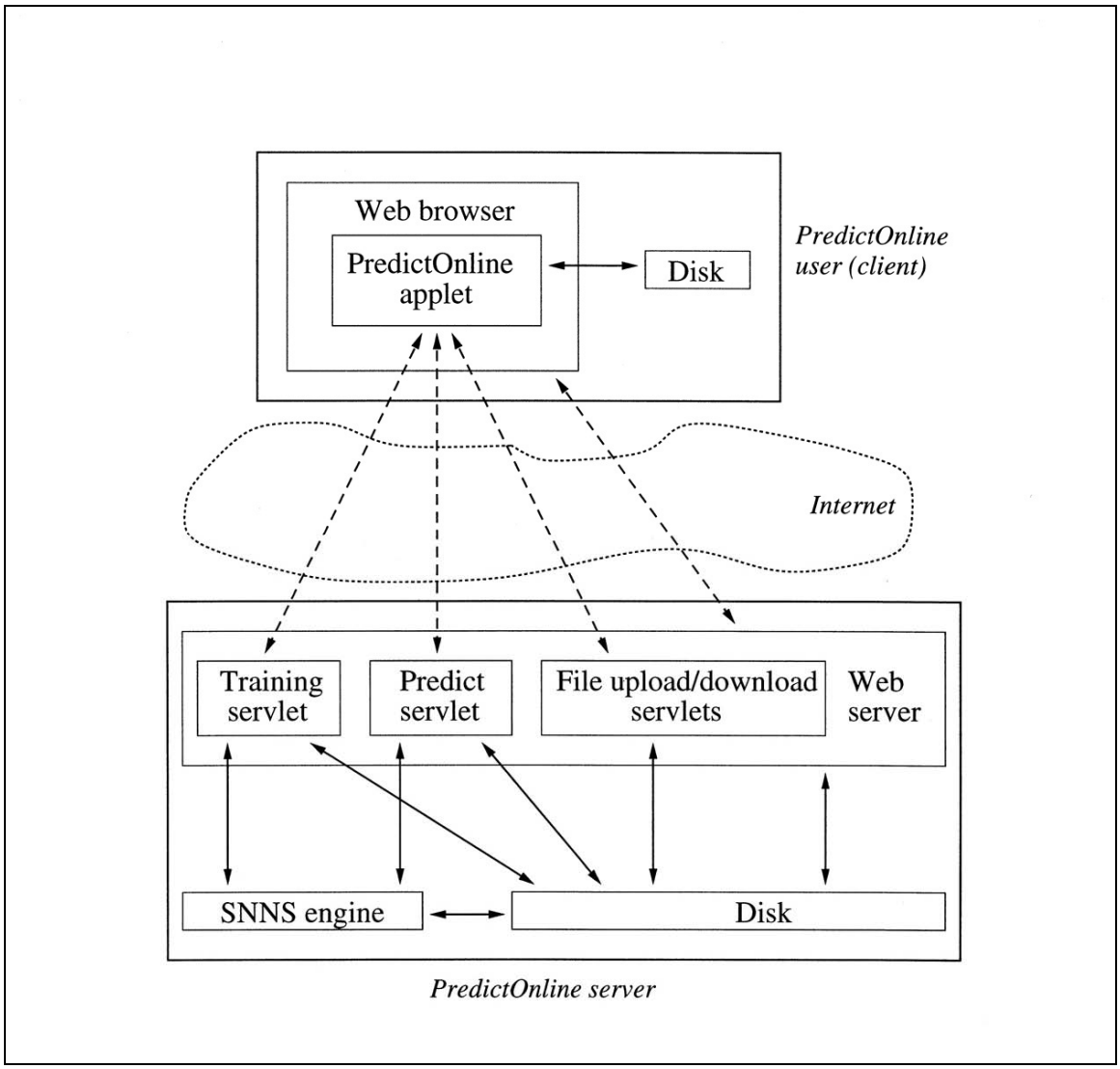

Fig. 7.3: Detailed architecture of *PredictOnline*.

PredictOnline supports multiple users. Each user will have a *PredictOnline* account on the server. Details on using PredictOnline are found in the REACT Software "User's Manual," included in the appendices.

7.2 Fuzzy Rank

7.2.1 Introduction

It can be both statistically dangerous and not computationally feasible to use all available attributes as inputs for a neural network (or in any regression relationship); therefore, software (FuzzyRank) was developed based on a fuzzy-ranking algorithm to select attributes best suited for predicting production indicators. The algorithm statistically determines how well a particular input (regional data or data attribute) could resolve a particular output (production indicator) with respect to any number of other inputs using fuzzy curve analysis.

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

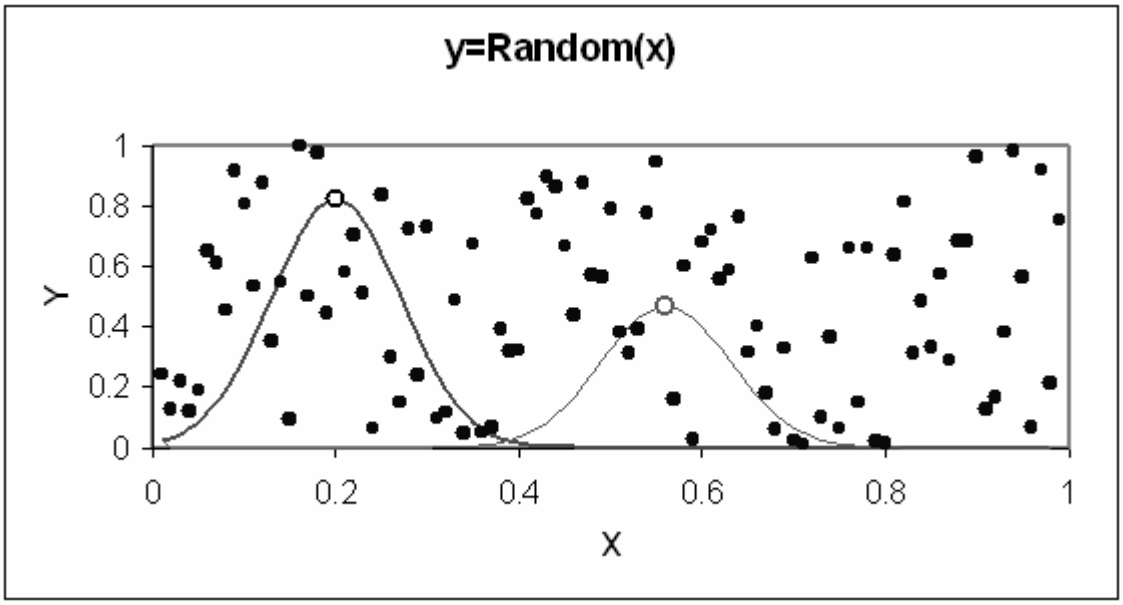

Fig. 7.4: One hundred random points between 0 and 100. Two sample fuzzy membership functions are illustrated.

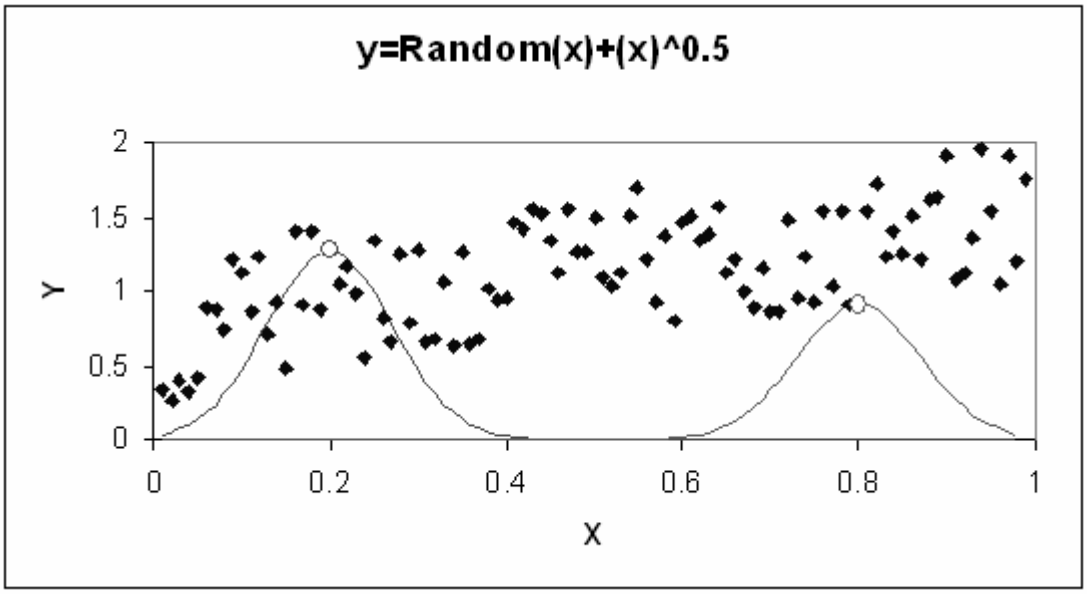

Fig. 7.5: The same one hundred random points with a simple trend added; two sample fuzzy membership functions are shown.

For each data (x_i, y_i) a "fuzzy" membership function is defined using the following relationship:

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

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

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

Here, N is the size of the data set or the total number of fuzzy membership functions. Figure 7.6 shows the curves for the data sets shown in Figs. 7.4 and 7.5. This simple example illustrates the ability of the fuzzy ranking approach to screen apparently random

data for obscure trends such as the correlation between seismic attributes and reservoir properties [Balch, 1999].

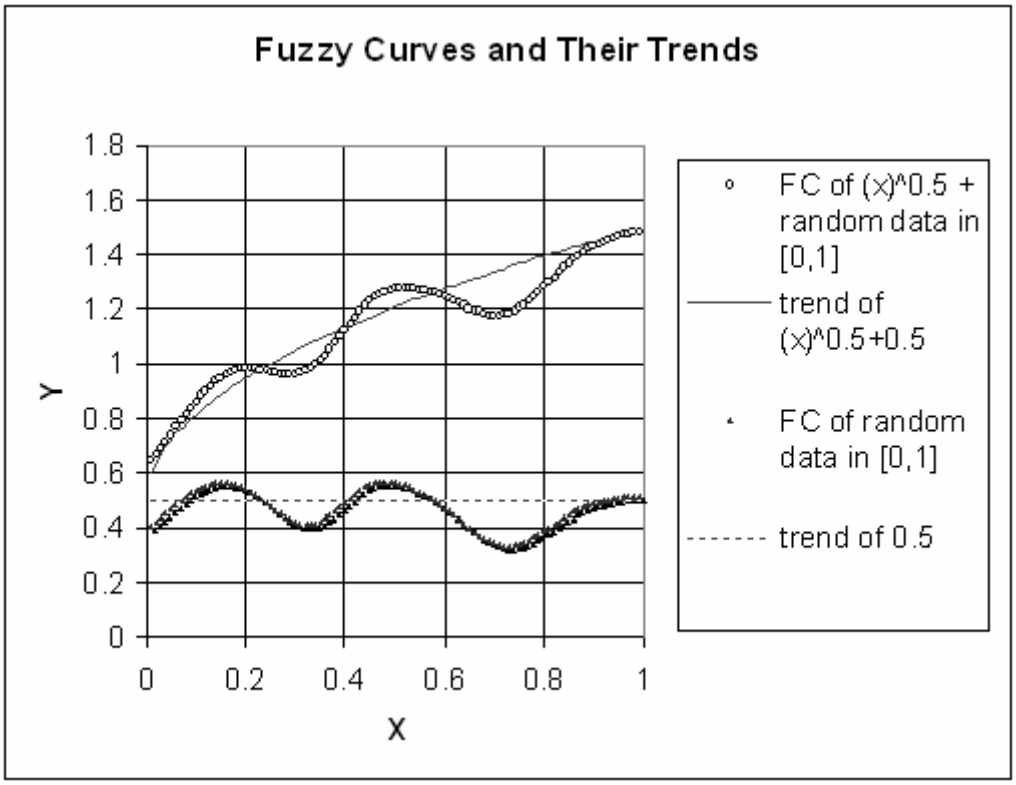

Fig. 7.6: Fuzzy curves for the two data distributions illustrated in Figs. 7.4 and 7.5. Curves are the summation of the fuzzy membership functions for each point. Value is given to trends with monotonic vertical variations.

Based on the deviation from a flat curve, each attribute is assigned a rank, which allows a direct estimation of attributes that contribute the most to a particular regression.

Experience [Weiss, 2000] suggests that numerical rank can best be used to eliminate attributes that have low rank, but that a direct visual inspection of the curves themselves is needed to select attributes for use in forming regressions. In examining these curves, two factors are considered: 1) the rank, which is defined as the vertical difference between the maximum and minimum points, and 2) the shape of the curve itself. Monotonically increasing or decreasing curves with relatively high rank are optimal and are the most easily modeled data.

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

7.2.2 Fuzzy Rank Coding

A Two-Stage Fuzzy Ranking System (FuzzyRank) was designed with the following four functionalities:

- Project management
- Ability to upload raw data in text format and view
- Rank the data and output significant inputs
- Download results

FuzzyRank is built on a three-tier model, which facilitates the need to separate business logic from the GUI and the backend database. According to the model, three separate well-defined processes, or modules, run on different layers.

1. A Presentation Layer was written in Java Applets that implement the interactive interface and presents data in any Java capable browser on the user side. The interface accepts user requests generated by clicking on the menu items, and sends them to the Business Logic Layer.

2. The Business Logic Layer was written in Java Servlets that translate data management requests from users to SQL statements, so that these requests are forwarded to the Data Layer and answered queries are returned, or it executes a Fuzzy Ranking algorithm written in Java.

3. The Data Layer, which is a Microsoft® SQL Server in FuzzyRank, manages the Data of FuzzyRank by executing SQL statement received from the Business Logic Layer.

SQL communicates with JDBC through Microsoft® ODBC. The SQL Server processes the SQL statements and sends the results back to the Business Logic Layer through the ODBC driver to the JDBC driver.

Fig. 7.7 shows the structure of FuzzyRank implemented using Java Technologies.

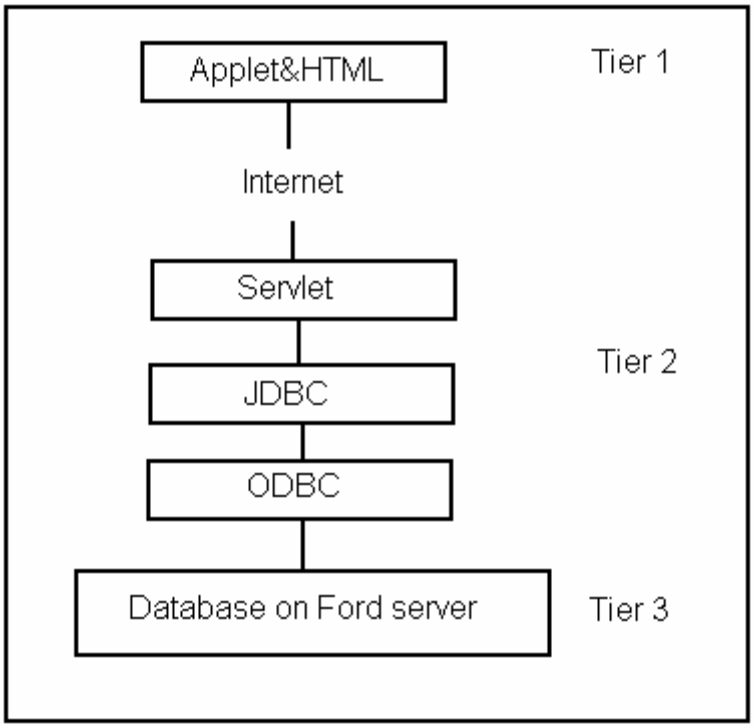

Fig. 7.7: FuzzyRank structure.

FuzzyRank can identify the number of inputs in an uploaded data file in text format with the delimitation of a space or a comma. Data and results are stored in the database using MS SQL Server. In MS SQL Server, “image” is one kind of data type. It is usually used to store pictures or image files. FuzzyRank uses “image” to store uploaded data and ranking results. Java Servlets accesses them through JDBC and ODBC. The following sample codes show how the select statement accesses the data of “image” type.

“

```
Clob clob = new BufferedInputStream( resultSet.getBinaryStream("data"));
```

”

To map it into a character large Object---Clob.

```
String mStatement="select data from FuzzyRank where fuzzyRank.userID='"+userID+"'
and fuzzyRank.projectName='"+projectName +"';";
```

```
System.err.println(mStatement);
try{
  resultSet=st.executeQuery(mStatement);
  resultSet.next();
  Clob clob = new BufferedInputStream( resultSet.getBinaryStream("data"));
```

Interface (Java Applets) runs on the user's computer (client side) and exchanges data with Java Servlets running on the server side. There are two ways to implement the communication between client (Applets) and server (Servlets):

- HTTP text stream
- HTTP object streams.

An HTTP object stream can be used to transfer binary data as well as textual data. This can be combined with object serialization to pass complete Java objects from a Servlet to an Applet or an Applet to a Servlet. Complex data can be passed this way with no need for parsing and interpretation. To communication efficiently and identify data type easily, an application protocol was designed and used in FuzzyRank communication. Since Applets are restricted to access user's local file, FuzzyRank uses JSP to implement the upload and download functions. The communication between Applet and Servlet was implemented based on the application protocol (See section 5.1.3).

More information about the FuzzyRank software is included in the "User's Guide" in the appendices.

7.3 Reserves Estimation

7.3.1 Methods

One novel use for the FEE Tool is to use it as a method of estimating the oil reserves in the Lower Brushy Canyon formation. The idea was to link the total production at a well with the FEE Tool estimate at that well. Then, applying this to all recommended estimates throughout the system, an estimate of reserves could be obtained. (Results of the expert system, given in Chapter 3.2, indicate a numerical output of 0.65 or higher as a recommendation.)

The following steps outline the process that was used to determine the reserves with the FEE Tool:

1. Wells were selected from the list of wells by considering wells that had 30015 as the first five digits of their API number and produced from the Lower Brushy Canyon. (The API number selection was made so as to favor wells with longer production histories.) These wells were randomly selected using the sheets developed to use while reviewing completion cards.

2. For these wells, ONGARD, a part of the GO-TECH website developed by the Petroleum Technology Transfer Council (PTTC), was used to find the production data. ONGARD enables the user to search for a New Mexico well based on location, API number, name or formation. It returns monthly and cumulative production data for the well. [PTTC, 2004] The oil per month and the cumulative oil were recorded for each well selected.

3. For each well, the x-axis represented the number of months in production and the y-axis represented either the monthly production or the cumulative production. These variables were used to develop cubic regression curves, using Minitab, a statistical software package. Other types of regression curves were tried; however the cubic functions provided the best fit. Once the regression analyses were completed, five wells were selected for which the R-squared values were high, indicating a good fit between the curve and the monthly production. In all cases studied, the cumulative data showed a very good fit with the cubic regression curve. For the five cases selected on this basis, the regression equation was used to determine the time (in number of months) until the monthly production went to zero, as well as the time when the monthly production decreased to 100 bbls (as this is often used as an end of productive life). A sample of the production vs. time and the cumulative vs. time graphs with the regression curves is given in Figs. 7.8 and 7.9.

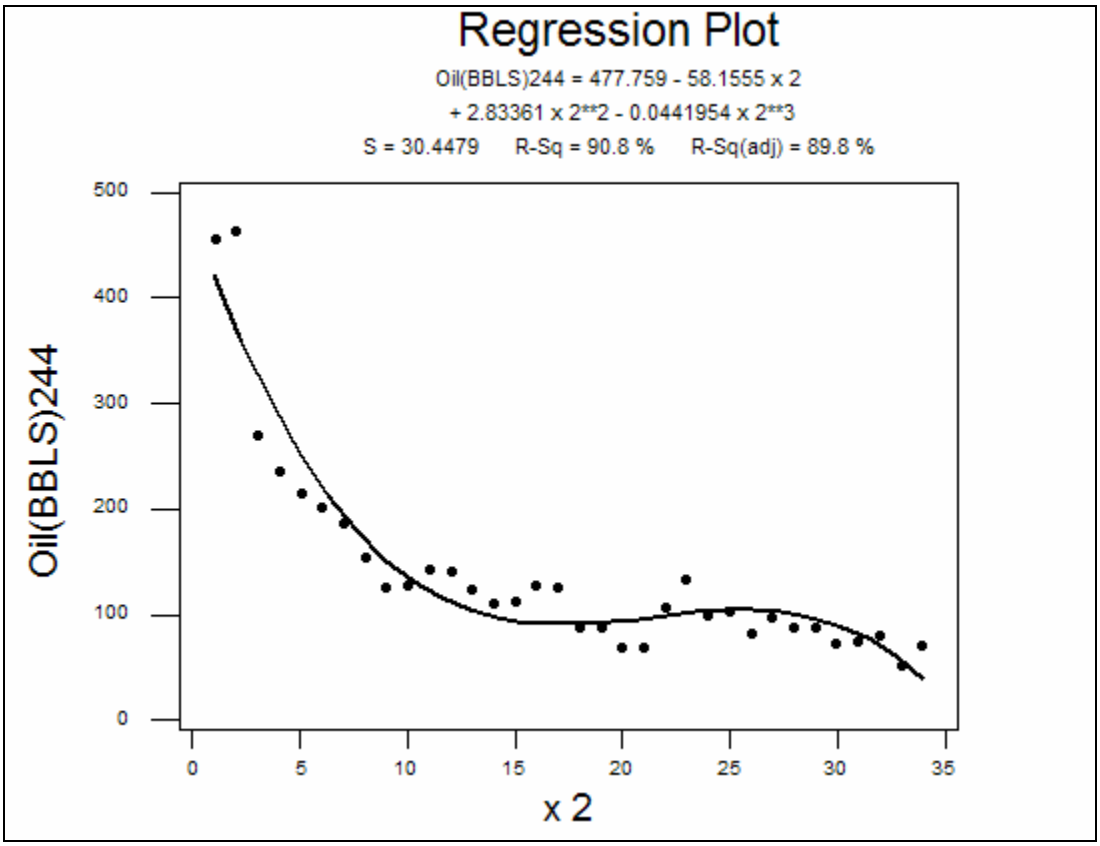

Fig. 7.8: Cubic regression plot in which monthly production (on the vertical axis) is related to time in months (on the horizontal axis). The upper data gives the polynomial equation and the correlation coefficient. An R^2 value of 90.8% indicates a good correlation.

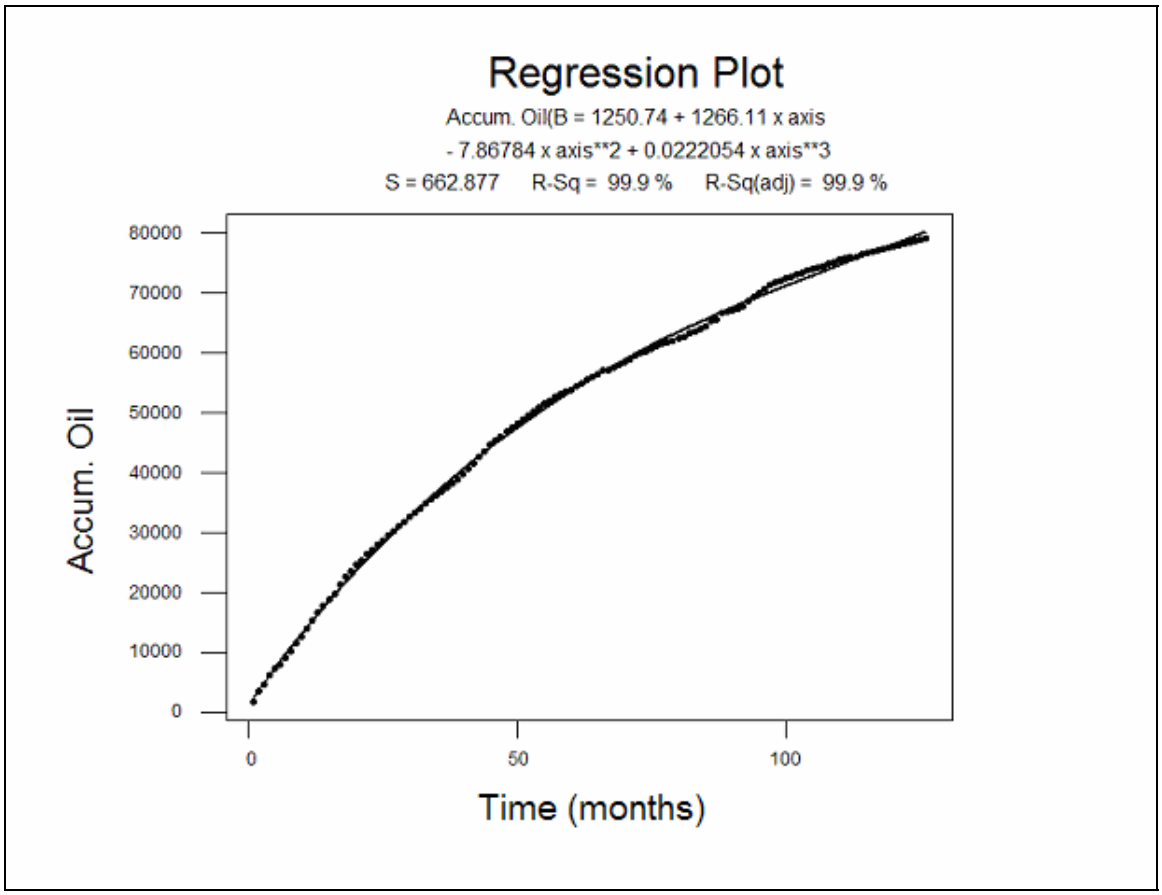

Fig. 7.9: Cubic regression plot for cumulative production and time (months), showing an excellent fit as given by the R^2 coefficient.

This value, which was obtained by using the Scientific Notebook® equation solver, was then used as the input into the regression equation for the cumulative production to find two total production values, one using the 0 bbls value as the end of productive life, and one using the 100 bbl value.

4. Two ratios of the average first year production to the complete production were computed using both the 0 bbl and 100 bbls "end of productive life" values for each well. Therefore, 10 ratios were determined, five using 0 bbl as the end of productive life and five using 100 bbls as the end of productive life. For each set of these five ratios, the mean was found, resulting in two values representing the ratio of the first year production

to the complete production. These two values are (for 0 bbl) 0.354 and (for 100 bbls) 0.437.

5. For each well in the list of 1000 wells, total production was computed by dividing the first year production by each of the two ratios.

6. The wells were then divided into bins based on the FEE Tool estimate. Since the FEE Tool cutoff value that separates the recommended locations from the remainder of locations is 0.65, only those wells with estimates greater than or equal to 0.65 were considered.

7. The next step was to find the number of gridpoints in each of the estimate categories and multiply by the 100 bbl or 0 bbl values in the same table, then sum the products and subtract out the cumulative recovery values given in Table 7.1. This is expressed in the equations given below.

Variables:

u = FEE Tool estimate (Table 7.1, col. 1)

n = number of wells (1000 well set) that fall into each estimate level (Table 7.1, col. 2)

N = number of gridpoints (from 60,478 gridpoint set) that fall into each estimate level (Table 7.1, col. 5)

A = 100 bbl cumulative production multiplier for each estimate level (Table 7.1, col. 3)

B = 0 bbl cumulative production multiplier for each estimate level (Table 7.1, col. 4)

Reserves (using 100 bbl as the end of productive life) = $\sum_{i=1}^{25} A_i N_i - \sum_{i=1}^{25} A_i n_i$

Reserves (using 0 bbl as the end of productive life) = $\sum_{i=1}^{25} B_i N_i - \sum_{i=1}^{25} B_i n_i$

Table 7.1: Cumulative Recovery Average per Well for Each Estimate Level

u	n	100 bbl value	0 bbl value	N
0.65	10	27174	33546	689
0.66	16	41135	50780	687
0.67	18	29968	36994	626
0.68	14	33615	41496	563
0.69	20	38031	46947	404
0.7	22	44131	54478	351
0.71	38	38150	47095	333
0.72	47	29846	36844	287
0.73	30	31451	38825	224
0.74	40	33910	41860	220
0.75	39	37333	46086	177
0.76	38	30233	37322	159
0.77	64	36049	44501	202
0.78	58	43521	53725	142
0.79	47	38677	47745	134
0.8	55	40393	49864	131
0.81	68	38331	47319	124
0.82	49	41774	51569	105
0.83	64	43727	53979	91
0.84	49	42239	52143	77
0.85	53	36576	45151	71
0.86	34	49654	61296	46
0.87	27	43395	53569	27
0.88	17	54817	67669	19
0.89	7	53445	65976	8

7.3.2 Results

Using the method outlined above, the reserves were calculated as 171,612,995 bbls using the 100 bbls per month value as the end of productive life, and 211,851,015 bbls using the 0 bbl value. One way these two values could be interpreted is to consider that the economic recoverable reserves fall between 170 million barrels and 210 million barrels.

7.4 Other Projects

7.4.1 Oil Price Forecast

Future oil price is a fundamental parameter in assessing the risk of any oil or gas production venture. One aggregate of speculation by experts on the purchasing and selling of crude oil is the Goldman Sachs future's price of oil. These experts try to reasonably predict the price of a barrel of oil a month in advance. Figure 7.9 is the 30-day average of these experts' predictions preceding the strike date. The average is compared to the Navajo refinery posted price of West Texas Intermediate on the strike data. Notice that from June 1996 through October 1997 the experts did an excellent job. However, from November 1997 to March 1999, the error is approximately 33% or about $5/bbl more than the posted price and from May 1999 to December 2000 the error is about 25% or $7/bbl less than the posted price. The predictions presented in Fig. 7.10 are crossplotted in Fig. 7.11. The R^2 value is 0.72, yielding an 85% overall correlation coefficient.

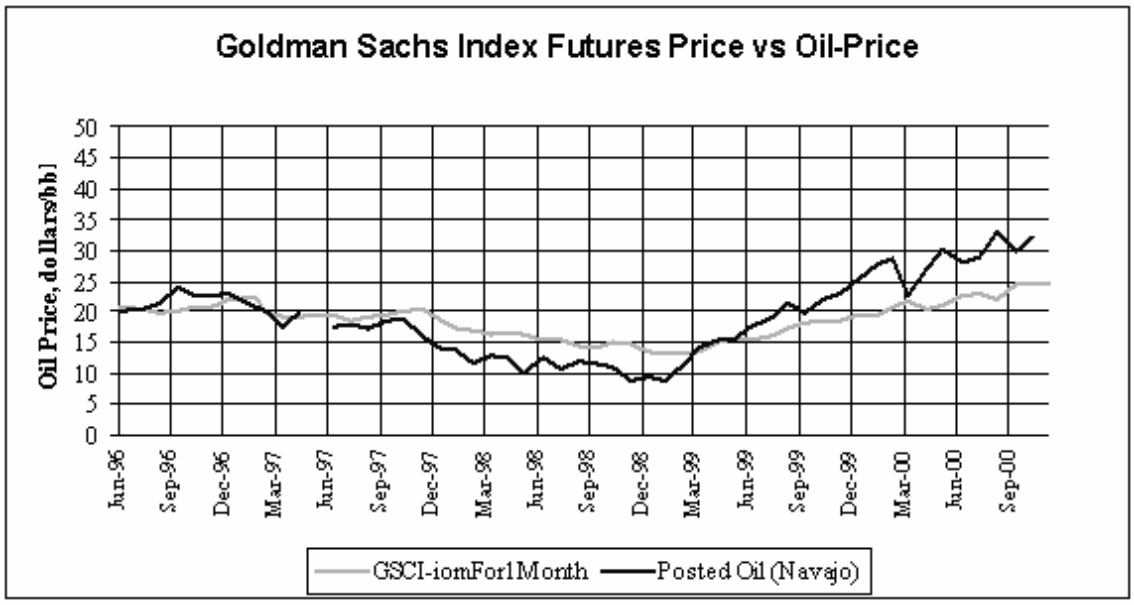

Fig. 7.10: Actual WTI oil price vs.30-day future price (time format).

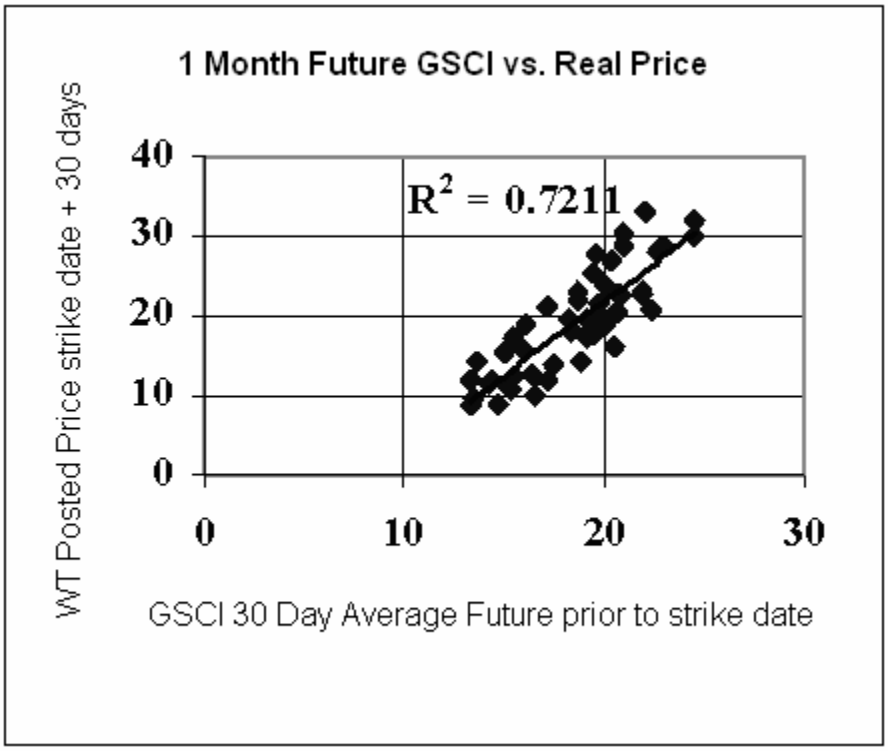

Fig. 7.11: Actual WTI oil price vs. 30-day future price (crossplot format).

The future price of commodities other than oil is also the subject of speculation by experts. The 90-day future price of the euro vs. the yen was examined using crossplots similar to the oil futures versus posted price, the hope being that euro/yen traders might indirectly have insight to the future price of oil. Figure 7.12 shows the crossplot of the WT Posted Price of oil vs. the 90-day average of the euro/yen. Based on the R^2 of 0.96 (98% correlation coefficient) there appears to be a strong relationship between the euro/yen future price and the posted price of WT intermediate, at least for this small dataset.

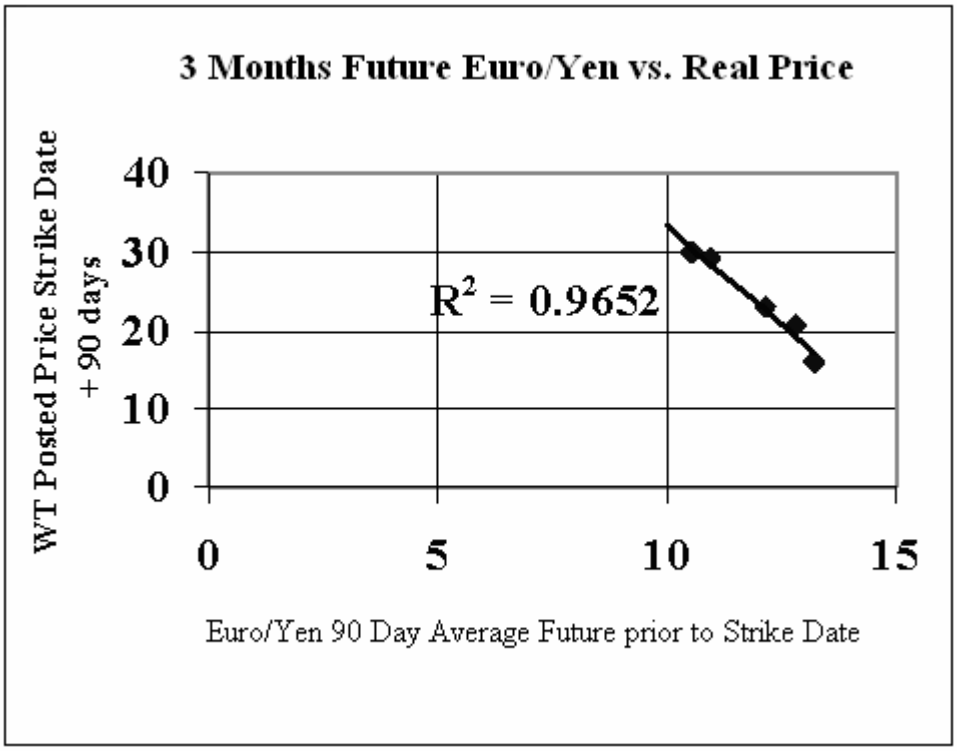

Fig. 7.12: Actual WTI oil price vs. euro/yen 90-day future price.

The relationships between the three-month future price of the euro/pound, 30-year Treasuries, 10-year Treasuries, and the Future Dow Jones with the posted price of WT intermediate oil were also examined in a similar manner. The results based on the goodness of the best-fit line are summarized in Table 7.2.

Table 7.2: Goodness of the Relationship between Commodity Future Price and Oil Price

Commodity	Correlation Coefficient, %
Goldman Sachs future price of oil	85
Euro/Yen	98
Euro/Pound	96
30-year Treasuries	94
10-year Treasuries	94
Future Dow Jones	93

The results of this preliminary analysis, albeit with a small dataset, suggest that the future price of some commodities other than oil may be useful when predicting oil price.

Assuming that the correlation coefficient describes experts' ability to forecast the future, it appears that the futures price of the euro/yen and euro/pound are closely tied to the price of oil. This is not as surprising as one might think, as both the euro and yen (for example) are currencies for nations and regions which on a whole are dependent on oil imports to fuel their industries, and hence their economies.

A strong concern, however, is that these futures may be strongly affected by many of the same factors that affect the accuracy of futures prices and therefore break down prior to periods of change, such as a sudden war, or other unexpected event.

7.4.2 Bulk Volume Oil Predictions

Determining the water saturations using wireline logs in thin-bedded turbidites such as the Lower Brushy Canyon is difficult. For example, the crossplot in Fig. 7.13 shows that bulk volume oil (ϕS_o) calculated from log estimates of S_w results in BVO values much greater than those measured in a core. These errors in S_w calculation frequently result in uneconomical completions, as shown by the non-commercial completions in the Fig. 7.14 map of Lower Brushy Canyon wells. Consequently, current Brushy Canyon completion decisions include expensive core information to provide an acceptable indicator of oil saturation to compensate for the S_w calculation problem. Completion decisions can be improved and less core data is needed using a method that correlates wireline logs with core measured BVO.

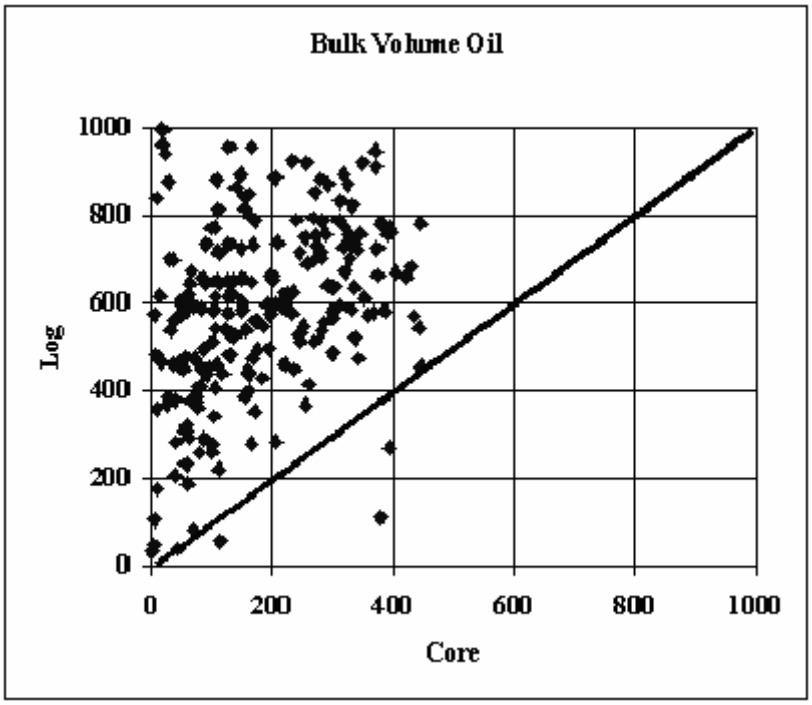

Fig. 7.13: Extreme difference between log and core ϕS_o values.

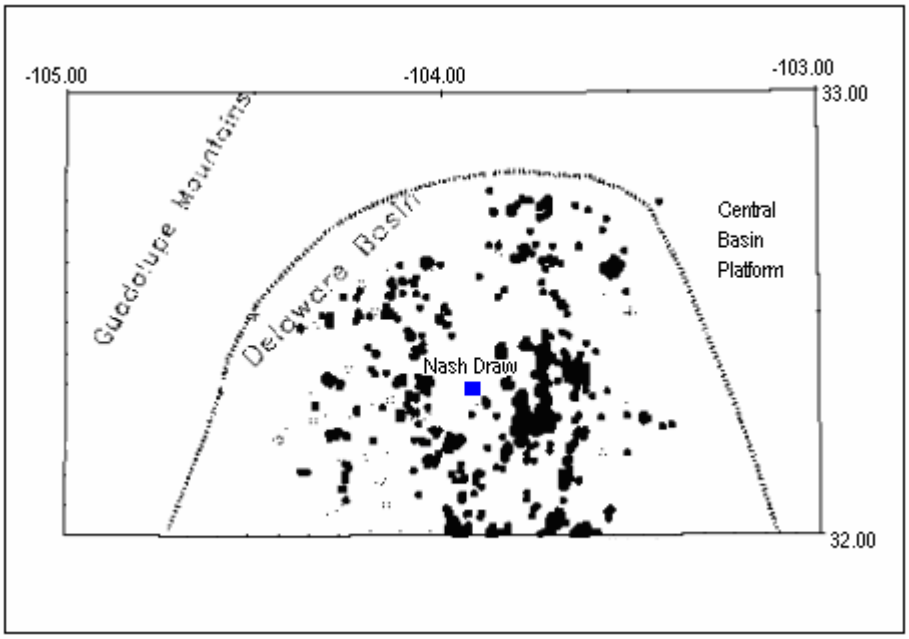

Fig. 7.14: Dry hole locations.

PredictOnline was used to train a complex 4-6-5-2-1 neural network to 90+ % correlation coefficient using density porosity, neutron porosity, and shallow and deep resistivity logs

as input variables. The neural network was trained and tested to predict the BVO product from the Nash Draw Well #23 whole core analysis. The neural network BVO log is shown in Fig. 7.15. It is noteworthy that several networks trained to ~ 90% correlation coefficient provided that the records to weights ratio exceeded 2.5.

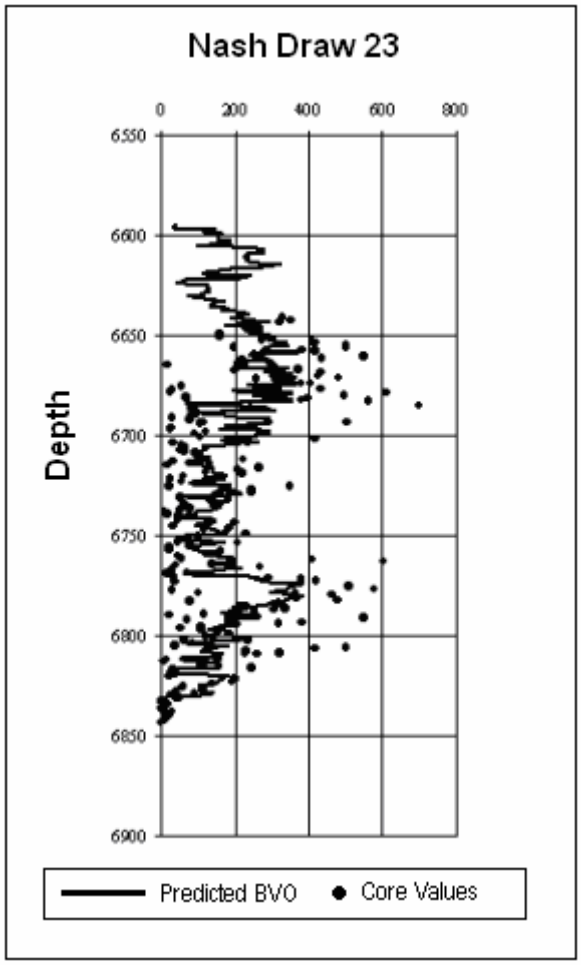

Fig. 7.15: BVO log from trained neural network.

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

The BVO logs constructed with the neural network predictions are shown in Figs. 7.16-7.20 at the end of this section. The measured bulk volume oil calculated from sparse sidewall core plug data is included with the BVO curve (dark curve). The gamma ray log

(fine line) is included on all plots for completeness. The plots are intended to illustrate the goodness of the predictions or perhaps a problem with relying on sporadic core plugs (compared to whole core data). Nash Draw #23 well information was included with the 14 wells as an aid to visually correlate the measured values with the predicted BVO log. The visual correlations indicate that the BVO log rarely captures the measured data exactly, but trends are evident.

The BVO log statistical parameters (average, standard deviation, and sum) are shown in the upper left hand corner of the BVO logs. Intuitively, a high average or sum of BVO should correlate with high production. The standard deviation of the BVO log is related to the spread in the BVO values. Table 7.3 shows the statistical values of each well's BVO log and a production indicator. The production indicator is the average of the first 12 full producing months.

Table 7.3: BVO Log Statistics

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

The plot in Fig. 7.21 shows that the Sum BVO generally correlates with monthly oil production as the production indicator. The addition of the average and the standard deviation to the sum as correlating parameters improves the correlation coefficient considerably, as seen in Fig. 7.22.

The trained neural network also was used to predict BVO logs using the density porosity, neutron porosity, and shallow and deep resistivity logs from 19 additional Lower Brushy Canyon wells as input variables. The statistical parameters (average, standard deviation, and sum) were calculated and used to generate plots of actual first year production versus predicted production for the entire 34 wells (Fig. 7.23).

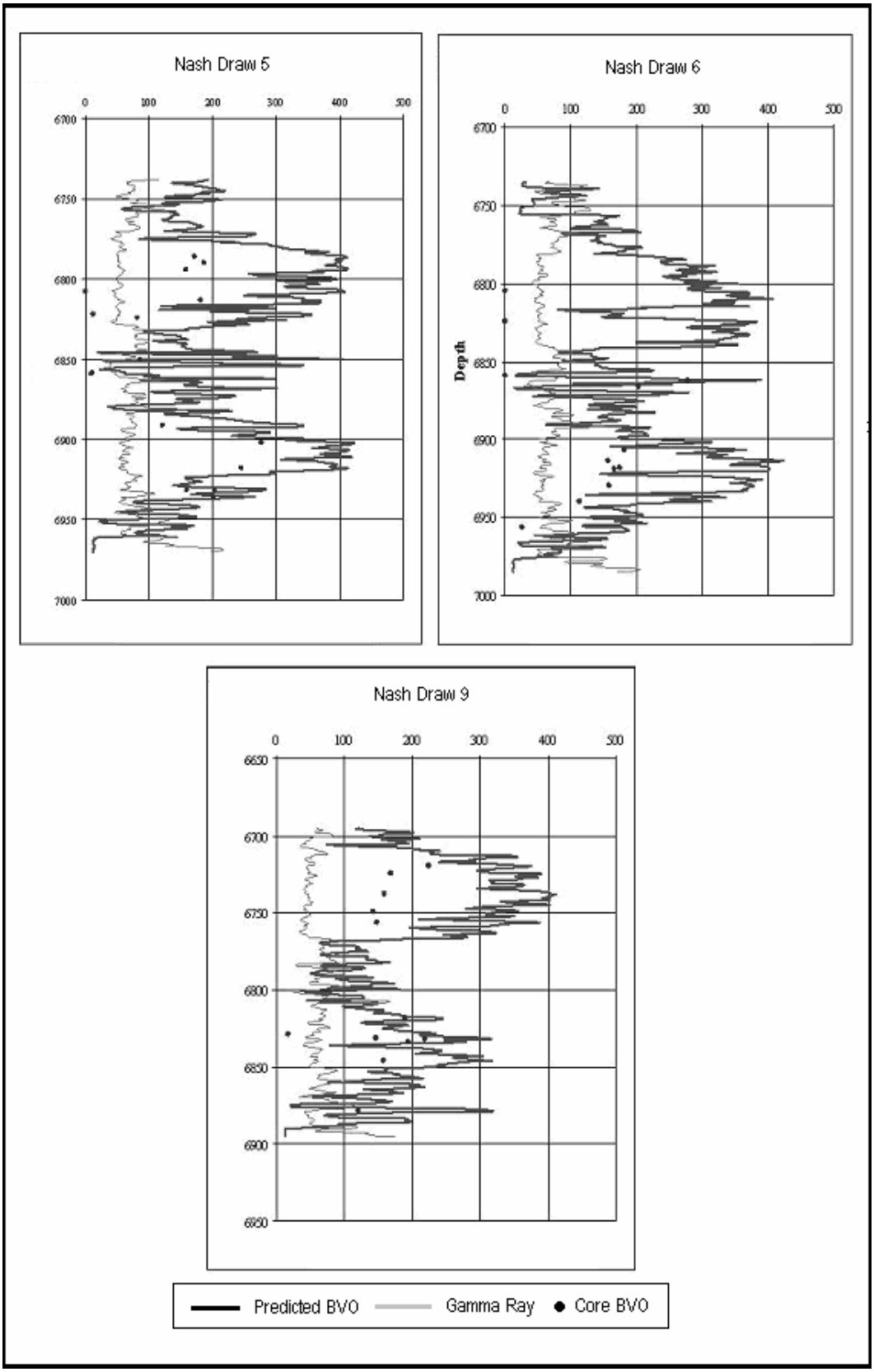

Fig. 7.16: Neural network-predicted BVO, wells 5, 6, and 9.

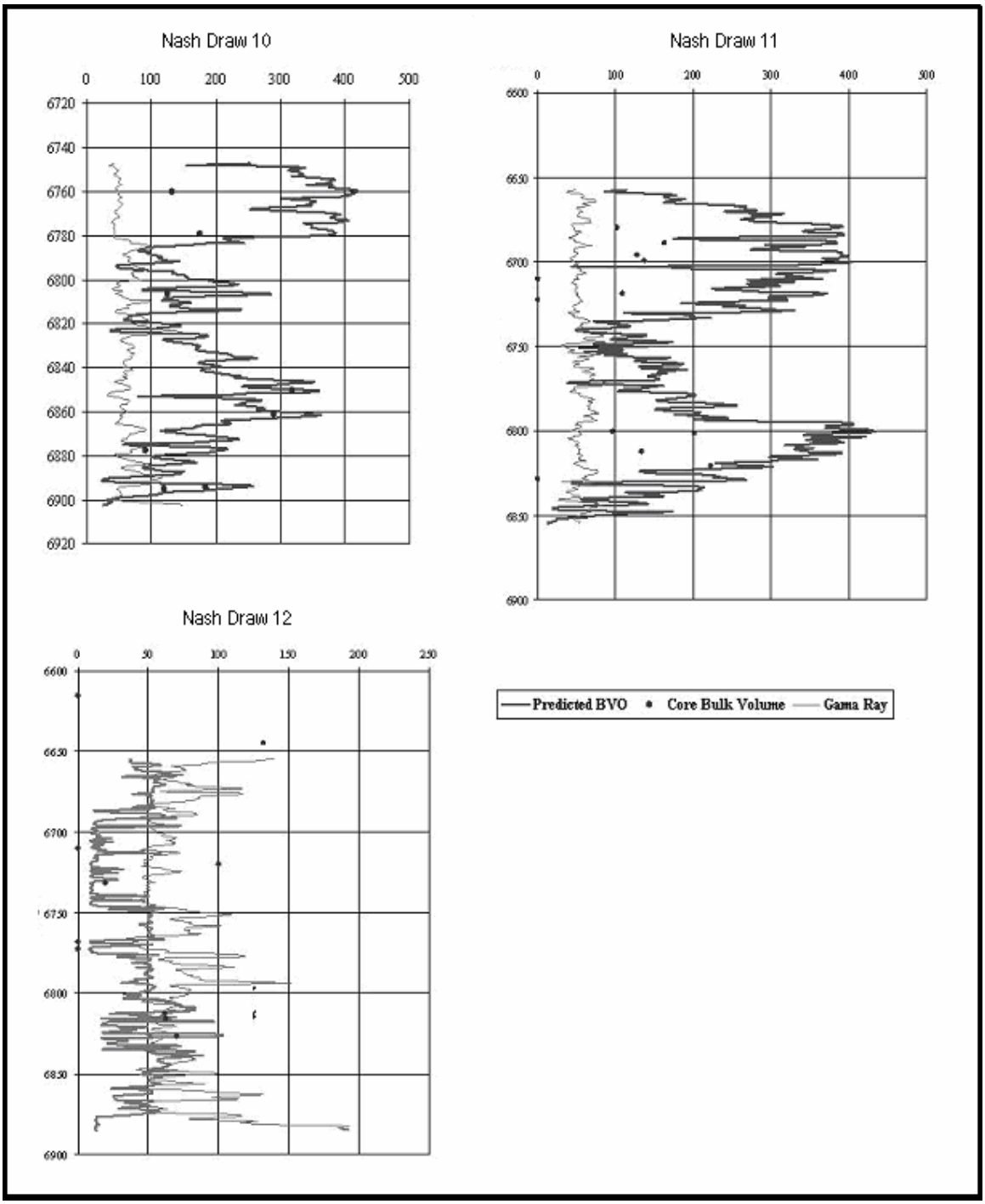

Fig. 7.17: Neural network-predicted BVO, wells 10, 11, and 12.

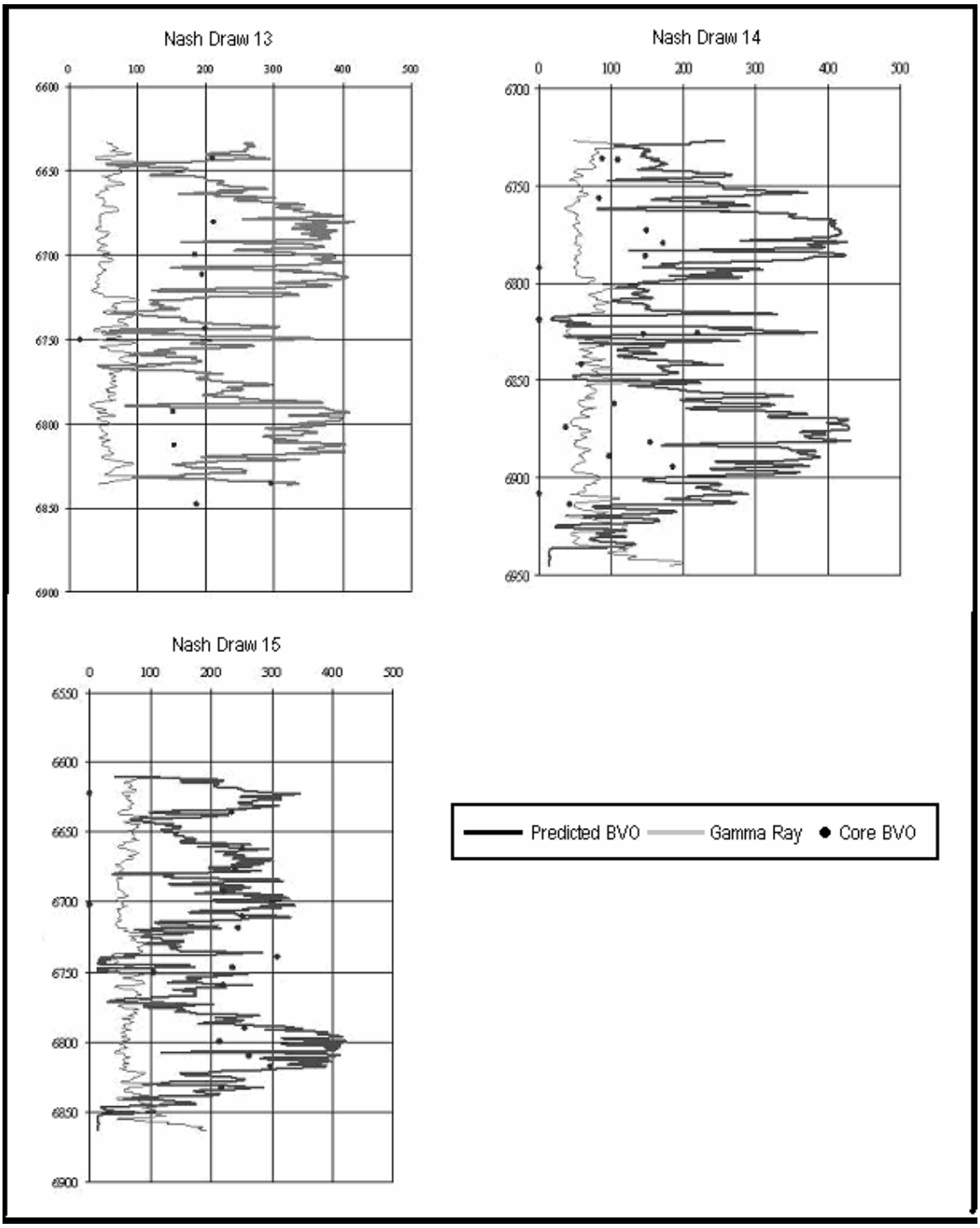

Fig. 7.18: Neural network-predicted BVO for wells 13, 14, and 15.

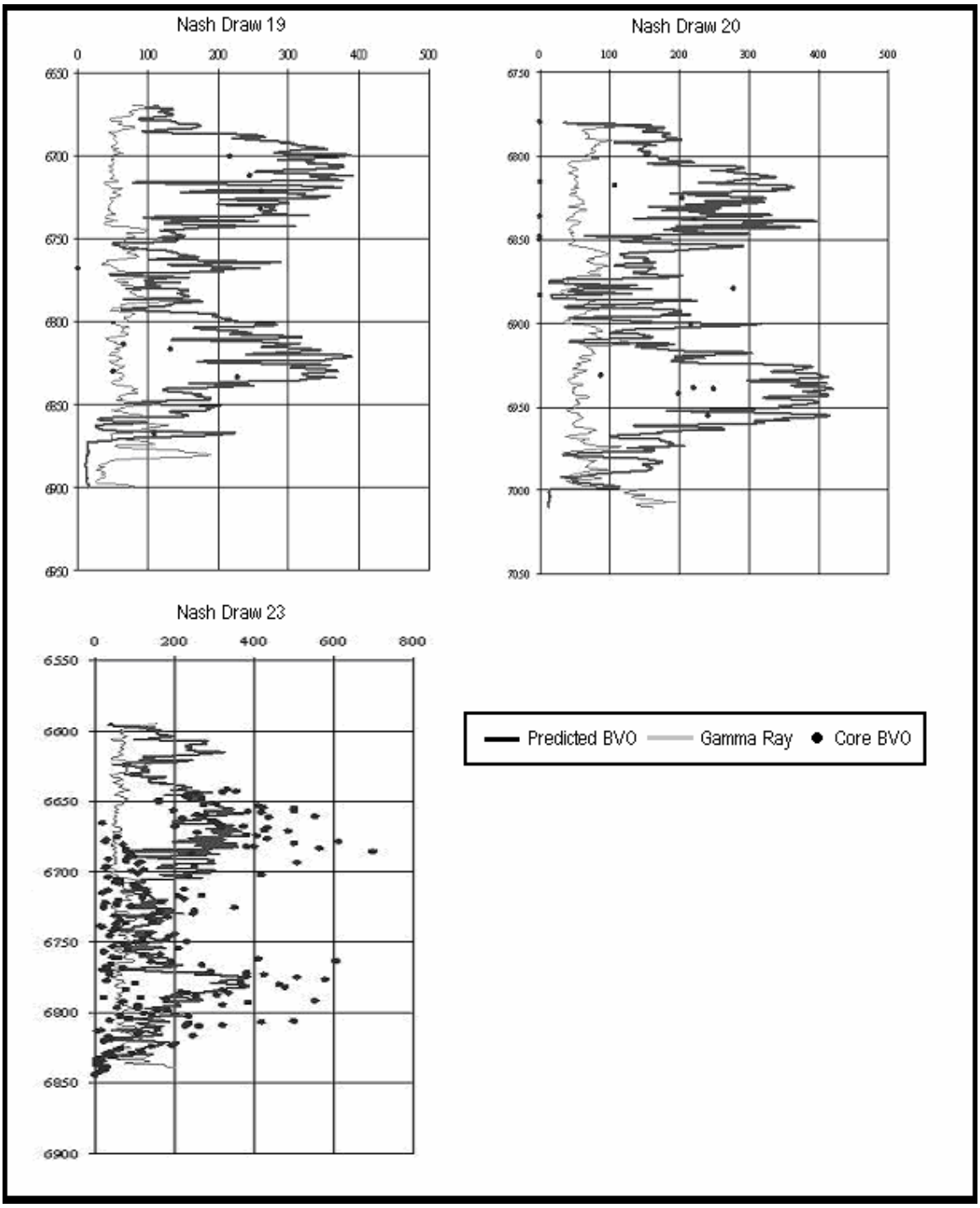

Fig. 7.19: Neural network-predicted BVO for wells 19, 20, and 23.

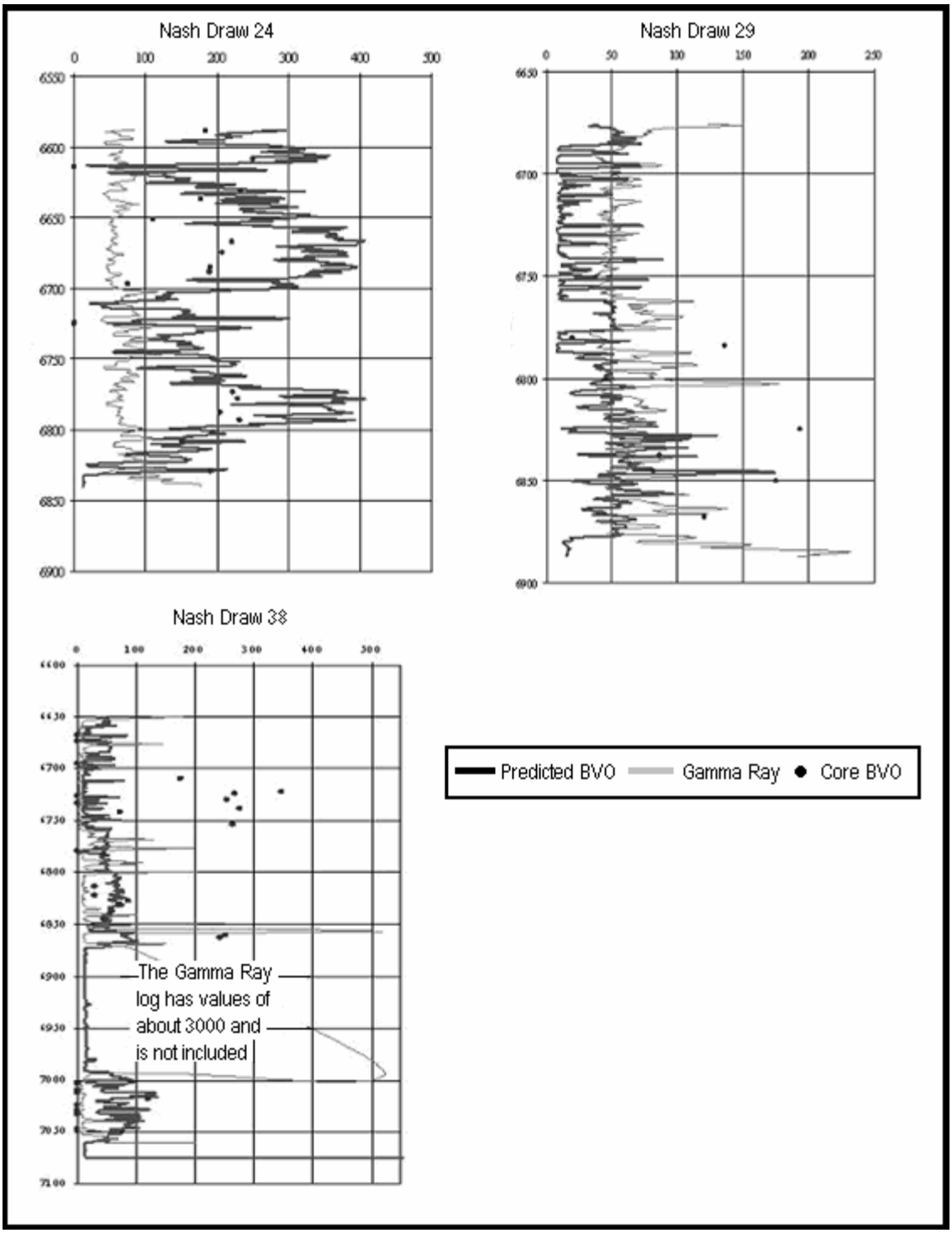

Fig. 7.20: Neural network-predicted BVO for wells 24, 29, and 38.

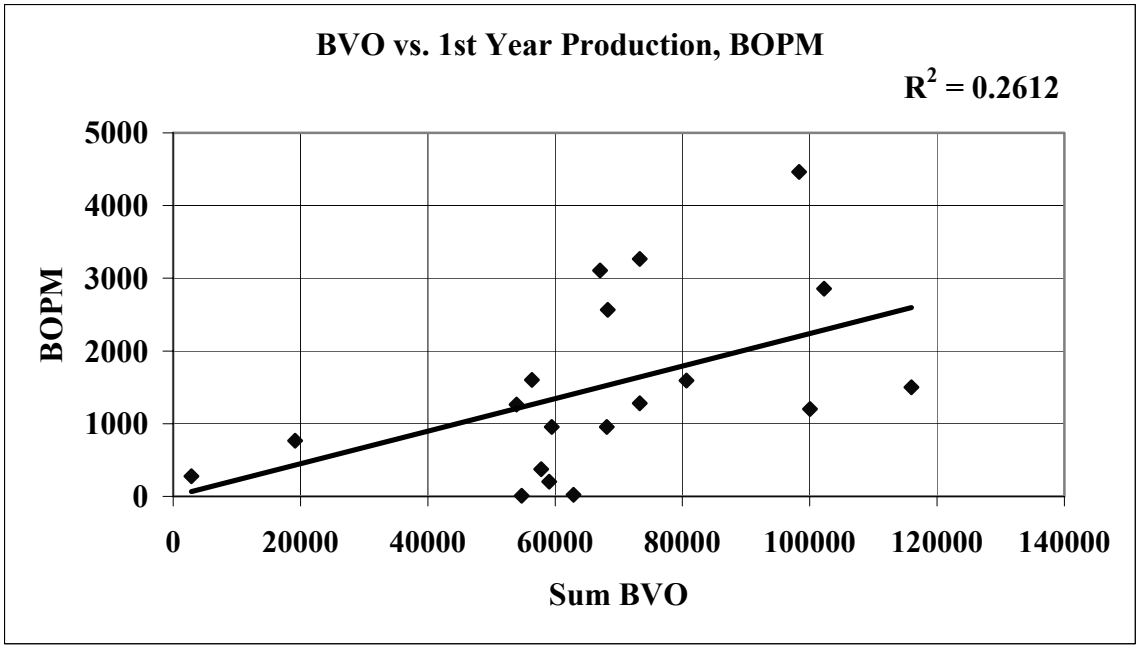

Fig. 7.21: General correlation between Sum BVO and initial production.

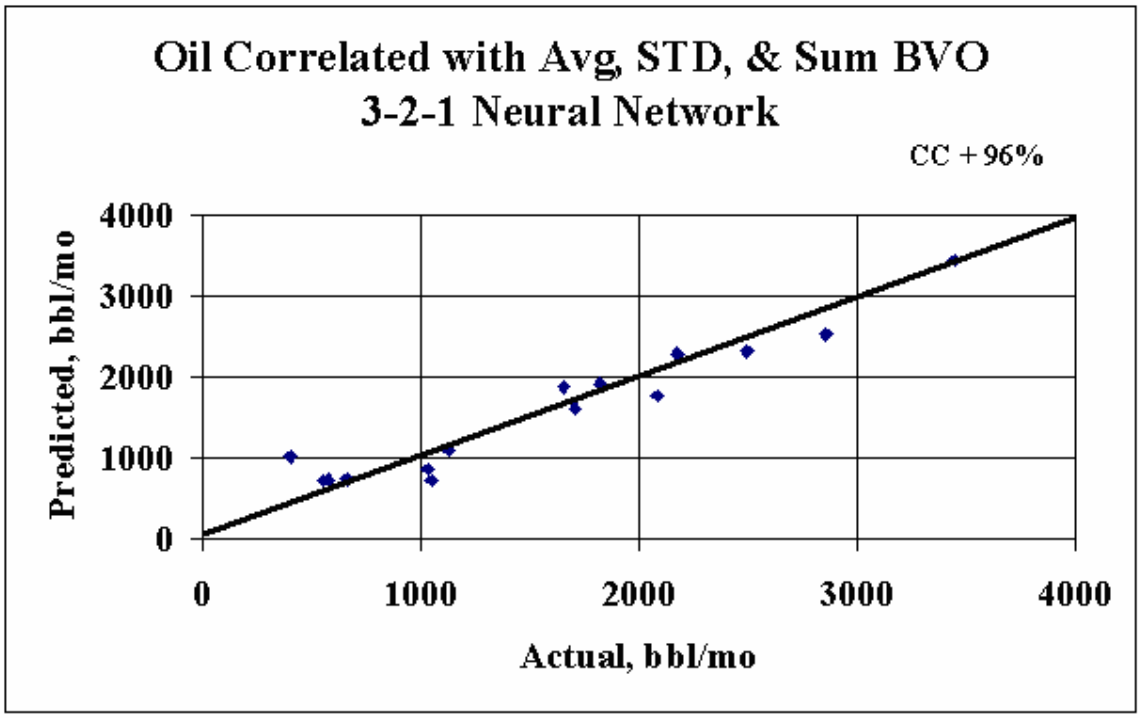

Fig. 7.22: Neural network correlation using BVO log statistics as input.

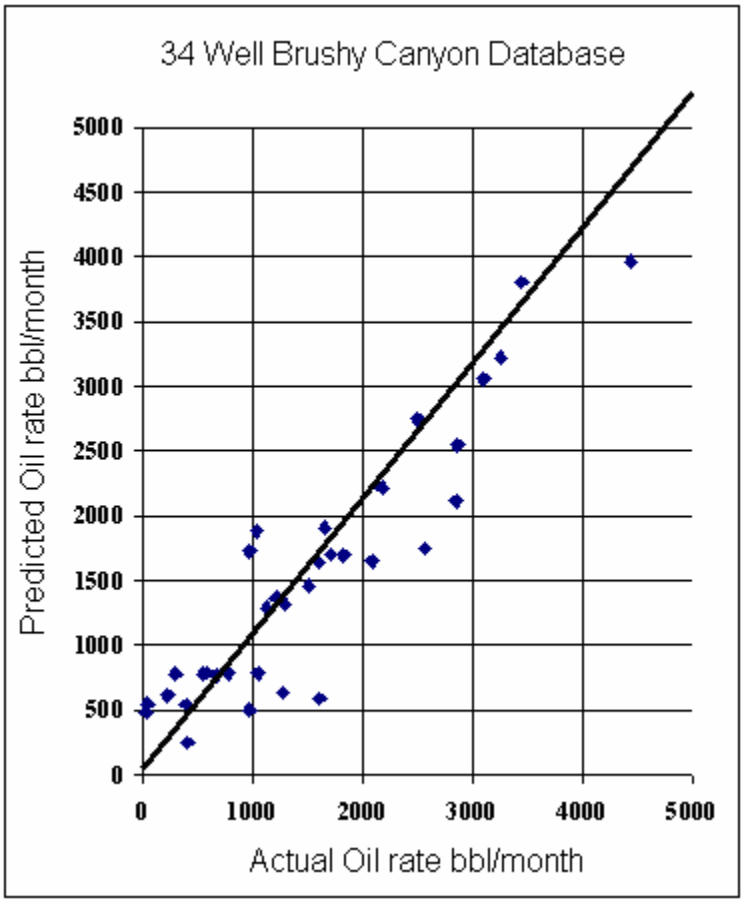

Fig. 7.23: Correlation based on BVO log statistics and initial production.

7.4.3 Web Based Data Management System (WDMS)

A key component to the success of this project is the development of a dynamic, Web-accessible database for storing, managing, accessing, and analyzing data, including the data developed for the FEE Tools. The WDMS also includes a tool to allow users to view digitized well logs. As part of this project, approximately 200 well logs from the New Mexico part of the Permian Basin were digitized. As the data files can be quite large, the system must be efficient and useable by persons with varying degrees of computer literacy.

The WDMS consists of three parts:

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

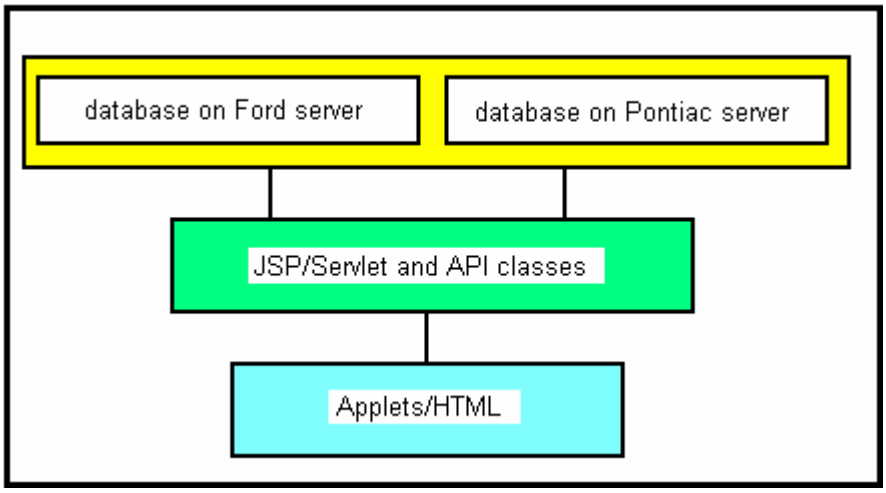

Fig. 7.24: Structure of WDMS tool.

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

The WDMS Interface consists of three tiers:

- A Presentation Layer was written in HTML (or generated by JSP files) and Java Script that implements the interactive interface and presents home pages in any Java capable browser on the user side. The interface accepts user requests generated by clicking on the menu items and buttons of those homepages, and sends them to the Business Logic Layer.

- The Business Logic Layer was written in JSP, Java Bean and JDBC and it translates requests from users to SQL statements. These requests are forwarded to the Data Layer, and answered queries are returned.
- The Data Layer, which is a Microsoft® SQL Server in WDMS, manages the data associated with the FEE Tool project by executing SQL statement received from the Business Logic Layer. SQL communicates with JDBC through Microsoft® ODBC. SQL processes the SQL statements and sends the results back to Business Logic Layer through the ODBC driver to the JDBC driver.

Architecture of WDMS

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

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

Aside from the user interface, the other important feature of WDMS is the API interface. The Applications Programming Interface (API) is a series of JAVA programs which

allows the FEE Tool system to directly interface with the databases, and to both examine and mine the data, including the generation of heuristic rules for the expert system to apply regionally. The API also allows the user to indirectly control the responses of the expert system via interpreted user commands (entered via browser menu selection). In the overall system architecture the user interface and the API (presentation layer) are parallel with the business logic layer interpreting between the two, and the databases (data layer).

The features of WDMS include the following:

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

More information about WDMS, including a user's guide, is found in the appendices.

Conclusions

The objective of this project was to develop an artificial intelligence system for the oil and gas industry that would draw upon a wide variety of information to provide realistic estimates of risk in the manner of a human "expert." "Fuzzy logic," a system of integrating large amounts of inexact, incomplete information with modern computational methods to derive usable conclusions, had already been demonstrated as a cost-effective computational technology in many industrial applications.

In the oil and gas industry, 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. Like the "expert" systems used in other disciplines and industries that have demonstrated beneficial results, researchers envisioned a state-of-the-art exploration "expert" tool, relying on a computerized database and computer maps generated by neural networks, to be developed through the use of "fuzzy" logic, a relatively new mathematical treatment of imprecise or non-explicit parameters and values. Project results now demonstrate that oil prospecting risk can be reduced with the use of a properly developed and validated "Fuzzy Expert Exploration (FEE) Tool."

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.

During the life of the FEE Tool Project, an immense amount of data on the Delaware Basin and Devonian Carbonates were accumulated: geology, structure, production, regional information such as gravity, and local data, such as well logs. These data, organized and cataloged into several online databases, are now available for the project's expert systems and users as needed and as appropriate in analyzing production potential. Maps of production potential for the Lower Brushy Canyon formation of the Delaware Basin and the Devonian Carbonates of southeast New Mexico have been generated and can be modified by users by altering rules previously defined by human exploration experts in the target formations, and statistical rules defined by the database, using an interactive on-line expert system. A number of new and useful tools and technologies to support these efforts have been generated including: online useable interfaces for neural network analysis (PredictOnline); ranking of potential inputs using

fuzzy logic (FuzzyRank); expert systems able to make prospect evaluations for the Lower Brushy Canyon and the Devonian Carbonates (FEE Tools); and a web interface for accessing the databases and expert system software (WDMS). The two expert systems created through this project, the Delaware FEE Tool and the Devonian FEE Tool, are both available online and have now been used by producers to evaluate prospects. Additionally, stand-alone versions were produced for both tools, and user-requested enhancements such as modifying the output formats, a batch mode, and providing downloadable data files were made during a no-cost extension of the project.

Throughout the project, additional work was performed applying neural networks, fuzzy ranking algorithms and the fuzzy expert systems to diverse projects. These include using neural networks to correlate well logs and predict oil prices, and using the Delaware FEE Tool as a reserves estimating tool.

The following is a year-by-year summary of the project's accomplishments:

Year 1

- Ninety percent of geologic, geophysical, production and price data were assimilated for installation into the database.
- Visual correlations between derivatives of regional geophysical data with field locations were determined, strongly suggesting that neural network architectures could be found to correlate regional attributes with individual well production.
- On a local scale, given open-hole log information, a neural network was trained to predict the product of porosity and oil saturation as reported in whole core analysis. This showed that a direct indicator of oil show could be available from log information, an important in the thin-bedded Delaware sand reservoirs.
- Fuzzy ranking was used to prioritize 3D seismic attributes that were then correlated to formation depth with a neural network. The results were superior to those obtained using linear interpolation or low order polynomial interpolation as time-to-depth conversion tools.
- A radial basis function neural network was developed and used as a log evaluation tool. An interactive web based MLP, PredictOnline, was coded in Java and made available to consortium members for beta testing.

- A draft design of the Fuzzy Expert Exploration (FEE) Tool system based on readily available software was completed and a Java Expert System Shell, JESS, was developed to facilitate expert rule development.

Year 2

- Data acquisition of the Brushy Canyon Formation was completed and installed in several online databases, ready for access by external programs such as Web applications.
- Bulk volume oil (BVO) was successfully predicted using neural networks with wireline logs as inputs.
- Regional attributes were gridded to a 40-ac bin (gridblock) size, and fuzzy ranking procedures were applied to determine which attributes are best able to predict production trends in the Delaware Basin.
- A study to determine the ability of an artificial intelligence system to predict depth using seismic attributes in a Delaware field was completed and the results were published.
- Programming the expert system was undertaken, and a decision tree program was coded in Java Expert System Shell (JESS) that allows development and tabulation of rules and relationships between rules that can be used by the expert system.
- The design of the expert system itself was clarified and an expanded system was created where several distinct factors such as geologic/geophysical data, trap assessment, and formation assessment could be operated on in parallel to increase efficiency of the overall system.
- Coding of the Java interface, which users can use to access data in the online databases and run the expert system, was completed. Development of the interface tied together the data and the expert system programs coded in JESS while allowing user customization and informative reports of results to be retrieved.

Year 3

- A preliminary map of production potential for the Delaware Basin was generated.

- Online useable interfaces for neural network analysis (PredictOnline) were created.
- Ranking of potential inputs using fuzzy logic (FuzzyOnline) was completed.
- A preliminary Expert System able to make rudimentary drilling decisions was developed.
- A web interface for accessing the databases and Expert System software was developed.

Year 4

- A map of production potential for the Delaware Basin was generated that can be modified by rules defined both by human experts in exploring the Delaware Basin, and by statistical rules defined by the database, using an interactive on-line Expert System.
- On-schedule delivery of the Brushy Canyon FEE Tool was accomplished, with the release of the web version of the software to public testing.
- The Devonian FEE Tool was implemented and the software alpha-tested prior to its release first to consortium members, then to the public.
- Work progressed on geologic data acquisition and analysis of the Siluro-Devonian carbonates: acquiring and mapping structural and stratigraphic data related to Siluro- Devonian reservoirs, traps and source rocks. A database of 465 wells that have penetrated the Siluro-Devonian carbonate section was constructed and an extensive production database was compiled on reservoirs productive from Siluro-Devonian carbonate reservoirs.

Year 5

- The Delaware FEE Tool was released to users via the REACT homepage, and generated interest among producers and explorationists. The website has received over 5500 hits at the time of this report.

- The Devonian FEE Tool was completed, and found able to recognize good potential drill locations and identifying areas to focus seismic surveys. Emphasis during this period was directed toward the final development of the Devonian Fuzzy Expert Exploration (FEE) Tool.
- A new "User's Guide" was prepared for all the REACT software developed through the course of this project (included as an appendix to this report).

Year 6 (No-cost extension)

- Consortium members, who had beta tested the software for both FEE Tools made a number of recommendations to improve the ease of use and utility of the software. These recommendations were addressed during the no-cost extension.
- Software was designed to allow users to check the FEE Tools response to large areas simultaneously. This batch mode software also allows the import and export of expert system responses via text files or spreadsheet files.
- Stand-alone versions of the Brushy Canyon FEE and Devonian FEE Tools were created and tested. The software allows users to run the software on their own computer and replaces the online databases with text files. Though slower to operate, and requiring more robust user hardware than the on-line versions, these stand-alones provide additional security and the ability to more fully customize the systems by users.
- A training session for the Devonian Tool was held in December 2004.

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Appendices

Appendix A: Knowledge Base for the Delaware FEE Tool

Trap Assessment

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

Available Data in Answerbase: Producing well data available to 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 less than 0.05 and oil show exists and if:

- 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 available in Answerbase Dip is measured in degrees

- If dip angle > 2.968 strongly enhance (flag =2)
- If 1.668 < dip angle ≤2.968 enhance (flag = 1)
- If -.932 < dip angle ≤ 1.668 no change (flag = 0)
- If -2.232< dip angle ≤-.932 reduce (flag = -1)
- If dip angle ≤ -2.232 strongly reduce (flag = -2)

Data: Calculated from distance computed above and subsea elevation in geological database

Step3: Thickness of the Brushy Canyon sand at prospect, data in Answerbase

Central basin (Depth of prospect ≤ -2000 ft subsea) 10% porosity thickness

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

Basin margins (Depth of Prospect > -2000 ft subsea) 15% porosity thickness

- 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 ≤ 20 prospect not changed (Flag = 0)

Step 4: Sand pinchout in the vicinity of prospect, data in 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 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, and we will calculate a value for sand thickness trends.

Central basin (Depth of prospect ≤ -2000 ft subsea) use 10% 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 subsea) 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: What is the TOC% at the location? Data in Answerbase:

- If TOC%> 1.0, starting estimate x = 0.7
- If 1.0 ≥ TOC% > 0.5, x = 0.5
- If TOC% ≤ 0.5, x = 0.2

Step 2: Thermal maturity of the source rock

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?

Up-dip sand pinch-out or thin-out

- 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)

No up-dip sand pinch-out or thin-out

- 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

Initial estimate is based on production potential estimate from Neural Network map, which has a prediction for each potential site in the basin.

Step 1: Crisp Option

- 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 1: Fuzzy option (leaning toward this) uses fuzzy memberships to define value of prospect

- PBOPM < 500, z = none
- 500 < PBOPM < 1500, z = Low
- 1500 < PBOPM < 2500, z = Medium
- 2500 < PBOPM < 4000, z = High
- PBOPM > 4000, z = 0.9 = Very High

Step 2: distance to higher predicted production than is at the prospect.

- 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

Small area

- If std of PBOPM (p) < 121.5 then enhance estimate (flag = 1)
- If 121.5 ≤ p < 1375 then estimate not changed (flag = 0)
- If p ≥ 1375 then estimate reduced (flag = -0.5)

Large area

- If std of PBOPM (p) < 389.6 then enhance estimate (flag = 2)
- If 389.6 ≤ p < 1854 then estimate not changed (flag = 0)
- If p ≥ 1854 then estimate reduced (flag = -1)

Step 4: Gross Thickness – Net lower Brushy Canyon Interval

Central basin (Depth of prospect ≤ -2000 ft subsea)

- 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 subsea)

- 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?

- 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?

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

Step 7: Regional adjustments.

- If prospect is located in the central basin (depth ≤ -2000 ft subsea) then enhance prospect slightly (Flag = 1)
- If prospect is located in the western margin (depth > -2000 ft subsea) then prospect is slightly degraded. (Flag = -1)

Appendix B: Knowledge Base for the Devonian FEE Tool

Structure

Step 1: Does the location show evidence of a paleo-structure? Data in Answerbase,

- If adjusted paleo output = 4, then x = 0.8
- If adjusted paleo output = 3, then x = 0.7
- If adjusted paleo output = 2, then x = 0.5
- If adjusted paleo output = 1, then x = 0.3
- If adjusted paleo output = 0, then x = 0.1

Step 2: Does the Regional map show structure (based on relief) in the area of the prospect?

Available data in Answerbase: Need an algorithm to determine relief computationally; will be based on Abo, Mississippian, or Woodford depending on location.

- If no significant structural relief, (structural relief < 2 ft) structural starting estimate: no change (Flag = 0)
- If structural relief < 50 ft, slightly enhance (Flag = 0.5)
- If 50 ft ≤ structural relief < 100 ft, slightly enhance (Flag = 1)
- If 100 ft ≤ structural relief < 200 ft enhance (Flag = 1.5)
- If structural relief > 200 ft, enhance (Flag = 2)

Step3: Is the structure fault bounded?

- If fault doesn't penetrate San Andres, enhance (Flag =1)
- If fault penetrates San Andres, degrade (Flag =-1)
- Unable to determine, unchanged (Flag=0)

Note- step 3 and 5 were removed, step 6 becomes step 5, Step 4 becomes step 3.
Step 5: Is the structure verified by Seismic data?

- If yes, then enhance strongly (Flag =2)

Trap

Step 1: Seal, or cap.

- If there is no Woodford then y = 0.05
- If Woodford < 80ft thick then y= 0.2
- If 140 ft ≥ Woodford ≥ 80 ft, then y=0.4
- If 200 ft ≥ Woodford ≥ 140 ft, then y=0.60
- If Woodford ≥ 200 ft, then y=0.70

Step 2: How much closure is estimated on the structure? (Closure is measured in feet, per Selley's definition)

- If closure < 50 ft, do not change (Flag=0)
- If 50 ft ≤ closure < 250 ft, enhance (Flag =0.5)
- If 250 ft ≤ closure < 500 ft, enhance (Flag =1)
- If closure ≥ 500 ft, enhance (Flag =2)

Step 3: Is there potential for fracture-induced porosity? Answerbase supplies value based on flexure calculation?

- If Flexure is strongly indicated, enhance (Flag=1)
- If Flexure is moderately indicated, enhance (Flag=0)
- If Flexure is not indicated, no effect (Flag=0)

Step 4: Potential for other porosity? User provided.

- If yes, then enhance (Flag = 1)
- If No, degrade, (Flag =-1)
- Unable to determine (default Flag =0)

Step 5: Does seismic show stratigraphic porosity?

- If indications are strong, enhance (Flag=1)
- If Indications are weak (or if this step is skipped) no change (Flag=0)
- If no indication, degrade (Flag=-1)

Formation

Step 1: Woodford TOC. What is the estimated TOC at the prospect location?

- If no Woodford exists then y=0.05
- If Woodford TOC < 2.0 then y = 0.2
- If Woodford TOC {2,3} then y = 0.4
- If Woodford TOC {3,4} then y=0.6
- If Woodford TOC > 4 then y=0.75

Step 2: Woodford Thickness

- If there is no Woodford then degrade strongly (Flag = -2)
- If Woodford < 50ft thick then degrade (Flag = -1)
- If 200 ft ≥ Woodford ≥ 50 ft, then do not change (Flag = 0)
- If 300 ft ≥ Woodford ≥ 200 ft, then enhance (Flag =1)
- If Woodford ≥ 300 ft, then enhance strongly (Flag =2)

Step 3: What is the generative potential of the Woodford Shale at the prospect. Measured using PI*TOC*Ft pay

- If GP is zero (No Woodford), then prospect is degraded (Flag = -1)
- If GP < 200 then prospect is enhanced (Flag = 1)
- If GP is in {200,300}, then prospect is enhanced (Flag = 2)

Regional

Step 1: Regional predictive map value for production. Will try to come up with a predicted production estimate based on mapped data. Alternately the user can provide analog well data. Number ranges will have to come from producing wells perhaps. Maybe use a DST vs. production regional map?

In oil province:

- If PBOEPM < 825, z = 0.1
- If 825 ≤ PBOEM < 1700, z = 0.3
- If 1700 ≤ PBOEM < 4000, z = 0.5
- If 4000 ≤ PBOEM < 11000, z = 0.7
- If PBOEM ≥ 11000, z = 0.9

In gas province (if user provided in MCF): Note that if the user wishes to input values in MCF, the relationship used here is 6 MCF = 1 BOE, so the cutoff values need to be multiplied by 6 if the user wishes to use this option.

- If PMCFPM < 4950, z = 0.1
- If 4950 ≤ PMCFPM <10200, z = 0.3
- If 10200 ≤ PMCFPM < 24000, z = 0.5
- If 24000 ≤ PMCFPM <66000, z = 0.7
- If PMCFPM > 660000, z = 0.9

Step 2: Proximity of nearby producers on same structure. Structure size ranges determined in part by statistics.

Small structure:

- If there are no wells on the structure, prospect is degraded slightly (Flag =-0.5)
- If there is one well on the structure, prospect is unaffected (Flag =0)
- If there are two or more wells on the structure, prospect is degraded (flag =-1)

Medium Structure:

- If there are no wells on the structure, prospect is degraded slightly (Flag =-0.5)
- If there is one well on the structure, prospect is enhanced (Flag =0.5)
- If there are two wells on the structure, prospect is enhanced (flag = 1.0)
- If there are three or more wells on the structure, prospect is degraded (flag =-0.5)

Large Structure:

- If there is no wells on the structure, prospect is degraded slightly (Flag =-0.5)
- If there is one well on the structure, prospect is enhanced (Flag =0.5)
- If there are two or more wells on the structure, prospect is enhanced (flag =1.0)
- If there are 3-4 wells on the structure prospect is enhanced (Flag=1.5)
- If there are 5 or more wells prospect is enhanced (Flag=2).

Step 3: Location on structure compared to other wells

Small structures:

- If the prospect is higher on structure than any existing wells, enhance (Flag=1)
- If the prospect is similarly located structurally, degrade slightly (Flag = 0)
- If the prospect is lower than existing production, degrade heavily (Flag =-1)

Medium Structures:

- If the prospect is higher on structure than any existing wells, enhance (Flag=1.0)
- If the prospect is similarly located structurally, degrade slightly (Flag =-0.5)
- If the prospect is lower than existing production, degrade (Flag =-2)

Large Structures:

- If the prospect is higher on structure than any existing wells, enhance (Flag=0.5)
- If the prospect is similarly located structurally, no change (Flag =0)
- If the prospect is lower than existing production, degrade slightly (Flag =1.0)

<u>Step 4:</u> Is the structure supported by gravity data. Verified by comparison.

- If yes, Enhance (flag=1)
- If indeterminate, no change (Flag =0)
- If no, degrade (Flag =-1)

Step 5: Is the structure part of a regionally productive trend? Use some sort of trend analysis, allow maps to be checked.

- If yes, Enhance (flag=1)
- If indeterminate, no change (Flag =0)
- If no, degrade (Flag =-1)

Appendix C: User's Guide for REACT Software

Acknowledgements

The New Mexico Petroleum Recovery Research Center (PRRC) and the Reservoir Evaluation and Advanced Computation Technologies (REACT) group of the PRRC acknowledges the support of this project through the Department of Energy's National Petroleum Technology Office under DOE contract DE-AC26-99BC15218 "Risk Reduction with a Fuzzy Expert Exploration Tool", Jim Barnes DOE Project Manager.

Special thanks go to Ron Broadhead and the New Mexico Bureau of Geology and Mineral Resources for their insights and access to data. We would also like to thank the explorationists who contributed their experience with the Delaware Basin and Devonian Carbonates in the development of the expert system. Finally, we also thank the many graduate students in computer science and petroleum engineering who have worked on creating the FEE Tools.

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CHAPTER 1: Introduction to the Fuzzy Expert Exploration Tool Systems

1.1 Overview

The Fuzzy Expert Exploration Tools (FEE Tools) are expert systems designed to help minimize exploration risk when prospecting for oil. The first FEE Tool was developed for use in the Lower Brushy Canyon formation of the Delaware Basin, and the second FEE Tool was developed for the Devonian Carbonates of Southeast New Mexico. The FEE Tools are interactive, and allow users to provide their own information securely or use information that has been developed and stored in the Tools' answer bases. Users can also determine which factors to use in their customized analyses.

1.1.1 Components of the FEE Tool

The components of the FEE Tools 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.

1.1.2 Results

For each location the user provides to one of the FEE Tools, the result of the analysis is given as excellent, very good, average, below average, poor, or very poor. 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" from the Delaware tool is shown below.
In addition to the pie charts, histograms are available comparing the numerical final estimate at the location of interest to the final estimates for the entire system or the set of all available producing wells.

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.

1.2 System Requirements

The FEE Tools are 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/index.jsp`

1.3 Security

To access the FEE Tools and begin using them, 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.

1.4 Getting Started–Creating a Project

The first steps involved in creating and locating a prospect are the same for the Delaware and Devonian FEE Tools. Subsequent chapters will deal with the specific input and output screens for the Delaware and the Devonian Tools.

To start using the FEE Tools, begin at the gateway page, found at ford.nmt.edu.
The FEE Tools can be accessed by clicking on either "Delaware Basin Fee Tool" or the "Devonian 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 of your choice, 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 below:

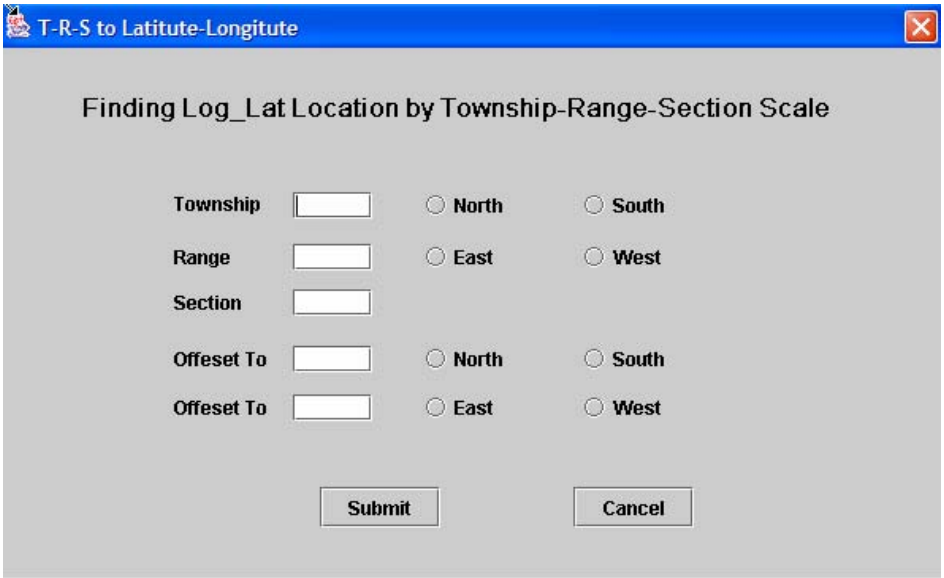
Begin by creating a new project using the **Project** pull-down menu and selecting **New**. From this menu you may also open an existing project, close or delete a project or exit the program.

1.5 Location of Prospects

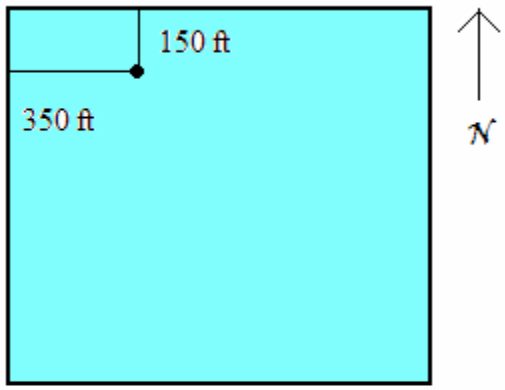
Once your new project is created, the next step is to input the location data for the prospect you are interested in. The form to input the location is located in the pull-down menu: **Input data**.

Location information is entered using (decimal) latitude and longitude values. A tool to convert township, section and range inputs into latitude and longitude is also provided. The Delaware FEE Tool also allows input in units of UTM feet.

The **T-R-S to Lat-Long** converter requires **Township, Range, Section** and **Offset**.



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



Section offsets
150 ft north
350 ft west

1.6 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 go to the **Input Data** menu instead and select **Location**, you can use the **Submit** button to resubmit your location data. This has the effect of restoring all trap, regional and formation data to the original database values, as well as allowing any updates to the system to be applied.

1.7 Help Files

The quick start instructions are available to you on the FEE Tool front pages. 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.

CHAPTER 2: Delaware Basin Trap Assessment

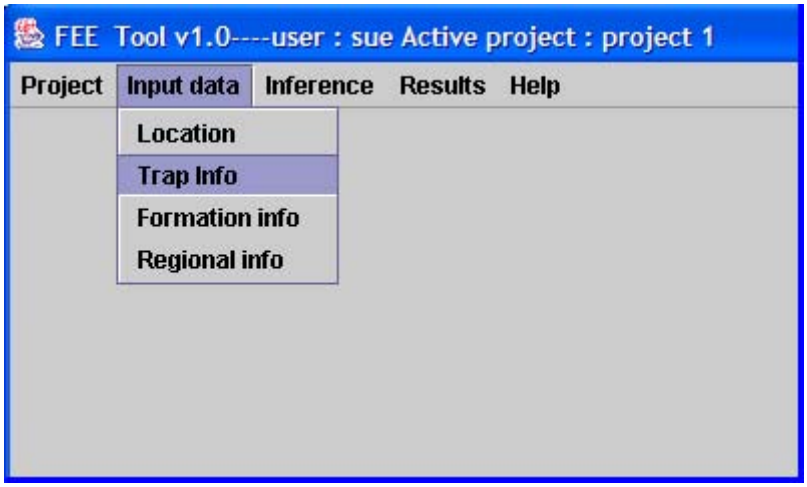
The next few chapters will discuss the specific input and output interfaces for the Delaware Basin FEE Tool. Chapters 2, 3, and 4 will cover the data input for the three assessments the Delaware FEE Tool uses in its analysis, chapter 5 will cover the output, and chapter 6 provides a complete example.

2.1 Overview

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. Some rules, such as rules relating to recent oil shows, require user input.



2.2 Reviewing and Entering Data

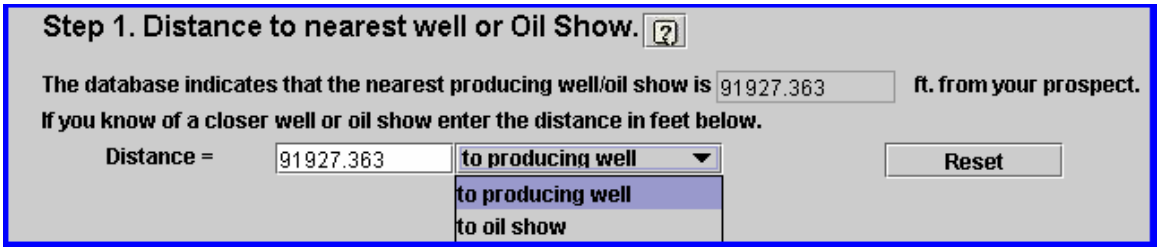
For most of the steps in the trap, formation and regional assessments, you will have the opportunity to review the values provided by the answer base and enter your own values. For each step, there is a **Help** button, which provides information on the format to use if you input your own values. At the bottom of each screen is a reset button, which resets all of the values on the screen to the previous values. This may be the answerbase value,

or it may be a value you entered previously. If you wish to restore all the original answerbase values after a number of modifications, return to the screen where you entered the location, and re-submit the location.

2.2.1 Distance to the Nearest Well or Oil Show

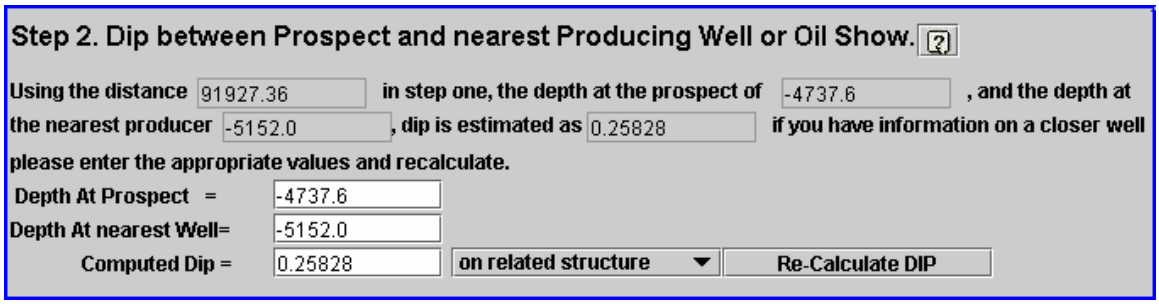
The initial trap estimate is based on the distance to the nearest producing well or oil show. The answer base contains this distance computed using wells completed before March 2000. The wells used are successful wells that have some or all production from the lower Brushy Canyon formation. If you have 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.

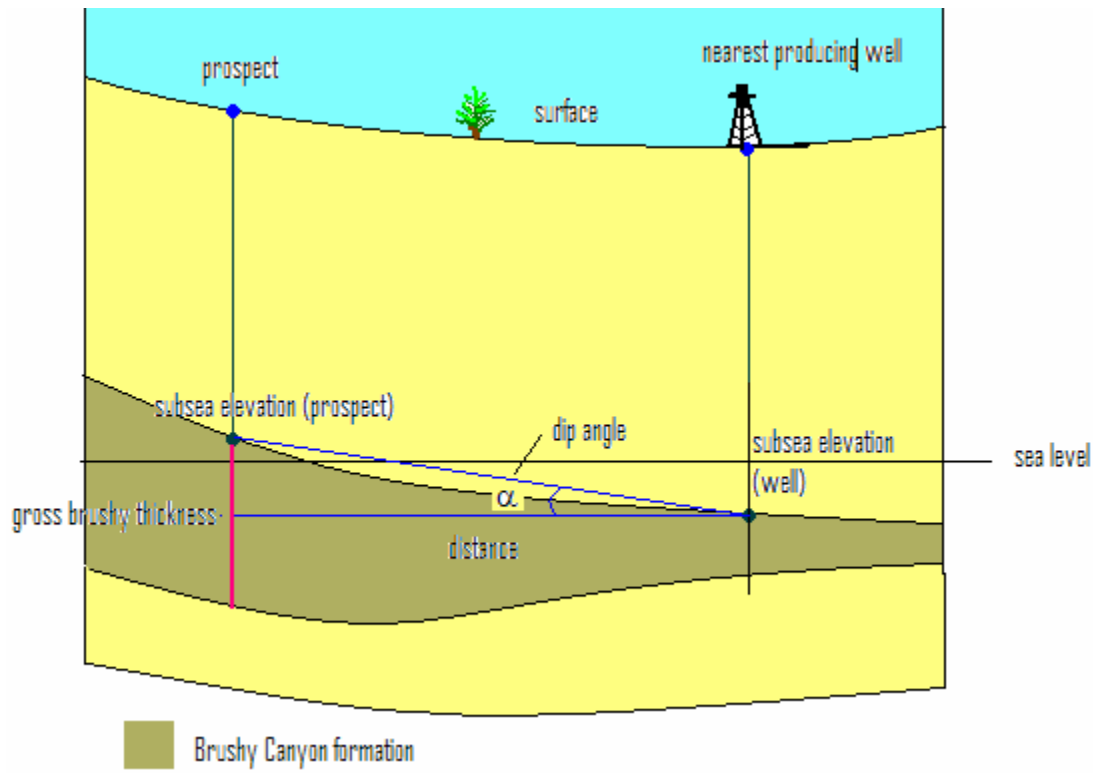
The next box is for user input. **Oil Show** is selected using the pull-down menu and the **Reset** button resets the distance to the previous value.



2.2.2 Dip between Prospect and Nearest Producing Well or Oil Show

The cutaway picture of the Delaware Basin 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.





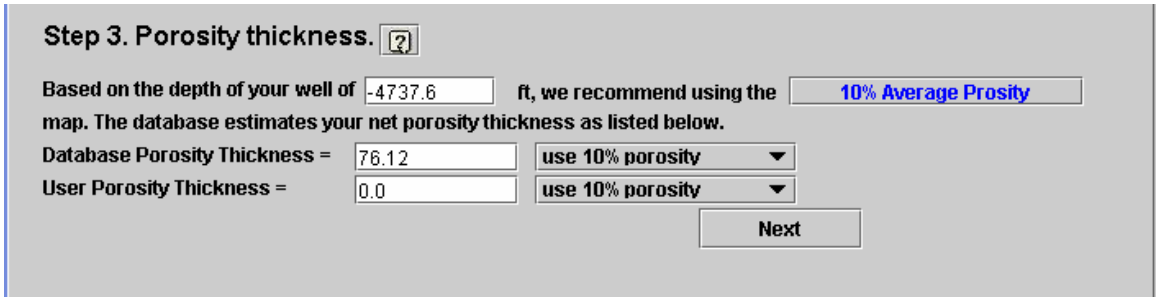
If a new distance was provided in **Step 1**, a new dip angle must be computed here. In order for the program to recalculate the dip value, you will need the depth (relative to sea level) to the top of the formation at the well the new distance is based on. To make this conversion, if necessary, subtract 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:

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

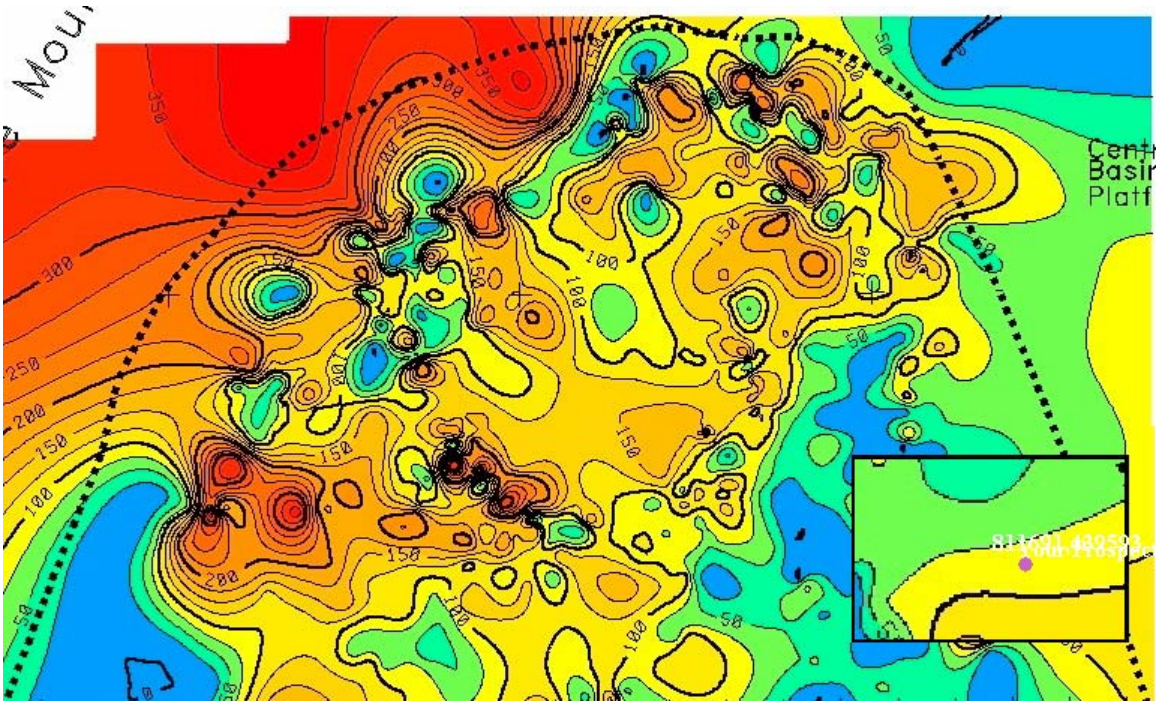
d_w= user supplied distance to nearest producing well or oil show (as provided in the new distance box in **Step 1**)

2.2.3 Porosity Thickness

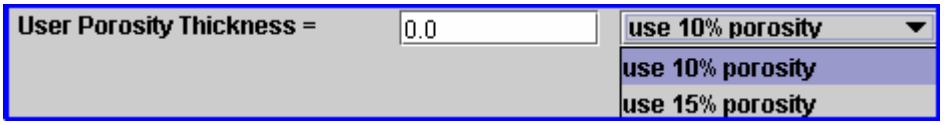
Step 3 involves the thickness (in feet) of the porous sand in the formation at your prospect. There are two possible database provided values for this thickness, based on a 10% porosity thickness or a 15% porosity thickness. The FEE Tool selects a value for thickness based on the location of your prospect 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** button. 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.



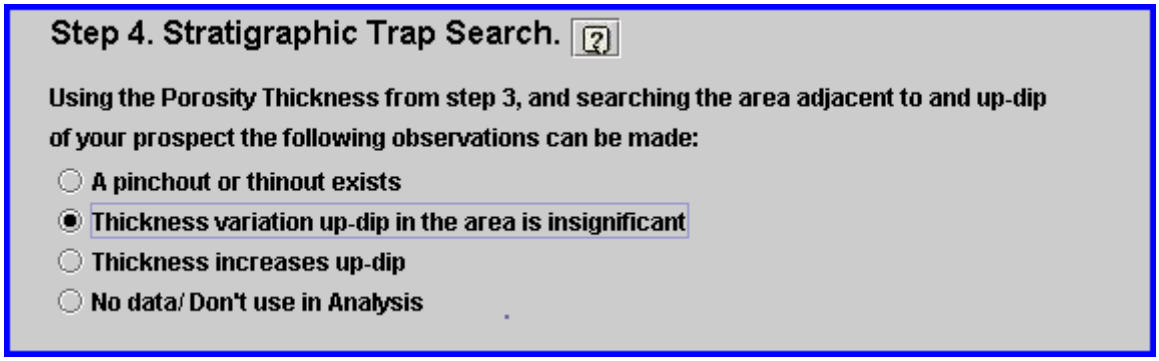
To enter your own value for the thickness of the porous sands, use the scroll menu to select the appropriate porosity map to use. You might base this on the location of your prospect in the basin, or on the nearest value to a company's cut-off porosity.



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.

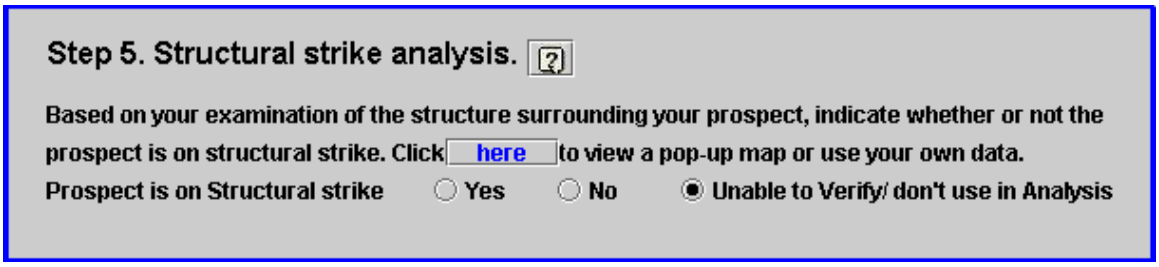
2.2.4 Stratigraphic Trap Search

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**. 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.

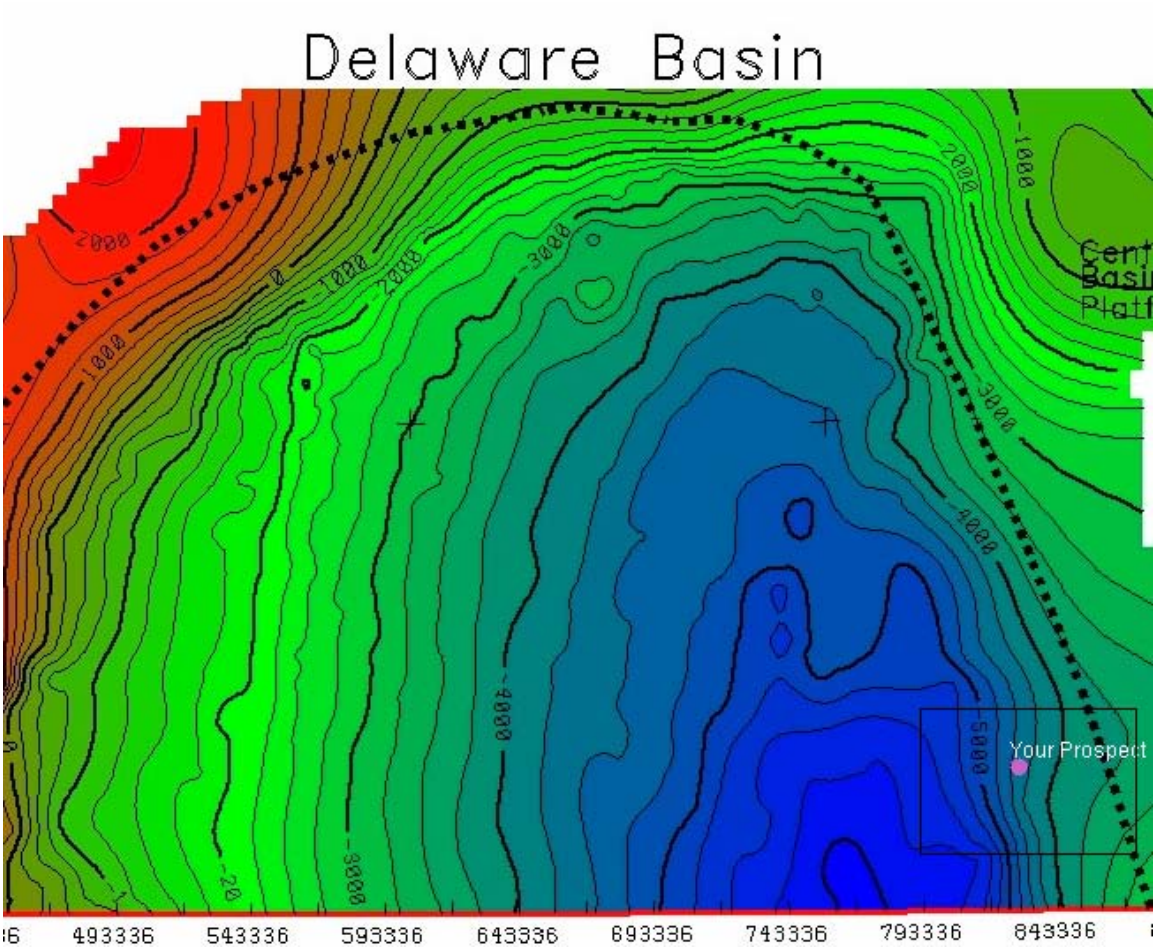


2.2.5 Structural Strike Analysis

Step 5 allows you to examine a map of the structure by clicking on the link. A section of the structure map is shown below. The structure map functions in the same way as the porosity thickness map described in **Step 3** (left mouse button zooms in, right mouse button zooms out).



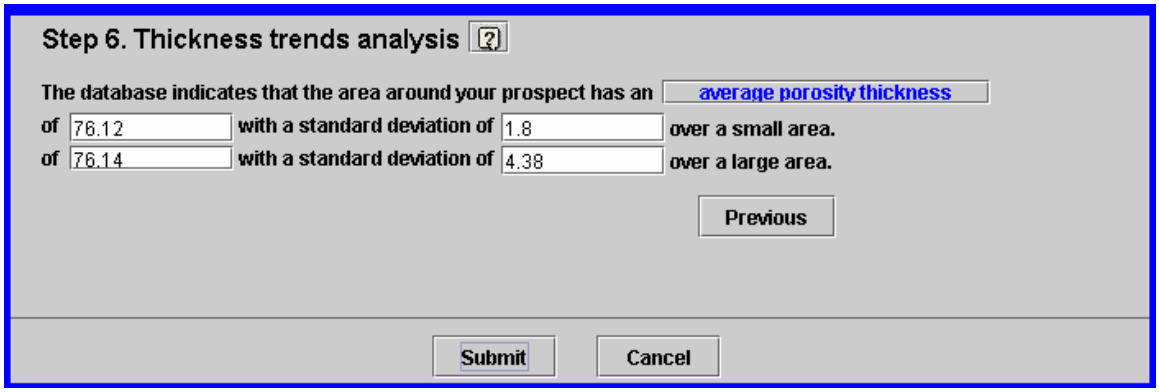
After examining that map (or your own structure map of the region) if you determine that the prospect is on structural strike, then select the **Yes** button. You may also choose to omit this section by leaving the default selection (**Unable to Verify/Don't Use in Analysis**).



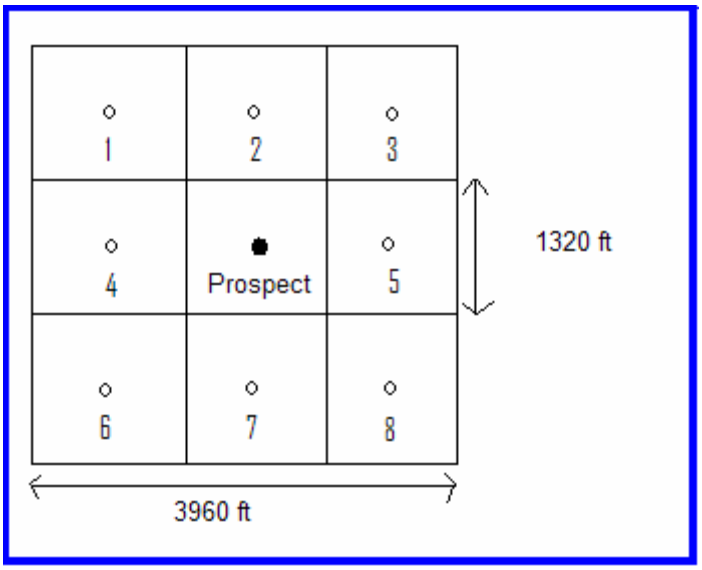
2.2.6 Thickness Trends Analysis

The final step to input the data for the trap assessment is **Step 6**, the **Thickness trends 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, 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), created by stepping out one step (1320 ft) in each direction, is shown below. 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.

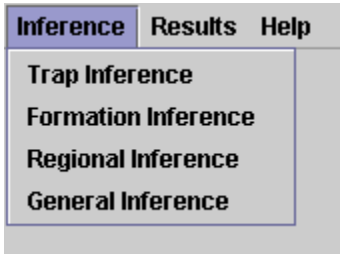


Once this data has been reviewed, the input for the trap assessment is complete. At this point, you may use the previous button to review the inputs for steps 1 through 3, or use the **submit** button to exit this form. You may then continue with the Formation Assessment, discussed in chapter 3, or look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

2.3 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 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.

CHAPTER 3: Delaware Basin: Formation Assessment

3.1 Overview

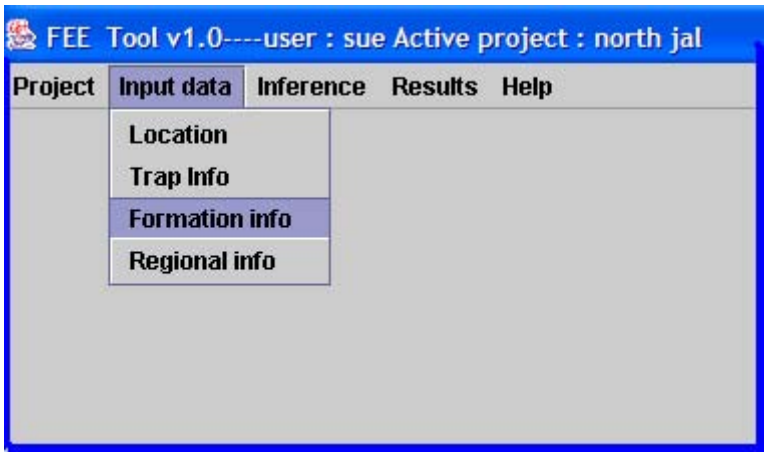
The formation assessment is where the potential location is evaluated based on factors relating to the origin and migration of petroleum. The criterion used in this assessment includes:

- 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.

3.2 Reviewing and Entering Data

Begin reviewing and entering data for the formation assessment by returning to the **Input data** option and selecting **Formation info**.



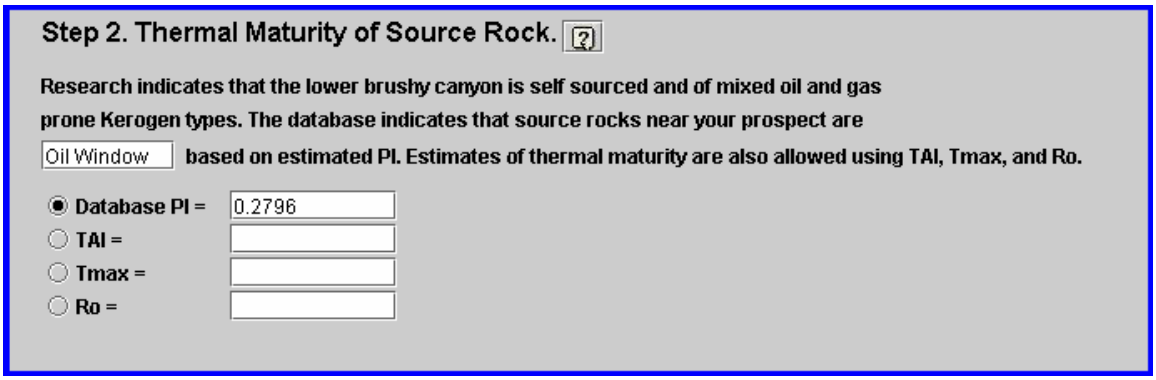
As with the trap assessment, you will have the opportunity to review the data available in the answer base for your prospect and add to or change the data. The **reset** button is available at the bottom of the screen to reset the data back to the previous values.

3.2.1 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**. As in previous steps, you may modify this value by simply replacing it with a new value.

3.2.2 Thermal Maturity of Source Rock

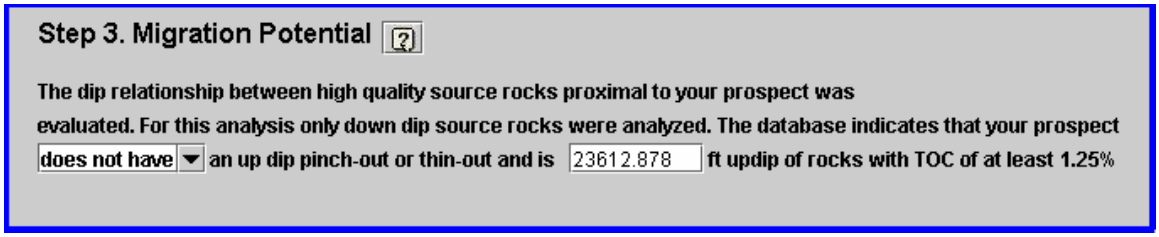
In this step, the value of PI (production index) is shown. You may use this value of PI, or replace it with your own. Instead of PI, you may also select a different measure of thermal maturity (T_{max}, R_o or TAI). Use the radio button to select which measure you wish to use, and enter the appropriate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



3.2.3 Migration Potential

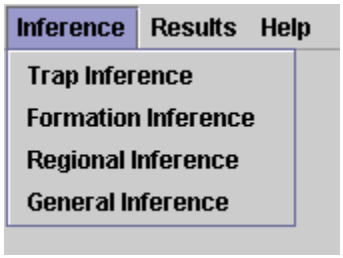
In **Step 3, Migration Potential,** the FEE tool searches the region to find the nearest down-dip source rock. For this analysis, a down-dip source rock location is defined as a location with a subsea elevation lower than the prospect's subsea elevation and a TOC value of at least 1.25%.

If the TOC value shown in the first step is already greater than 1.25% (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 4** of the Trap Assessment (**Stratigraphic Trap Search**) is reported here.

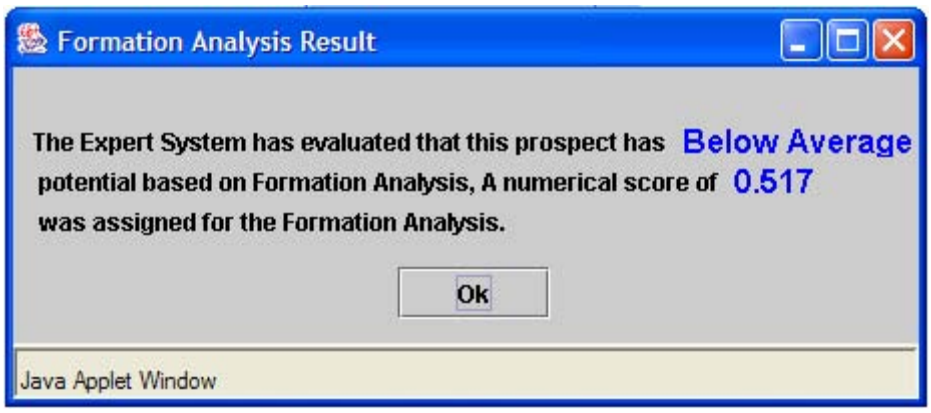


3.3 Output from the Formation Assessment

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**.



Here is 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, discussed in chapter 4.

CHAPTER 4: Delaware Basin: Regional Assessment

4.1 Overview

The regional assessment focuses on the predicted production at your location. Production is predicted for each location using an artificial neural network (discussed in Appendix C- Predict Online). 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

4.2 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 previous formation data.

4.2.1 Initial Production

Step 1 of the regional assessment involves the initial production as predicted by the neural network. This value is shown in the box below. 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. Units are in barrels of oil per month (BOPM) averaged over the first twelve months.

Step 1. Initial Production

A regional analysis using computational intelligence to predict production potential estimates that your prospect should produce 5.9 BOPM average for the first twelve months. If you have another way of estimating production potential (analog well, etc) Please enter your own value.

4.2.2 Proximity of Better Production

Step 2 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.

Step 2. Proximity of better production

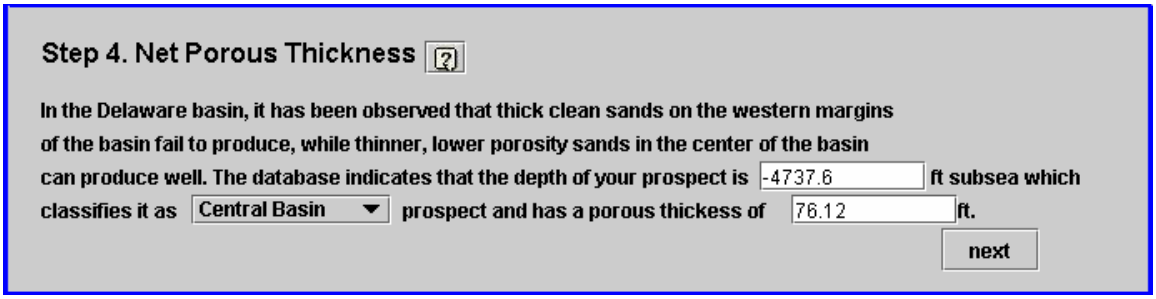
The proximity and quality of nearby production has an affect on the success of a new prospect. The database indicates that your prospect is within 23612.878 ft of predicted production of 500.0 BOPM.

4.2.3 Uniformity of Predicted Production

Step 3 is similar to the thickness trends analysis in the trap assessment. 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.

4.2.4 Net Porous Thickness

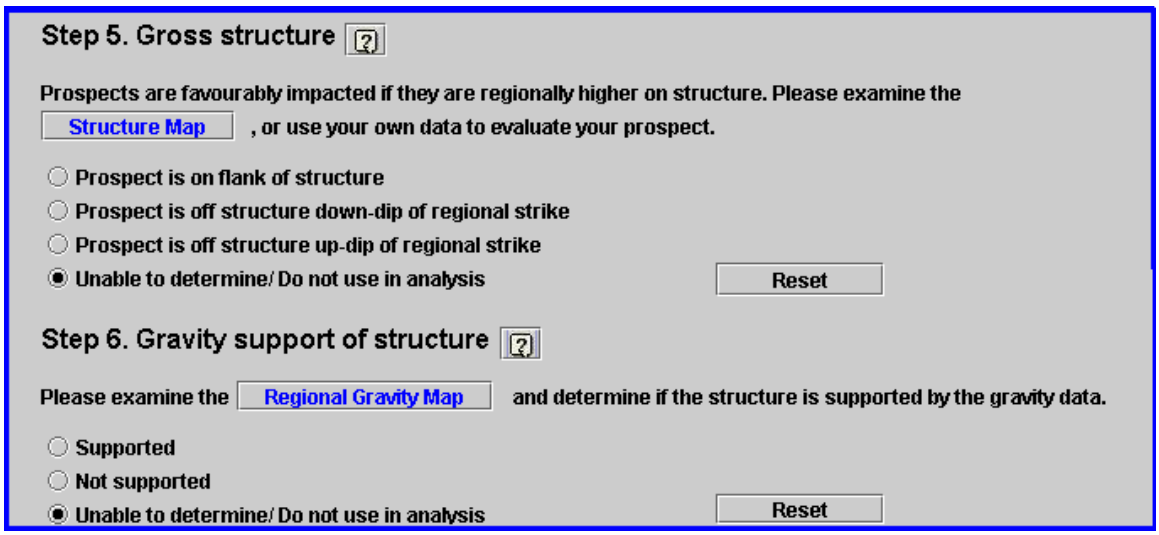
Step 4 involves the net thickness of the porous sands at the prospect location. Based on the location of your prospect (margin or central basin) the FEE tool uses either a 15% porosity thickness value or a 10% porosity thickness value.



Once this step is complete, click on **next** to finish the Regional Assessment.

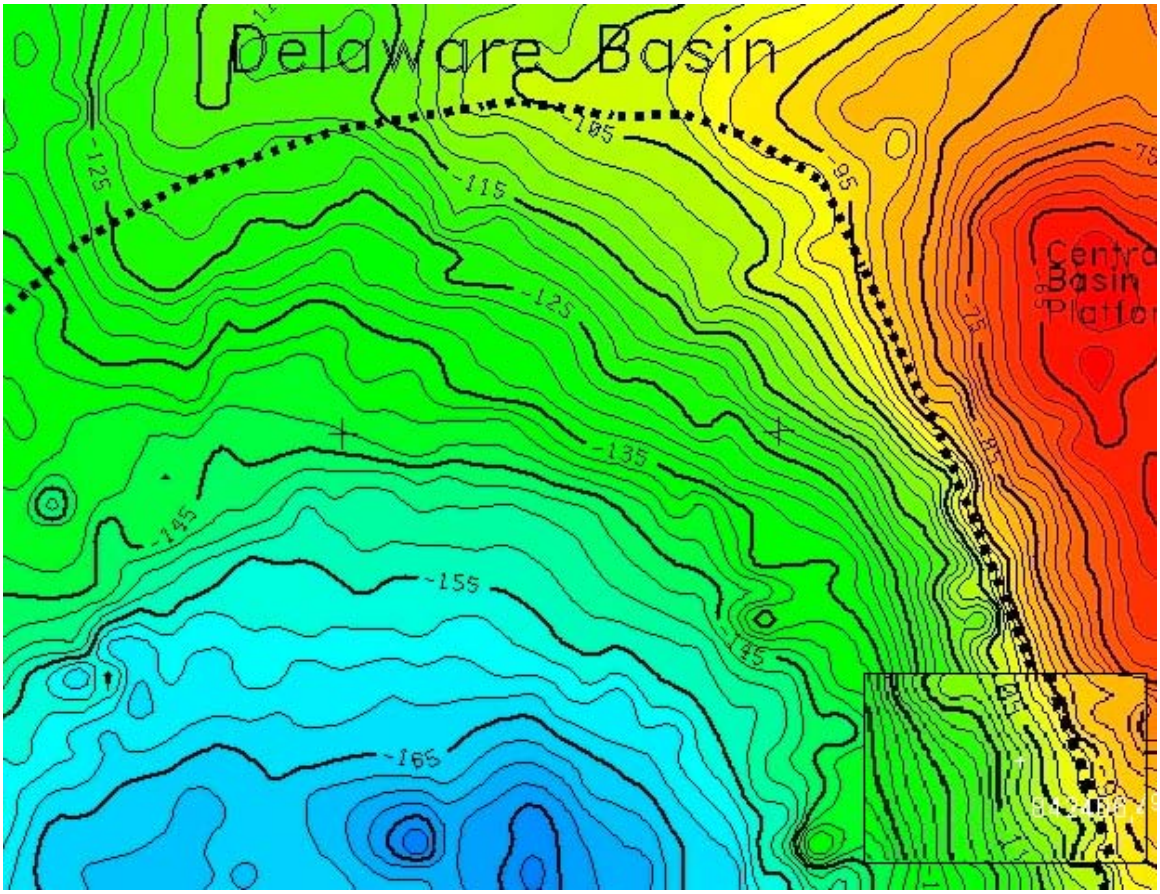
4.2.5 Gross Structure

Step 5 involves observing a structure map. This map is available by clicking on the **Structure Map** button.



This map functions 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 (a section of the structure map is shown in section 2.2.4).

4.2.6 Gravity Map

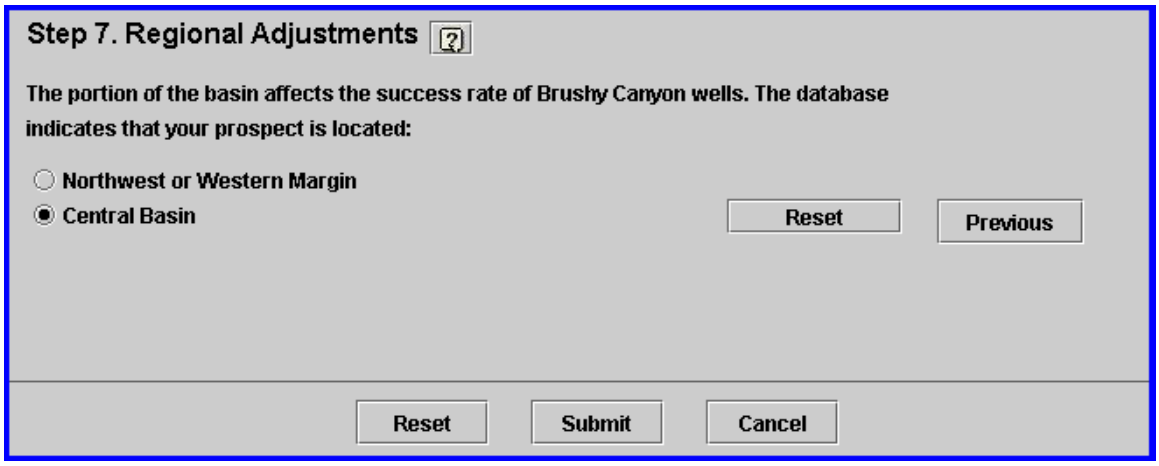


The gravity map (shown above) is accessed by clicking on the **Regional Gravity Map** button in **Step 6, Gravity support of structure**. This map can be used to determine if the gravity data supports the structure.

4.2.7 Regional Adjustments

Step 7, the final step, involves a regional adjustment. 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.

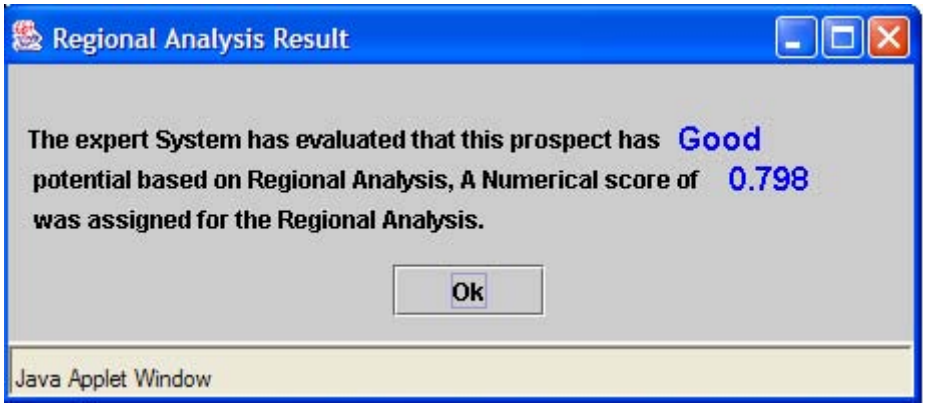
This finishes the data entry. Use the **Previous** button to review the first screen of the Regional Assessment input, the **Reset** button on the bottom of the screen to reset any changed values on this screen to their previous values, or the **Submit** button to enter this data.



4.3 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 and click on **Regional**.

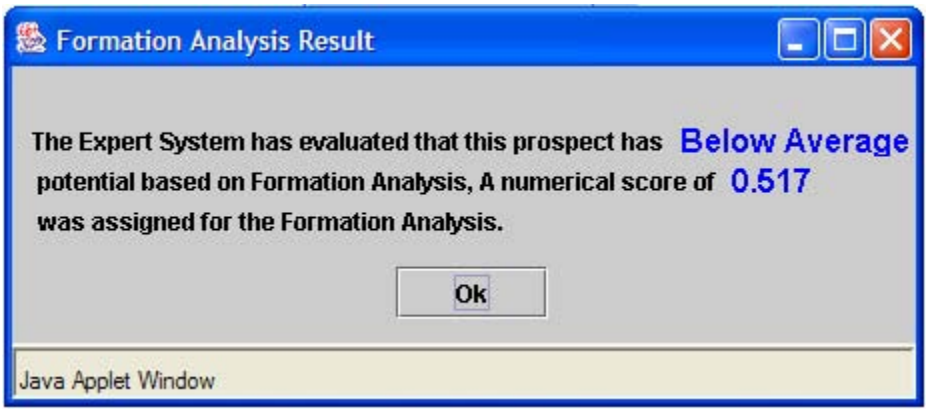
It is possible to view this result (as well as the trap and formation analysis results) prior to reviewing and modifying the data. To do that, simply go to the **Inference** menu prior to inputting data. This will give you a value based on the database information alone, which can be used to compare to the value after you have modified some of the inputs.



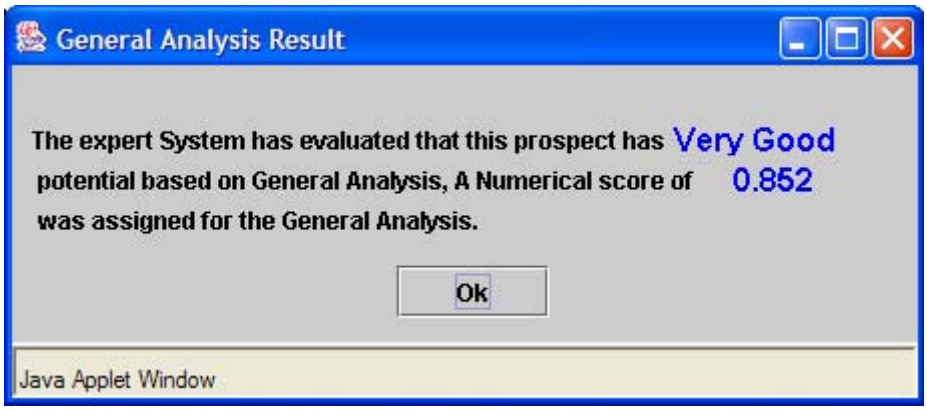
CHAPTER 5: Delaware Basin: Results

5.1 Inference

The **Inference** menu 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, as seen in this example from the Formation Analysis.



The trap, formation and regional values can be obtained upon completion of these steps and have been discussed briefly in the proceeding chapters. The general (or overall) value is a weighted average of these three values.



5.2 Results

The **Results** menu 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.

5.2.1 Summary

Below 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.

Your prospect has been evaluated by the Expert system to be a [Very Good] risk using a combination of factors in three categories: *Trap Assessment, Formation Assessment, and Regional Assessment.* This summary will provide means to compare and contrast your well to other prospects that the unadjusted model has predicted in the same range and to identify potential analog wells using a combination of graphs and tables.

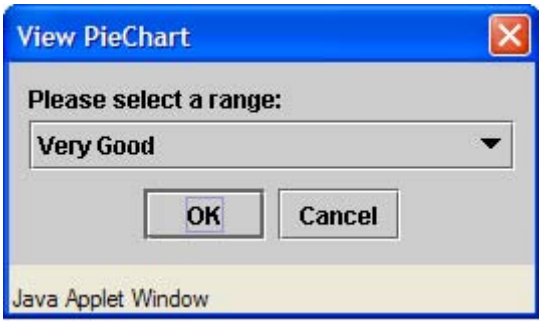
The [Pie Chart] menu allows you to examine how your prospect compares to actual wells by comparing the ***Predicted Prospect Quality*** of your well to that predicted for actual brushy canyon wells using the basic information available to the system. The initial plot shows the distribution of wells with similar predictions into four categories: *Very Successful* wells, *Successful* wells, *Marginal* wells, and *Dry* holes. For comparative purposes you can examine charts of other ***Predicted Prospect Quality*** ranges to contrast the overall distribution of successful wells using the **Pie Chart** menu bar.

The [Bar Chart] menu shows the relationship between your prospect and the overall distribution of predicted success rate values for two data sets, selectable using the **Bar Chart** menu bar. The first data set is the ***Predicted Prospect Quality*** at known wells which have either targeted the lower Brushy Canyon and been reported dry, or have full or mixed production from the lower Brushy Canyon. The second chart shows how your prospect compares to ***Predicted Prospect Quality*** at 60,478 potential 40 acre drill sites in the New Mexico part of the Delaware Basin.

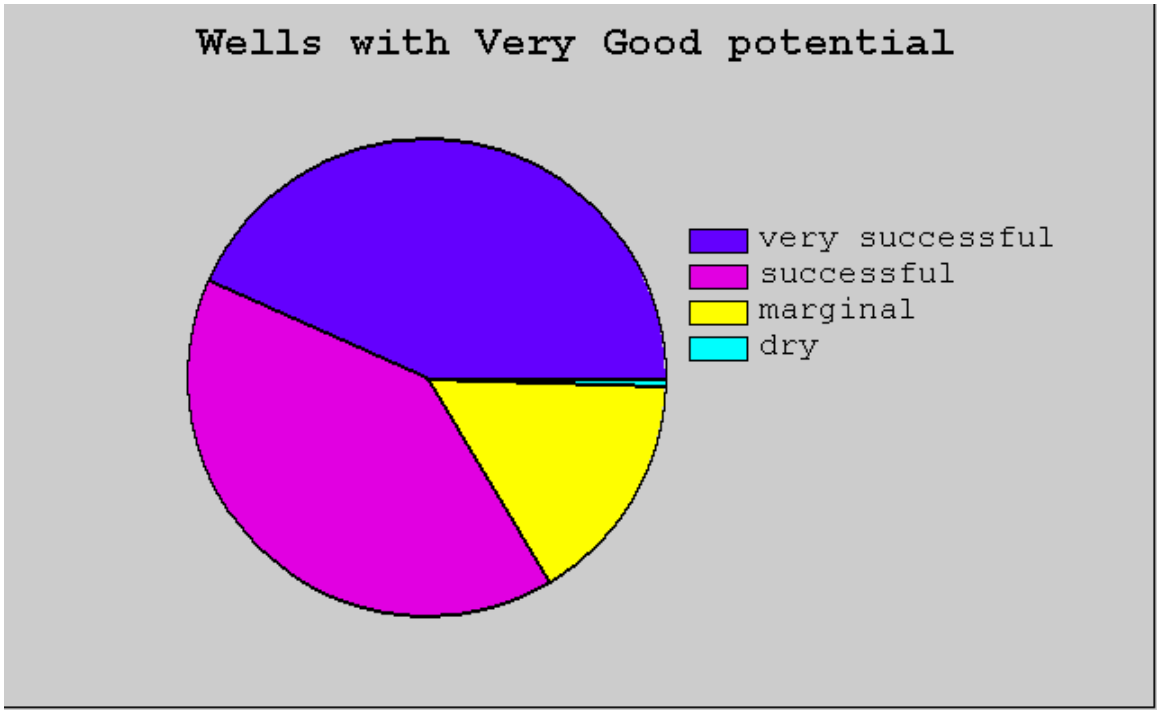
The [Table] menu contains a variety of tables summarizing important aspects of the data used to make the analysis, linguistic variables approximating the ranges of responses from the Expert System, and information about wells that are nearest to your prospect in both ***distance*** and ***Predicted Prospect Quality*** to help you identify potential analog wells. Well listings include API numbers which can be used to link to additional information about the area of the prospect available in the [Web-based Data Management System.] If you wish to examine monthly production data at one of these wells please link to [ONGARD] and enter the API number in the search field.

5.2.2 Pie Charts

The pie charts provided for your 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."



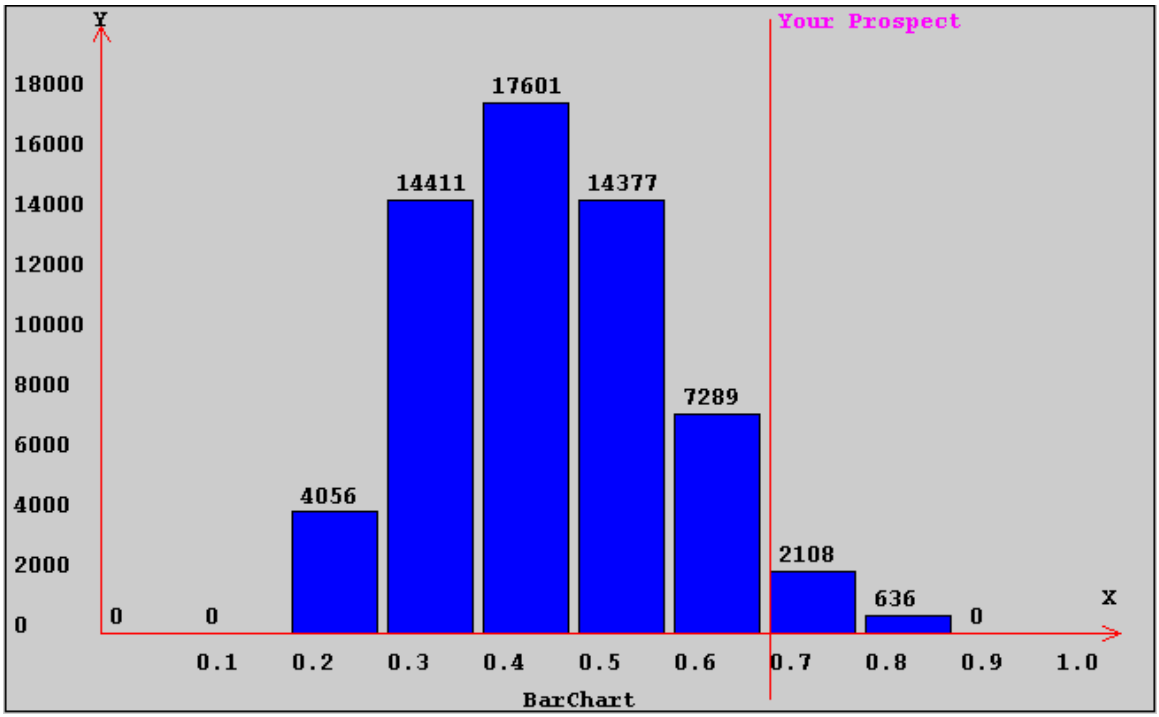
Selecting the **Very Good** option brings up the following pie chart. This chart shows the relative production levels for completed wells that were evaluated using the FEE Tool to have "Very Good" potential. For comparison, you may view similar pie charts for other outputs.

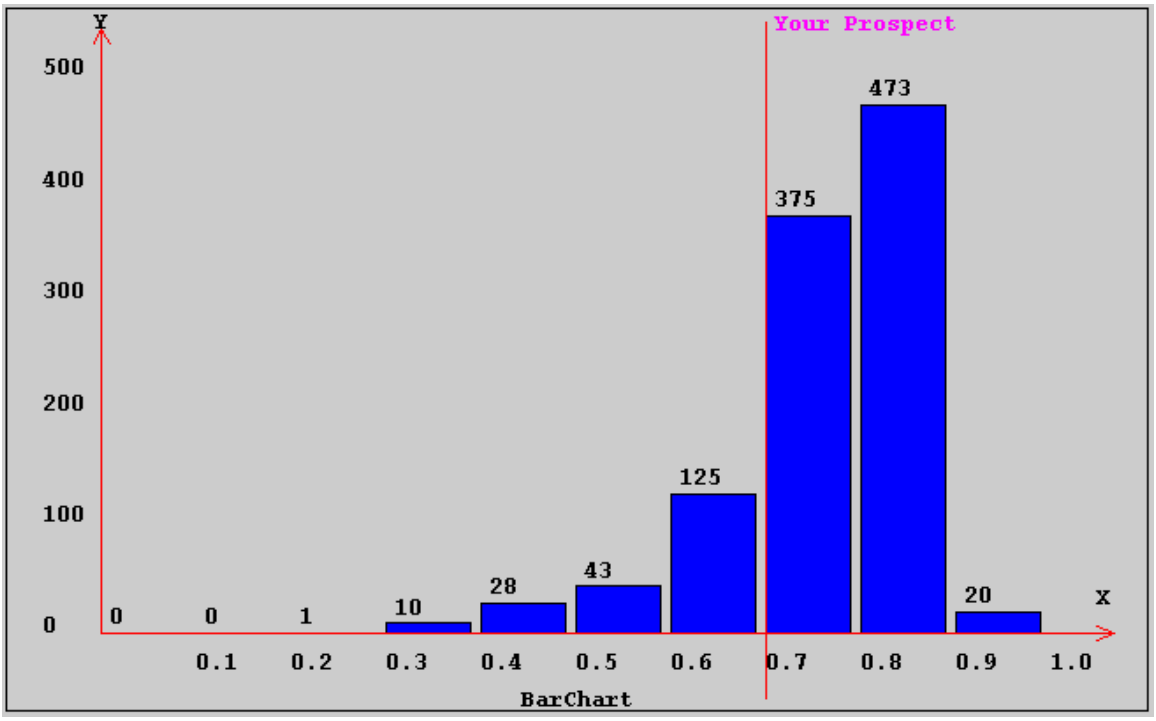


5.2.3 Histograms

There are two histograms available. The first shows your numerical output or prospect quality (found in **Inference - General**) in relation to the numerical outputs for the entire system. The second shows your prospect quality in relation to the numerical outputs for

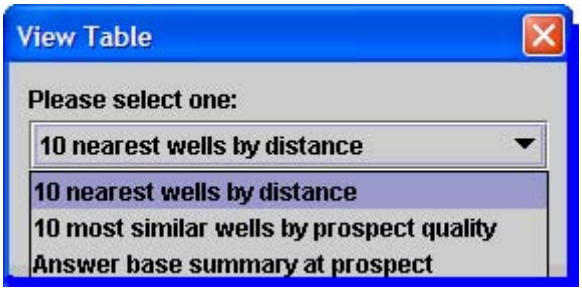
all the wells in the basin producing out of the Lower Brushy Canyon. An example of both histograms is provided below.





5.2.4 Tables

The table menu consists of three tables to help you evaluate your prospect. The available tables are shown in the table menu below.



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 third 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.

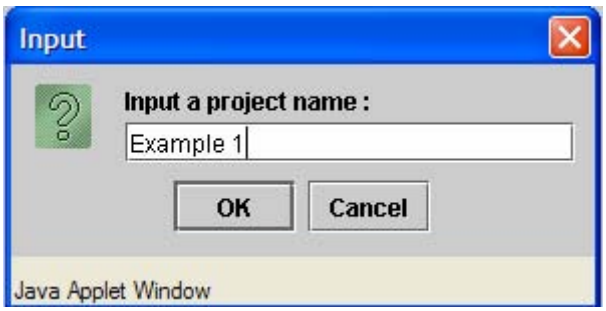
CHAPTER 6: Example Project with the Delaware FEE Tool

In this section, we will walk through an example project, from the creation of the project to the final evaluation.

Create the project

To create the project, click on **New** in the **Project** menu.

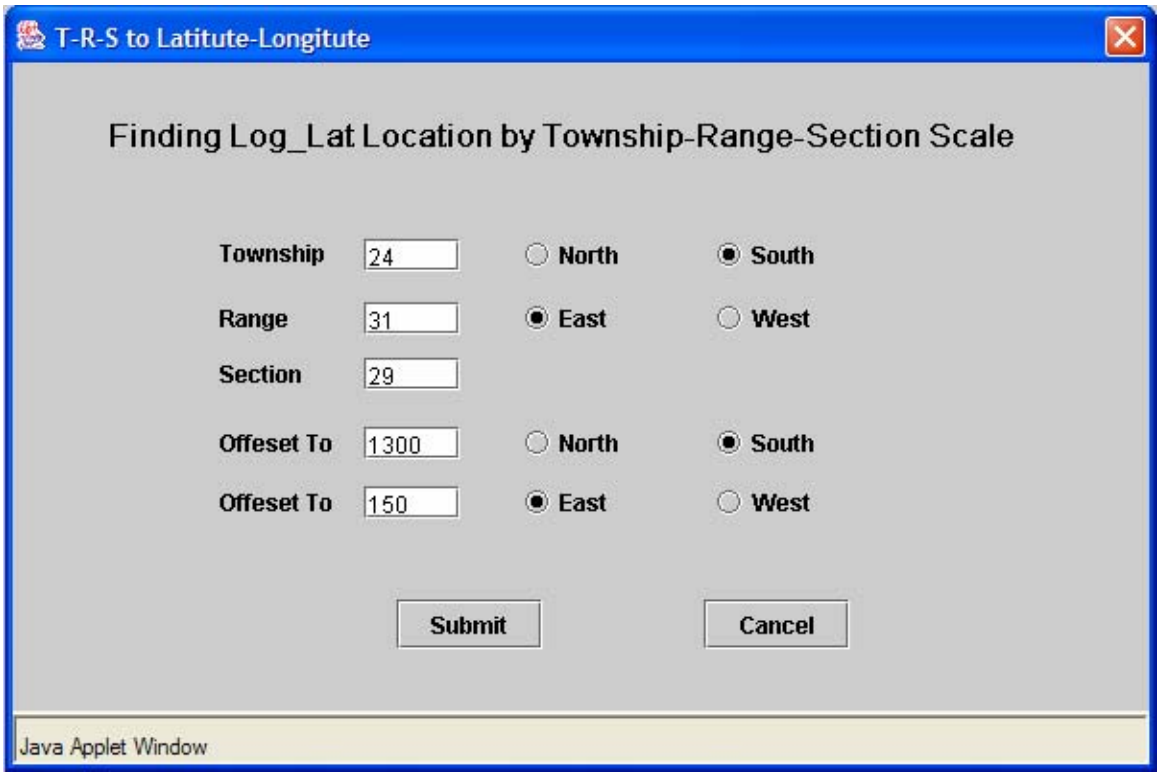
The name for this project will be Example 1. Once the project is named, click **OK** and proceed to the next step, inputting the location data.



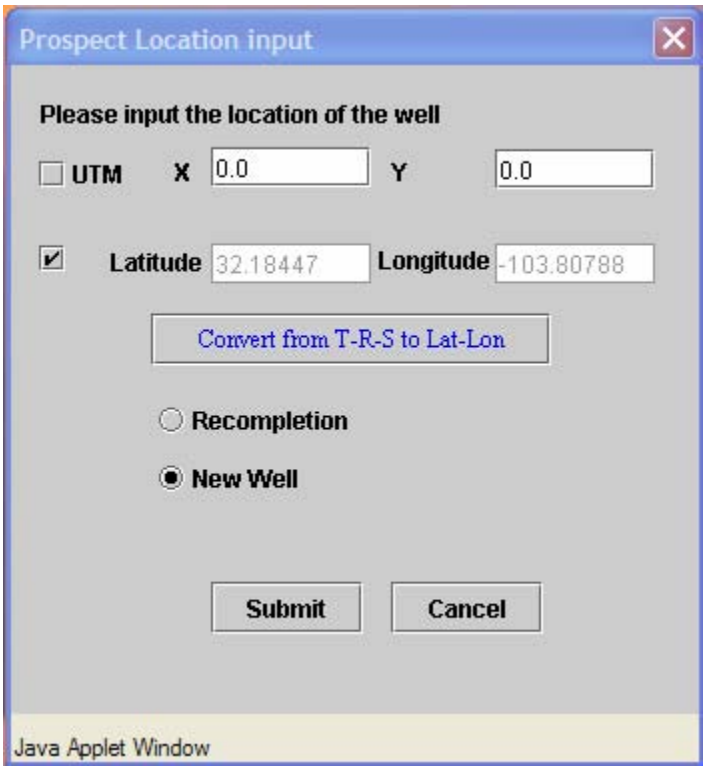
Location Data

As discussed in chapter 1, location can be input in a variety of ways. In this example, we will begin with township, section and range, which will then be converted to latitude and longitude. We will use the location (in TRS) of 24S 31E 29.

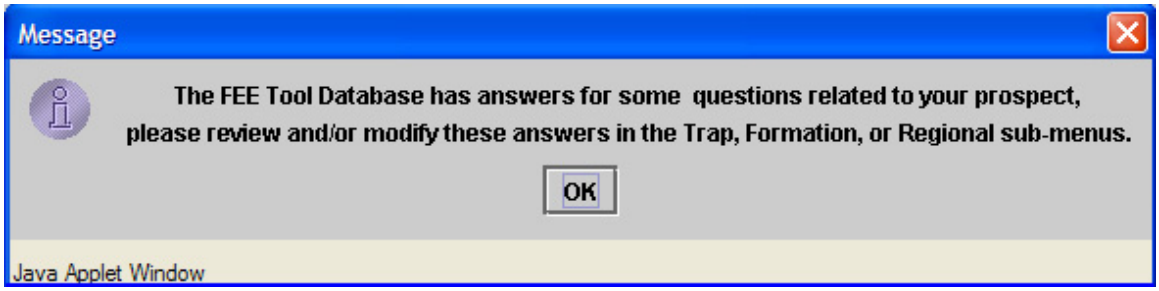
Begin by going to the **Input data** menu and selecting **Location**. Then, choose the **Convert from T-R-S to Lat-Lon** link to convert to latitude and longitude. For this example, the offsets will be 1300 ft south and 150 ft east.



Once this is entered, click the **Submit** button, which takes you back to the location entry menu.



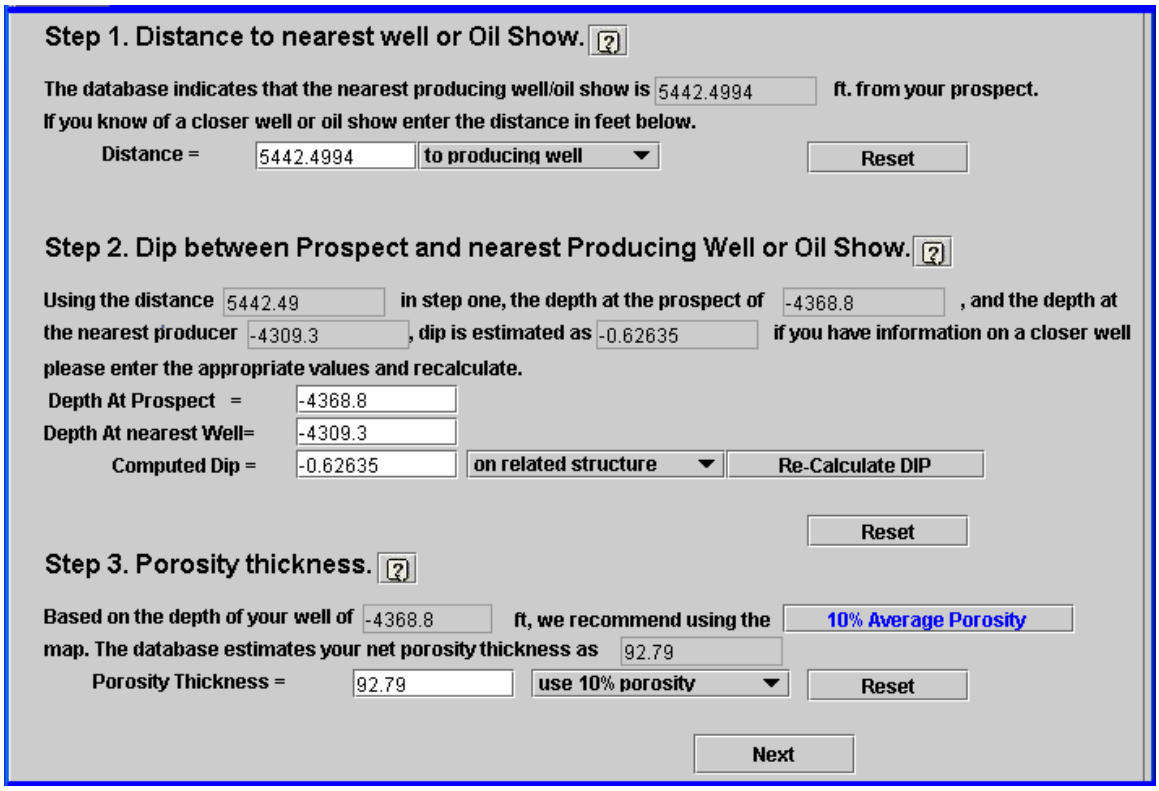
The converted location is shown in the **Latitude** and **Longitude** boxes. At this point, we will select **New Well**, and press the **Submit** button. The following message tells us that our location is in the region for which the answer base has values. We will review and modify these values in the next steps.



Reviewing and Modifying Answers

The next step is to review and/or modify the answers in the trap, formation and regional assessment menus. We will begin by looking at the first page of the **Trap Info** found under the **Input Data** menu.

The first page of the trap assessment looks as follows:



From this page, we can see that the nearest producing well is about 5442 feet from the location in question. For this example, we will use the database-provided value. If we were to change it, however, we would input the new distance and indicate if the distance was from a producing well or an oil show using the pull-down menu. If a change is made in **Step 1**, the dip angle computation in **Step 2** will not be correct. To correct this to reflect the change, enter the depth (subsea elevation – discussed in chapter 2) of the top of the formation at the well used for the new distance value and use the **Re-Calculate Dip** button. You can reset back to the previous values by using the **Reset** button next to the step, or the **Reset** button at the bottom of the screen, to restore all of the values on the screen back to their previous values. If you wish to be certain to restore all values to the original answerbase defaults, re-submit the location on the **Input Location** screen.

The thickness of the porous sand is given as 92.79 feet, which comes from using a 10% porosity map. You may view this map by clicking on the **10% Average Porosity** link.

To move on to the next page of the trap assessment information, click on **Next**.

From this page, we note that according to the database there is a significant increase in the thickness of the formation in the direction that is most updip from the location of our prospect. We have the option of keeping this selection, selecting another option, or electing not to use this in our analysis. In order to show how user input can affect the

inference results, we will select a different option. Before a change is made, however, it is often a good idea to go to the **Inference** menu and see what the result is using just the default data. This provides a means of comparing the effect of changes to the default data on the inference results. Prior to making any changes, the inference results for the trap assessment were a numerical value of 0.573 and a corresponding linguistic value of "Below Average."

Before submitting this modified data, let's review the remaining two steps. **Step 5** allows you to examine a structure map. A close-up of the structure map with the prospect shown is provided below. (Information on how to maneuver around the maps is provided in chapter 2.)

Based on this map, you may select yes or no, based on whether or not the map (or your own map) indicates that the prospect is on structural strike. You may also keep the default value, **Unable to Verify/Do not use in Analysis**. For this example, we will keep the default value.

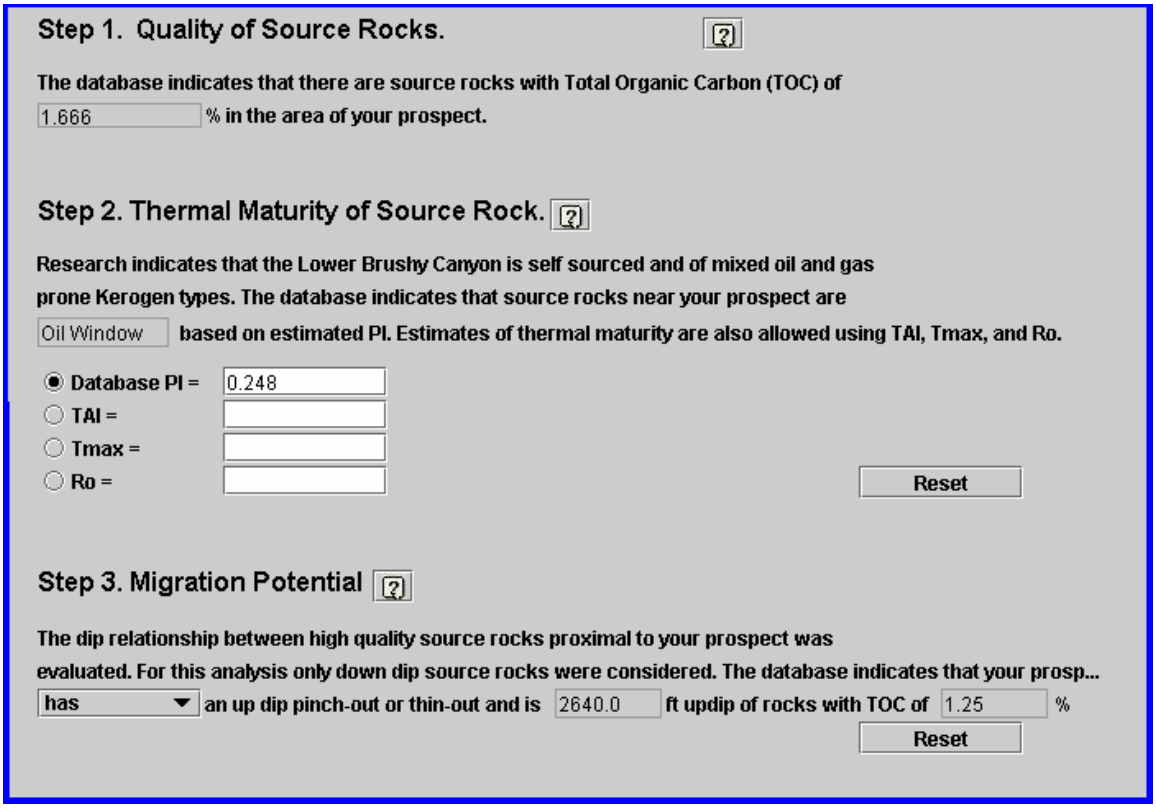
Step 6, the final step, indicates the consistency of the thickness values by providing a mean and a standard deviation of thickness values over a large and a small region surrounding your prospect.

Once you are satisfied with the Trap Assessment information, click on the **Submit** button. Return to the **Inference** menu to compare the results to the values seen prior to making any changes. The new inference results are a numerical score of 0.681 and a corresponding linguistic variable of "Average."

To continue reviewing and modifying data for this location, return to the **Input Data** menu and select **Formation Info**. **Step 1** gives the percentage of total organic carbon (TOC) at the location. This value is determined by using mapping software to interpolate values collected across the region. **Step 2**, the PI, is determined using a similar technique. In our case, the TOC percentage indicates good source rock at the location.

Both this value and the PI value can be altered if you have other information. You may also select another method of measuring thermal maturity and provide a value.

Step 3 looks for downdip sources of high TOC. This step is important for the migration potential, especially in cases where the TOC at the location of the prospect is low. Once this data has been reviewed, click on the **Submit** button on the bottom of the screen.



At this point, you can return to the **Inference** menu if you wish to review the result of the **Formation Assessment**. In this case, with no changes made to the inputs, the numerical result is 0.908, with a linguistic value of "Excellent."

To continue reviewing and entering data, go to the **Input Data** menu and select **Regional Info.** The first screen of this section is shown below with the default values.

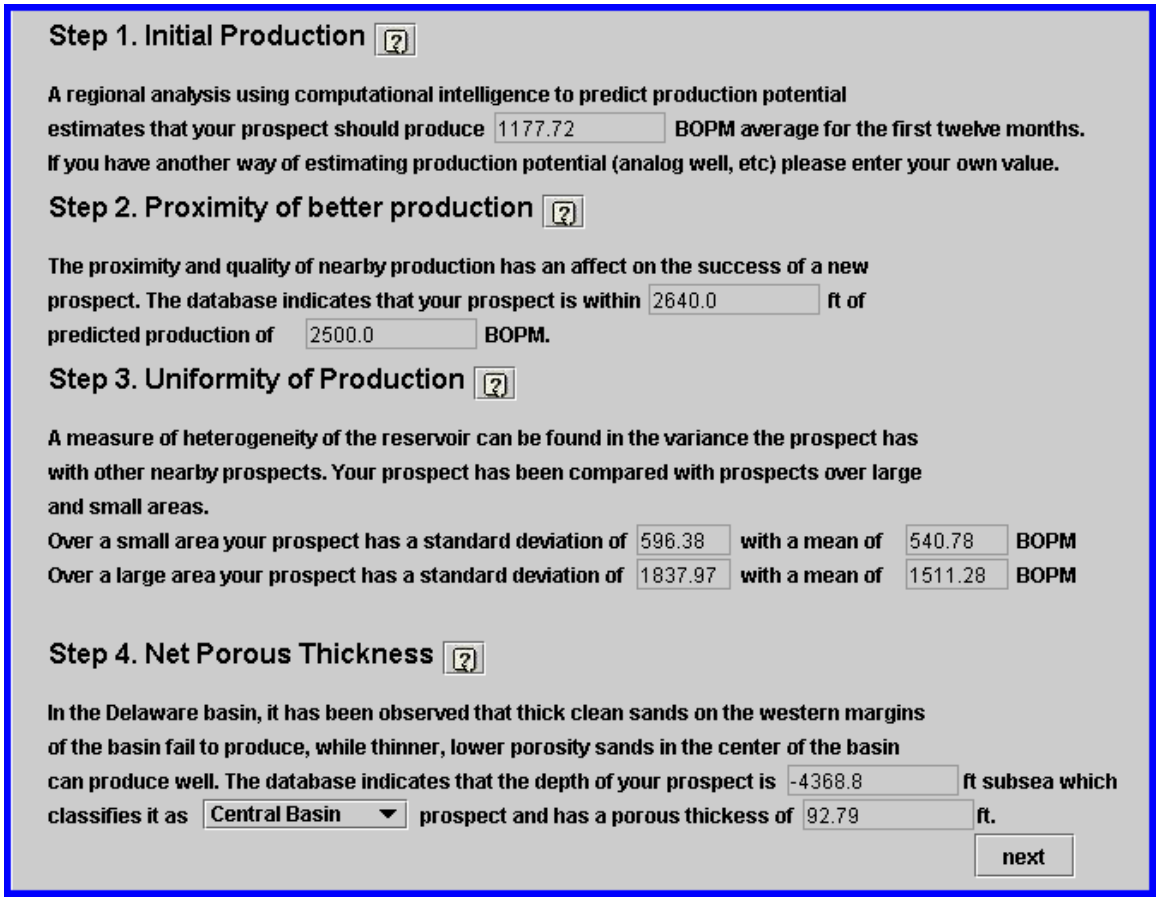
Step 1 of this assessment gives a value of 1177.72 BOPM. This value is a prediction based on the use of a neural network.

Step 2 shows the distance to higher predicted production. Based on the same neural network results, predicted production of 2500 (or more) BOPM is found 2640 feet away from this location.

Step 3 is a consistency step, similar to the **Step 6** in the Trap Assessment. In this case, the predicted production values are used as inputs.

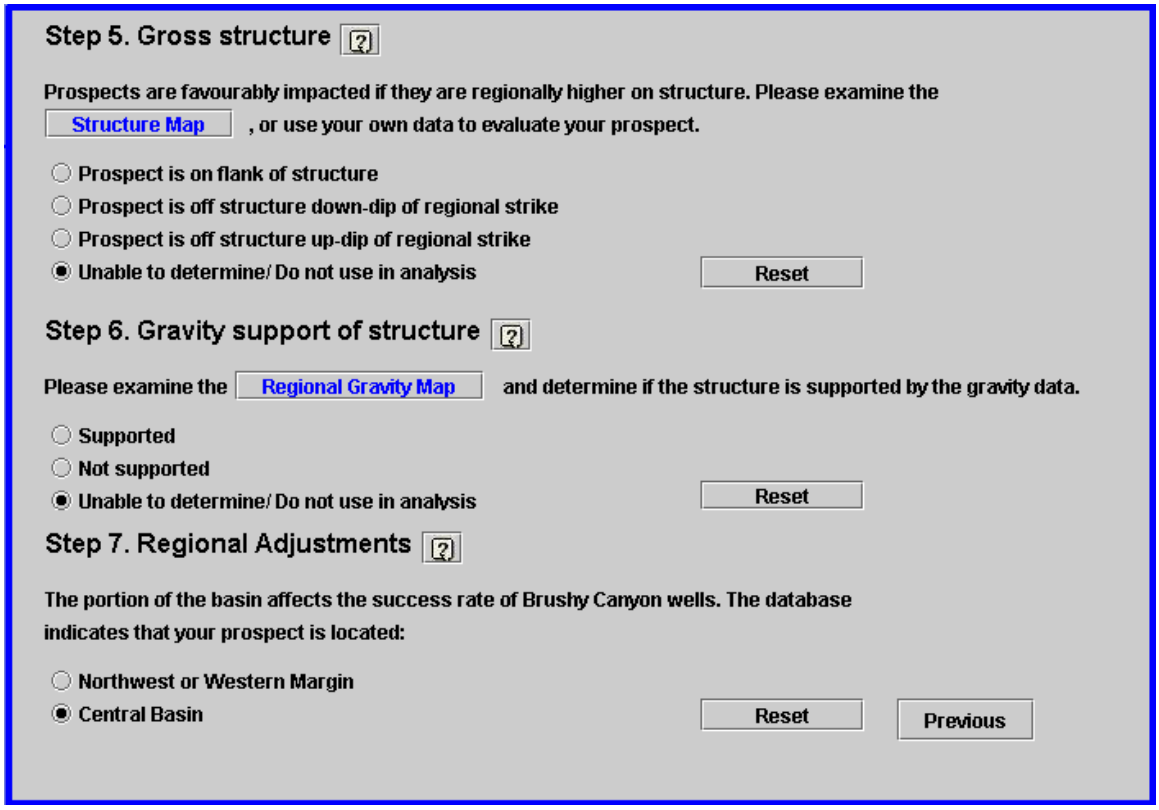
Step 4 shows the thickness of the porous sands, which should be the same as shown in the Trap Assessment. (If this value had been modified in the Trap Assessment, it should also be modified here.) This step also indicates whether or not the prospect is on the northwestern margin of the basin. This prospect is not located on the northwestern margin of the basin, which can be confirmed by looking at the maps.

Once this has been reviewed, select **Next** to move to the next screen.



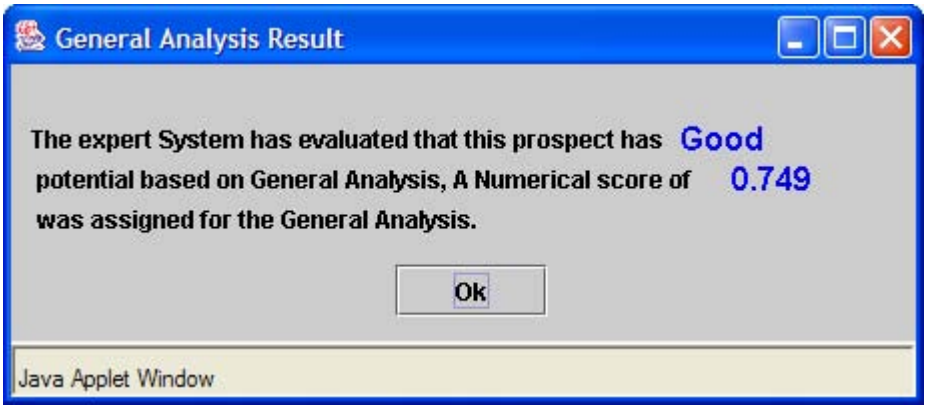
In the last screen, **Step 5** revisits the structure map seen in the Trap Assessment. This is followed by **Step 6**, a chance to review a gravity map to see if it supports the conclusion made by observing the structure map. Both of these maps navigate in the same way as the previous maps. **Step 7**, the final step, uses the same information as shown in **Step 4**, indicating whether or not the prospect location is central or on the northwest margin of the basin. Once again, if a change was made in **Step 4**, it should also be made here.

Once this final page has been reviewed, the results from the Regional inference can be checked. The results for this location are 0.715 and “Good.”



Results

Now that all the data has been reviewed, we can see the overall results. First, we can review the general inference results.



We can follow this up by going to the **Results** menu and viewing the **Summary** page. The summary page also shows the result of "Good" and links to pages where we can view pie and bar charts.

Your prospect has been evaluated by the Expert system to be a [Good] risk using a combination of factors in three categories: *Trap Assessment, Formation Assessment, and Regional Assessment.* This summary will provide means to compare and contrast your well to other prospects that the unadjusted model has predicted in the same range and to identify potential analog wells using a combination of graphs and tables.

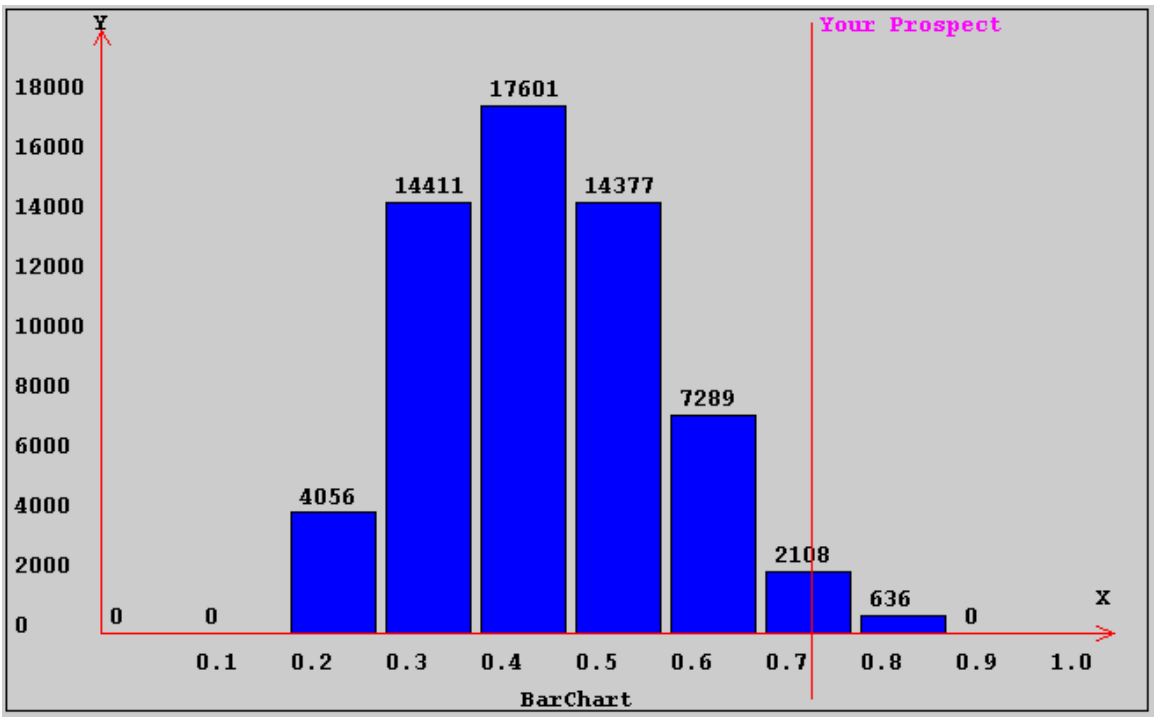
The [Pie Chart] menu allows you to examine how your prospect compares to actual wells by comparing the ***Predicted Prospect Quality*** of your well to that predicted for actual brushy canyon wells using the basic information available to the system. The initial plot shows the distribution of wells with similar predictions into four categories: *Very Successful* wells, *Successful* wells, *Marginal* wells, and *Dry* holes. For comparative purposes you can examine charts of other ***Predicted Prospect Quality*** ranges to contrast the overall distribution of successful wells using the **Pie Chart** menu bar.

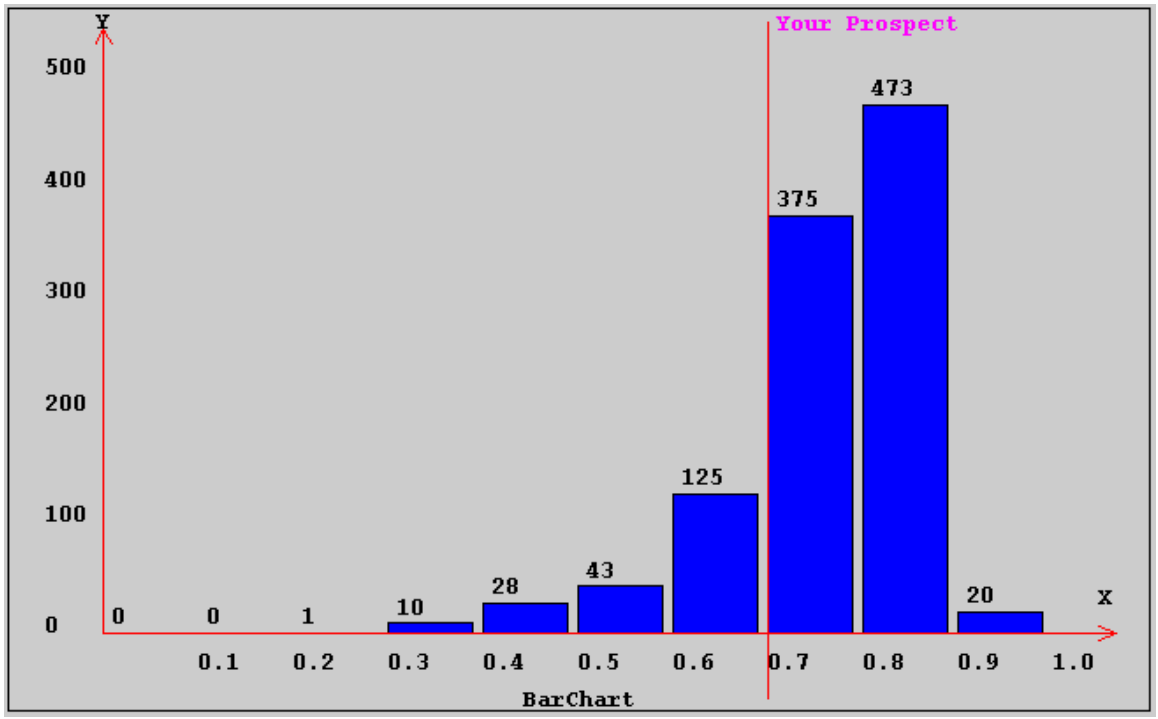
The [Bar Chart] menu shows the relationship between your prospect and the overall distribution of predicted success rate values for two data sets, selectable using the **Bar Chart** menu bar. The first data set is the ***Predicted Prospect Quality*** at known wells which have either targeted the lower Brushy Canyon and been reported dry, or have full or mixed production from the lower Brushy Canyon. The second chart shows how your prospect compares to ***Predicted Prospect Quality*** at 60,478 potential 40 acre drill sites in the New Mexico part of the Delaware Basin.

The [Table] menu contains a variety of tables summarizing important aspects of the data used to make the analysis, linguistic variables approximating the ranges of responses from the Expert System, and information about wells that are nearest to your prospect in both ***distance*** and ***Predicted Prospect Quality*** to help you identify potential analog wells. Well listings include API numbers which can be used to link to additional information about the area of the prospect available in the [Web-based Data Management System.] If you wish to examine monthly production data at one of these wells please link to [ONGARD] and enter the API number in the search field.

The pie chart for wells with a score of "Good" is shown below. For comparison sake, you may also view pie charts for scores of "Very Good," "Average," etc.

Next, we will look at the two histograms. The first one shows the numerical output compared to the numerical outputs of all points in the region, and the second shows the numerical output compared to the numerical outputs from producing wells.





Finally, you can review the tables for information about other wells with similar numerical outputs from the FEE Tool. Here is the table for the 10 wells with the closest numerical outputs. The production is given in barrels of oil per month (BOPM) averaged over the first year.

10 most similar by prospect quality

[API]	[Predicted_Quality]	[OilVol]
3002532138	0.749	718.0
3002531617	0.749	1203.0
3001527962	0.749	873.0
	0.749	0.0
3002534706	0.75	525.0
3002532657	0.75	809.0
3002531720	0.75	374.0
3001527171	0.75	2614.0
3002534479	0.748	720.0
3001526777	0.748	1822.0

Java Applet Window

At this point, you have a variety of options. You can return to the **Input Data** menu and update or change values and determine the effect those changes have on the results, you can save this project and create a new project using a different location, or you can use the ONGARD or WDMS sites to get more information about the wells shown in the tables.

CHAPTER 7: Devonian Carbonate: Structure Assessment

This chapter and the following chapters discuss the specific input and output screens used by the Devonian Carbonate FEE Tool. Chapters 7, 8, 9, and 10 focus on the input screens for the four assessments used by the Devonian FEE Tool, chapter 11 discusses the available outputs and chapter 12 provides an example of a complete project using the Devonian Tool.

7.1 Overview

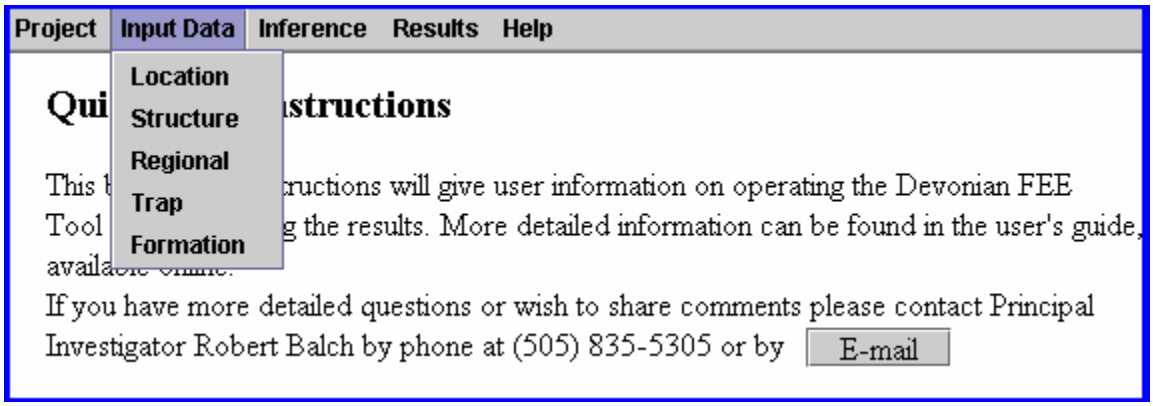
To begin the process of evaluating your location using the Devonian Carbonate FEE Tool, first create a project and input the location of the project (in latitude and longitude or township, section and range). The process of creating a project and entering location data is the same as when using the Delaware Basin FEE Tool. This is covered in sections 4, 5, and 6 of chapter 1.

The Devonian FEE Tool is built around four assessments, structure, regional, trap and formation. Each of the four assessments has a screen or series of screens where you can review the available data from the answer base and replace it with your own information.

The structure assessment looks at the following:

- Paleo structure
- Structural relief
- Fault bounding
- Seismic data

To begin reviewing and entering data, go to **Input Data** and click **Structure.**



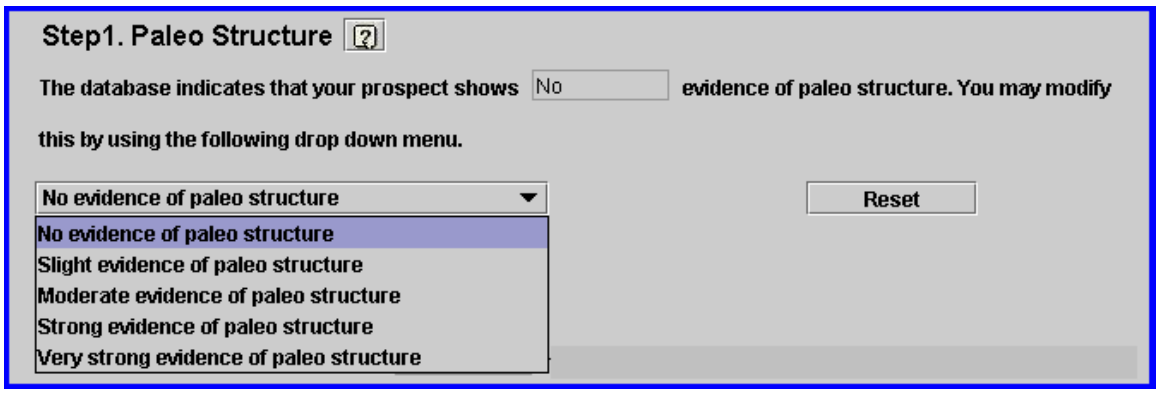
7.2 Reviewing and Entering Data

For most of the steps in the structure, regional, trap and formation 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 previous values.

7.2.1 Paleo Structure

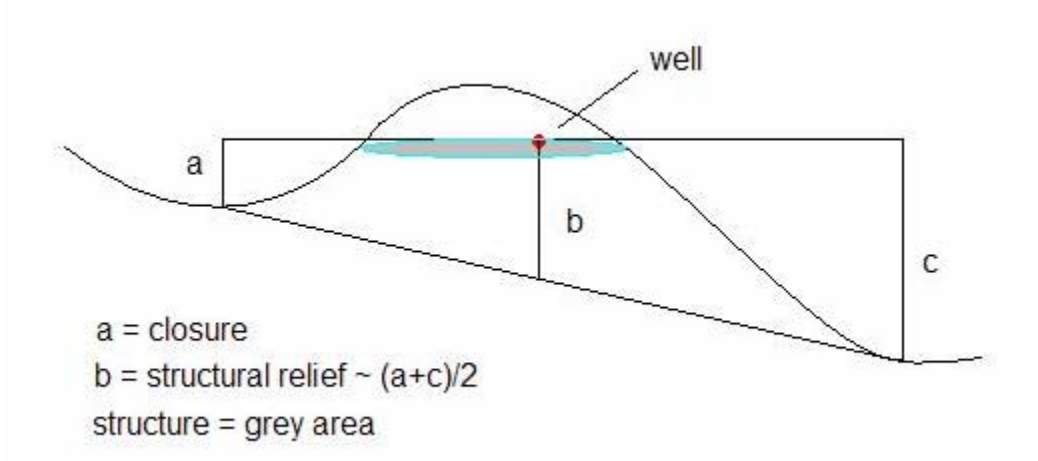
Step 1 in the structure assessment involves the existence of a paleo structure. This requires looking at the older structure, and is approximated in this case by considering the Abo–Mississippian thickness. An algorithm was developed to compare this thickness at a point to the thickness at the surrounding points, in order to give an indication of the presence of paleo structure. The results of this algorithm were converted into the linguistic choices shown below.



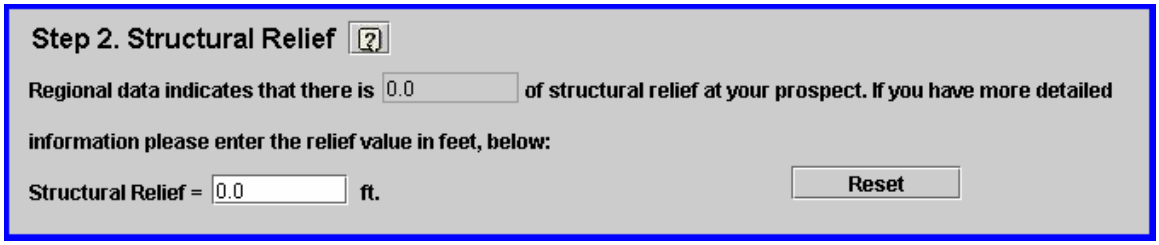
You may use the pull-down menu to make a different selection based on your own maps or methods of determining paleo structure.

7.2.2 Structural Relief

At different places in the Devonian FEE Tool, values for structure, structural relief and closure are used as inputs. For this application, the terms are defined as shown in the graph below. Structure is an area measure, while structural relief and closure are linear measurements, given in units of feet. If the structure is not on an underlying slope, structural relief is the same as closure.

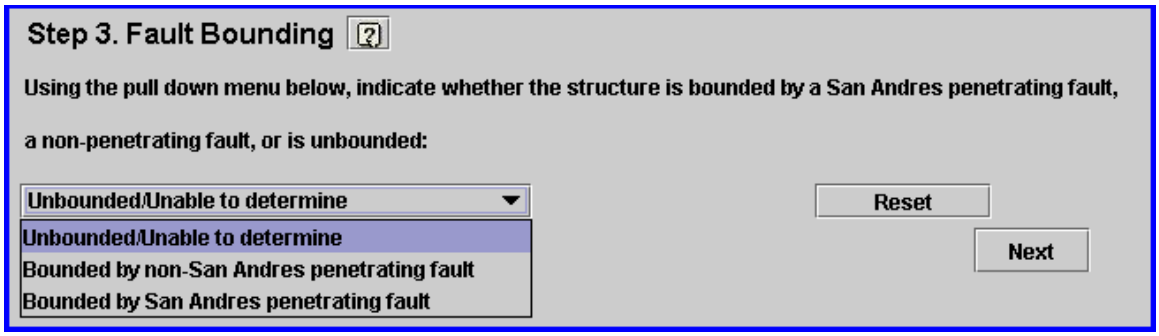


In **Step 2**, as with previous steps, you may provide your own value for structural relief in units of feet.



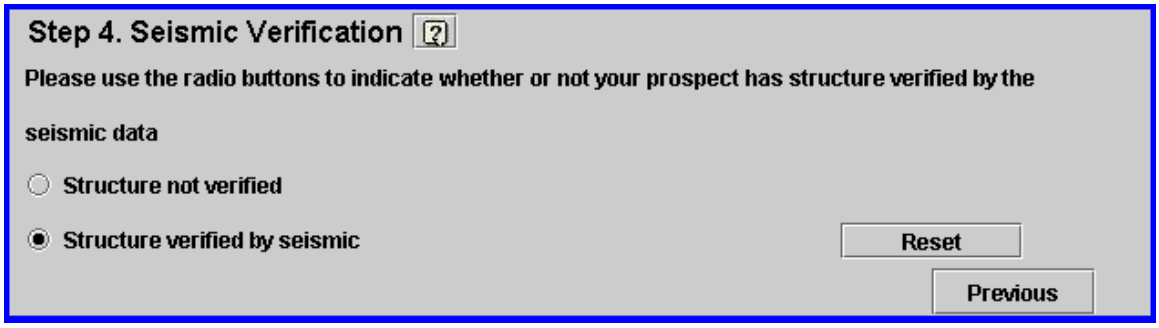
7.2.3 Fault Bounding

Step 3 involves user input about the fault structure surrounding their prospect location. The existence of a fault can be beneficial to the prospect's potential, by acting as a trap, or it can detract from the potential for production at that location and depth by acting as a conduit. If your data indicates that your structure is fault bounded, please use the pull-down box below if you wish to use that in the analysis.



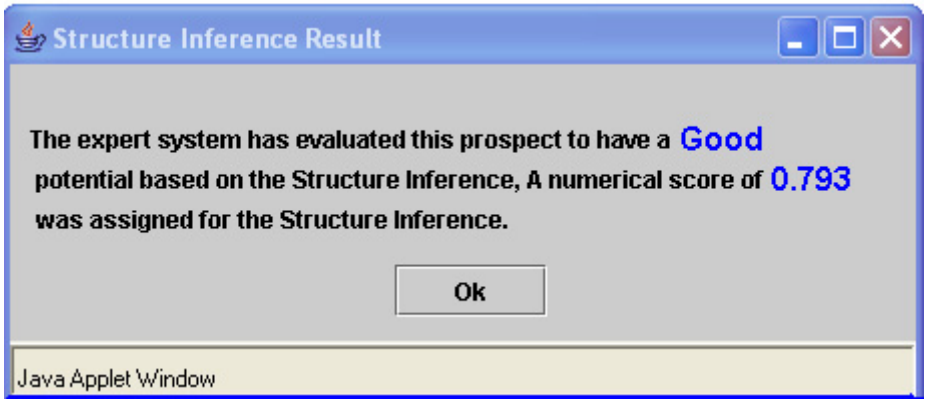
7.2.4 Seismic Verification

Seismic data is often used in evaluating Siluro-Devonian prospects. If you have access to seismic data that you wish to have considered in the analysis, you may enter it here in **Step 4**.



7.3 Structure Inference

Once you have examined and updated the structure data, you can look at the results of this analysis for your prospect by clicking on **Structure Inference**. You can also use this tool to evaluate how your changes to the default values affected the results. To do that, open the **Structure Inference** window before and after updating the structure data.



CHAPTER 8: Devonian Carbonate: Regional Assessment

8.1 Overview

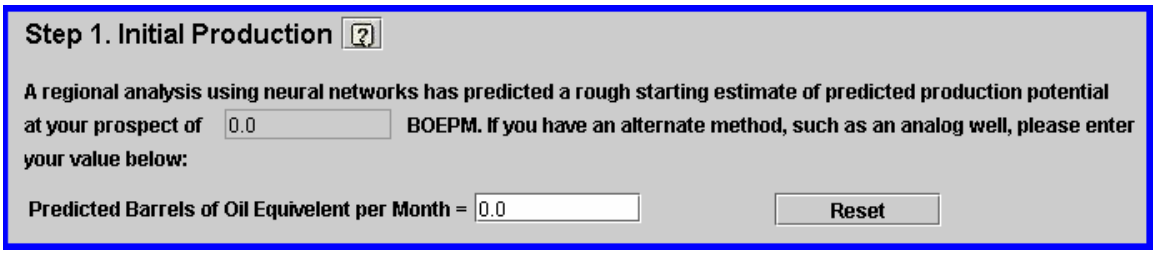
This branch of the Devonian FEE Tool assesses your prospect based on the following:

- A neural network derived value of predicted production
- Size (area) of the structure, if any
- Number of wells on the structure
- Location of wells on the structure relative to your prospect
- Gravity data to support structure
- Existence of a productive trend

8.2 Reviewing and Entering Data

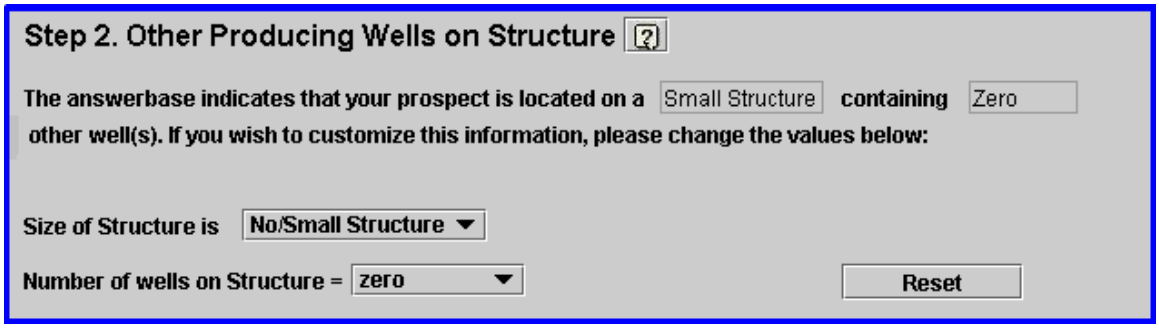
8.2.1 Initial Production

The answerbase value shown in **Step 1** is a predicted production value computed by a neural network (PredictOnline). The units are given in "predicted barrels of oil equivalent per month" using a conversion of 6mcf = 1boe, in order to include both the oil and gas production in one value. As with other steps, if you have a different value you would like to use for predicted production, you may include it in the analysis.



8.2.2 Other Producing Wells on Structure

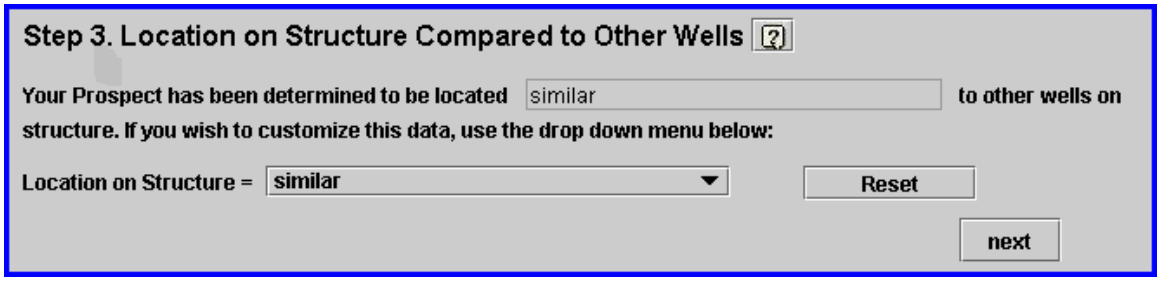
Step 2 in the regional assessment considers two things, the size (area) of the structure the prospect is on, and the number of other producing wells on the structure. The answerbase has an estimate for both of these values, and as with other steps, you may provide a more accurate value if you wish.



In order to update either the size of structure or the number of wells, use the provided pull-down menus. As with other steps, be sure to hit the submit button if you have updated any of the data on this page.

8.2.3 Location on Structure Compared to Other Wells

If the **Step 2** indicated that there were additional wells on the structure, **Step 3** involves the position of those wells on the formation structure with respect to your prospect. The possible inputs for this step are either higher than existing wells, lower than existing wells, similar to existing wells, or an option to skip this step.



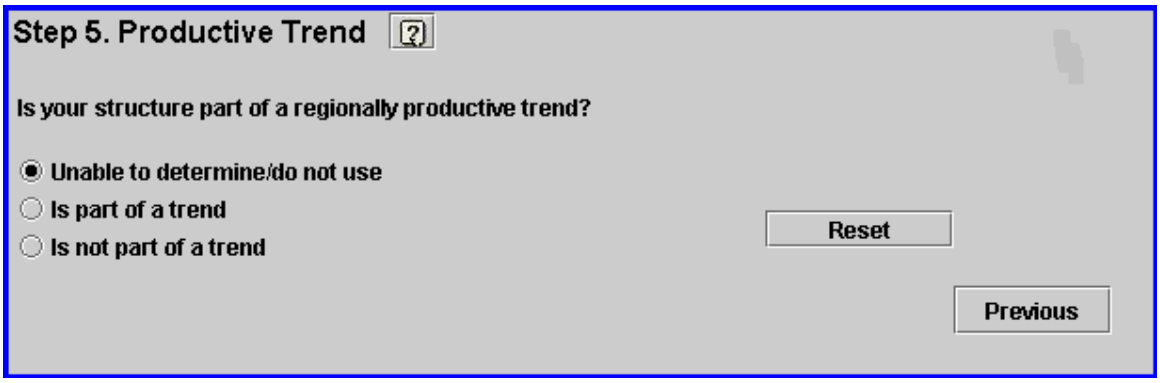
This is the last question on this page of the regional assessment. There are two more queries for this assessment on the following page. To save any changes you may have made on this page, use the **Submit** button, and then use the **Next** button to review and update the answerbase data for the last query.

8.2.4 Gravity Support of Structure

For this step, a gravity map of the region is provided. Clicking on the **Gravity Map** button will open up this map, which you can navigate with your mouse, using the left mouse button to zoom in. You may use this map, or a map of your own, to determine if gravity data supports the structure data provided.

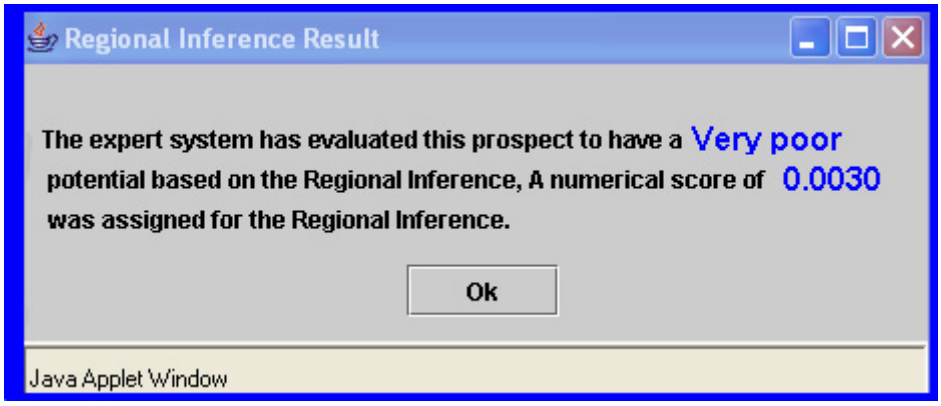
8.2.5 Productive Trend

For **Step 5**, the final step in this assessment, you may provide information indicating that your prospect is part of a regionally productive trend.



8.3 Regional Inference

As with all four assessments, you may check the numerical and linguistic outputs for the Regional Assessment by going to the **Inference** menu and selecting **Regional**. You may do this at any time during the process, if you wish to determine how a change in inputs affects this part of the overall assessment.



CHAPTER 9: Devonian Carbonate: Trap Assessment

9.1 Overview

This assessment looks at the quality of the trap. The following five things are considered:

- Seal or Cap (usually the Woodford Shale for this formation)
- Closure on Structure
- Potential for Flexure Fracturing
- Potential for Other Porosity
- Seismic Verification

For the first three queries, the answerbase contains values derived from data available for this project. As with the other assessments, you will be able to review this answerbase data and modify it if you so choose. The final two steps require user input in order to be considered in the assessment.

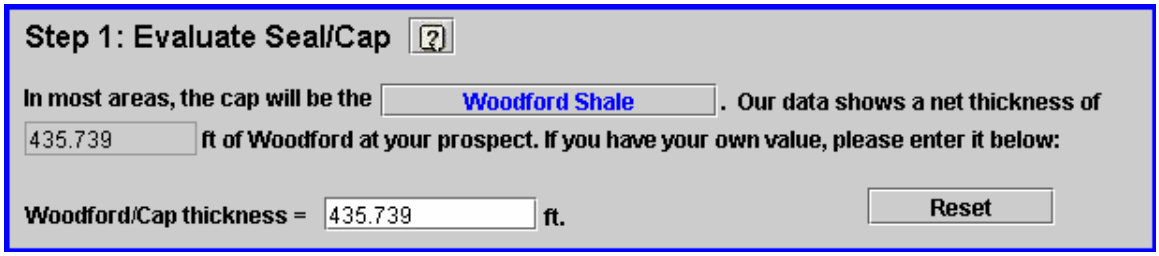
As with all other assessments, you may first review the numerical output based on the answerbase values by clicking on **Inference**, then **Trap**.

9.2 Reviewing and Entering Data

9.2.1 Evaluate Seal/Cap

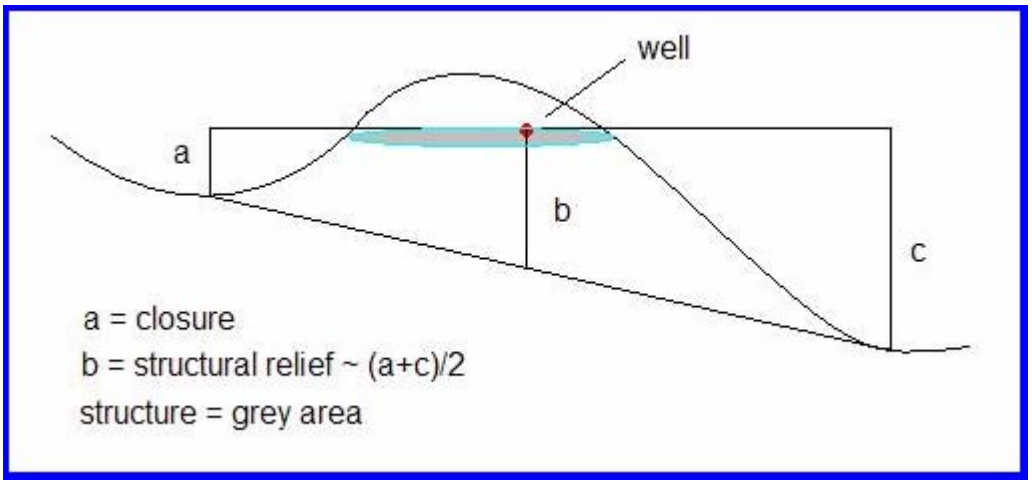
Step 1 looks at the thickness of the Woodford shale at your prospect's location. The answerbase provides a value, and a map of the Woodford shale thickness is also provided. To navigate this map, use the left mouse button to zoom in and the right mouse button to zoom out. As with other maps, the location of your prospect is noted.

You may replace the answerbase value with your own value for Woodford shale thickness in feet. The **Reset** button on this step and all others will return you to the previous value.

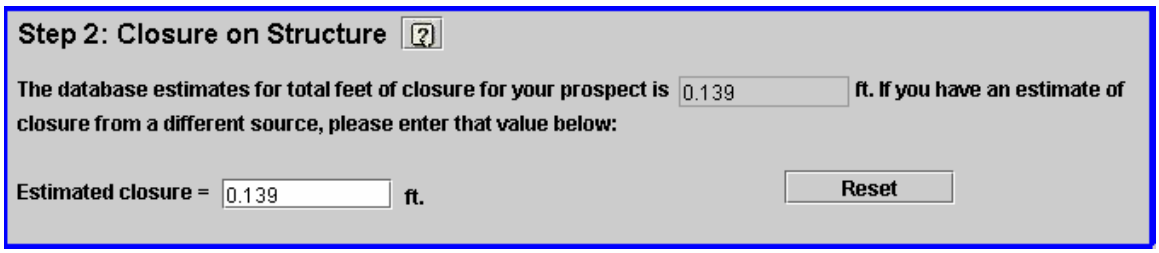


9.2.2 Closure on Structure

Step 2 involves the amount of closure, measured in feet, at your prospect. The definition of closure used here is given in the diagram below:

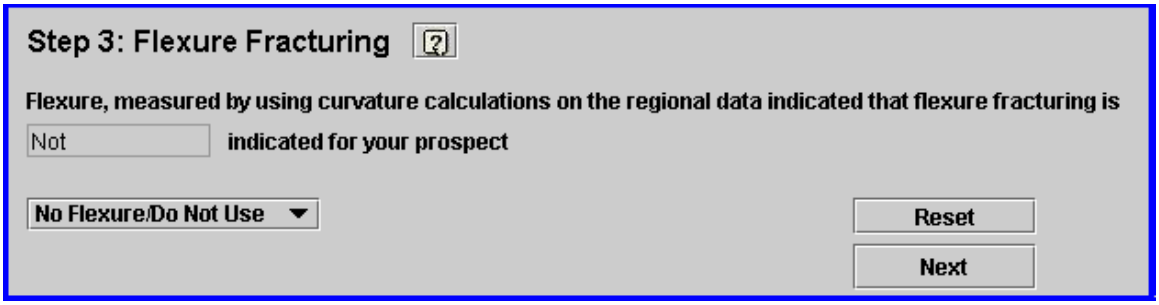


The answerbase contains values for closure at your prospect, which you may replace with your own value in the step below.



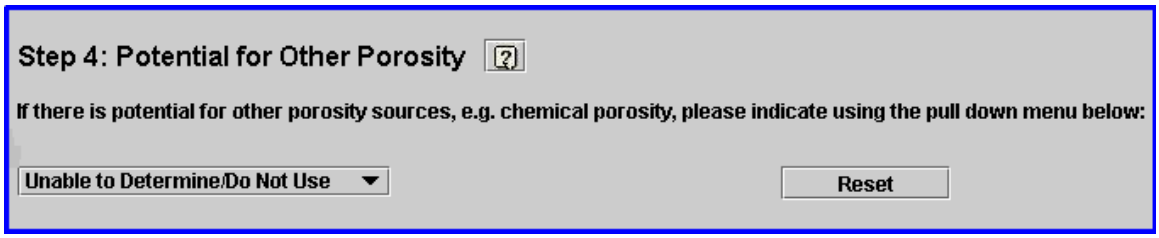
9.2.3 Flexure Fracturing

In **Step 3**, the potential for flexure fracturing is considered. The answerbase value for this step is the result of a curvature calculation on the structure's surface. Places with a high degree of curvature were considered to have potential for flexure fracturing.



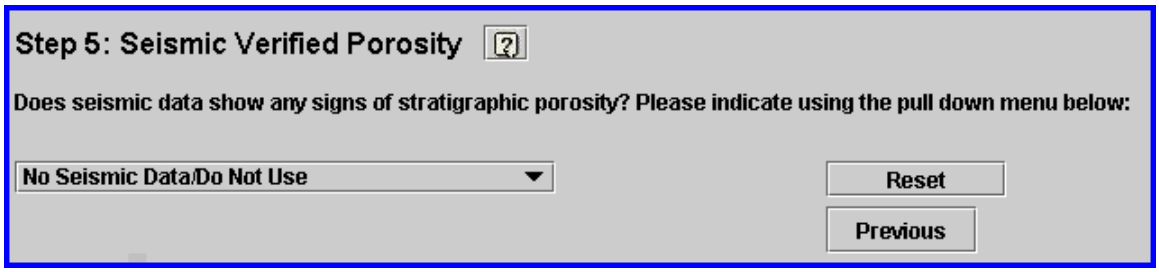
9.2.4 Potential for Other Porosity

Step 4 is provided for the user to be able to consider the potential for other porosity. No answerbase values are provided for this step, and it may be omitted from the analysis.



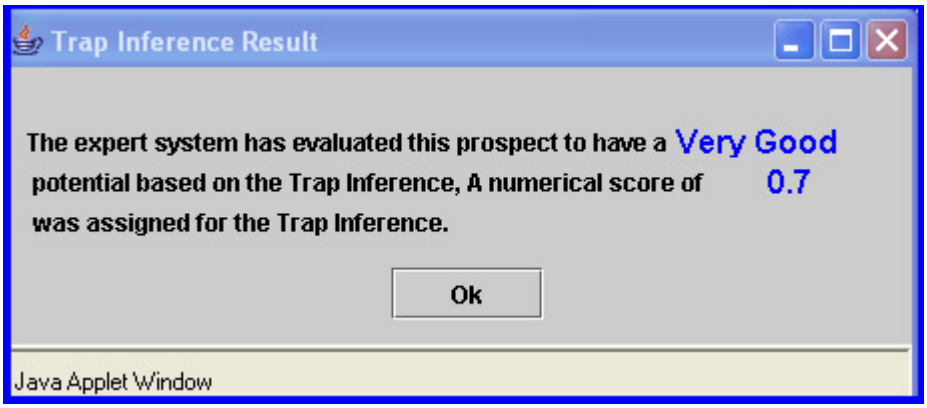
9.2.5 Seismic Verified Porosity

Step 5, the final step of the trap assessment, allows you to input seismic data. As with the previous step, the default answerbase value is to omit the step.



9.3 Trap Inference

After you have reviewed and updated the data in the assessment, you may review the output for this branch of the tool by clicking on **Inference**, and then **Trap**. This also may be done at other points in the process if you want to evaluate how a change in inputs affects the output.



CHAPTER 10: Devonian Carbonate: Formation Assessment

10.1 Overview

In this final assessment, the following things are considered:

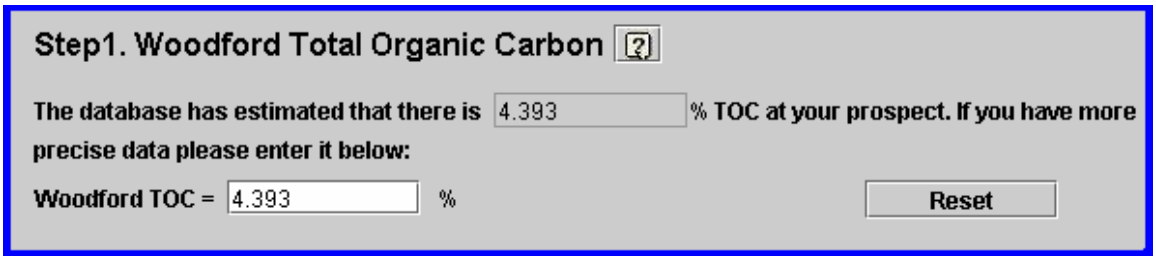
- Percentage of Total Organic Carbon in the Woodford Shale
- Thickness of Woodford Shale (the primary source rock)
- Migration Potential

As with the other assessments, you may review and update data on this screen. If you are planning on entering your own data, it's a good idea to view the formation inference prior to entering data. That way, when you review it after submitting your updated values, you can measure the effect your changes had.

10.2 Reviewing and Entering Data

10.2.1 Woodford Total Organic Carbon

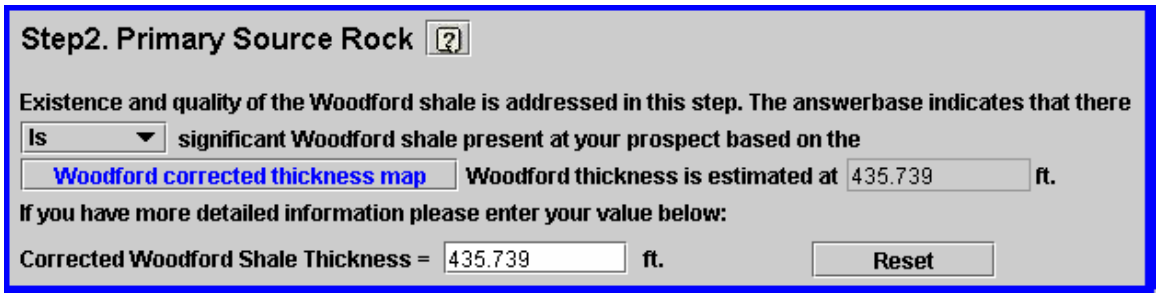
This value in **Step 1** is based on an interpolation of Total Organic Carbon (TOC) over the region. If you have more accurate data, you may replace the answerbase value with your data.



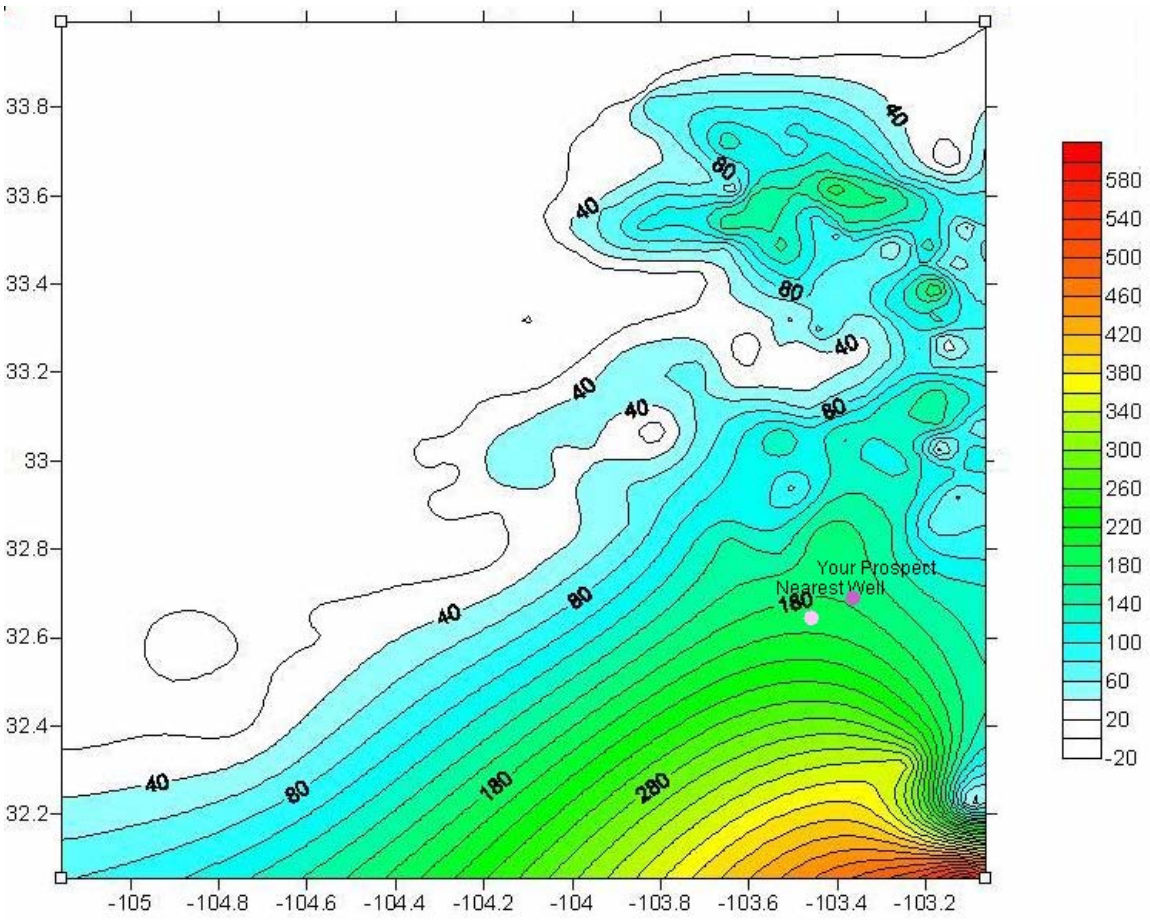
As with other steps, you may use the **Reset** button to return to the previous value.

10.2.2 Primary Source Rock

Step 2 considers the thickness of the Woodford Shale. (This is also considered in **Step 1** of the trap assessment.) The first part of the query is to determine whether or not there is significant Woodford shale at the prospect location. The second part of the query provides an answerbase value for the thickness of the Woodford shale, measured in feet. You may replace this value with your own value, and you may also use the drop down buttons to toggle **is/is not** significant Woodford shale.



With this step, as with the first trap assessment step, the following map of the interpolated values is provided. The left mouse button will zoom in to a location and the right mouse button will zoom out. When a location is selected, the map also provides a location given in grid units (1 grid unit = 2640 feet)

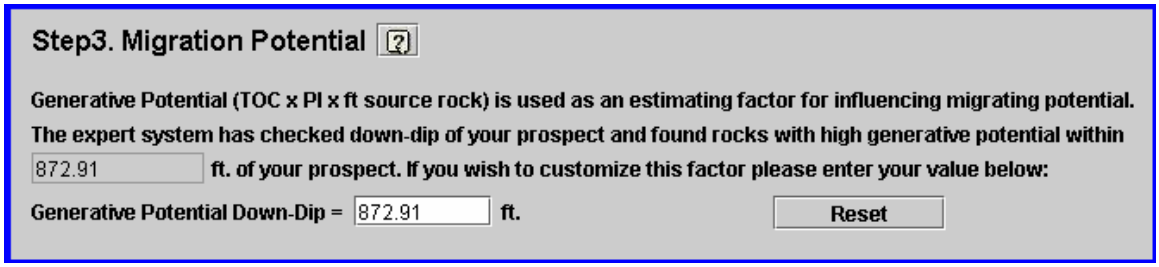


10.2.3 Migration Potential

In **Step 3**, the value provided by the answerbase is a distance (in feet) to the nearest down-dip location with a high generative potential. A shorter distance would indicate a better migration potential.

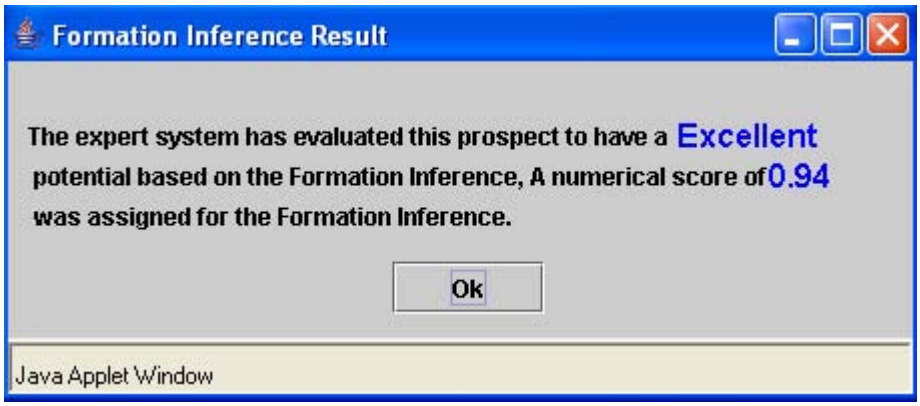
For this step, generative potential is measured using the formula TOC*PI*Woodford Thickness, where TOC is total organic carbon, PI is the production index or transformation ratio and Woodford thickness is the thickness of the Woodford shale at the location.

PI is calculated by pyrolysis of a kerogen sample, and is then interpolated over the entire region. With this value, as well as the TOC and Woodford thickness values used in the previous steps, a numerical value of generative potential is computed. Locations with a significantly high value of generative potential are then noted, and the distance from the prospect to the nearest downdip location of high generative potential is found.



10.3 Formation Inference

Once the data has been reviewed and entered, the numerical results of the formation inference are available by clicking on **Inference**, then **Formation**. As with all inference values, this value is a number between 0 and 1, and is provided along with a linguistic value to help interpret it. The four inference values, structure, regional, trap and formation, are combined using a weighted average to compute the general inference. The general inference and other means of viewing the results of the Devonian FEE Tool will be discussed in the next chapter.

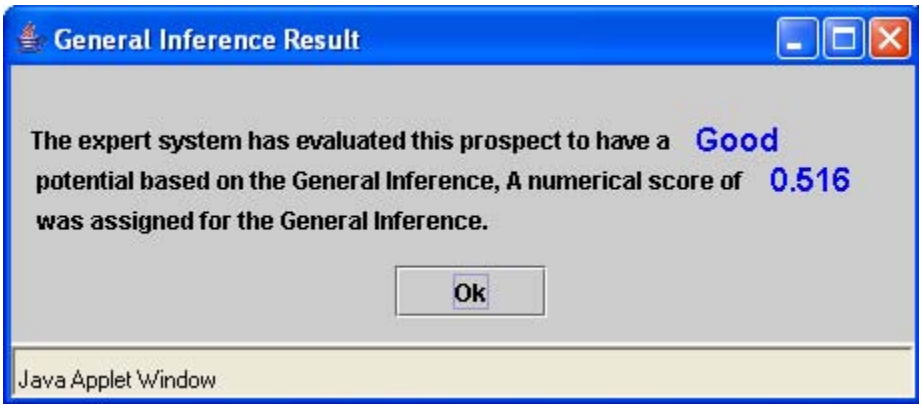


CHAPTER 11: Devonian Carbonate: Results

11.1 Inference

The main result of the Devonian FEE Tool is the numerical quality estimate, a number between zero and one, with values close to one indicating a good prospect. The quality estimate is calculated by taking a weighted average of the estimates for each assessment. Since users can view the estimate for each assessment, they may alter the weighted average to determine a new quality estimate, or they may use the default weighting scheme of 45% structure, 15% trap, 25% formation and 15% regional.

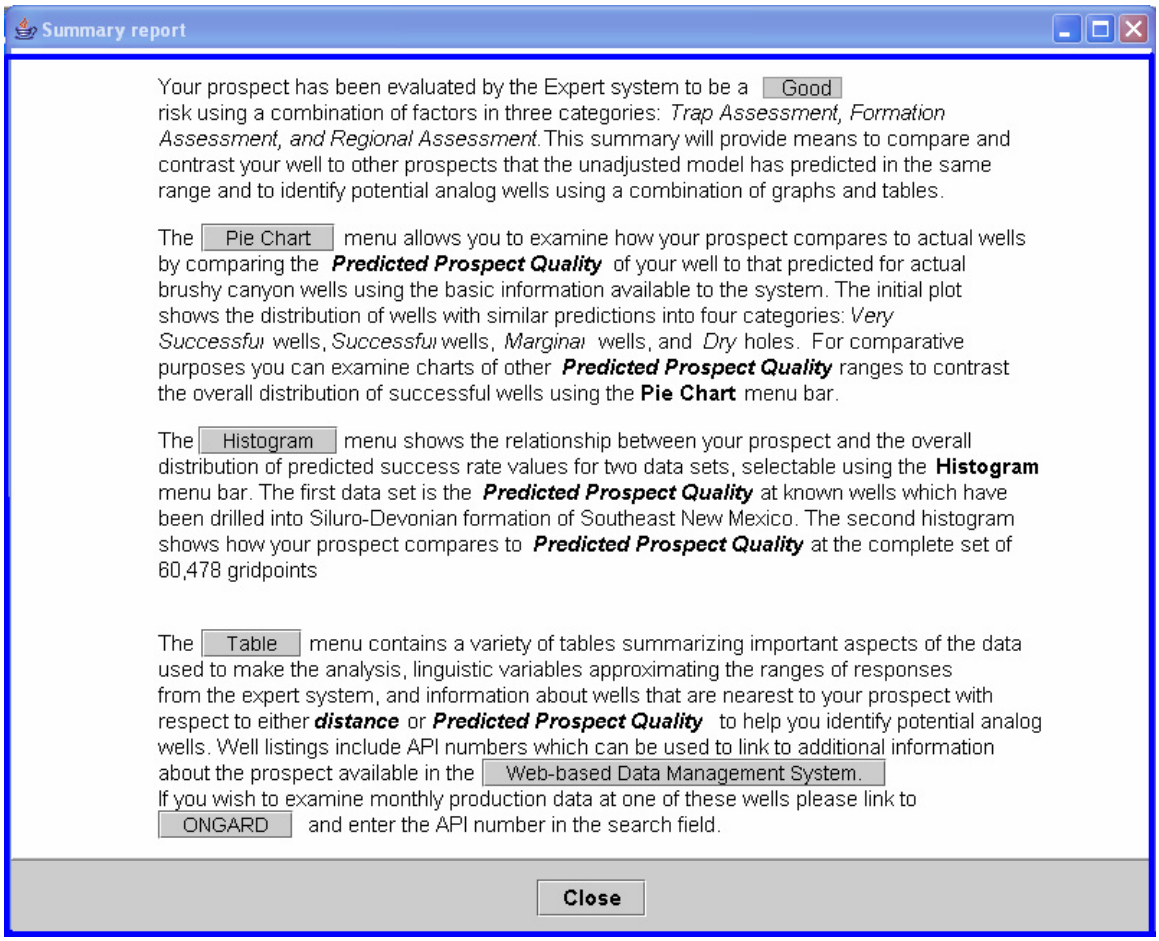
The numerical quality estimate, along with a linguistic value to help interpret it, is found by clicking on **Inference**, then **General**.



11.2 Results

The **Results** section of the FEE Tool provides a number of tools for you to use in interpreting your results. There are five options found when clicking on the **Results** option: **Summary, Pie Chart, Histogram, Table** and **Download**.

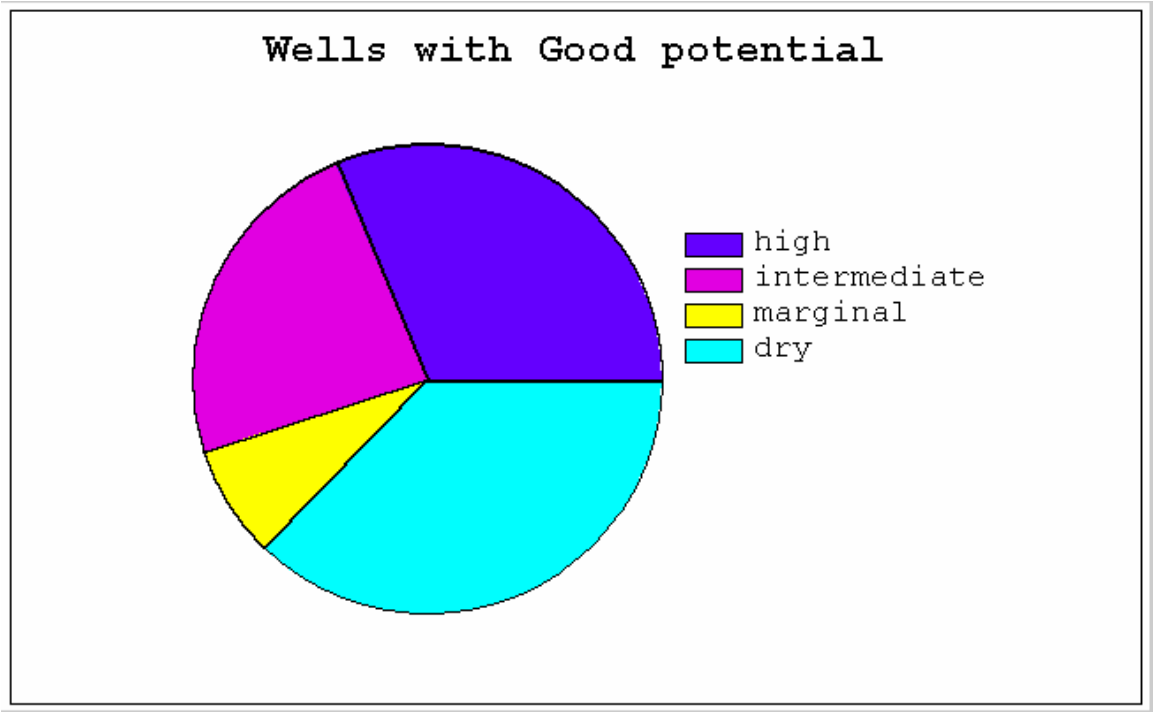
The summary page provides a brief summary of the results for your prospect, links to the other results features, and links to other helpful tools. The first paragraph provides the same linguistic value as found with the quality estimate.



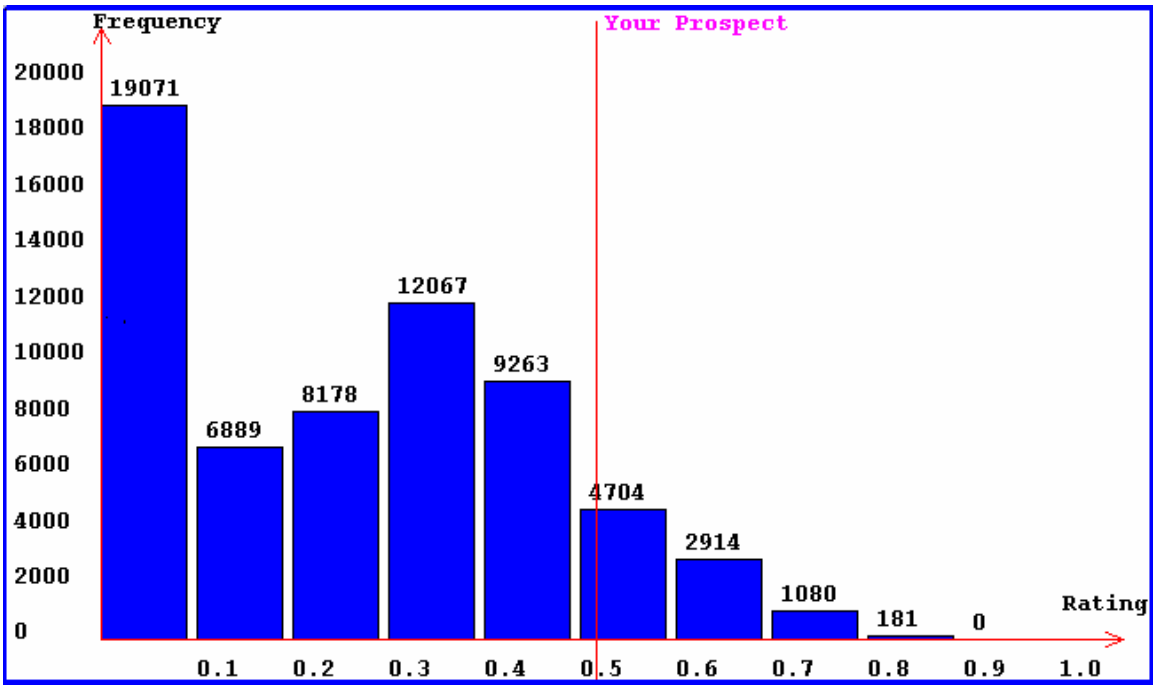
The summary pages include links and descriptions of the other result options. The first is the pie charts, where for each linguistic variable output (i.e. good) there is a pie chart showing the quality of producing wells at that output.

An example of the pie chart for ‘good’ is given below. This shows wells divided up into four categories based on production level. All of the wells in this pie chart have quality estimates falling in the ‘good’ range.

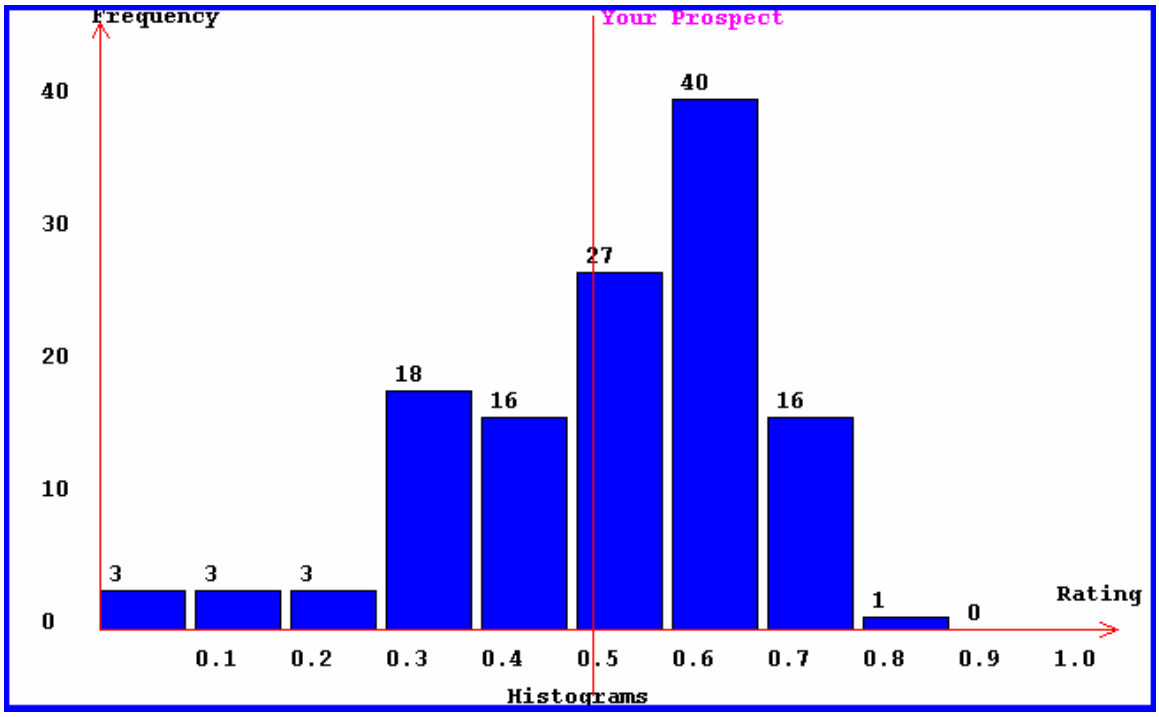
The pie charts can be reviewed for all categories of linguistic variables, and the same pie chart menu can be accessed by going to **Results**, then **PieChart**.



Two histograms are also provided to help you analyze your results. The first shows where your prospect fits with regard to the numerical estimates for all points in the region.



The next histogram shows where your prospect is with respect to producing wells in the region.



The next paragraph describes the available tables. There are three tables available, the first containing the 10 closest producing well by distance, the second containing the 10 closest producing wells by quality estimate, and the third containing an answerbase summary at the prospect location. The first two tables contain the wells API numbers, and the two links in the last page of the summary paragraph (**ONGARD** and **WDMS**) can be used to get further details about those wells. In these tables, oil volume is given in BOEPM (barrels of oil equivalent per month) averaged over the first producing year. The **ONGARD** database contains full production information on these wells.

The table and histogram menus are also available on both the summary page and by clicking on **Results** and scrolling down. Finally, a download feature is also available on the **Results** menu

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CHAPTER 12: Example Project with the Devonian FEE Tool

In this chapter, the complete process of using the FEE Tool to evaluate a prospect will be illustrated.

Step 1: Create a Project

To begin the process of using the FEE Tool, click on **Project**, then **New**. You will then be asked to name your project. For this example, the project name is "Sample 1."

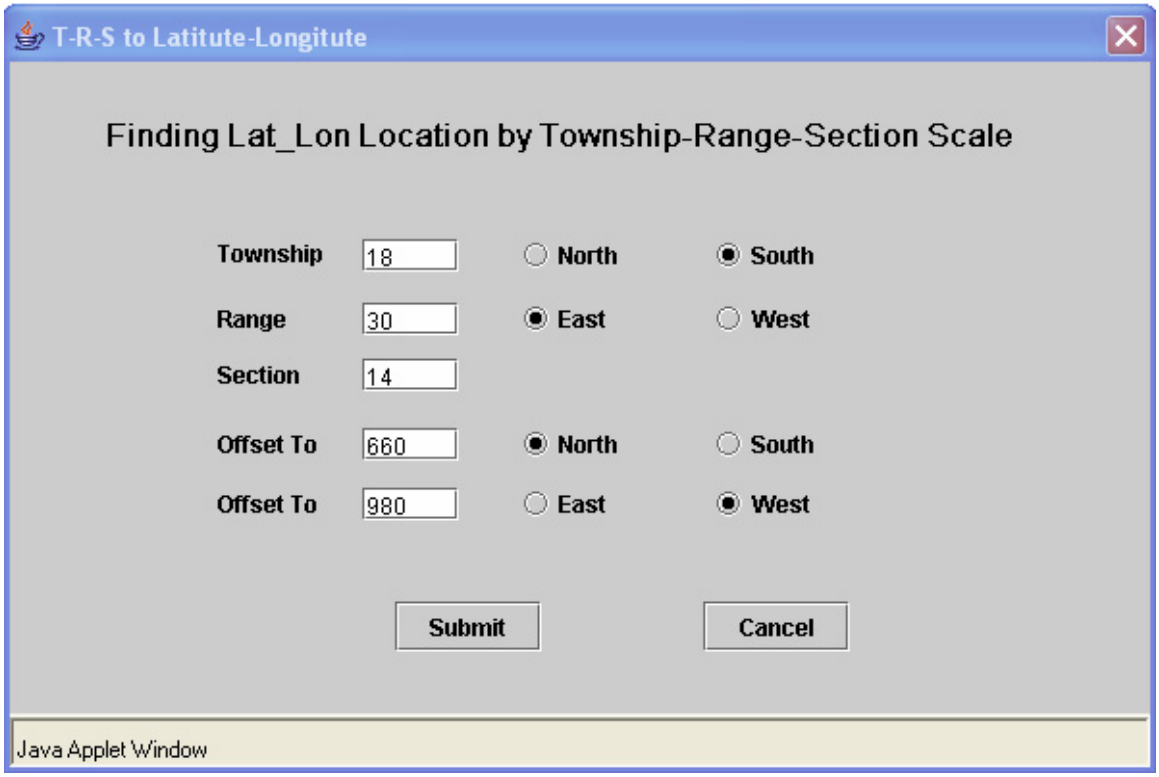
Once you have named the project, click **OK** to close this window. A second window will pop-up telling you that project "Sample 1" has been created. Click **OK** to close this window. You can use the other features in the **Project** menu to manage your projects (open, close, new or delete).

Step 2: Enter Location Data

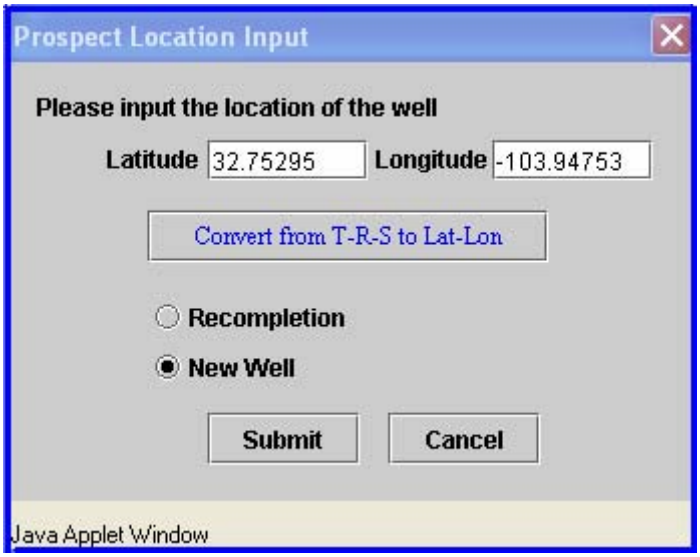
The next step is to enter location data. For this example, the location chosen to evaluate is:

Township: 18 S
Range: 30 E
Section: 14
Offset to 660N, 980W

To enter this information, go to **Input Data**, then **Location**. Then select **Convert from T-R-S to Lat-Lon**. The following screen will pop-up for entering T-R-S location data.



Once you have entered your data, click **Submit**. This will take you back to the previous screen, where you will see the latitude and longitude coordinates for the point you entered. Click **Submit** again to enter this location information for the project. A message box will appear stating that the answerbase has data for this location. Click **OK** to close this box.



Step 3: Review and Update Assessment Data

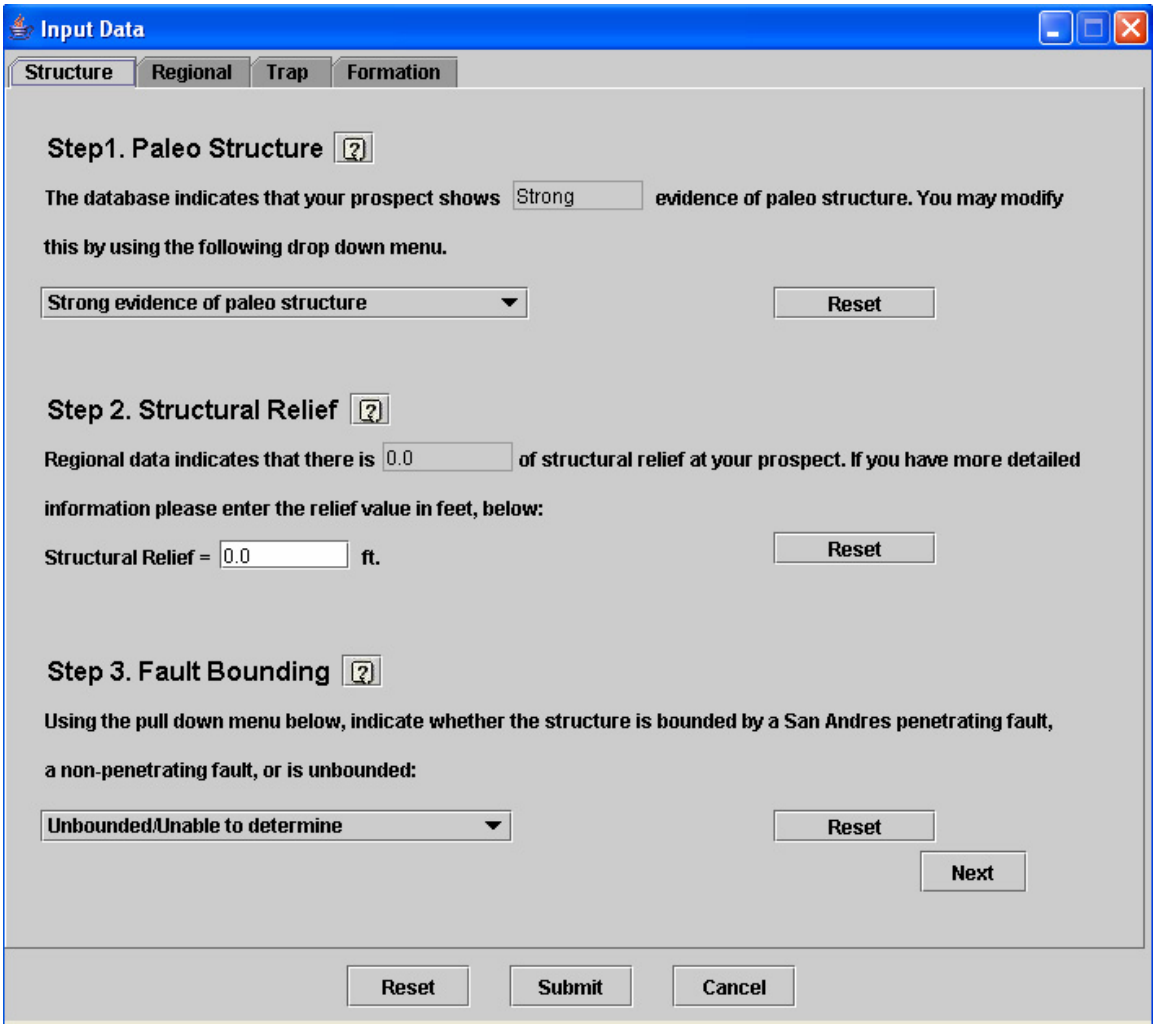
Once the location is entered, the answerbase data for the prospect is available for review. You may also make changes to the answerbase data for a number of steps if you have better or more up to date data sources. If you are planning on making any changes, it is a good idea to review the inference values of the four assessments prior to this change to help determine the affect the changes have on the output.

To review the inference data, click on **Inference**, then on the assessment you wish to view. For this location, the initial inference values for the four assessments and the overall assessment are:

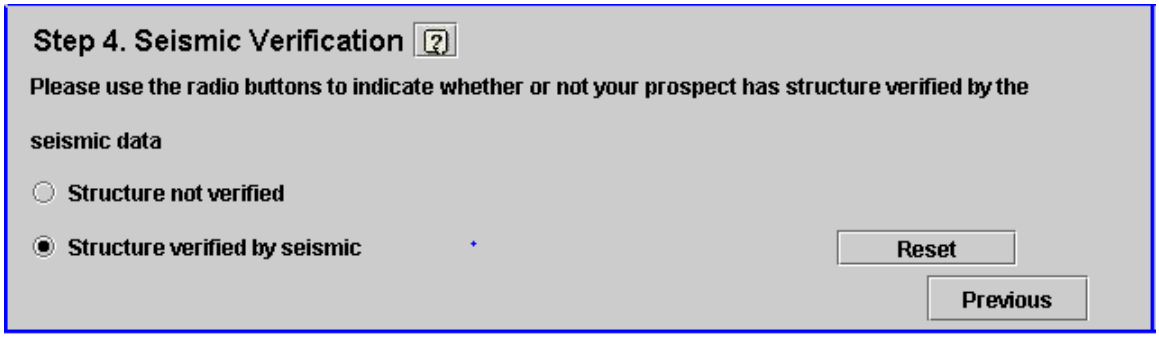
Structure: 0.489
Regional: 0.031
Trap: 0.226
Formation: 0.638
General: 0.356

It would be possible at this point to go to the results section and get more information about the results based solely on the answerbase values available to the expert system. This would be a good approach if you had no external data you wished considered, or if you wanted to quickly review a number of possible locations.

To investigate this location in more detail, return to the **Input Data** menu and begin reviewing the individual assessments. The first assessment is the **Structure** assessment. This is a two page assessment, with four questions. The first two questions have answerbase values, and the second require user input to be considered in the computation of the structure estimate. For this example, there is strong evidence of a paleo structure, which contributes to the higher value of the structure inference, but no structural relief. If no change is made, these windows can just be closed so that the next assessment can be reviewed, while if a change is made, the **Submit** button must be selected at the bottom of the relevant page.



In order to review the effects of a change in one of these, toggle the **Seismic Verification** button, then click **Submit** at the bottom of the second page.

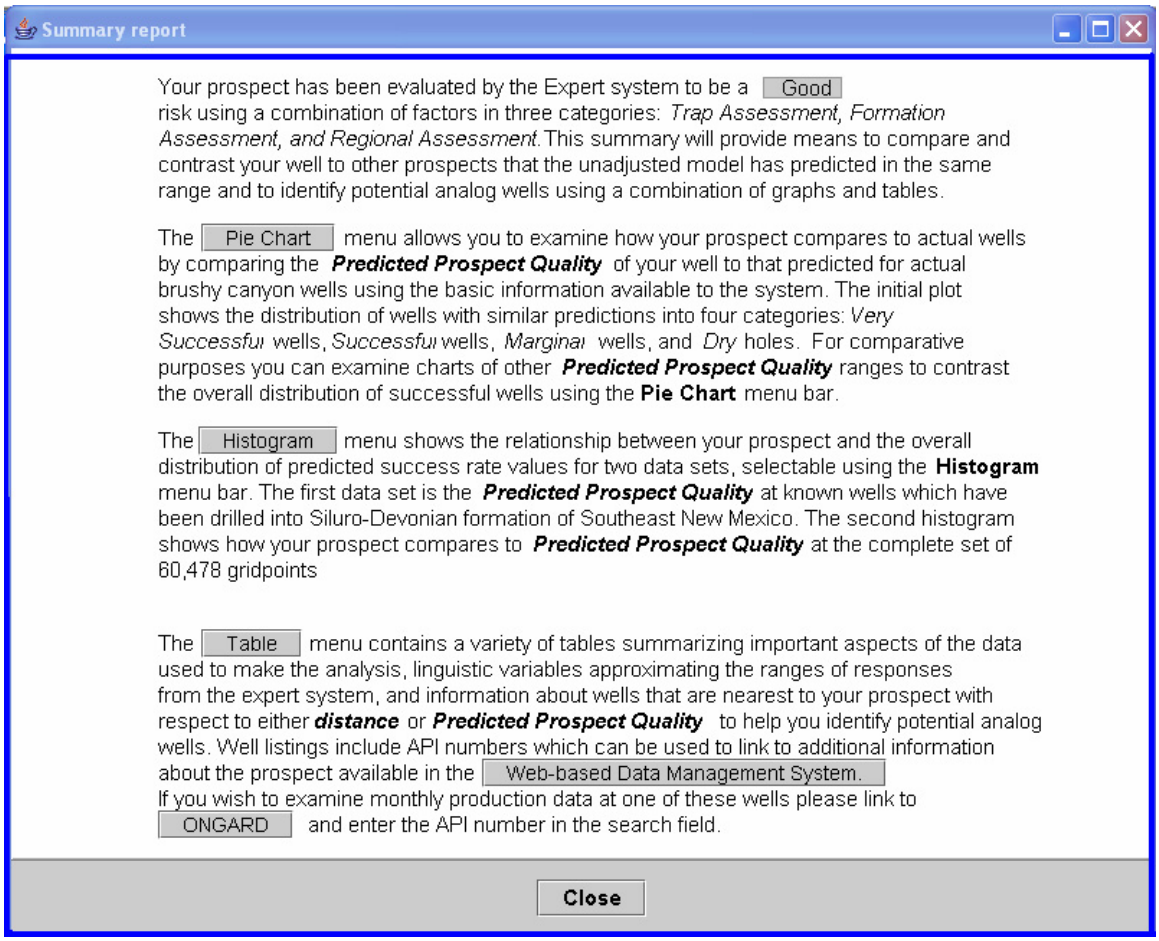


With this change, you can now check the structure inference results. The new structure inference value is 0.887, showing how the addition of seismic data positively influenced the outcome. This change also increased the general inference to 0.456. You may review the other three assessments in the same way, and make changes as you see fit.

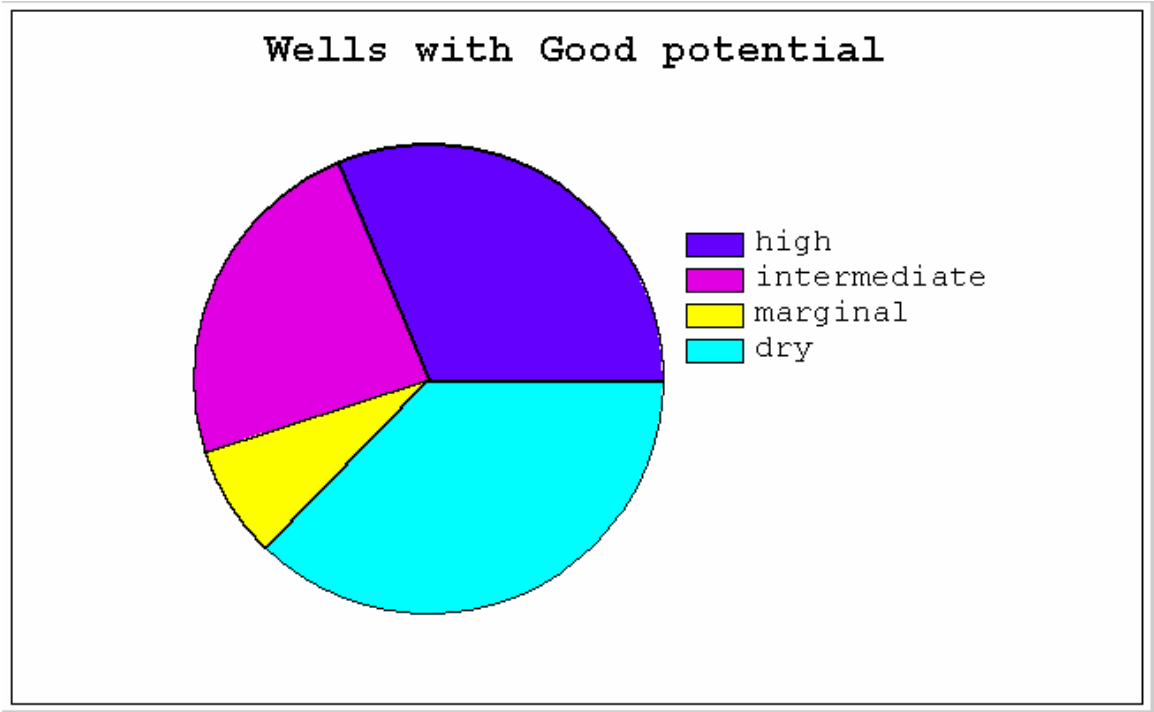
Step 4: Results

Once you have completed your review of the four assessments, you're ready to look at the results. If you have not done so already, first go to the **Inference** menu and check the **General** inference. With the one change made in **Step 3**, the general inference is 0.456, which is associated with the linguistic variable of "Good." This is the value that will be plotted on the histograms in the **Results** menu. You can modify that value by using your own weighing scheme on the four individual inference values.

The summary page for this project at this point looks like:

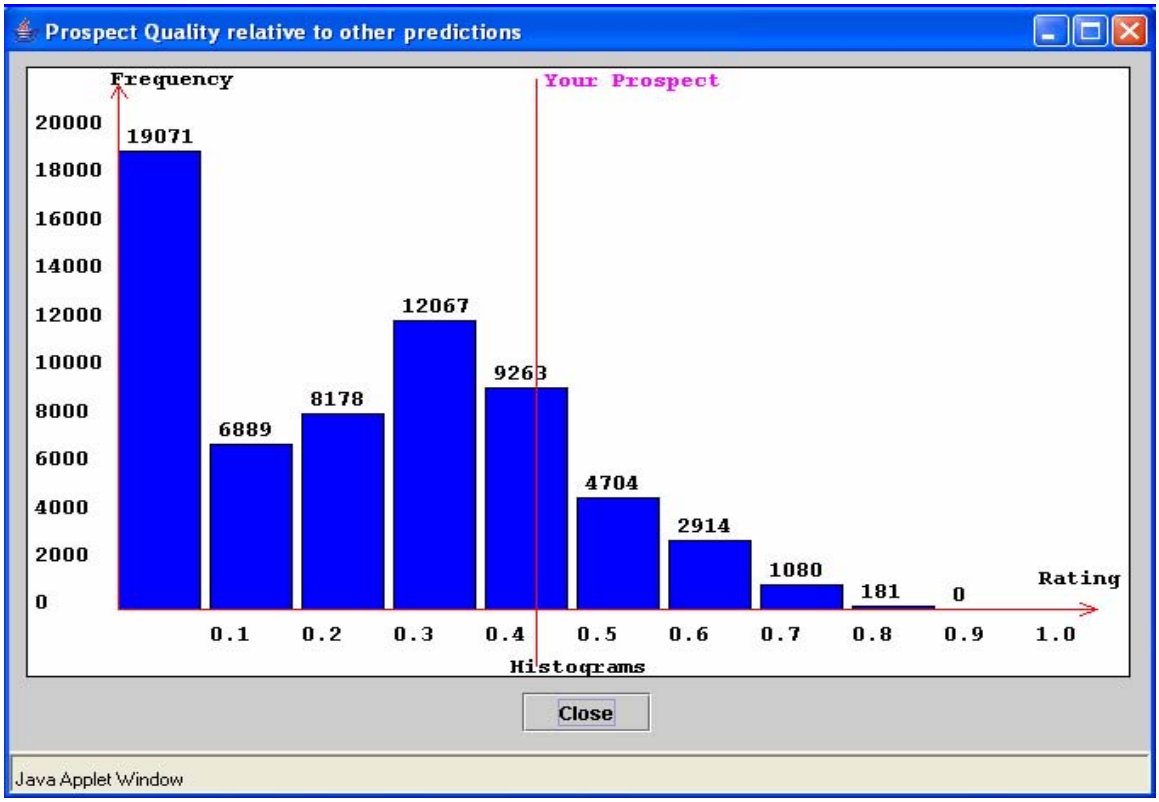


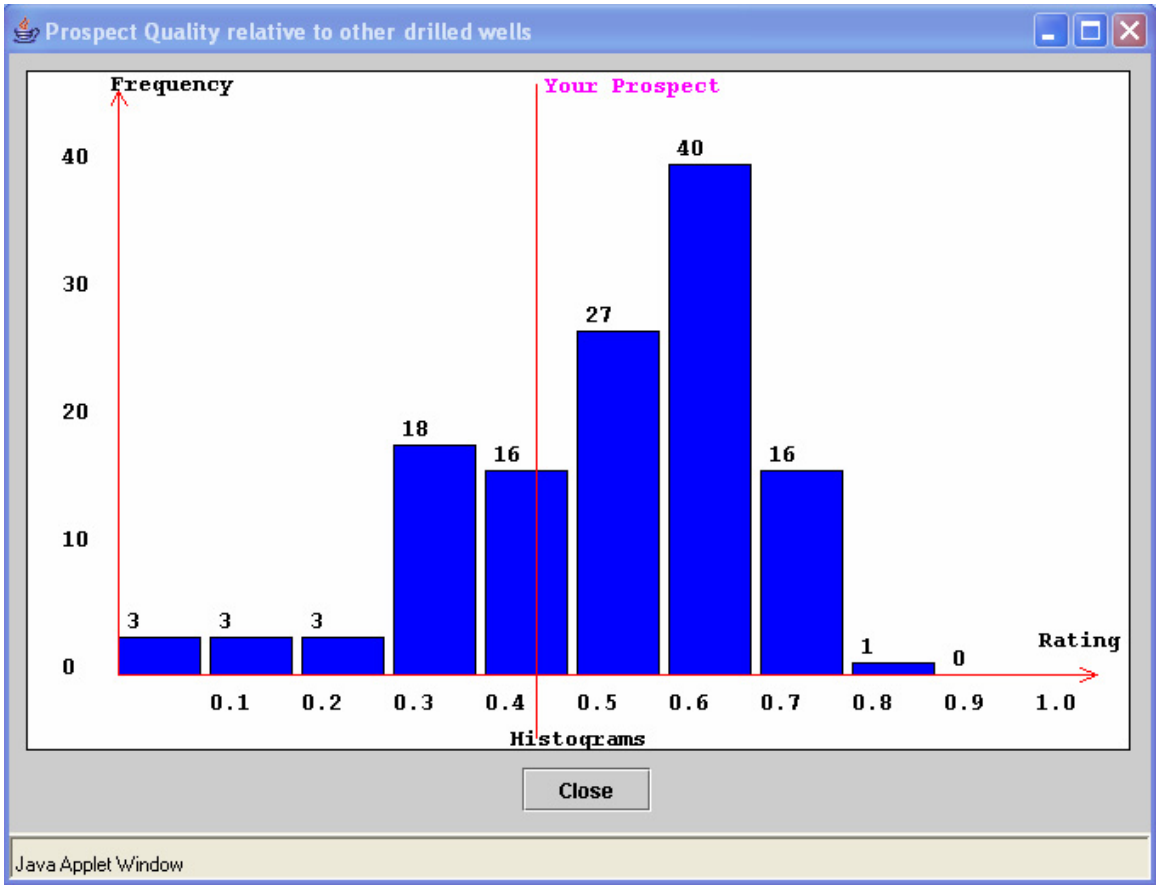
The pie chart for the "Good" category is shown below. You can also use the pie chart menu to look at pie charts in other categories for comparison.



You can now review how your prospect compares to the other locations by clicking on the **Histogram** menu. The first histogram compares your prospect to all the estimates for the entire system, and the second compares your prospect's estimate to the estimates at producing wells. These histograms are given below. When you are done reviewing the histogram, click on **Close** to close the window.

The variety of approaches for reviewing data provides a good basis for evaluating the well. You can use the pie charts to get an estimate of the likelihood of a dry hole, you can use the histograms to get an idea of where your prospect fits in the overall picture, and you can use the **Inference** menu to see how improved data affects the prospect's potential.


Prospect Quality relative to other predictions
Frequency
Your Prospect
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
19071
6889
8178
12067
9263
4704
2914
1080
181
0
Rating
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Histograms
Close
Java Applet Window


Prospect Quality relative to other drilled wells
Frequency
Your Prospect
40
30
20
10
0
3
3
3
18
16
27
40
16
1
0
Rating
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Histograms
Close
Java Applet Window

Appendix A1: Delaware Basin Quick Start Instructions

Dr. Robert Balch
Principal Investigator
Petroleum Recovery Research Center
New Mexico Tech

Quick Start Instructions

Detailed instructions are being developed. This basic set of instructions will give the user information on operating the Delaware Basin FEE Tool and interpreting the results.

If you have more detailed questions or wish to share comments please contact Principal Investigator Robert Balch by phone at (505) 835-5305 or by email at balch@prrc.nmt.edu.

Step 1:

Create a project

Each prospect that you wish to evaluate will need its own project. To create a new project, select **New** from the **Project Menu**. Enter an appropriate name to identify the prospect and click the **OK** button. Your project is now created and defaults to being the active project.

You can manage your prospects using the **Project** menu to **Open**, **Close**, or **Delete** prospects. When your session is over you can also **Exit** the FEE Tool from the **Project** menu.

Step 2:

Locate Your Prospect

The location of your prospect needs to be entered into the database before relevant data can be obtained from databases or modified by the user.

Select the **Location** item on the **Input Data** menu. In the pop-up you can enter your location UTM x and y or as Latitude and Longitude coordinates. A button to convert from Township-Range-Section to latitude and longitude is available as well. Once your coordinates are entered, toggle the radio button to indicate whether the well is a **New Well** or a **Recompletion** and select the **Submit** button.

Step 3:

Review and modify

Select the **Trap Info** item on the **Input Data** menu. Data for the Lower Brushy Canyon Formation for your prospect will be summarized in questionnaire form, allowing the user to review, and modify information the Expert System uses to evaluate prospect potential (and inversely drilling risk).

Review or modify answers in each of the three major categories: **Trap, Formation, and Regional** by selecting the tabs in the top of the applet. Each section has on-line help files that can be viewed by selecting the **Help** [?] button following the subheadings.

When all sections are complete select **Submit** to save your customized answers.

Step 4:

Processing by the Expert System

Under the **Inference** menu select the **General Inference** item. The resulting pop-up gives you a linguistic indication of the quality (or lack of) for your prospect, as well as a numerical value in the set {0, 1}.

You may also examine the inference results for each of the three major analyses independently by selecting the **Trap Inference**, **Formation Inference**, or **Regional Inference** menu items.

Step 5:

Interpreting the Results

Select the **Summary** item from the **Results** menu. The **Summary** pop-up contains a linguistic interpretation of the quality of your prospect. Details on the available **Pie Charts**, **Histograms**, and **Tables** that are available to compare your prospect to other Lower Brushy Canyon wells can be found in this applet along with links to more information about the prospect location from the FEE Tool databases, and production information at nearby or analog wells.

Appendix B1: Devonian Quick Start Instruction

Quick Start Instructions

This basic set of instructions will give the user information on operating the Devonian FEE Tool and interpreting the results. More detailed information can be found in the user's guide, available online.

If you have more detailed questions or wish to share comments please contact Principal Investigator Robert Balch by phone at (505) 835-5305 or by email at balch@prrc.nmt.edu.

Step 1:

Create a project

Each prospect that you wish to evaluate will need its own project. To create a new project, select **New** from the **Project** menu. Enter an appropriate name to identify the prospect and click the **OK** button. Your project is now created and defaults to being the active project.

You can manage your prospects using the **Project** menu to **Open**, **Close**, or **Delete** prospects. When your session is over you can also **Exit** the FEE Tool from the **Project** Menu.

Step 2:

Locate Your Prospect

The location of your prospect needs to be entered into the database before relevant data can be obtained from databases or modified by the user.

Select the **Location** item on the **Input Data** menu. In the pop-up you can enter your location in latitude and longitude or use the built in function to convert from Township-Range-Section and offsets to latitude and longitude. Once your coordinates are entered, toggle the radio button to indicate whether the well is a **New Well** or a **Recompletion** and select the **Submit** button.

Step 3:

Review and modify

Select the **Trap** item on the **Input Data** menu. Data for the Devonian region for your prospect will be summarized in questionnaire form, allowing the user to review and

modify information the expert system uses to evaluate prospect potential (and inversely drilling risk).

Review or modify answers in each of the four major categories: **Structure, Trap, Formation,** and **Regional** by selecting the tabs in the top of the **Input Data** menu. Each section has on-line help files that can be viewed by selecting the **Help** [?] button following the sub-headings.

When all sections are complete select **Submit** to save your customized answers.

Step 4:

Processing by the Expert System

Under the **Inference** menu select the **General Inference** item. The resulting pop-up gives you a linguistic indication of the quality (or lack of) for your prospect, as well as a numerical value in the set {0, 1}.

You may also examine the inference results for each of the three major analyses independently by selecting the **Structure Inference, Trap Inference**, **Formation Inference**, or **Regional Inference** menu items.

Step 5:

Interpreting the Results

Select the **Summary** item from the **Results** menu. The **Summary** pop-up contains a linguistic interpretation of the quality of your prospect. Details on the available **Pie Charts, Histograms**, and **Tables** that are available to compare your prospect to other Devonian wells can be found in this menu item along with links to more information about the prospect location from the FEE Tool databases, and production information at nearby or analog wells.

Appendix C1: Predict Online

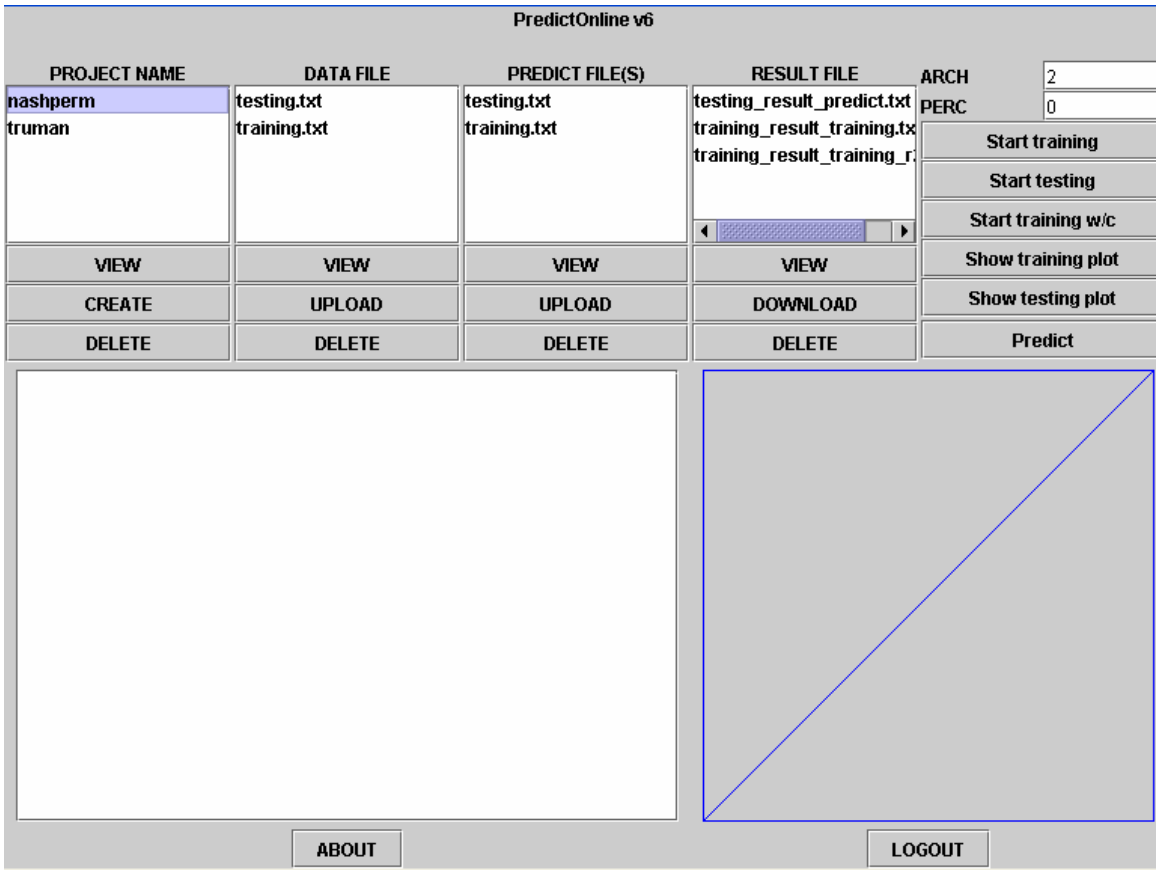
PredictOnline (v6) is a neural network program using a scaled conjugate gradient algorithm, which allows the user to design the architecture of a neural network, train the network and then use it to predict the desired output. Scaled conjugate gradient (SGA) algorithms do not require the user to set up any parameters and are one of the fastest neural network algorithms. A weakness of the SGA is that it sometimes stops at a local minimum, indicated by a low value of the r^2 coefficient. To avoid this problem, the user can design different architectures until satisfied with the value of the r^2 coefficient.

As an example of how a neural network can be used in this context, consider a well for which both log and core data are available for a number of points. Since core data is rarer than log data, a neural network that could predict outputs from a core analysis from log data only would be a useful tool. To develop such a tool, a file is created with selected log data and the desired core output at each measurement interval. This file is used to train the neural network. Various architectures can be tried, until a satisfactory network is developed, as measured by an r^2 coefficient. Once this network has been developed, a file containing only the log data is uploaded, and the neural network predicts the desired output.

The following discussion is a quick overview on how to use PredictOnline. More detailed instructions are available at the REACT group home page. As with the FEE Tool, a password is required to access PredictOnline. For information, please contact the principal investigator, Dr. Robert Balch, at (505) 835-5305 or at balch@prrc.nmt.edu.

Training the Network

This is the main screen of the PredictOnline software after logging in. To begin, create a project by using the **CREATE** button under **PROJECT NAME**. Project names cannot contain blank spaces or characters (except for the underscore).



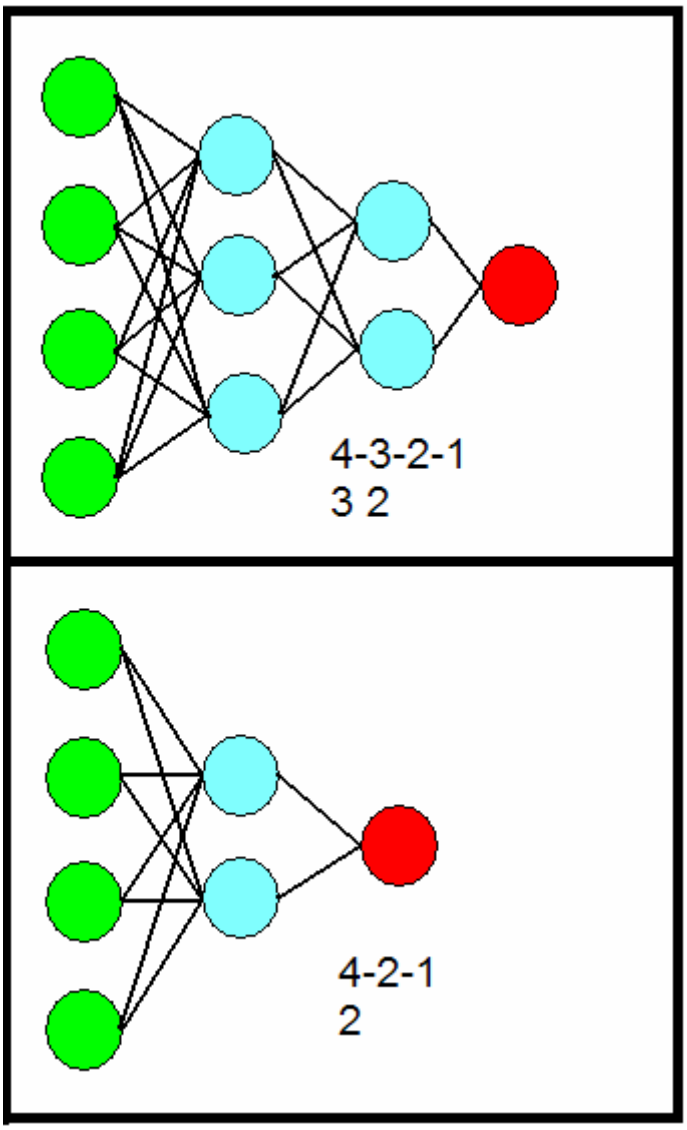
Once a project has been created, the next step is to upload the training file. The training file should contain one column for each of the inputs and a column with the desired output. For example, if you wish to use the density porosity log, the neutron porosity log, and the deep and shallow resistivity logs as inputs, and porosity as the output, you will have five columns. This file needs to be saved as a text file (MS-DOS) before it is uploaded to PredictOnline, and should contain nothing except the data. The data file names also cannot contain blank spaces or characters, except for the underscore. Use the **UPLOAD** button, found under the heading **DATA FILES** to upload your file. You can then use the **VIEW** button to review your file.

This is a section of the training text file, training.txt, located in the project "nashperm."

12.35796	10.95687	0.761219466	0.798280405	0.0141
12.26929	10.8962	0.745757721	0.78639078	0.013
11.45856	10.75751	0.710823683	0.757305668	0.0494
10.99607	11.01295	0.699933936	0.750982543	0.0621
11.12615	11.46186	0.695435268	0.749769543	0.0509
11.84594	11.86979	0.694496392	0.747322454	0.0573
12.26404	12.07957	0.684823826	0.739792205	0.095
12.1006	12.17758	0.69669705	0.753514884	0.0135
10.94726	12.05988	0.698923967	0.759261306	0.0105
9.46349	11.48265	0.69983946	0.762259819	0.0154
9.14738	11.88223	0.671561589	0.735103649	0.0739
9.954	12.88112	0.644256364	0.704908583	0.0223
11.53813	14.26971	0.602305298	0.662114411	0.0138
12.35881	15.14189	0.558378525	0.615389208	0.0391
13.26688	14.99623	0.559188189	0.619626476	0.0445
12.01361	14.49653	0.582515612	0.647374167	0.0274
10.23213	13.75425	0.583068353	0.651302249	0.0126
9.22176	12.84457	0.575351829	0.647767209	0.0541

In this example, the first four columns contain the inputs (in this case, the neutron and density porosity and the log of the deep and shallow resistivity), and the last column contains the permeability, measured from core samples.

The next step is to design an architecture. Since there are four inputs and one output, designing an architecture involves deciding on the amount and structure of the hidden nodes. The following two graphs are examples of neural network architecture. For each graph, the inputs are shown in green, the outputs in red, and the hidden nodes in light blue. Two notations are shown with each drawing, the first listing all of the nodes, including the input and output, and the second showing only the hidden nodes. The second method is how the architecture is recorded for PredictOnline. The example screen shown above is using the 4-2-1 or 2 architecture.



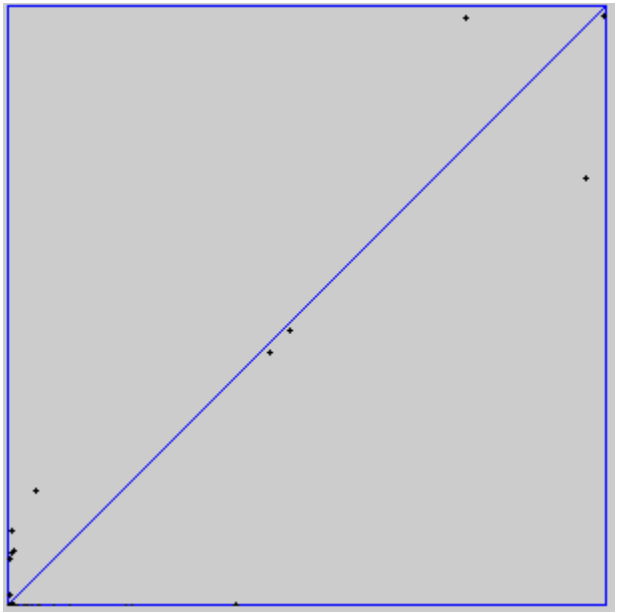
A rule of thumb to use when designing an architecture is that the number of connections should be less than one half of the number of data points available (the number of rows). In the first architecture shown above, the number of connections is 4*3+3*2+2*1 or 20. Using a complex network architecture with a small amount of data can result in overtraining, producing unreliable results.

When the architecture is selected and the value placed in the box next to **ARCH**, the next step is to decide on a percentage split of your file for training and testing. You can elect to use your entire file for training, or you may reserve some portion of it for testing. The percentage you wish to reserve for testing is indicated in the box next to **PERC**. Enter the value you select as a whole number, i.e. 10 for 10%.

When the training file has been uploaded and the architecture and percentage determined, use the **Start Training** button to train the network. You will see the training progress in the lower left window. When the process is complete, you will find the following information at the bottom of that window.

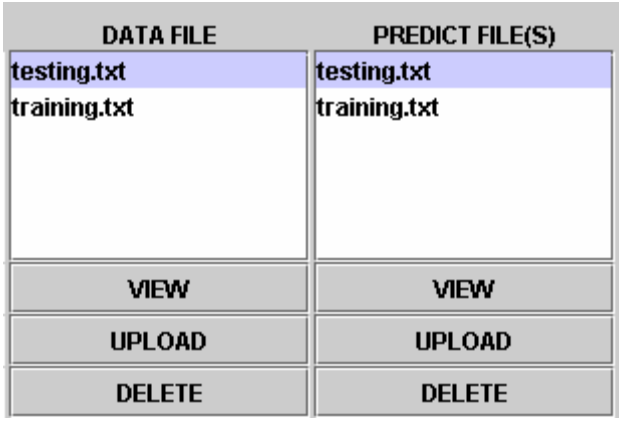
```
total cycles trained: <undef>
the best  MSE = 0.00462796
result has been store into your project folder
train (r2 r) = (0.84850 0.92114)
end
```

The closer the r2 and r values are to one, the better the network performed. It is a good idea to perform the training on a network a couple of times to check for consistency. You can also generate a scatter plot to visually evaluate the performance of the network by clicking on **Show training plot**.

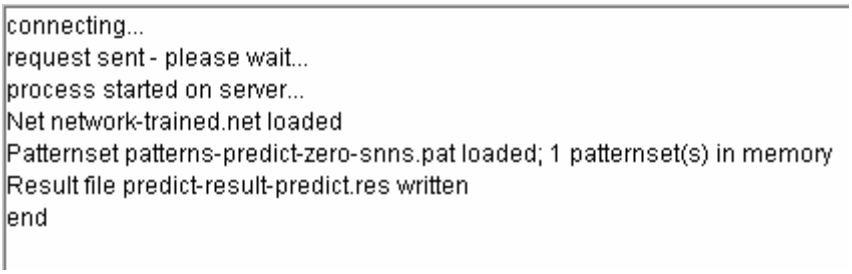


Using the Network for Predictions

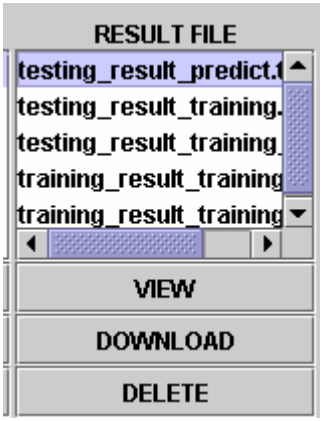
Now that the network is trained, upload a file with just the inputs. This file needs to be in the same format as the file you uploaded to train the network, but with one less column. You will notice that when you upload a file, it appears both in the **DATA FILE** and **PREDICT FILE(S)** window. Highlight your file in both places, and then click on **Predict**.



Once again, this process will be viewed in the lower left window. Upon completion, you should see the message shown below.



This message gives you the name of the predicted file. The last column of this file contains the predicted values of the output based on the input you provided. In this example, the output column contains predicted permeability, based on the log inputs. Find this file in the last column and click the download button to save it. It will be saved as a text file, which you can then open with Excel or Notepad.

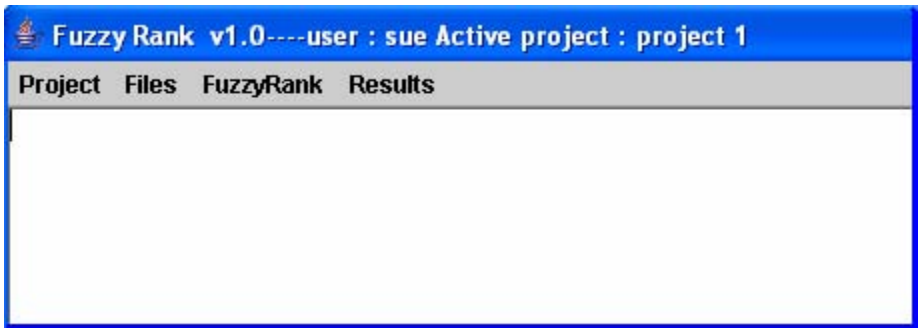


Appendix D1: Using the FuzzyRank Program

The FuzzyRank program, developed by members of the REACT group at the PRRC, provides a quick method to select the inputs for use in a neural network (such as PredictOnline) or other prediction algorithm. It is relatively simple to use, with an interface similar to the interfaces for PredictOnline and the Fuzzy Expert Exploration Tools. For more details on the fuzzy ranking algorithm used by this program, see the theory section.

In order to use the program, prepare a text (MS-DOS) file with the possible inputs stored in the first *n-1* columns and the desired output stored in the nth column. This file should not have any column headers.

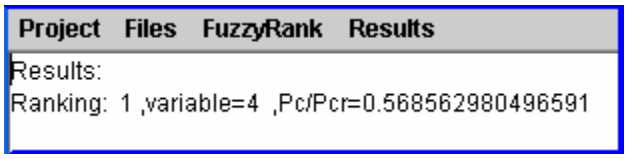
Once the file is created, log in to **FuzzyRank**. (To create an account, email Dr. Balch at balch@prrc.nmt.edu) Once you have logged in, you will need to create a project. From the menu at the top of the screen (shown below), select **Project** and then **New**. Then give your project a name.



Once you have created a project, you can upload your file to that project by clicking on the **Files** link. Clicking on **Upload** brings you to the file uploader. FuzzyRank and PredictOnline use the same tool for uploading files. Use the **Browse…** button to search your computer for the text file, and once you have selected it, click on **Submit file**.

After the file has been uploaded, you can proceed to the fuzzy ranking algorithm by clicking on **FuzzyRank**. Depending on the size of the file, this may take a few moments. When it is completed, you will see the results appear on the screen. The top variable is the most significant or best ranked input variable; the next is the second, and so on. A

sample output is given below. In this example, the **FuzzyRank** algorithm selected only one variable as being a significant input variable.



The variable number (4) indicates that the variable selected as being the most significant was located in the fourth column of the text file. In cases of multiple significant variables, the variables are ranked by the Pc/Pcr coefficient, with the highest value of this coefficient indicating the most significant input. For more information on interpreting the results, see the theory page.

Clicking on the **Results** button provides a second view of the results, as well as a tool to download the results to your computer, which can be especially valuable if there are numerous significant inputs.

Appendix E1: An Introduction to the Fuzzy Ranking Algorithm

The REACT software, FuzzyRank, can be used to select and rank the most significant inputs from a list of possible inputs. This can be done as a preliminary step prior to using an artificial neural network, such as PredictOnline, to predict outputs.

For example, a user wishing to predict oil saturation may have a variety of types of well log data to use as possible inputs, such as density porosity, gamma ray, neutron porosity, and deep and shallow resistivity. Using the fuzzy ranking algorithm (FRA) to rank these and other possible inputs prior to building a neural network can produce a more efficient network with a lower risk of overtraining.

The fuzzy ranking process begins with the construction of fuzzy curves and surfaces for each input variable. Consider a system where there are n possible input variables, one desired output variable and k data points.

Input 1	Input 2	….	Input n	Output
$x_{1,1}$	$x_{2,1}$		$x_{n,1}$	y_1
$x_{1,2}$	$x_{2,2}$		$x_{n,2}$	y_2
		.		
		.		
		.		
$x_{1,k}$	$x_{2,k}$		$x_{n,k}$	y_k

For each of the input variables, a Gaussian fuzzy membership function is generated at each data point as follows:

With this membership function defined, the fuzzy curve for the ith input is defined as: The fuzzy surface, a two dimensional fuzzy curve is defined using two input variables as:

Once the fuzzy curves and surfaces have been generated, they are analyzed in order to determine which input variables are best able to predict the output variables. The fuzzy ranking algorithm used by FuzzyRank uses the performance index to rank the inputs. The performance index is a method that involves looking at the mean square error between the fuzzy curve for the variable x_i and the output variable y. A small value of this performance index indicates that the variable is related to the output. A similar approach may also be taken for the fuzzy surfaces, which can also give information about whether or not two variables are correlated.

The FuzzyRank algorithm then normalizes the performance indices for the fuzzy curves and surfaces. This is done by computing fuzzy curves and surfaces for a random variable

generated by the code. The performance index for the fuzzy curve of x_i is divided by the performance index of this random variable in order to normalize it.

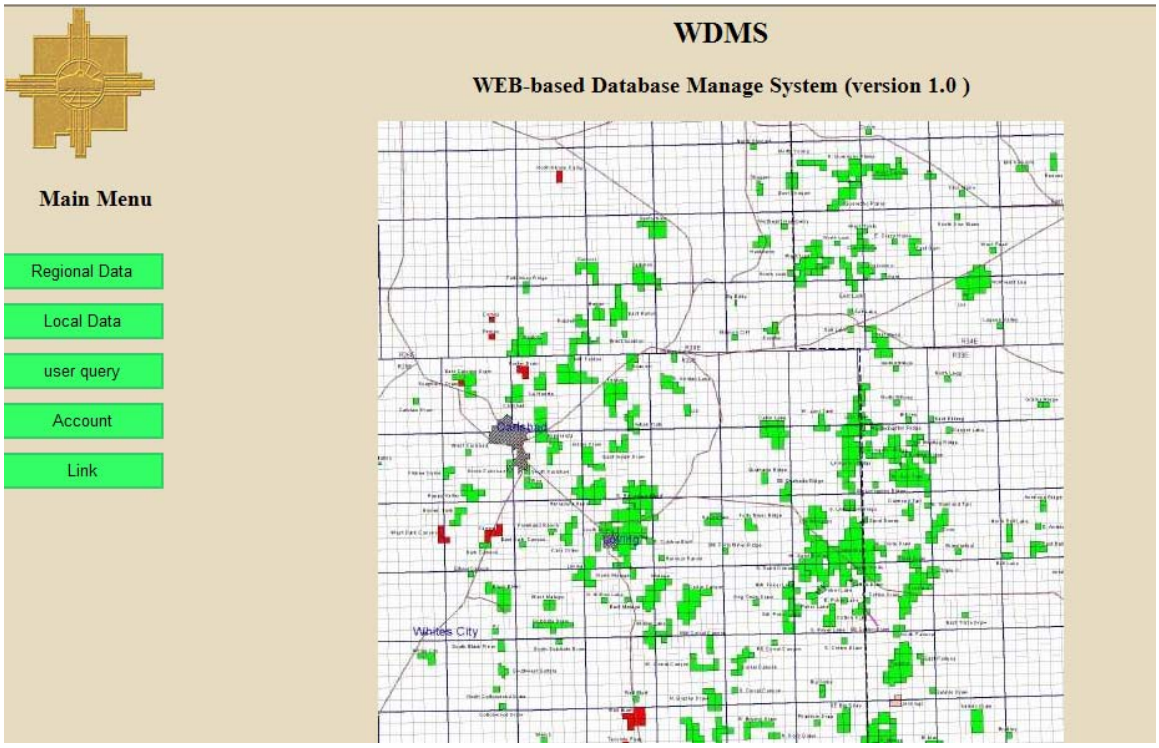
The FuzzyRank software provides this information in the Results screen. When the code is run, the output is a list of the best ranking variables. Each entry in this list contains the variable rank, the variable number and the normalized performance index for the fuzzy curve (or surface).

References

1. Lin, Y., *Input Identification and Modeling with Fuzzy and Neural Systems*, PhD Dissertation, New Mexico Tech, Socorro, NM 1994.
2. Hart, D.M., *Evaluation of a Multi Layer Perceptron Neural Network for the Time-to-Depth Conversion of the Nash Draw "L" Seismic Horizon using Seismic Attributes*, Masters Thesis, New Mexico Tech, Socorro, NM, 2001.
3. Postorino, M. and Versaci, M., "A Fuzzy Approach to Simulate the User Mode Choice Behavior", http://www.iasi.rm.cnr.it/ewgt/13conference/4_postorino.pdf, Mediterranean University of Reggio Calabria, Italy.

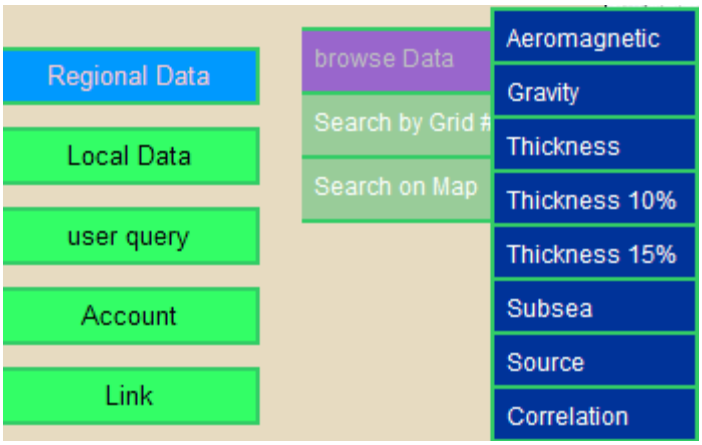
Appendix F1: WDMS – Web Based Data Management System

The Web Based Data Management System is a dynamic database containing information about the lower Brushy Canyon formation in the Delaware Basin. Data included in this database was used in the development of rules for the FEE Tool. Data retrieved from the WDMS can be downloaded in Excel or Access. The WDMS also includes maps of regional attributes viewable by the user.



Regional Data

The first menu option is **Regional Data**. Clicking on this option allows you to browse the data, search for a particular grid number, or search on the map.



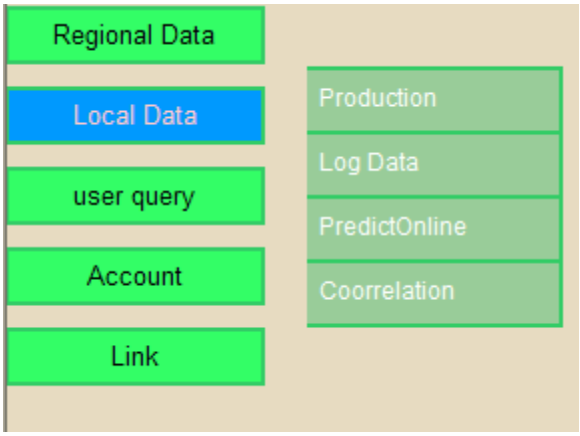
The available data, as seen in the menu above, includes the gross thickness of the lower Brushy Canyon formation, the thickness of the sands with porosity of 10% or greater, the thickness of the sands with porosity of 15% or greater, and the subsea elevation.
For all of these variables, the first and second derivatives in each direction are also available. The following screen shows the first page of results when choosing **browse Data** for **Thickness**. More data is available by scrolling to the right.

grid number	X	Y	Lat	Long	Brushy Thickness	Thk_dx	thk_dy	thk_dx2	thk_dy2	thk_dipaz	thk_dipmag
1	380320.0	378840.0	32.04096	-104.7196	306.69	4.52E-4	-0.00783	-6.23E-9	-2.22E-7	3.6377	0.00784
2	380320.0	377520.0	32.03733	-104.7196	315.92	4.52E-4	-0.00757	-5.88E-9	-2.11E-7	3.6432	0.00759
3	380320.0	376200.0	32.0337	-104.7195	325.15	4.52E-4	-0.00732	-5.53E-9	-2.01E-7	3.6488	0.00733
4	380320.0	374880.0	32.03007	-104.7195	334.38	4.52E-4	-0.00707	-5.18E-9	-1.91E-7	3.6543	0.00708
5	380320.0	373560.0	32.02644	-104.7195	343.62	4.52E-4	-0.00681	-4.83E-9	-1.81E-7	3.6599	0.00683
6	380320.0	372240.0	32.02282	-104.7195	352.85	4.53E-4	-0.00656	-4.48E-9	-1.7E-7	3.6654	0.00657
7	380320.0	370920.0	32.01918	-104.7195	362.08	4.53E-4	-0.0063	-4.14E-9	-1.6E-7	3.671	0.00632
8	380320.0	369600.0	32.01556	-104.7195	368.37	4.55E-4	-0.00613	-3.73E-9	-1.53E-7	3.6751	0.00614
9	381640.0	378840.0	32.04097	-104.7153	307.26	4.44E-4	-0.00783	-6.89E-9	-2.21E-7	3.6366	0.00784
10	381640.0	377520.0	32.03734	-104.7153	316.49	4.44E-4	-0.00757	-6.54E-9	-2.11E-7	3.6421	0.00759

last 10 points next 10 points

Local Data

The local data menu is shown below. Production and log data can be searched either through API number or pool. The other options PredictOnline and Correlation provide results for the well from running neural network or correlation studies. (See the Appendix discussing PredictOnline for more information)



The following two figures give an example of the production data available. The first shows the listing of pools, both by name and number. Once a pool is selected, the API numbers of wells in the pool are shown, and a specific well can be selected. The second figure is a section of the production data.

Pool ID	Pool Name
96872	WITTY SPRINGS;PICTURED CLIFFS (G)
17625	DIABLO;FUSSELMAN (ASSOCIATED)
96580	MIDWAY;UPPER PENNSYLVANIAN, WEST
81180	MCKITTRICK HILLS;MORROW (GAS)
96623	COLLINS RANCH; WOLFCAMP, NE. GAS
27260	GEM;DELAWARE, EAST
80980	MANY GATES;MORROW (GAS)
46709	MILNESAND;ABO
21650	E-K;BONE SPRING
79920	LAKE ARTHUR;PENN (GAS)
62305	VACUUM;PENN, NORTHWEST
76080	DOS HERMANOS;MORROW (GAS)
74720	CEMETERY;ATOKA, NORTH (GAS)
77190	FRONTIER HILLS;STRAWN (GAS)
75360	CRAWFORD PENN (GAS)
41850	LUSK;YATES, NORTHEAST

For this example, the pool numbered 41850 was selected, and the well with API number 3002527189 was selected.

Delaware Basin Production Information

Well ID:	3002527189	Pool ID:	41850	Pool Name :	null

Prodution Date	Status	Oil Volumn	Gas Volumn	Water Volumn	CO2 Volumn	Days of Production
1990-12-01	A	30.0	1.0	66.0	0.0	22
1990-05-01	A	76.0	1.0	31.0	0.0	31
1990-02-01	A	69.0	1.0	112.0	0.0	28
1990-07-01	A	72.0	1.0	30.0	0.0	30
1990-06-01	A	63.0	1.0	145.0	0.0	29
1990-08-01	A	66.0	1.0	31.0	0.0	31
1990-04-01	A	75.0	1.0	120.0	0.0	30
1990-11-01	A	49.0	1.0	240.0	0.0	30
1990-03-01	A	69.0	1.0	186.0	0.0	31
1990-01-01	A	78.0	1.0	62.0	0.0	31
1990-10-01	A	66.0	1.0	310.0	0.0	31
1990-09-01	A	69.0	1.0	60.0	0.0	30
1991-04-01	A	50.0	1.0	90.0	0.0	30
1991-12-01	T	0.0	0.0	0.0	0.0	0
1991-02-01	A	61.0	1.0	224.0	0.0	28
1991-08-01	T	0.0	0.0	0.0	0.0	0
1991-05-01	A	55.0	1.0	155.0	0.0	31

The user query allows users to query the database using SQL commands. Other menu items include a link for registering (creating an account) and logging in. Links to other pages of interest at the PRRC are also provided. By following a link to the PRRC home, you can also visit the GO-TECH website with statewide oil and gas production data.

Appendix D. Project Software

Table D1. Software Elements and Specifications by Major Component

Software Name	Version	Type	Lines	Bytes
Delaware FEE Tool	Online	Java Applets	18,140	663.567
		Java Servlets	8,465	313,814
	Standalone	Java Application	26,158	939,877
Devonian FEE Tool	Online	Java Applets	18,763	695,882
		Java Servlets	10,438	397,124
	Standalone	Java Application	27,006	929,043
PredictOnline	Online	Java Applets	2,942	99,707
		Java Servlets	2,805	94,536
	Standalone	Java Application	5,910	173,039
FuzzyRank	Online	Java Applets	2,004	69,884
		Java Servlets	2,015	65,408
	Standalone	Java Application	2,589	77,020
Total			127,235	3855,998

Programming Productivity

Table D4 lists Java software developed throughout the course of this project. According to Capers Jones, chairman of Software Productivity Research and a respected expert in the area of software development, the maximum productivity of a skilled Java programmer is 1,060 lines per month. These overall productivity estimates include: requirements analysis; the time needed to understand the problem; the time needed for testing; and the time required to ensure that the final product is stable. (It is important to note that only 30% of productivity is directly related to actual coding time.)

Therefore, the software generated by the project represents about 10 programmer years (127,235/1,060 = 120 programmer months = 10 programmer years). Most software development occurred in the final three years of the project. Full-time staff represents about half the programming effort, with an average of four to five graduate students working half-time representing the other half.

To ensure quality and productivity, the following process was followed in software development: First the requirements of the project were carefully analyzed; then the system structure was designed and divided into class levels; then tasks were distributed to student or staff programmers according to their ability. Students were given close instruction in order to accomplish these tasks. Core classes were designed and coded by REACT researchers. All software was written according to Java Conventions so that the codes are easy to read, understand and maintain.

All students that worked on the project, who subsequently graduated with computer science degrees, have obtained full-time employment in software development.

The 127,000 lines of software developed for the project represents nearly 2000 pages if printed. Therefore all software files are included on a compact disc, or can be found on the web at http://ford.nmt.edu. Complete lists of classes by project element, followed by first order software trees are included in this appendix in the order shown in Table D1.

Software Lists and Trees

Delaware Applets Files:

```
a. BarChart.java
b. BarFrame.java
c. ButtonEditor.java
d. ButtonRenderer.java
e. DataInput.java
f. DataObject.java
g. ExpertSystem.java
h. Feet2.java
i. FeetLogin1.java
j. FormationAssessment.java
k. FormationStep1Text.java
l. FormationStep2Text.java
m. FormationStep3Text.java
n. GetNearestWellLocation.java
o. HelpText.java
p. ImageGravity.java
q. ImagePhi10.java
r. ImagePhi15.java
s. ImageStructure.java
t. Instructions.java
u. LocationInput.java
v. LoginComm.java
```

```
w. MapClick.java
x. myWin.java
y. PieChart.java
z. PieFrame.java
aa.ProjectComm.java
ab.ProjectData.java
ac.ProspectLocation.java
ad.RegionalAssessment.java
ae.RegionalStep1Text.java
af.RegionalStep2Text.java
ag.RegionalStep3Text.java
ah.RegionalStep4Text.java
ai.RegionalStep5Text.java
aj.RegionalStep6Text.java
ak.RegionalStep7Text.java
al.RequestTable.java
am.ResultFrame.java
an.SendEmail.java
ao.StructureMap.java
ap.SummaryText.java
aq.TableData.java
ar.TableExample.java
as.TableException.java
at.TrapAssessment.java
au.TrapStep1Text.java
av.TrapStep2Text.java
aw.TrapStep3Text.java
ax.TrapStep4Text.java
ay.TrapStep5Text.java
az.TrapStep6Text.java
ba.TRSInput.java
bb.UserObject.java
bc.ZoomGravity.java
bd.ZoomPhi10.java
be.ZoomPhi15.java
bf.ZoomStructure.java
```

Delaware Applets File Tree:

```
FeetLogin1.java
   |-- LoginComm.java
   |-- Feet2.java
         |--Instructions.java
         |--LocationInput.java
                  |--TRSInput.java
                  |--ProspectLocation.java
         |--DataInput.java
                  |-- FormationAssessment.java
                          |--FormationStep1Text.java
                          |--FormationStep2Text.java
                          |--FormationStep3Text.java
                  |-- RegionalAssessment
                          |--RegionalStep1Text.java
                          |--RegionalStep2Text.java
                          |--RegionalStep3Text.java
```

```
                        |--RegionalStep4Text.java
                        |--RegionalStep5Text.java
                        |--RegionalStep6Text.java
                        |--RegionalStep7Text.java
                        |--ImageGravity.java
                                |--ZoomGravity.java
                                |--GetNearestWellLocation.java
                |-- TrapAssessment.java
                        |--TrapStep1Text.java
                        |--av.TrapStep2Text.java
                        |--aw.TrapStep3Text.java
                        |--TrapStep4Text.java
                        |--TrapStep5Text.java
                        |--TrapStep6Text.java
                        |--ImagePhi10.java
                                |--ZoomPhi10.java
                        |--ImagePhi15.java
                                |--ZoomPhi15.java
                        |--ImageStructure.java
                                |--ZoomStructrure.java
                        |--GetNearestWellLocation.java
               |-- ProjectComm.java
                        |--ProjectData.java
                        |--DataObject.java
        |-- BarFrame.java
                |--BarChart.java
        |-- PieChartFrame.java
                |-- PieChart.java
        |-- ResultFrame.java
        |-- SummaryText.java
                |-- SendEmail.java
                |-- ButtonEditor.java
                |-- ButtonRenderer.java
        |-- TableData.java
                |-- RequestTable.java
        |--LatLonInput.java
                |-- MPTRSInput.java
                |-- MPprojectComm.java
                |-- MPoint.java
        |-- HelpText.java
```

Delaware Servlets Files:

a. DataObject.java
b. FACharVariable.java
c. FAVariable.java
d. FeetDatabase.java
e. FormationAssessment.java
f. FuzzyInferenceAllPoint.java
g. GetDataServlet1.java
h. Grid.java
i. IntermediateResult.java
j. LoginServlet.java
k. MapClickServlet.java
l. Membership.java
m. Point.java
n. Position.java

o. ProjectData.java
p. ProjectDataTable.java
q. ProjectServlet1.java
r. ProspectLocation.java
s. RACharVariable.java
t. RAConstant.java
u. Range.java
v. RAVariable.java
w. RegionalAssessment.java
x. runIt.java
y. Section.java
z. TableData.java
aa.TestExec.java
ab.TrapAssessment.java
ac.TrapInference.java
ad.TrapRules.java
ae.UserObject.java
af.XYPoint.java

Delaware Servlets File Tree:

```
1.LoginServlet.java
       |-- UserObject.java
2.ProjectServlet1.java
       |--ProspectLocation.java
       |--DataObject.java
       |--ProjectDataTable.java
       |--DataObject.java
       |--FeetDatabase.java
                |--Grid.java
                |--ProjectDataTable.java
                |--XYPoint.java
                |--Point.java
                |--Position.java
       |--FormationAssessment.java
             |-- Membership.java
             |--FACharVariable.java
             |--FAVariable.java
       |--RegionalAssessment.java
                |--RACharVariable.java
                |--RAConstant.java
                |--Range.java
                |--RAVariable.java
                |--IntermediateResult.java
       |--TrapAssessment.java
                |--TrapInference.java
                |--TrapRules.java
                |--TestExec.java
       |-- Section.java
3. GetDataServlet1.java
       |--TableData.java
4. MPointServlet.java
```

Delaware Standalone Files:

a. BarChart.java

b. BarChart0.java
c. BarChart1.java
d. BarFrame.java
e. ButtonEditor.java
f. ButtonRenderer.java
g. DataInput.java
h. DataInput_M.java
i. DataObject.java
j. Delaware.java
k. DelwareData.java
l. DelwareRaw.java
m. DevSections.java
n. FACharVariable.java
o. FAFuzzified.java
p. FAVariable.java
q. FormationAssessment.java
r. FormationAssessmentClient.java
s. FormationStep1Text.java
t. FormationStep2Text.java
u. FormationStep3Text.java
v. GetDataServlet1.java
w. GetNearestWellLocation.java
x. GradeRaw.java
y. HelpText.java
z. ImageGravity.java
aa.ImagePhi10.java
ab.ImagePhi15.java
ac.ImageStructure.java
ad.Instructions.java
ae.IntermediateResult.java
af.LatRange.java
ag.LatRanges.java
ah.LocationInput.java
ai.Membership.java
aj.NewTrapAssessment.java
ak.PieChart.java
al.PieFrame.java
am.Point.java
an.ProjectComm.java
ao.ProjectData.java
ap.ProjectDataTableManager.java
aq.ProjectServlet1.java
ar.ProspectLocation.java
as.RACharVariable.java
at.RAConstant.java
au.Range.java
av.RAVariable.java
aw.RegionalAssessment.java
ax.RegionalAssessmentClient.java
ay.RegionalStep1Text.java
az.RegionalStep2Text.java
ba.RegionalStep3Text.java
bb.RegionalStep4Text.java
bc.RegionalStep5Text.java
bd.RegionalStep6Text.java
be.RegionalStep7Text.java
bf.RequestTable.java

```
bg.ResultFrame.java
bh.Section.java
bi.SendEmail.java
bj.SummaryText.java
bk.Support.java
bl.TableData.java
bm.TableExample.java
bn.TableMenuItemDataManager.java
bo.TestExec.java
bp.TrapAssessmentClient.java
bq.TrapInference.java
br.TrapRules.java
bs.TrapStep1Text.java
bt.TrapStep2Text.java
bu.TrapStep3Text.java
bv.TrapStep4Text.java
bw.TrapStep5Text.java
bx.TrapStep6Text.java
by.TRSInput.java
bz.TwoDimFileEntry.java
ca.TwoDimFileManager.java
cb.WellDataForTable1_Raw.java
cc.WellDataForTable1_Table.java
cd.WellDataForTable2_Raw.java
ce.WellDataForTable2_Table.java
cf.WellsWithClosestDistances.java
cg.WellsWithClosestEstimations.java
ch.XYPoint.java
ci.XYTwoDimFileEntry.java
cj.XYTwoDimFileManager.java
ck.YRange.java
cl.YRanges.java
cm.ZoomGravity.java
cn.ZoomPhi10.java
co.ZoomPhi15.java
cp.ZoomStructure.java
```

Delaware Standalone File Tree:

```
|-- Delaware.java
        |--Instructions.java
        |--LocationInput.java
                |--TRSInput.java
                |--ProspectLocation.java
        |--DataInput.java
                |-- FormationAssessmentClient.java
                        |--FormationStep1Text.java
                        |--FormationStep2Text.java
                        |--FormationStep3Text.java
                |-- RegionalAssessment
                        |--RegionalStep1Text.java
                        |--RegionalStep2Text.java
                        |--RegionalStep3Text.java
                        |--RegionalStep4Text.java
```

```
                |--RegionalStep5Text.java
                |--RegionalStep6Text.java
                |--RegionalStep7Text.java
                |--ImageGravity.java
                        |--ZoomGravity.java
                        |--GetNearestWellLocation.java
        |-- TrapAssessment.java
                |--TrapStep1Text.java
                |--av.TrapStep2Text.java
                |--aw.TrapStep3Text.java
                |--TrapStep4Text.java
                |--TrapStep5Text.java
                |--TrapStep6Text.java
                |--ImagePhi10.java
                        |--ZoomPhi10.java
                |--ImagePhi15.java
                        |--ZoomPhi15.java
                |--ImageStructure.java
                        |--ZoomStructrure.java
                |--GetNearestWellLocation.java
       |-- ProjectComm.java
                |--ProjectData.java
                |--DataObject.java
|-- BarFrame.java
        |--BarChart.java
|-- PieChartFrame.java
        |-- PieChart.java
|-- ResultFrame.java
|-- SummaryText.java
        |-- SendEmail.java
        |-- ButtonEditor.java
        |-- ButtonRenderer.java
|-- TableData.java
        |-- RequestTable.java
                |--GetDataServlet1.java
                |--TableData.java

|--LatLonInput.java
        |-- MPTRSInput.java
        |-- MPprojectComm.java
        |-- MPoint.java
|-- HelpText.java
|--ProjectServlet1.java
        |--ProjectDataTableManager.java
        |--ProspectLocation.java
        |--DataObject.java
        |--ProjectDataTable.java
        |--DataObject.java
        |--FACharVariable.java
        |--FAVariable.java
        |--FeetDatabase.java
        |--Grid.java
        |--GradeRaw.java
        |--ProjectDataTable.java
        |--XYPoint.java
        |--Point.java
        |--Position.java
```

```
                |--BarChart0.java
                |--BarChart1.java
                |--DelwareData.java
                |--DelwareRaw.java
                |--LatRange.java
                |--LatRanges.java
                |--YRange.java
                |--YRanges.java
                |--Range.java
                |--FormationAssessment.java
                        |-- Membership.java
                |--RegionalAssessment.java
                        |--RACharVariable.java
                        |--RAConstant.java
                        |--Range.java
                        |--RAVariable.java
                        |--IntermediateResult.java
                |--TrapAssessment.java
                        |--TrapInference.java
                        |--TrapRules.java
                        |--TestExec.java
                |--Sections.java
                        |--LatRange.java
                        |--LatRanges.java
                        |--XYPoint.java
                |--DelwareData.java
                        |--DelwareRaw.java
                        |--DelwareData.java
                |--DevSections.java
                        |--XYTwoDimFileManager.java
                                |--XYTwoDimFileEntry.java
        |--GetNearestWellLocation.java
                |--WellDataForTable1_Raw.java
                |--WellDataForTable1_Table.java
                |--WellDataForTable2_Raw.java
                |--WellDataForTable2_Table.java
                |--WellsWithClosestDistances.java
                |--WellsWithClosestEstimations.java
                |--TableMenuItemDataManager.JAVA
        |--DevSections.java
                |--XYTwoDimFileManager.java
                        |--XYTwoDimFileEntry.java
```

Devonian Applets Files:

```
a.AnswerBaseSummary.java
b.BarChart.java
c.BarFrame.java
d.ButtonRenderer.java
e.DataInput.java
f.DataObject.java
g.DevonianButtonEditor.java
h.DevonianLogin.java
i.DevonianRaw.java
j.DevonianRawWithUserInput.java
k.Feet2.java
l.FeetLogin1.java
```

```
m.Formation.java
n.FormationStep1Text.java
o.FormationStep2Text.java
p.FormationStep3Text.java
q..FormationStep4Text.java
r.fuzzy890.java
s.GetNearestWellLocation.java
t.HelpText.java
u..ImageGravity.java
v.ImageThickness.java
w.Instructions.java
x.LatLonInput.java
y.LocationInput.java
z.LoginComm.java
aa.MP.java
ab.MPoint.java
ac.MProjectComm.java
ad.MPTRSInput.java
ae.NumberField.java
af.PieChart.java
ag.PieFrame.java
ah.ProjectComm.java
ai.ProjectData.java
aj.ProspectLocation.java
ak.Regional.java
al.RegionalStep1Text.java
am.RegionalStep2Text.java
an.RegionalStep3Text.java
ao.RegionalStep5Text.java
ap.RegionalStep6Text.java
aq.RegionalStep7Text.java
ar.RequestTable.java
as.ResultFrame.java
at.SendEmail.java
au.Structure.java
av.StructureStep0Text.java
aw.StructureStep1Text.java
ax.StructureStep2Text.java
ay.StructureStep3Text.java
az.StructureStep4Text.java
ba.StructureStep5Text.java
bb.SummaryText.java
bc.TableData.java
```

Devonian Applets File Tree:

```
DevonianLogin.java
    |-- LoginComm.java
         |--UserObject.java
    |--Feet2.java
         |--LocationInput.java
                |-- TRSInput.java
                |--ProspectLocation.java
         |--DataInput.java
                |--NumberField.java
                |--ProjectData.java
                |--Formation.java
```

```
                |--FormationStep1Text.java
                |--FormationStep2Text.java
                |--FormationStep3Text.java
                |--FormationStep4Text.java
        |--Regional.java
                |--ImageGravity.java
                      |--ZoomGravity.java
                |--RegionalStep1Text.java
                |--RegionalStep2Text.java
                |--RegionalStep3Text.java
                |--RegionalStep4Text.java
                |--RegionalStep5Text.java
                |--RegionalStep6Text.java
                |--RegionalStep7Text.java
        |--Structure.java
                |--StructureStep0Text.java
                |--StructureStep1Text.java
                |--StructureStep2Text.java
                |--StructureStep3Text.java
                |--StructureStep4Text.java
                |--StructureStep5Text.java
        |--Trap.java
                |--ImageThickness.java
                       |--ZoomThickness.java
                |--TrapStep1Text.java
                |--TrapStep2Text.java
                |--TrapStep3Text.java
                |--TrapStep4Text.java
                |--TrapStep5Text.java
                |--TrapStep6Text.java
|--BarFrame.java
     |--BarChart.java
                |--ButtonRenderer.java
                     |--DevonianButtonEditor.java
|-- PieFrame.java
     |-- PieChart.java
|--ProjectComm.java
     |-- DataObject.java
|--GetNearestWellLocation.java
|--HelpText.java
|--Instructions.java
|--ProjectData.java
|--AnswerBaseSummary.java
|--RequestTable.java
      |--AnswerBaseSummary.java
      |--TableData.java
      |--TableException.java
|--ResultFrame.java
|--SendEmail.java
|--SummaryText.java
|--LatLonInput.java
      |--MPTRSInput.java
      |--MPoint.java
      |--MProjectComm.java
```

Devonian Servlets Files:

a. BinFeetFile.java
b. DatabaseConnection.java
c. DataExchangeServlet.java
d. DataObject.java
e. DataReadServlet.java
f. FAFuzzified.java
g. FeetDatabase.java
h. FeetToProjectData1.java
i. FormationInference.java
j. FormationMembership.java
k. FormationRules.java
l. FRank.java
m. FuzzifyVariable.java
n. FuzzyAllPoint.java
o. FuzzyInferenceAllPoint.java
p. fuzzyRankData.java
q. fuzzyTest.java
r. GetDataServlet1.java
s. GetNearestWellServlet.java
t. GetProjectData.java
u. GetProjectDataServlet.java
v. Grid.java
w. LingVarFuzzified.java
x. LoginServlet.java
y. MapClickServlet.java
z. Membership.java
aa.MemBuild.java
ab.NewTrapAssessment.java
ac.Point.java
ad.Position.java
ae.ProjectData.java
af.ProjectDataTable.java
ag.ProjectDataTable1.java
ah.ProjectServlet1.java
ai.ProspectLocation.java
aj.RAFuzzifiedDevonian.java
ak.Range.java
al.RegionalInference.java
am.runIt.java
an.SectionDatabaseConnection.java
ao.SqlJdbcTest.java
ap.StructuralAssessment.java
aq.StructureInference.java
ar.StructureInference1.java
as.StructureMembership.java
at.StructureRules.java
au.SummaryFrame.java
av.TableData.java
aw.TestExec.java
ax.TrapAssessment.java
ay.TrapInference.java
az.TrapInference1.java
ba.TrapMembership.java
bb.TrapRules.java
bc.TRSCode.java
bd.UserObject.java

Devonian Servlets File Tree:

```
1.LoginServlet.java
       |--UserObject.java
2.ProjectServlet1.java
       |--ProspectLocation.java
       |--DataObject.java
       |--ProjectData.java
       |--FeetDatabase.java
                |--ProjectDataTable.java
                |--Grid.java
                |--Position.java
       |--FormationAssessment.java
                |--FormationInference.java
                |--FormationMembership.java
                |--FormationRules.java
                |--MemBuilder.java
       |-- RegionalInference.java
                |--RAFuzzifiedDevonian.java
                          |--Point.java
                          |--Range.java
       |--TrapAssessment.java
                |--TrapInference.java
                |--TrapInference1.java
                |--TrapMemberShip.java
                |--TrapRules.jav
       |--StructuralAssessment.java
                |--StructureInference.java
                |--StructureInference1.java
                |--StructureMembership.java
                |--StructureRules.java
       |--Section.java
                |--XYPoint.java
3. GetDataServlet1.java
       |--TableData.java
4. MPServlet.java
```

Devonian Standalone Files:

```
a. AnswerBaseSummary.java
b. BarChart.java
c. BarChart0.java
d. BarChart0Test.java
e. BarChart1.java
f. BarChart1Test.java
g. BarFrame.java
h. BasinMarginMap.java
i. BTree.java
j. ButtonEditor.java
k. ButtonRenderer.java
l. charClass.java
m. DataInput.java
o. DataObject.java
p. DataOutPutStream.java
q. DataSorter.java
r. Devonian.java
```

s. DevonianBinIOTest.java
t. DevonianButtonEditor.java
u. DevonianData.java
v. DevonianRaw.java
w. DevRaw.java
x. DevSections.java
y. DevSectionTest.java
z. FeetDatabase.java
aa.Formation.java
ab.FormationInference.java
ac.FormationMembership.java
ad.FormationRules.java
ae.FormationStep1Text.java
af.FormationStep2Text.java
ag.FormationStep3Text.java
ah.FormationStep4Text.java
ai.Frame1.java
aj.ft.java
ak.GetDataServlet1(newest).java
al.GetDataServlet1.java
am.GetNearestWellLocation.java
an.GradeRaw.java
ao.Grid.java
ap.HelpText.java
aq.ImageGravity.java
ar.ImageThickness.java
as.Index.java
at.IndexApproach.java
au.Instruction.java
av.Instructions.java
aw.InstructionText.java
ax.IntermediateResult.java
ay.LingVarFuzzified.java
az.LingVariable.java
ba.LocationInput.java
bb.LoginComm.java
bc.LoginServlet.java
bd.LonRange.java
be.Membership.java
bf.MemBuilder.java
bg.myWin.java
bh.Node.java
bi.NumberField.java
bj.PieChart.java
bk.PieFrame.java
bl.Point.java
bm.ProjectComm.java
bn.ProjectConfig.java
bo.ProjectData.java
bp.ProjectDataObjectManager.java
bq.ProjectDataRaw.java
br.ProjectDataTable.java
bs.ProjectServlet1.java
bt.ProspectLocation.java
bu.RABooleanVariable.java
bv.RACharVariable.java
bw.RAConstant.java

bx.RAFuzzified.java
by.RAFuzzifiedDevonian.java
bz.RAIntegerVariable.java
ca.Range.java
cb.RAVariable.java
cc.ReadFeetFile.java
cd.Regional-back.java
ce.Regional.java
cf.RegionalAssessment.java
cg.RegionalAssessmentold.java
ch.RegionalGravityMap.java
ci.RegionalInference.java
cj.Regionalmajed.java
ck.RegionalStep1Text.java
cl.RegionalStep2Text.java
cm.RegionalStep3Text.java
cn.RegionalStep4Text.java
co.RegionalStep5Text.java
cp.RegionalStep6Text.java
cr.RegionalStep7Text.java
cs.RegionalStructureMap.java
ct.RequestProject backup.java
cu.RequestProject.java
cv.RequestTable.java
cw.ResultFrame.java
cx.Section.java
cy.SectionDatabaseConnection.java
cz.Sections.java
da.Seismic.java
db.SendEmail.java
dc.sf.java
dd.Stratigraphic.java
de.Structural.java
df.StructuralAssessment.java
dg.Structure.java
dh.StructureInference.java
di.StructureInference1.java
dj.StructureMap.java
dk.StructureMembership.java
dl.StructureRules.java
dm.StructureStep0Text.java
dn.StructureStep1Text.java
do.StructureStep2Text.java
dp.StructureStep3Text.java
dq.StructureStep4Text.java
dr.StructureStep5Text.java
ds.SummaryText(addException).java
dt.SummaryText.java
du.Support.java
dv.SurroundingGrids.java
dw.TableData.java
dx.TableExample.java
dy.TableException.java
dz.Test.java
ea.TestIndex.java
eb.TestJApplet.java
ec.TestPane.java

```
ed.testProjectDataTable.java
ef.Trap.java
eg.TrapAsse.java
eh.TrapAssessment.java
ei.TrapInference.java
ej.TrapInference1.java
ek.TrapInput.java
el.TrapMembership.java
em.TrapRules.java
en.TrapStep1Text.java
eo.TrapStep2Text.java
ep.TrapStep3Text.java
eq.TrapStep4Text.java
er.TrapStep5Text.java
es.TrapStep6Text.java
et.TRSCode.java
eu.TRSInput.java
ev.UserObject.java
ew.UsersTabe.java
ex.XYPoint.java
ey.Zoom2.java
ez.Zoom3.java
fa.Zoom3_bak.java
fb.Zoom4.java
fc.Zoom5.java
fd.ZoomAeromag.java
fe.Zoombopm.java
ff.ZoomCulture.java
fg.ZoomGravity.java
fh.ZoomGravity1.java
fi.ZoomIsopach.java
fj.ZoomPaleo.java
fk.ZoomPhi10.java
fl.ZoomPhi15.java
fm.ZoomPredictedProduction.java
fn.ZoomStructure.java
fo.ZoomThickness.java
fp.ZoomThickness1.java
fq._BFCollector.java
fr._BFFeetTableData.java
fs._BFInput.java
ft._BFOutput.java
fu._BFVectorSort.java
```

Devonian Standalone File Tree:

```
DevonianLogin.java
    |--Devonian.java
         |--LocationInput.java
                |--TRSInput.java
                |--ProspectLocation.java
         |--DataInput.java
                |--NumberField.java
                |--ProjectData.java
                |--Formation.java
                        |--FormationStep1Text.java
                        |--FormationStep2Text.java
```

```
                |--FormationStep3Text.java
                |--FormationStep4Text.java
        |--Regional.java
                |--ImageGravity.java
                      |--ZoomGravity.java
                |--RegionalStep1Text.java
                |--RegionalStep2Text.java
                |--RegionalStep3Text.java
                |--RegionalStep4Text.java
                |--RegionalStep5Text.java
                |--RegionalStep6Text.java
                |--RegionalStep7Text.java
        |--Structure.java
                |--StructureStep0Text.java
                |--StructureStep1Text.java
                |--StructureStep2Text.java
                |--StructureStep3Text.java
                |--StructureStep4Text.java
                |--StructureStep5Text.java
        |--Trap.java
                |--ImageThickness.java
                       |--ZoomThickness.java
                |--TrapStep1Text.java
                |--TrapStep2Text.java
                |--TrapStep3Text.java
                |--TrapStep4Text.java
                |--TrapStep5Text.java
                |--TrapStep6Text.java
|--BarFrame.java
     |--BarChart.java
                |--ButtonRenderer.java
                     |--DevonianButtonEditor.java
|-- PieFrame.java
     |-- PieChart.java
|--ProjectComm.java
     |-- DataObject.java
|--GetNearestWellLocation.java
|--HelpText.java
|--Instructions.java
|--ProjectData.java
|--AnswerBaseSummary.java
|--RequestTable.java
      |--AnswerBaseSummary.java
      |--TableData.java
      |--TableException.java
|--ResultFrame.java
|--SendEmail.java
|--SummaryText.java
|--LatLonInput.java
      |--MPTRSInput.java
      |--MPoint.java
      |--MProjectComm.java
|--ProjectServlet1.java
      |--BarChart0.java
      |--BarChart1.java
      |--DevonianData.java
      |--DevonianRaw.java
```

```
|--DevRaw.java
|--ProspectLocation.java
|--ProjectDataObjectManager.java
       |--ProjectDataRaw.java
       |--ProjectDataTable.java
       |--Grid.java
       |--Position.java
|--FormationAssessment.java
       |--FormationInference.java
       |--FormationMembership.java
       |--FormationRules.java
       |--MemBuilder.java
|-- RegionalInference.java
       |--RAFuzzifiedDevonian.java
              |--Point.java
              |--Range.java
|--TrapAssessment.java
       |--TrapInference.java
       |--TrapInference1.java
       |--TrapMemberShip.java
       |--TrapRules.jav
|--StructuralAssessment.java
       |--StructureInference.java
       |--StructureInference1.java
       |--StructureMembership.java
       |--StructureRules.java
|--Section.java
       |--XYPoint.java
       |--DevSections.java
       |--DevonianSections.java
       |--GetDataServlet1.java
|--TableData.java
```

PredictOnline Applets Files:

```
a.Codes.java
b.PLoginComm.java
c.Plot.java
d.PlotData.java
e.POCliSrvInterface.java
f.POException.java
g.PredictOnline.java
h.PredictOnlineLogin.java
i.PredictOnlineLogin_old.java
j.PredictRequest.java
k.RequestType.java
l.ResultFile.java
m.SearchableList.java
n.StartNetworkThread.java
o.Text1.java
p.TextFieldWithLabel.java
q.TrainingRequest.java
r.TrainingServlet.java
s.UserObject.java
```

PredictOnline Applets Files Tree:

```
PredictOnlineLogin.java
         |--PLoginComm.java
         |--UserObject.java
         |--PredictOnline.java
               |--Codes.java
               |--Plot.java
               |--PlotData.java
               |--POCliSrvInterface.java
                      |--POException.java
               |--PredictRequest.java
                      |--RequestType.java
               |--ResultFile.java
               |--SearchableList.java
               |--StartNetworkThread.java
               |--TextFieldWithLabel.java
               |--TrainingRequest.java
```

PredictOnline Servlets Files:

```
a.Codes.java
b.FileDeleteServlet.java
c.FileDownloadServlet.java
d.FileObjectServlet.java
e.FileOps.java
f.FilePlotServlet.java
g.FileUploadServlet.java
h.PlotData.java
i.POCliSrvInterface.java
j.POServlet.java
kPredictRequest.java
l.PredictServlet.java
m.Range.java
n.RequestType.java
o.ResultFile.java
p.ResultFileStatic.java
q.ServerInfo.java
r.TrainingRequest.java
s.TrainingServlet.java
```

PredictOnline Servlets File Tree:

```
1. FileDeleteServlet.java
2. FileDownloadServlet.java
3. FileObjectServlet.java
         |--FileOps.java
                |--Range.java
4. FilePlotServlet.java
         |--PlotData.java
5. FileUploadServlet.java
6. POServlet.java
7. PredictServlet.java
        |--PredictRequest.java
                |--RequestType.java
        |--POCliSrvInterface.java
```

```
        |--ResultFile.java
        |--ResultFileStatic.java
        |--ServerInfo.java
8. TrainingServlet.java
        |--TrainingRequest.java
        |--Codes.java
        |--POCliSrvInterface.java
```

PredictOnline Standalone Files:

```
a.AutoTrain.java
b.Codes.java
c.DirInfo.java
d.fileFilter.java
e.FileOps.java
f.FilePlot.java
g.Frame1.java
h.Frame1_AboutBox.java
i.PFileFilter.java
j.PlotData.java
k.Predict.java
l.Predict1.java
m.QuickTrain.java
n.Range.java
o.RequestType.java
p.ResultFile.java
q.ResultFileStatic.java
r.TrainWc.java
```

PredictOnline Standalone File Tree:

```
Predict.java
     |--AutoTrain.java
     |--Frame1.java
            |-- Frame1_AboutBox.java
     |-- FilePlot.java
            |--PlotData.java
     |--Codes.java
     |--DirInfo.java
     |--fileFilter.java
     |--FileOps.java
     |--FilePlot.java
     |--Predict1.java
     |--QuickTrain.java
     |--PFileFilter.java
     |--Range.java
     |--RequestType.java
     |--ResultFile.java
            |--ResultFileStatic.java
     |--TrainWc.java
```

FuzzyRank Online Applets Files:

```
a.DataObject.java
b.FuzzyRank.java
c.FuzzyRankLogin.java
```

```
d.LoginComm.java
e.ProjectComm.java
f.ResultFrame.java
g.UserObject.java
```

FuzzyRank Online Applets File Tree:

```
FuzzyRankLogin.java
   |--LoginComm.java
   |--UserObject.java
   |--FuzzyRank.java
          |--DataObject.java
          |--ProjectComm.java
          |--ResultFrame.java
```

FuzzyRank Online Servlets Files:

```
a.DataObject.java
b.FRank.java
c.fuzzyRankData.java
d.LoginServlet.java
e.ProjectServlet1.java
f.UserObject.java
```

FuzzyRank Servlets File Tree:

```
1. LoginServlet.java
       |--UserObject.java
2. ProjectServlet1.java
       |--DataObject.java
       |--FRank.java
       |--fuzzyRankData.java
```

FuzzyRank Standalone Files:

```
a.DataObject.java
b.FRank.java
c.FuzzyRank.java
d.fuzzyRankData.java
e.ProjectServlet1.java
f.ResultFrame.java
```

FuzzyRank Standalone File Tree:

```
FuzzyRank.java
      |--DataObject.java
      |--FRank.java
      |--fuzzyRankData.java
      |--ProjectServlet1.java
      |--ResultFrame.java
```