U.S. DEPARTMENT OF THE INTERIOR

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A SUGGESTED RATIONALE AND SELECTED BIBLIOGRAPHY FOR USING RULE-BASED EXPERT COMPUTER SYSTEMS (ARTIFICIAL INTELLIGENCE) IN RECURRENT PETROLEUM RESOURCE ASSESSMENTS

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PURPOSE

This report explores in non-technical terms the potential for using existing U.S. Government computer hardware and commercially-available expert systems software to standardize, integrate, query, and analyze geologic databases. The use of expert systems can be incorporated as a feasible tool during the initial information-gathering phases of appraising undiscovered onshore United States oil and gas by the Branch of Petroleum Geology of the U.S. Geological Survey. Although expert systems could eventually be developed to guide the entire national assessment process, which is a major recurrent undertaking by perhaps more than seventy-five scientists who must characterize 80 provinces, my report is purely an overview. A con-ceptual framework is presented for logical possibilities of using current computer technology to handle spatial information. The report limits its scope to a small prototype representing one geographic assessment province in the Colorado Plateau of northern Arizona. The report is not a project proposal, but rather a rationale for the future development of expert systems in resource appraisal work.

The ideas and conclusions of this generalized report are not the end result of an extensive research project. For well over a decade expert systems have been researched and utilized to help solve geologic problems (see Duda and others, 1977; Duda, Gaschnig, and Hart, 1979; and, Ennis, 1983). More recent expert systems have been used to classify sedimentary basins and estimate undiscovered worldwide petroleum resources (Miller, 1986a). Cheong (1990) has described and implemented them to "Organize the available geologic data for characterizing hydrocarbon fields, plays, and prospects and sedimentary basins uniformly in terms of their essential geologic characteristics." Morgan and others (1988), Pai (1988), and Strobel (1989) are several other current developers with the foresight to use expert systems to assess petroleum resources.

Although most expert systems developed to date have been useful, they nonetheless require significant refinements; most complex expert systems are built by trial and error. My views and presentation on the potential role of expert systems in the Branch of Petroleum Geology (Geologic Division, U.S. Geological Survey) are simply intended to call attention to a neglected area of research in petroleum resource assessment. The report attempts to stimulate further interest into geologic investigations that could result in a more highly structured decision-making process, and hence faster and more reliable resource assessments.

Once again I emphasize that my intent is to generally discuss and advocate the use of innovative expert systems in conjunction with our presently used methodology; it is **NOT** to completely replace the current pre-quantitative methodology. This report has no immediate relevancy to the quantitative calculations and algorithms currently used by the U.S. Geological Survey. The reader should not construe this report as criticism of existing methods, or an attempt to modify our current probabilistic or analytical methodologies which have been "tested by fire" over many years. On the contrary, my motivation is to make the difficult job of qualifying, and hence quantifying, undiscovered resources easier. With the existing commercial expert systems, our general strategy should be to integrate and manipulate the various geologic databases owned by, or accessible to, the U.S. Geological Survey. My purpose is to cite the importance of, and to promote the efficacy of, an assessment system using current computer technology to automate human expertise. I advocate the building of a small prototype assessment expert system by a small multidisciplinary team of scientists. The report may help to provide the basic ingredients for future work. It is beyond the scope of this work to actually build a prototype system.

The second objective of this report is to suggest some relevant literature references for understanding the geology of northern Arizona; this can be a starting point in building a master, custom-designed database. It is easier to design expert system rules if one knows what kind of knowledge is available. Provincial rules can be adjusted if the system needs to be applied to surrounding geographic areas, or if the knowledge is expanded. References in this report were selected to initially cover: 1) the general geology of northern Arizona, which is the suggested test area where development of the database for an expert system appears to be ideally suited, 2) historical investigations of theoretical and applied resource appraisal methodology, 3) theoretical and applied artificial intelligence and expert systems, and 4) the origin and occurrence of petroleum.

References in this report were also selected in order to provide a solid basis for writing valid expert system rules using the principles of modern petroleum geology. The wide extent of the references will allow a geologist beginning an assessment project to apply state-of-the-art computer-based technology and methods. For any interested reader who might like to compare predicted versus actual oil and gas resources, the history of the petroleum resource assessment in the United States has been provided in the selected references.

JUSTIFICATION

We obviously live in an electronic world (the "age of information and communication") where the proliferation of information (and hopefully, knowledge) grows exponentially, doubling every five years. I believe within this plethora of scientific data and databases there is an unrealized potential, or at least an under-utilized application, for using state-of-the-art, menu-driven, rule-based "expert systems" (within the domain of artificial intelligence) to help manage our petroleum assessment information. Expert systems basically handle complex, real-world problems and are much more sophisticated than the "electronic light table" concept held by some. These systems solve problems using a convergent model of expert human reasoning, reaching the SAME CONCLUSION (single output) from a multitude of input data/information that a human would reach if given an equivalent problem. They are an extension of the expert's mind. Expert systems, as described in this report, can be used as a consultation process, i.e., helping to frame intelligent questions in combination with, or as an adjunct to, existing probablistic methodology for the oil and gas assessment of both mature and frontier petroleum provinces.

Successfully-implemented rule-based expert systems have flexibility and, hence, have wide-spread use in all disciplines of science and in the management of the U.S. economy today; thus, the ideas presented herein are not revolutionary, but rather a suggestion to integrate selected surface and subsurface databases of the U.S. Geological Survey, and interface them with commercially developed software. An expert system could manage these databases for the maximum accuracy, benefit, and productivity of resource-assessment scientists.

The efficacy and intensity of petroleum exploration is a function of the perceived risk of finding the remaining resources. It depends not only on the size of the undiscovered economically-recoverable oil and gas resources but on many physical, economic, and institutional factors, in addition to the current state of science and technology. Politics, prices, energy policies and regulations, environmental considerations, world production and distribution strategies, and other well-known supply-and-demand factors control exploration (e.g., see Adelman, 1980; Akins, 1986; Barss, 1978; Beck, 1991; Bohi, 1981; Bohi and Montgomery, 1982; Fisher, 1987; Kash and Rycroft, 1984; Ketelsen, 1987; Linden, 1973; Masters, Root, and Attanasi, 1991; McCloy, 1986; Petzet, 1991; and Thiel, 1979). These supply-and-demand factors are not addressed in this report because much literature already exists on the driving forces of exploration; they are simply beyond the realm of consideration of expert systems as outlined in this report. The eventual implementation of expert systems for resource assessment and the numbers generated should provide an evaluation (incentive or impediment) of exploration's efficacy rather than an understanding of the problems associated with the cause-and-effect of supply and demand.

Additionally, the efficacy of petroleum exploration, locally or regionally, depends on the validity of the assessment model used and on how thoroughly potential hydrocarbon plays are evaluated. These are factors that each scientist can individually control based upon the extent and quality of the wide array of geologic information that is synthesized and presented to those who must systematically quantify it. The references covering resource assessment methodology and results in this report are cited because it is important for the reader to know where and how the undiscovered, economically recoverable, conventional petroleum resource numbers/estimates have originated, and to know why the different methodologies used over the past century have resulted in significantly different resource estimates for conventional petroleum.

Work on the next national petroleum assessment has begun; Geological Survey open-file reports by individual province geologists are due for publication in early 1995 and the combined national totals of all geologic provinces are due in early 1996. Unconventional petroleum resources producible in a borehole, such as coalbed methane, gas hydrates, and tight-gas sands, will be included for the first time in these estimates/reports. Undoubtedly, these inclusions will prove to be an added complexity and challenge to achieving consistent and creditable results.

Resource assessment methodology, with or without expert systems, is not precise and probably never will be. Although the methodology is continually evolving and being refined, the work incorporates much subjective judgment and "educated guessing" about the prerequisite geologic factors needed for hydrocarbon accumulation. Undiscovered resources are continually being converted into reserves, and the steady improvements in technology are other factors influencing the validity of resource assessment estimates.

Diversity of estimates over time has depended upon the methodology used (Miller, 1986b). Expert systems, however, can provide consistency by forcing the assessors to think about the empirical associations (i.e., addressing and writing the rules required in expert systems) in geology that are prerequisite to hydrocarbon accumulations in sedimentary basins. The theoretical principles of nature and geology are not the fundamental rules of a rule-based system. The inferred relationships and qualities, or "rules of thumb", among source rocks, reservoirs, traps, and timing of generation, migration, and trap formation, for example, are the bases for writing rules. Rules and empirical associations can be codified in expert systems to screen out all cases that are beyond the limits of any plausible existence, or that violate any of the necessary prerequisites for hydrocarbon accumulations. This is not to say that innovative rules cannot be incorporated; they can be added or subtracted at the will of the investigator.

INTRODUCTION

Artificial intelligence (i.e., application of computers to solve problems formerly requiring human brainpower) is the "technological glue" that holds expert systems together and helps the user with the large amount of data and choices to be made. The field of artificial intelligence ("thinking machines") probably began in the mid-to-late 1950s when computer scientists first "taught" machines to play chess, and when cognitive psychologists and engineers attempted computational logic, general problem-solving, symbolic integration, and pattern recognition with machines. These early attempts either failed or proved only marginally successful because the tasks were too difficult; thus, research on artificial intelligence generally fell out of favor until the early 1970's. With rekindled interest, numerous artificial intelligence applications were begun in the early 1970's and by the late 1970's significant applications, as expert systems, had been successful (Shapiro, 1987). Today, expert computer systems, using symbolic knowledge, can simulate or imitate the human reasoning process (Hinton, 1992). Furthermore, they have the ability to clearly explain their conclusion(s).

An expert system is essentially identical to a "knowledge-based system". Briefly, expert systems process information (which can be non-numerical), structure knowledge, reason by analogy, and solve problems. The component parts of an expert system are: 1) a user interface, 2) an inference engine, and 3) one or more topic-specific (knowledge) database(s). For this last component, computer networking should be able to provide any Geological Survey scientist access to a wide array of data. Modern computer "interfaces", or bridges of communication, can integrate the plethora of traditional, highly-sophisticated, software packages with expert systems.

For one to use expert systems, one does not need to be a computer programmer, nor be proficient in writing complicated system languages. The logic is already built into the inference engine, which by following logical paths, draws the decision or conclusion, and the user/developer needs only to know: 1) the principles of petroleum geology, and 2) a thorough understanding of the subsurface geology in the area to be assessed, in order to write valid "if-then"- and "true-false"-type rules. By prompting the user for additional information, a use of expert systems forces the "knowledge engineer" to construct databases that specifically address the attributes of oil and gas accumulation.

As problem-solving aids in our society, expert systems have been developed to do a variety of impressive general-to-specific tasks; a very small sampling of the many thousands of applications currently being used include: identification of hazardous materials, controlling NASA's space shuttles in flight, federal tax planning, employee performance evaluations, interpreting aerial imagery, aiding archaeologists in finding burial sites, diagnosing medical diseases (some of the earliest applications), diagnosing auto problems and recommending corrective actions, interpreting seismic data and seismic lines, preventing confidential government information from being disclosed, predicting business trends, controlling particle accelerators, speech and written signature recognition, weather forecasting, legal strategy, deciphering chemical/molecular structures, professional football game predictions, zoning ordinance enforcement, trouble-shooting scientific instruments, reviewing computer security systems, identifying fossils, military intelligence applications, determining search strategy to find lost persons, playing chess against the world's champion Gary Kasparov (and winning!...some of the times), water-resource and forest management, stock-market forecasting, horse-racing predictions, analyzing bank loan applications, designing pipelines, determining the fastest routes for airplanes and ambulances, operating quality control systems, making classification schemes in science, analyzing dip meter data, solving genetics problems, controlling humanoid robots having automated sensing, reasoning, and planning capabilities. (See the selected references section of this report for specific papers that describe many of these applications).

Certainly, if computer programs can accomplish the tasks listed above, they can make life easier for geologists (see Ennis, 1983) and Maslyn, 1986) who must assess oil and gas potential. Expert systems are being used more and more because many of mankind's present-day problems do not have algorithmic solutions. Much time and lots of money are spent collecting important and valuable knowledge and data about problems. Expert systems are an excellent way to apply this information and to save it for posterity. These systems are good at modeling and simulating real-world heuristic processes where there is only partially-known information.

OVERVIEW OF PLAY ANALYSIS METHODOLOGY IN PETROLEUM RESOURCE ASSESSMENT

The framework for the assessment process, play analysis, currently endorsed by the U.S. Geological Survey to assess undiscovered hydrocarbons, can be divided into four main phases as described below. Hydrocarbon plays are families of similar prospective and/or discovered accumulations of oil and/or gas having commonality in their depositional systems, and hence related to usually one geologic formation. The boundaries of plays are limited by commonalities in generation or migration of hydrocarbons, or in reservoirs or traps. Expert systems initially should be set up to do the first, second, third, and eventually part of the fourth stages of the petroleum assessment process as described below:

1) Play delineation and characterization;
2) A province geologist is assigned to an area of the United States where this "expert" has a good understanding of such factors as the stratigraphy, tectonic and thermal evolution, reservoir and source-rock characteristics, types of traps in the basin, petroleum production history (if any), amount of exploration, and knowledge of subsurface data (seismic, boreholes, etc.). Given his/her conceptual model, the expert has a good intuition of where future discovery wells may or should be drilled;
3) Analysis is made of the databases covering such attributes and aspects listed under #1 above;
4) The province expert synthesizes all data and information and makes iterative subjective interpretations of where the economically-recoverable oil and gas fields will most likely be found. In order to quantify the total resources of an area, the province geologist must provide probability distributions of the undiscovered accumulations (both size and number of accumulations for the seven fractiles - 100, 95, 75, 50, 25, 5, and 0). Making accurate predictions in the face of uncertainty is the most subjective part of the assessment, and a difficult task (Capen, 1976);
4) Quantitative estimates of the probability distribution are forecast by the "expert" in concert with other resource methodology professionals.

Since 1909, the national assessment of undiscovered oil and gas resources by the federal government has been a recurring labor-intensive task. For examples of these assessments, see: Dolton and others, 1981; Egloff, 1952; Garland, Carrales, and Conway, 1974; Hubbert, 1974; Mast, 1978; Mast and others, 1979, 1988, 1989; Mast and 4 others, 1989; Masters, 1979; McCulloh, 1973; Miller and others, 1975; Netschert, 1958; Potential Gas Committee, 1967, 1973, 1979, and 1987; Pratt and Brobst, 1974; Rice, 1986; Sheldon, 1976; Theobald, Schweinfurth, and Duncan, 1972; U.S. Geological Survey, 1922; U.S.

Geological Survey and the Minerals Management Service, 1988; U.S. Department of the Interior, 1960; and, Weeks, 1950. The next national assessment of oil and gas is currently underway with the new estimates due in 1994 and the formal report due in 1995; it will be more complex than previous assessments because it will include several categories of unconventional hydrocarbons.

During the last 40-50 years, many methods of qualitative and quantitative hydrocarbon resource analysis have been developed by many researchers for area/size-scales ranging from site-specific to local basin to regional to continental. Some of the more significant methods include: extrapolation of historical trends; areal- or volumetric-yield methods; discovery modeling; basin analog methods; geochemical material balance equations; historical extrapolation; and, direct subjective assessment methods (Charpentier and Wesley, 1986; Crovelli, 1987; Crovelli and Balay, 1986; Dolton and others, 1981; Forman and Hinde, 1985; Haun, 1975; Kudryashova and Starik-Bludov, 1940; Lee and Wang, 1982; Linstone and turoff, 1975; Mast and others, 1979; Menard, 1981; Miller, 1981 and 1986b; Moody and Geiger, 1975; Neruchev, 1964; Netschert, 1958; Podruski and others, 1988; Resnick, 1987; Rice, 1986; Root and Attanasi, 1992; Steinhart and Bultman, 1983; White, 1980; White and Gehman, 1979).

The Branch of Petroleum Geology informally defined and described "a petroleum play" in order to provide common ground for the several dozen geologic province experts who used the play analysis method in their national oil and gas assessment (U.S. Geological Survey, 1984). This document stated,

> "A play consists of a group of prospects and/or discovered fields [or accumulations] having common geologic characteristics such as source rock, trapping mechanism, structural history, etc, [which] may contain gas and/or oil. (Geological Survey of Canada, 1982).
>
> The <u>play concept</u> explains hydrocarbon accumulation and relates the deposits and prospects contained in the play to the common geologic elements which control generation, migration, and entrapment of hydrocarbons. In its fullest form the play concept considers all significant aspects of structure, stratigraphy, geochemistry and geologic history, even though knowledge of these may be uncertain.
>
> Plays may be confirmed or may be purely hypothetical, where there is not assurance as to their existence. However identified, plays have both discrete geologic and geographic limits. Plays are commonly described on a stratigraphic basis, where the group of prospects and/or accumulations have the same basic trap type and reservoir facies. In this context, a stratigraphic interval may contain one or more plays, which may overlap geographically, and plays in different stratigraphic intervals may be geographically coincident, partially overlapping, or mutually exclusive.
>
> Prospects within a play have relatively common risk and

similar probability distributions of geological variables. Although a play is an aggregate of one or more prospects and/or accumulations which are conceived as having similar characteristics and sharing common geologic elements, it can be described, in some instances, in broad enough terms to include a degree of internal diversity. For example, certain structural plays may have mixed reservoir types, or some major stratigraphic- or structural-setting plays may have mixed trap types. However, combining distinctly different accumulations or prospect types into a single play can result in mixed populations which are difficult to analyze and can cause problems in risking."

The play analysis method, according to Charpentier and Wesley (1986),

> "is a more detailed form of volumetric yield analysis. Whereas areal yield and volumetric yield methods primarily use geologic data, play analysis is performed at a scale detailed enough to use both geologic and deposit size data. The methods consist of generating and then combining estimates of the number of undiscovered deposits and estimates of the sizes of undiscovered deposits. Often the estimates of sizes of undiscovered deposits are calculated using geologic data, such as structure sizes, reservoir thicknesses, and porosities, in a volumetric equation. The deposit size estimates may also come directly from analog deposit size data or from a combination of deposit size and historical data by way of a discovery model. Because of the more detailed scale of play analysis, risk is more likely to be assessed separately than it would be for areal or volumetric yield studies. Prospect analysis is a subset of play analysis; it is the special case where the number of prospects in a given play is determined to be one. Baker et.al. (1984), Bird (1984), Canada Department of Energy, Mines, and Resources (1977), Lee and Wang (1983a,b), Miller (1981, 1982a), Procter and Taylor (1984) and L.P. White (1981) are some of the main references."

Allen and Allen (1990), Perrodon (1980, 1983, and 1992), Perrodon and Masse (1984), and Magoon (1987, 1988a,b, and 1992), in their efforts to refine the qualitative assessment of oil and gas resources, have proposed a scheme for characterizing and classifying potential and existing petroleum-generating systems of the United States. These systems model the genesis, migration, and trapping of petroleum with respect to source rocks, reservoir rocks, and seals. Identification of these models not only seems to be a logical first step but is essential in the strategy and goal toward eventual computer description of all knowledge about an accumulation, or potential accumulation, of petroleum. The remaining task is to specify rules that can characterize not only the petroleum system (play ?) but also the surrounding areas, which may be upgraded to play status (or downgraded to non-play status) when additional subsurface information becomes available. Magoon has also indicated that petroleum systems may provide reasonable quantitative estimates of the total amount of petroleum in the system. Magoon (1988b) stated:

"Geologists are continually looking for new ways to organize information or data into arrays to be interpreted in innovative ways to answer a specific question. One of the oldest ways, but still a very useful one, is to organize information into a geologic map. Over the last four decades, many new maps have been invented by petroleum geologists that related to the reservoir rocks, structure, stratigraphy, and source rocks. With the advent of the computer, a plethora of ways to organize geologic information is available; in fact, finding the proper way to organize is sometimes a problem. As more geological, geophysical, and geochemical information about petroleum occurrence accrues, there is a need to organize and categorize our ideas into conceptual models based on geologic processes. These models must then be classified so that comparative studies can be carried out.

The petroleum system is proposed as a unique approach to research, exploration, and resource assessment. A petroleum system includes all those elements that are essential for an oil and gas deposit to exist in nature. The basic elements include a petroleum source rock, migration path, reservoir rock, seal, and trap. All elements must be placed correctly in time and space for a petroleum system to occur. A petroleum deposit includes high concentrations of any of the following substances: thermal and microbial matural gas, condensate, oil, and solid bitumen. The description of a petroleum system includes its stratigraphic limits, geographic extent, and geologic timespan. The system is named using the stratigraphic nomenclature for the source rock and the most important reservoir rock; these two names are then separated by a hyphen. The confidence that a particular source rock generated hydrocarbons that are trapped in a certain reservoir is expressed in the level of certainty; known(!), hypothetical (.), or speculative (?)."

Each of the above noted assessment methods has its own advantages and disadvantages, depending on the geographic area being assessed, and each "has had its place" in the continuing refinement of methods. Some methods can be combined. My report addresses an application to only the currently used (national assessment) play-oriented method (see Mast and others, 1989; White, 1981). In the play analysis method the basic unit of analysis is the stratigraphic unit. A petroleum play is larger than a single prospect but smaller than a sedimentary basin. There is a high degree of commonality among geologic characteristics for each play, i.e., homogeneity of geology, but much less commonality between plays. A general description of the play analysis method is provided herein as Appendix B.

OVERVIEW OF KNOWLEDGE-BASED EXPERT SYSTEMS

As an emerging discipline of science in America, artificial intelligence enjoyed a great enthusiasm in the early 1960s with anathema coming in the late 1960's to early 1970s, and a resurgent explosion of interest in the 1980s. In the last 10 years, thousands of articles have been written about expert systems, which is a branch or application of artificial intelligence.

For the reader who wants more information on expert systems (knowledge engineering), i.e., their construction and applications, refer to some of these selected references: Aleksander and Burnett (1987), Barr, Cohen, and Feigenbaum (4 volumes 1979-1989), Buchanan (1986), Bundy (1986), Charniak and McDermott (1985), Coombs and Alty, 1984; Dabrowski and Fong (1991), Davis (1982, 1989), Davis and Lenat (1980), Deering, 1985, Duda (1981b), Duda and Gaschnig (1981), Duda and Shortliffe (1983), Fang, Shultz, and Chen (1986), Fetzer (1988), Fox (1984), Gevarter (1983, 1984a,b, and 1987), Harmon and King (1985), Harris (1989), Hayes-Roth, Waterman, and Lenat (1983), Jackson (1985), Maggio (1988), Michie (1979, 1982), Nau (1983), Nilsson (1980), Rauch-Hindin (1985, 1986), Rich and Waters (1986), Risch and others (1988), Rosenberg (1986), Rychener (1985), Schorr and Rappaport (1989), Shapiro (1987), Slagle and Hamburger (1985), Smith (1984), Stock (1987), Tanimoto (1987), Thompson and Thompson (1985), Walker (1988), Waterman (1986), Weiss and Kulikowski (1984), Williams (1984), and Winston and Brown (1979). Buchanan (1986), in particular, has an extensive bibliography on expert systems.

Some references that specifically address the development of expert systems and directly or indirectly address their application to resource assessment include: Andriole (1985), Bailey and Thompson (1990), Barr and Feigenbaum (1982), Bundy and others (1985), Calkins and others (1980), Cartwright and Leonard (1990), Cheeseman (1983), Cohen and Feigenbaum (1986), Coulson and others (1987), Davis and Lenat (1980), Duda (1980a), Duda, Gaschnig, and Hart (1979), Duda and Shortliffe (1983), Fang, Shultz, and Chen (1986), Fowler (1987), Gale (1986), Gallant (1985), Gordon and others (1987), Hayes-Roth and others (1983), Hinton (1985), Joshi (1985), Kearney (1990), Klimasauskas (1991), Leonard and Fried (1989), Leonard, Fried, and Milam (1989), Lightwave Consultants (1985), Maggio (1988), Maslyn (1986), McCammon (1990), Miller and others (1990), Minasi (1990), Morese (1987), Neuron Data (1989), Nilsson (1980), Pallatto (1989), Paperback Software (1988), Parker (1986), Rauch-Hindin (1985), Rejerski and Kapuscinski (1990), Rich (1983), Richie and Hanna (1984), Riedel and Tway (1990), Robinson and others (1987), Schultz and others (1988), Sciple (1991a,b), Shafer (1991), Smith (1984), Smith and Baker (1983), Stanley (1990), Stock (1987), Stout (1985), Summers (1989, 1990a,b, and 1991a,b), Swartout (1983), Tanimoto (1987), Walker (1987, 1988), Waterman (1986), Weiss and Kulikowski (1984), Winston (1984), and Zivy (1984).

Overview articles by Schaub (1989), Fang, Shultz, and Chen (1986), and Charland (1988) in Appendix A of this report describe in non-technical terms how expert systems should, and do, work. These general articles cite many interesting interdisciplinary uses of expert systems. Lastly, magazines, such as AI Expert and GIS World, plus periodicals, such as The Knowledge Engineering Review (quarterly, Cambridge University Press), Artificial Intelligence, IEEE (Institute of Electrical and Electronic Engineers) Computer, and The International Journal of Geographic Information Systems (quarterly beginning in 1987, Taylor & Francis, Ltd., New York) all provide broad perpectives on developing expert systems and the rapidly changing developments in the fields of artificial intelligence and knowledge engineering.

Essentially, the knowledge engineer uses interviews and other methods to extract and document the special knowledge of human experts. Using convergent thinking, "if-then", "yes-no", or "true-false" rules are applied to input and followed to a single decision or conclusions matching those that a human expert would provide. Expert systems can combine traditional procedures with heuristic rules, cross-plots, uncertainty handling, judgment-making, pattern-matching, and Bayesian inference. These expert systems can use their hypothetical reasoning to pursue multiple scenarios in order to find the best solution and to compare, contrast, and rank the advantages of each.

Rule-based reasoning is more powerful than structured query language, and rules can be linked into a reasoning network containing a complex logic of experimental investigation that the analyst wishes to pursue automatically (Maidment, D.R., 1990, pers. comm., Univ. of Texas, Austin). This higher level of problem-solving capability in expert systems and greater efficiency in "technology transfer" preclude the need to always write formal reports, or hold a seminar, or rewrite a program every time a resource assessment is mandated. Information is automatically updated and preserved for future generations of scientists. Expert systems also make excellent teaching devices because the user/rule-writer is forced to identify the processes required for hydrocarbons, for example, to accumulate and then ask the right questions. The program becomes a consultant to future users. Mistakes, such as creating excessively large hydrocarbon plays or geologically diverse plays, would be minimized.

Petroleum geologists and computer scientists in academia and industry have been developing expert systems for years. Examples of several applications include: data analysis of oil well logging tools (Rauch-Hindin, 1985), prospecting (Maslyn, 1986), sedimentary environment/facies interpretation (Shultz and others, 1986; Shultz and others, 1988; and, Stout, 1986), selection of reservoir models, wireline log interpretation (pattern recognition), drilling engineering, well testing, and formation damage analysis (Denton, Kuo, and Startzman, 1989). Dae-Kyo Cheong (1990) has written a Ph.D. dissertation at the University of South Carolina which incorporated a knowledge-based expert system to characterize hydrocarbon fields. The BEICIP Corporation of Rueil-Malmaison, France, has developed three commercially-available software programs (MATOIL, GENEX, and TEMIS-PACK) that provide an integrated quantitative basin analysis. These programs determine the hydrocarbon-generation potential of basins by analyzing subsidence, thermal history, gas-oil ratios, explusion, and timing of entrapment. Lastly, R.M. Maslyn (consultant, Denver, CO) has written an expert system called EXPLOR...

> "that enhances prospect generation by providing an initial set of prospect leads. The leads, developed using exploration rules,

from petroleum geologists, are evaluated by geologists, and with further work can become drillable prospects. The program's mapping portion is written in a high-level procedural language to optimize gridding and contouring. A backward-chaining Prolog-based expert system generates prospect leads. Input data include well locations, status, target information structure values, secondary formation structure values used for isopaching, target shows, geologic environment, and the targeted exploration feature's average size. Output includes structural leads with 3- and 4-way closure, stratigraphic leads, and leads derived from indirect evidence, such as downward projected structure and favorable isopach trends. Prospect leads are output with graphic symbols on a map, and an accompanying printout details individual prospect leads." (Denton, Kuo, and Startzman, 1989).

SOME DEVELOPMENTS OF EXPERT SYSTEMS, INCLUDING THOSE BY THE U.S. GEOLOGICAL SURVEY

Expert systems are not "new." They began evolving in the late 1970's and early 1980's from other computer programs used for geologic model creation and for statistical analysis, e.g., the Kriging process as explained in Clark (1982), Cubitt and Henley (1978), Davis (1986), and Verly and others (1984). During this time period, the U.S. Geological Survey supported scientific research that developed and utilized these early interactive computer programs for assessing undiscovered mineral resources (see Finch, 1980; Kork, 1981; McCammon, 1980 and 1982; McCammon and Agterberg, 1982; McCammon, Botbol, Clark, Sinding-Larsen, and Olson, 1978). Perhaps 12-15 years ago expert systems research was avante-garde at such laboratories as Stanford Research Institute, and programming-intensive programs for mineral resource assessment were being written, such as PROSPECTOR (Alty and Coombs, 1984; Campbell, Hollister, Duda, and Hart, 1982; Duda, 1980 and 1981a,b; Duda, Hart, Nilsson, Reboh, Slocum, and Sutherland, 1977; Duda and others, 1978; Duda and Reboh, 1984; Gaschnig, 1981 and 1982a,b; Hart, Duda, and Einaudi, 1978; Maslyn, 1986; McCammon, 1983, 1984 and 1990; McCammon and others, 1984; and, Reboh, 1981). The U.S. Geological Survey began publishing articles on PROSPECTOR in the early 1980's.

According to these authors, a prototype system was developed that evaluated the mineral resources of five major tectonostratigraphic terranes in parts of Maine, New Hampshire, and Vermont, against the five models that were constructed. Each of the models consisted of a rule-based method for evaluating the likelihood of occurrence of one or more ore deposits. PROSPECTOR combined both Bayesian and fuzzy logic techniques. (Fuzzy logic in general utilizes such statements as "very likely", "maybe", and "probably not".) The program incorporated the knowledge of 26 types of mineral deposits. It ascertained additional information from the user and then classified and assessed the mineral potential. The total effort devoted to PROSPECTOR was about 30 man-years, but Fox (1984) stated that it, "is reputed to have paid for its development many times over from mineral deposits that it located."

Campbell and others (1982) and Waterman (1986) have claimed that PROSPECTOR identified the location of a previously unknown ore-grade mineralization (molybdenum deposit) in a partially explored area of Washington. This appears to be the first ore body find using a computer-based expert approach. Maslyn (1986), however, noted that the deposit, although hidden, was suspected. Walker (1987) noted that:

> **"the PROSPECTOR program accurately predicted the location of a mineral deposit missed by human experts in over 60 years of searching."**

PROSPECTOR has also been used in oil and gas exploration (Fritz, 1985). Fritz mentioned in her article that John Stout of Petroleum Information, Denver, CO, used the microcomputer program (expert system shell) to build a model of world economic rules for oil and gas exploration; the model gives the best estimates of a basin's undiscovered resources and oil and gas economics of the area -- and the explorationist can then be on the way toward finding the first hydrocarbon prospect. Miller (1986a), based on the PROSPECTOR model, designed a feasible system called muPETROL which used basin analogs that forecast petroleum potential. She stated that:

> "The techniques involved provide new insights into the logic for defining more explicit geologic concepts and reasoning relative to an understanding of the global tectonics and geologic nature of sedimentary basins."

With the earliest Survey efforts, scientists were painstakingly inventing the tools of artificial intelligence/expert systems and decision analysis; later they could experiment with real-world applications. Dick McCammon, John Kork, and Nancy Bridges of the U.S. Geological Survey have used geologic decision analysis to obtain preliminary quantitative estimates of the undiscovered uranium resources for the Grants Mineral Belt area in the San Juan basin of northwestern New Mexico. They applied their genetic, regional-scale model to test data gathered by their colleagues. Krystinik and Clifton (1985) published results of an expert system that interpreted sedimentary environments. At the Fourth USGS Artificial Intelligence Special Interest Group (AISIG) meeting, April, 1988, in Reston, Virginia, attendees heard lectures on 12 major expert systems projects currently underway in the Survey (TIC TALK, July-Aug., 1988, Technology Information Center, p. 6-7); applications ranged from geophysics to mapping to basin analysis.

Some rather impressive commercially-available programs quickly superceded the early Survey labor-intensive attempts. Software companies saw the need in American business and science and hurried to develop their own. A major advantage of commercial software is that their software is continuously upgraded and improved. Some of the share-ware (e.g., Lightwave Consultants, 1985; Thurber, 1987) and off-the-shelf commercial programs currently available range from very simple public domain (shareware) inference engine/decision-tree inquiry programs to sophisticated professional programs that can "learn" as they iteratively acquire and process complicated information (see Hinton, 1992, and van Camp, 1992).

Neural network software (Caudill, 1987, 1988; Stanley, 1990), or artificial neural networking (Summers, 1991b), or structured connectionist networks (Feldman and Ballard, 1982; Feldman, Fanty, Goddard, and Lynne, 1988) simulates biological intelligence (Caudell, 1992; Feldman, 1985). Neural networking is also referred to as parallel distributed processing where many linked computational processes spread over many scales are synchronized. Such software is good at predicting trends, recognizing patterns (e.g., Widrow and Winter, 1988), and making generalizations. This type of computer processing is a powerful adjunct to expert systems and could be incorporated into the expert system developed to assess hydrocarbon potential. Neural nets "learn" from example, that is, they are self-teaching from trial and error experience, whereas expert systems reason (see Hertz, Krogh, and Palmer, 1991; and, Hinton, 1985.).

Two nice features about neural networks are: they do not have to be programmed, and they can cross-correlate thousands of variables. On the other hand, neural networks cannot explain the reasoning process. Neural networks, because they resemble the layered neuron network in the human brain, are good at solving problems that humans can easily solve. Stanley (1990), however, points out that a complicated neural network program may have 325 neurons and 20,000 connections, but the human brain has about one hundred billion neurons and ten million billion connections; in other words, one human brain is roughly equivalent to all of the personal computers ever built. For comparison of human brains and computers, see the articles by Searle (1990) and Churchland and Churchland (1990).

If a commercially-available neural network program were utilized, i.e., set up and tested for a small oil-producing area of the Geological Survey's northern Arizona assessment area, one could train it to look at surrounding areas within the northern Arizona province and adjacent Paradox basin and San Juan basin provinces for other potential hydrocarbon plays. Neural nets can handle fuzzy variables; they can build new rules as the system "learns" by studying the past. Networks are useful tools in finding obscure relationships in imperfect or noisy data (Summers, 1990b). According to Summers (1991b), "Another plus is that neural networks can operate under adverse circumstances. Just as you can sometimes recognize a face even if partially covered by a hat, neural networks can sometimes work even if information is missing or contradictory information is present, allowing workable solutions to be found, in some cases, under non-optimal conditions."

In 1987 Materna related, "The long-promised age of machines that can understand speaker-independent continuous speech, recognize images, learn from their environment, adaptively change to new circumstances and automatically operate in the real world may now be dawning." Nearly all newly developed application-software have neural nets embedded in them. In fact, at this time, the application of neural networks is demanding greater popularity than large-scale artificial intelligence efforts (Penn, 1991). The neural networks technology is having the effect of reducing operating costs and increasing productivity in American business and industry.

Inexpensive ($200-800) commercial neural networks are available that handle expert systems (Dvorak, 1989; Middlewood, 1991), e.g., BRAINMAKER vers. 2.1 (California Scientific Software, Grass Valley, CA), and NEUROSHELL (Ward Systems Group, Inc., Frederick, MD). Some commercial expert systems include: EXPLORENET 3000 (HNC, Inc., San Diego, CA), CxPERT (Software Plus, Crofton, MD), KNOWLEDGEPRO, LEVEL 5, PERSONAL CONSULTANT EASY, and SYMBOLOGIC ADEPT: REDEFINING EXPERT SYSTEMS (Symbologic, Redmond, WA). More expensive ($1,000-2,000) expert systems are available that run on all platforms, e.g., IBM PC/XT/AT, are EXPERT-EASE (Perrone & Associates, Inc., San Francisco, CA), 1ST CLASS (AI Corp, Waltham, MA), and NEURALWORKS PROFESSIONAL II (Neural Ware, Inc., Pittsburgh, PA.

Programs such as these, and those listed below, have liberated Survey scientists from "re-inventing the wheel"; the scientist "expert" now only needs to pull his/her development tool off the shelf and follow the cookbook. The user simply writes the rules, and for neural networks, tells the program what to learn. Brody (1989) has commented that:

> "In the days before commercial expert system shells, people built their own from scratch, usually using an artificial intelligence language like Lisp or Prolog. Building the entire expert system usually required at least three people: the 'domain expert', whose area of expertise was being milked for the project; the 'knowledge engineer', who built a rule tree on paper based on interviews with the domain expert; and the programmer, who actually constructed the expert program."

Eric Summers (U.S. Geological Survey, Information Systems Division, Reston, VA) has characterized some commercial, general purpose expert systems as follows (many are owned by the U.S.G.S.):

KES II - applies rules, HT (hypothesis testing), and Bayesian logic. It runs on PC, VAX, IBM mainframe, and Unisys systems. Cost is $4,000-40,000 depending on interface.

VP-EXPERT - can do only backward chaining with rules and runs on IBM PC/XT/AT. Cost is $100-250.

KEE (knowledge expert environment) and ART (artificial reasoning technology) - hybrid systems with frames, rules, and instances. They run under Common Lisp on Symbolics, TI, and 386-class 32 bit desktops; Cost is $70,000-80,000. KEE is available on the U.S. Geological Survey's GIS Lab SUN artificial intelligence system.

KEYSTONE, NEXPERT, and GOLDWORKS - systems with frames, rules, and instances. They do perhaps 70-80 percent of functions of the KEE and ART systems, but at 10 percent of their cost. They run on Unix, 80386, 68020 desktops and use Lisp. Cost is about $10,000.

As a point of information, the difference between forward-chaining and backward-chaining is the difference between deductive and inductive reasoning, respectively. In forward-chaining all rules are fired/tested in the knowledge base and the system determines as many conclusions or truths as possible. The system knows everything about everything because it looks at the whole model, and it keeps cycling through all the rules. For example, given a certain set of medical signs and symptoms, what disease is likely to be present? In backward-chaining all the rules are not fired/tested, i.e., the system assumes the truth of a goal and tries to prove it. It asks the minimal number of questions in looking only for a particular thing (goal-oriented). In backward-chaining the program works backward from a goal to determine what knowledge is necessary to prove that a goal is true. There is no difference in forward- or backward-chaining if all the goals are determined. An example of backward-chaining is the process one goes through when buying a new car. The person knows what s/he wants (the rules) in terms of color, style, make, price, performance, etc. S/he now must search all the new car dealers (knowledge base/database) in the United States to find exactly where the car is located that exactly matches the requirements.

Caudill (1990) and Summers (1991a) have written technical reviews of another professional expert system. Their evaluations are for the MAHOGANY Professional expert system shell by Emerald Intelligence of Ann Arbor, MI. Summers (1991a) stated:

> "MAHOGANY runs on a variety of equipment including IBM AT and Apple Mac II. The version I used runs on the Apple Mac II, costs $495, and requires 1 MB of RAM and 1 MB of disk storage space. MAHOGANY is an object-oriented expert system shell that supports classes with multiple inheritance and forward- and backward-chaining reasoning capabilities. Included are a rule and object editor and a set of example knowledge bases to help the beginner learn how to use expert systems. A 1-day training class at Ann Arbor is offered by Emerald Intelligence and will be necessary for most first-time knowledge base developers."

GEOGRAPHIC INFORMATION SYSTEMS (GIS) IN EXPERT SYSTEMS

Intelligent Geographic Information Systems (GIS) can be one of the tools of an expert system, just as the use of neural networks (described above) can be a powerful component. Miller (1988, 1989) of the Office of Energy and Marine Geology, Reston, VA, and Miller, Latzke, and Schachte (1990) have been using GIS and artifical intelligence/expert systems techniques to develop a prototype knowledge-based system for the three-dimensional analysis of the San Juan basin of southwestern Colorado and northwestern New Mexico. Their focus to date is on constructing isopach and structure maps of the four major hydrocarbon reservoirs and over-laying production and GIS maps -- a 3-D modeling of what is already known. This work, although a monumental first effort in using the available computer technology, does not by itself predict new reservoir formations, i.e., deeper unexplored reservoirs/plays. Their geologic information is primarily from the tens-of-thousands of San Juan basin wells encoded in the Well History

Control System (noted in next chapter). They are using NEXPERT OBJECT software which is also described below. According to Miller:

> "The major objectives of the project are to explore the feasibility of applying (1) GIS digital mapping techniques to integrate and manipulate spatial and attribute data, combining complex data sets (geographical, geological, and geophysical databases) into resultant overlay maps for multivariate exploratory data analysis, and (2) expert systems techniques that simulate the logic of basin experts to model geologic concepts, to document and analyze geologic attributes, and to interpret the history of a sedimentary basin."

Software programs that manage, integrate, analyze, solve problems, and produce maps from GIS spatial databases for field-size exploration areas have already been developed and tested. Examples are summarized in Bonham-Carter (1992), Leonard and Fried (1989), Leonard, Fried, and Milam (1989), and Seller, 1991.

The age of the merger of GIS and the expert system has arrived. According to Leonard, Fried, and Milam (1989),

> "One thing is clear: GIS technology has real application to the petroleum industry, but its potential has not yet been realized." Maggio (1988) has commented that such a merger of GIS and expert systems, "Will provide a land-based resource management tool that will allow the manager and researcher to take advantage of both. The GIS can serve as a spatially-referenced data base management system which supplies and stores data needed in the simulation modeling component of the expert system." Miller, Latzke, and Schachte (1990) concluded, "GIS technology can provide new analytical tools for innovative research in geological interpretation, for updating information data bases, and for developing new concepts in basin analysis and resource appraisal methodology."

With respect to GIS's capability, Cartwright and Leonard (1990) have stated,

> "Explorations geologists and geophysicists deal with data that is inherently spatial. They are concerned with the coincidence and interdependence of important geological features. It is important not only that these features exist, but also where they exist and in what relation to their surroundings. The GIS's ability to combine various layers of data and apply spatial operators to the data is well-suited to finding zones for potential exploration.
>
> The GIS may be used as a tool to integrate information from disparate sources into a common frame of reference. Hardcopy maps in various scales, tabular information, digital products and image data from aircraft and satellites all are required by the explorers: the GIS will incorporate various data into a single database with a common registration and coordinate system. Once this geographic data is integrated, the GIS not only assists the explor-

ationists in the search for known patterns, but may even reveal new spatial relationships that were previously indistinguishable.

One of the features that distinguishes a GIS from a simple mapping system is the GIS's ability to associate specific attributes with various spatial features. This ability is absolutely vital to petroleum because there are so many attributes and tabular data associated with well locations and seismic lines. The exploration professional must be able to generate sophisticated queries on the attributes in a database and display the matching features graphically. Wells, pipelines and boundaries also must be able to be shown with different symbols or colors depending on a particular attribute."

Computer scientists working in the U.S. Geological Survey Rocky Mountain Mapping Center, Branch of Research, Technology, & Applications (Central Region's GIS Lab, building 25, Denver Federal Center), can assist with the undertaking of the geologist's digital mapping, modeling, or data integration problems and apply state-of-the-art GIS/expert "synergistic" systems solutions (AI Applications, 1989; Soller and others, 1990). For example, network bridges or interfaces have been written between ISM/IVM (interactive surface modeling/interactive volume modeling) and ARC/INFO. ARC/INFO is a GIS that automates, manipulates, interprets, and illustrates geographic information (database-oriented mapping). The Information Systems Division of the U.S. Geological Survey (Ferrigno, 1990, January, Developments) has written a review on the GIS TUTOR software available in the Reston Technology Information Center. For in-depth information about GIS, consult Antenucci and others (1991), Federal Interagency Coordinating Committee on Digital Cartography (1988), Geographic Information Systems World (1990), Peuquet and Marble (1990), and Ripple (1987). Many other GIS articles are cited in the selected references. Petroleum Information Corporation of Denver, CO, uses GIS software called VOYAGER. VOYAGER is an interface to ARC/INFO which manages disparate oil and gas databases.

According to Miller, Latzke, and Schachte (1990), ARC/INFO...

"..is built around a hybrid data model that organizes geographic data using a relational and topological model. This facilitates efficient handling of two generic classes of spatial data: locational data, describing the location and topology of point, line and area features; and attribute data, describing characteristics of these features. Locational data are simply structured with cartographic X,Y coordinate data to identify arc, node, and polygon relationships."

ISM/IVM is currently the most popular mapping program in the Branch of Petroleum Geology. In 1990 it was thought that an ARC/INFO - ISM/IVM interface would probably be available by the end of calendar year 1991, but its future is now doubtful (T.R. Vogel, 1992, personal communication, U.S. Geological Survey, National Mapping GIS Lab). Vogel is developing the specifications of an interface for a prototype expert system (see AI Applications, 1989). This system will analyze groundwater quality. What has already been learned in this effort can be directly transferred to resource assessment expert systems.

Another useful interface, between NEXPERT OBJECT vers. 2.0 (Ballou, 1990; Neuron Data, Inc., 1989; Johnson, 1989; Lisker, 1989; Nordwall, 1989; and Rasmus, 1989) and ARC/INFO, is currently being built. NEXPERT OBJECT (Pallatto, 1989) may be the software shell of choice in my opinion for any initial investigations into actual implementation of expert systems by the Branch of Petroleum Geology. This expert system includes a unified database bridge that allows users access to many databases, such as ORACLE, RDB, INGRES, and SYBASE, and lets them create SQL (structured query language) queries (Fox, 1990) to non-SQL flat files residing in LOTUS or EXCEL spreadsheets.

NEXPERT OBJECT software is one of the most powerful and comprehensive expert system development tools presently available. Knowledge, in the form of understandable rules, can be used to prove hypotheses (backward chaining) or to draw conclusions from data (forward chaining). The same knowledge can be used in both reasoning modes. The structure of the data and the sequence and relationships of the rules can be graphically depicted. Its rule structure permits parallel thinking and cross-connection of hypotheses from different parts of a problem in a way not readily accomplished in procedural programming languages. More importantly, compared to a programming language like C, NEXPERT OBJECT is more understandable and easier to use for programming rules. This shell runs on DOS, OS/2, and MacIntosh networks. The architecture enables users to access other expert system databases on LAN file servers, Sun Microsystems workstations, Digital Equipment minicomputers, Apple Computers, and IBM mainframes. Summers (1990) of the U.S. Geological Survey's Information Resources Management office has written a technical review of the NEXPERT OBJECT software.

ARC/INFO developed by ESRI (Environmental Systems Research Institute, Boulder, CO) is a command line driven system licensed by the U.S. Geological Survey. Hardware platforms supported include mini-computer, workstation, and PC. Operating systems supported include PRIMOS, UNIX, VMS, and DOS. Data are imported from digital formats such as DLG (digital line graphics), DEM (digital elevation models), DTED, SIF, DXF, DIME, TIGER, and IGES.

According to ESRI, their product is a complete GIS (geographic information system) with capabilities of data input, processing, analysis, output, and management. ARC/INFO is a vector-based GIS which uses an arc-node topologically structured data format to store coordinate data. Attribute data is stored in INFO (a relational database management system) data files which are integrated with the coordinate and topological data files. ESRI has a separate software product called GRID/GRIDTOPO for manipulating and analyzing raster data. ARC/INFO has conversion routines for reading and writing ESRI's and ERDAS's (Earth Resources DATA Analysis System) raster data files. The ESRI/ERDAS live link capability allows simultaneous display of ARC/INFO vector data on ERDAS raster image data on an ERDAS display monitor. Workstation versions of ARC/INFO ver. 5.01 allow simultaneous display of ARC/INFO vector data on a number of raster data formats.

The ARC/INFO software is capable of contouring, transforming projections, and performing spatial analysis. Output devices include Tek Ink Jet, Tek Thermal, CalComp Electro, CalComp Pen, and Matrix Camera. Finally, ARC/INFO interfaces with ERDAS, GRASS (geographic analysis support system -- an easy to learn rule-based processor), SPANS (spatial analysis), and GSMAP ver. 7.0 (a Survey-written mapping/illustration program by Gary Selner, Denver Federal Center).

SOME GOVERNMENT DATABASES ACCESSIBLE FOR PETROLEUM RESOURCE ASSESSMENT

Two-hundred twenty-three databases owned by the U.S. Geological Survey have been described in circular 817. Many databases have been added since this circular was published in 1979; its revision in 1983 described 311 major databases and files. Of course not all these databases have relevancy to petroleum resource assessment, and my guess is that they are woefully under-utilized and some probably suffer from lack of quality control. Mankin (1991) reported that his committee found weaknesses in the databases used by the U.S. Geological Survey in its most recent assessment; for example, more seismic data needs to be incorporated into the evaluation of potential plays. The Geological Survey does, however, maintain a library of multi-channel seismic data in its National Energy Research Seismic Library in Denver, Colorado (Hutchinson, Taylor, and Zihlman, 1990; Taylor, 1992).

Presently, the Information Systems Division (ISD) of the U.S. Geological Survey (National Center, Reston, VA) is collecting information on databases from industry, academia, and all levels of state and federal governmental agencies. Its steadily growing directory, called the Earth Science Data Directory (ESDD), has about 2400 databases referenced (as of June, 1991) of which about 170 can be accessed through the Survey. The data is available on the AMDAHL 5890 mainframe computer and on CD-ROM by subscription from a nonprofit library service organization. ISD is continually looking for contributors to its directory. Natural resource data include computerized indices, files, hard copy records, maps, and files.

Three kinds of petroleum databases are described by Pearson and Ellwood (1987). They list 66 online databases of which most are of the actual data type; the remainder are of a bibliographic and textual type.

Additionally, many databases not included in the above noted U.S. Geological Survey circulars have been constructed either manually or with digitizers by individual Survey scientists. No one probably really knows how many databases have been developed by individuals for their own use, as opposed to technical service projects (TSPs) developed through contract with business (e.g., Petroleum Information, Corp.). Or for that matter, no one may really know how many revised and cleaned-up searchable databases could be available if there were a comprehensive master list. The various state geological surveys also have databases that can be accessed, e.g. see Reynolds and Trapp (1986) for databases in Arizona. The National Geophysical Data Center of the National Oceanic and Atmospheric Administration (U.S. Department of Commerce) in Boulder, CO, offers a wide array of database products and services. It sells products covering over 50 disciplines. Those solid-earth geophysical databases applicable to searching by expert systems include aeromagnetics, gravity, seismic reflection and refraction, geothermics, geochemistry, remote sensing, geographic boundaries, topography, and well logs. Another Department of Commerce agency, the Information Resources and Services Division of the National Institute of Standards and Technology in Gaithersburg, MD, has published descriptions of hundreds of databases, many of which relate to earth science, geology, geophysics, and petroleum (Cunningham, 1990).

Many Geological Survey Branches have such indigenous data in formats not readily useable by others in the federal government. Some of these databases are not available even as open-file reports. Getting databases reformatted into manipulatable files is perhaps one of the inevitable obstacles to greater appreciation and usage of the information by the end-user geologist. However, some common microcomputer spreadsheet software programs, such as LOTUS and QUATTRO, and EXCEL are capable of restructuring databases (Varney, 1992).

Many of the newer large databases (technical services retrievals) have been purchased from Petroleum Information Corporation, Denver, CO, Oklahoma University (Petroleum Data Systems), and consultants such as Richard Nehring. These are down-loaded custom-designed databases specific to petroleum resource assessment problems. Databases include the NRG Associates Significant Oil and Gas Field File which contains data on approximately 10,000 oil and gas fields in the United States, and the Petroleum Geochemistry File (OGDB) which contains data covering rock-eval, isotope, gas analysis and chromotography, organic mass spectrometry, vitrinite reflectance, and hydrous pyrolysis analyses. Hutchinson (1976), Takahashi, Dyman, and Magoon (1983), and the National Research Council (1988) discuss these and other data systems (and their management) which are most frequently used by petroleum geologists in the U.S. Geological Survey.

The U.S. Geological Survey also maintains other digital databases on specific basins, such as the Powder River basin, the Paradox basin, the Uinta basin, and the Denver basin. Information types include porosity, permeability, vitrinite reflectance, drill stem tests, pressure and flow, and stratigraphy. A database called GAS_ANALYSIS containing 30,000 gas sample analyses and 44 variables is available from the U.S. Bureau of Mines.

One of the more important databases for resource assessment is the WHCS (Well History Control System) developed by Petroleum Information Corporation, Denver, CO. Detailed information on more than 2.2 million wells in the United States resides in this database. Over 2.4 million well logs and 7.0 million formation tops are available from

Petroleum Information. Customized retrievals can be procured from the WHCS, and all data can be down-loaded onto PC diskettes. Under contract, Petroleum Information can also supply such products as base maps, digitized topographic maps (7 1/2 degree quadrangles and others of smaller scale), structure maps, lease-ownership maps, field maps, geographic analysis investigation maps, fracture/porosity maps, hydrocarbon distribution maps, lithologic trend maps, seismic data, coalbed methane exploration activity data, hydrocarbon play maps, production data, drilling activity data, satellite imagery maps, bibliographic information, and so on. The only limit to the Survey's acquisition of these off-the-shelf and customized retrievals is its ability to pay for them.

Personnel in the Information Systems Division of the U.S. Geological Survey, Reston, VA, can provide computer users with information about all Survey databases, services, and facilities. They publish a monthly bulletin, Developments, promulgating their information resources which includes product reviews, ADP acquisition, training, personnel contacts in all U.S. Geological Survey facilities, and other vital links between computers and scientists. The Technology Information Center in building 53, Denver Federal Center, provides a similar service and publishes Tic Talk as their vehicle of information exchange.

HOW ARTIFICIAL INTELLIGENCE AND EXPERT SYSTEMS MIGHT BE USED FOR HYDROCARBON PLAY ANALYSIS

Resource assessment work is an inexact science and always will be until all petroleum has finally been produced. And, no one will ever know precisely when that will happen. Thus, it is not surprising that some of the above noted assessments (methodology section) are sometimes confusing or misinterpreted (National Research Council, 1975) and controversial; the reliability of such assessments (...and effectiveness of exploration used by industry) have been questioned, labeled as biased, and met with less than enthusiastic responses (e.g., see Century, 1980; Cochran, 1986; Douglas, 1974; Gillette, 1975; Hayes, 1979; Kerr, 1989; Mankin, 1991; Menard and Sharman (1975); North, 1978; Parent and Linden, 1975; Rocky Mountain Association of Geologists, 1981; Schantz, 1978; Steinhart and Bultman, 1983; Time Magazine, 1978; Warman, 1971; and, Wilson, 1973). Mankin (1991), in his report for the National Reseach Council, noted that in the 1989 national assessment by the Department of the Interior, there was "an absence of a clearly defined assessment procedure that was unambiguously understood by all members of the assessment team." That report also concluded, "The USGS management had provided insufficient manpower, funds, and incentives to carry out a national oil and gas assessment at a uniform level of excellence in all dimensions."

There is no doubt that explaining and defending assessment methodology with expert systems will lend more objectivity for those who wonder how assessment numbers are generated. Petroleum assessments must be an ongoing process by teams of scientists who spend most of their time doing resource assessments -- it should not be a sporadic, high-intensity, eleventh-hour effort that inconveniences the assessors who would rather be conducting other research. In the absence of a permanent U.S. Geological Survey team, the application of expert systems to assessment work would supply the essential continuity that excellence and credibility demand.

For over 80 years the U.S. Geological Survey has been accumulating data and knowledge on the occurrence of hydrocarbons in the United States (U.S. Geological Survey, 1980)...it is the leader of the national expertise which studies resources (not reserves). However, the time is at hand when all of this knowledge needs to be aggregated into interactive computer repositories. Petroleum assessment is a task begging for a greater utilization of expert systems. If implemented, a coordinated strategy to characterize the petroleum potential of ALL of the United States (not just all federal lands, or all Indian Reservations, or all hydrocarbon plays, or all wilderness areas, et cetera) could prove highly efficacious by reducing total man-hours and by producing greater compatibility among provinces. When one compares the published literature on expert systems theory and applications, the conclusion is evident that the U.S. Geological Survey is probably several years behind the rest of the world in using "the modern genre of user-friendly" expert systems to assess petroleum resources.

Expert systems can: 1) manipulate a large number of variables at once, 2) lend themselves to the automation of qualitative criteria to reach valid conclusions, and 3) rapidly output graphics. There is a wealth of important multivariate spatial data about specific geographic/sedimentary basins that is in great demand on a daily basis. Management of this information is of paramount importance; it can be accomplished using expert systems -- a logical next step in the refinement of the science we are charged with doing. Expected results from an expert system developed to assess an area might be a series of composite maps showing the probability distributions and estimated field sizes for specified fractiles. Undoubtedly, new concepts of petroleum occurrence will also be developed.

Every square mile of the United States has some (...however small) petroleum potential -- it's just a matter of degree... being defined by current economics and politics, and being able to put limits on the problem. In defining a petroleum play one must put his/her "best-guess" geographic boundaries on it according to the operational definition of a play at any point in time; i.e., the condition might exist that all plays shall contain at least 1.0 million barrels of oil. It stands to reason that given the same or additional subsurface information, any of the non-play areas in the year 1992 may become a play in another assessor's opinion. This may be particularly true 25, 250, or even 25,000 years from now. So why not go ahead and assess the "non-play" areas now?; there is no adverse consequence if we are dealing with probabilities.

In the "art and science" of Search and Rescue, the technique of continuously assessing the "probability of detection" is termed "shifting probabilities" (see Shea, 1988). This is done after an important clue is found by a field team, or if the mission coordinator accepts the presumption, or finds hard evidence, that the victim/lost person may be moving from one search sector to another. As search teams return to mission base, their estimates of "probability of detection" per their sector are factored into a new "moving probability". A field team that does not find any clues in their assigned sector will be cause to reassess the probability of detection based on this "negative information". As one can see, time can be an important factor in the assessment process. Whether the problem is assessing where a lost person may be found, or where new resources may be discovered, as information, positive or negative, is received, real-time estimates can be easily revised using computer programs. Because few geologists can accurately predict what the ecomomics of exploration, price-cost ratios, public demand, et cetera, will be 100 or more years from now, expert systems afford advantages by being able to routinely guide and generate "shifting probabilities" (resource assessments).

I am certain that many geologists have wondered about the rhetorical questions, "Is that Precambrian outcrop hiding a petroliferous basin beneath a thrust sheet?",...(see Gries, 1983), or "Is there oil under that volcanic field?"...(see Shirley, 1985), or "Will hydrocarbons be preserved at 30,000-foot drilling depths in that basin?", or "Did that oil really migrate 200 miles updip?", or "Are there other 20 million barrel fields in northeastern Arizona producing from igneous rocks?" ...(see McKenny and Masters, 1968 and 1970), or "Should the Late Proterozoic Chuar Group source rocks of northern Arizona be identified as a petroleum play?" (see Desborough and others, 1984; Lambert, 1989; Murray, 1965; P'an, 1982; Pawlewicz and Palacas, 1992; Rauzi, 1992; and, Reynolds and others, 1988). The rules in expert systems can be written to accomodate uncertainties, such as these possibilities.

To understand the simple strategy suggested in this open-file report, we can assume that the population of the United States represents the total set of objects which we wish to analyze for marketing purposes. Just as oil and gas accumulations have many attributes, the general population has many characterizing attributes contained in databases that marketing experts analyze to target specific groups for specific products. Information residing in these computer files contains such attributes as marital status, occupation, family dwelling type, annual income, type of credit card(s), number and age of family members, highest educational level, type and year of car(s) driven, number of cats/dogs as pets, magazine subscriptions, types of vacations taken, brands of food eaten, number of times per month a video is rented, residing in urban/rural/bedroom community, hobbies enjoyed, types of appliances owned, and so on.

The hydrocarbon assessment/potential problem is likewise broken down into defining various combinations of attributes into subsets, i.e., everybody has a five or nine digit mailing zip code that serves to delineate mail distribution boundaries. In highly successful micromarketing techniques, attributes are aggregated according to mailing zip code, and each zip code is characterized according to, let's say, 100 attributes. The product being marketed is targeted to only specific zip codes. But, instead of mailing zip codes, geologic zip codes could be defined in the expert system by using rules to search out the information required in the diversity of geologic databases.

Each state of the U.S. may have from several to as many as 50 unique geologic areas that could be assigned "geologic zip codes", and that can be characterized according to their attributes of total thickness of basin strata or depth to basement, thickness of each stratigraphic unit, age of oldest sedimentary strata, thermal maturity and total organic carbon of source rocks, distance from nearest oil production, clastic to carbonate ratio of the statigraphic section, relative age of traps, types of folds, traps, and seals, degree of post-trap faulting, and so on. In place of the 136 onshore petroleum provinces assessed (Mast and others, 1989), the geologic attributes of perhaps 1,000 "geologic zip codes" can and should be profiled for the United States. It is just a matter of time (maybe 10-25 years ?) before this level of data collection is accomplished by the U.S. Geological Survey, regardless of whether or not it is done under the guise of petroleum assessment. Each zip code can eventually have a "probability statement" synthesizing the hydrocarbon potential.

Perhaps the biggest advantage in using expert systems is that the geologic province experts set up uniform databases and write uniform rules that query these databases. A continuum or flow of information is created and passed from one expert to the next over many years. There is no need to start over every time a new national assessment effort is made. Each province expert becomes "an official data custodian" and makes an orderly transfer of this data when he or she changes projects or retires. Therefore, for example, if a U.S. Congressman wants resource information "ASAP" about a small tract of land in his/her state, it is available at the touch of a few computer keys and the traditional "brush fires" and "bombs-with-short-fuses" scenarios are avoided. Use of expert systems forces collection of pertinent data. It forces better organization of data. It forces a logical sequence of analysis. It forces a better end-product. It forces uniformity in thinking. Petroleum assessment will take a step up from the province geologist's "intuitive gut-feeling covert reasoning" (which can be important) to a higher degree of "overt (verifiable and trustable to all future workers) reasoning."

As stated previously, expert systems are NOT a replacement for play analysis, but rather a workable tool to help identify potential hydrocarbon plays. According to Dolton and others (1981) in the play analysis method, "the amount of hydrocarbon in a play or prospect is determined by use of a reservoir engineering equation, taking into account geologic risk factors. Often the input for such variable (such as thickness of reservoir rocks and porosity) of this equation is in the form of a probability distribution that is known or estimated. Monte Carlo methods commonly are used to generate a probability distribution for the amount of hydrocarbon."

The geologic risk factors and the estimation of probability distributions of the above-quoted definition are the key factors being addressed in this report. Expert systems can easily manage and input/output this information in a user-friendly, interactive, mappable form.

LIMITATIONS TO IMPLEMENTATION

According to Waterman (1986), "Building an expert system requires a major investment of time, money, energy, and faith. If the problem is appropriate, and if adequate resources are committed, the investment will be repaid many times over. But even the smoothest development effort will have rough spots. Some of them cannot be avoided." He also states that gathering the resources necessary to enter the expert system arena may pose a significant challenge, e.g., "Personnel competent to design and develop the system are scarce, and few of the high-level support tools and languages are fully developed or reliable. In fact, many of them are new and untested."

And, as with all scientific endeavors, the availability of easily-accessible, cost-effective, high-quality field data determines the value, and hence significance, of the final outcome. The initial data acquisition phase for resource assessment may take, for example, eight to twelve months for an area the size of the San Juan basin, or three to six months for the 930-square-mile Ute Mountain Ute Indian Reservation in southwestern Colorado.

Good database design is essential. The design should be an effective, practical, sharable, and standardized one that may take many months to perfect. Some databases are flat files (two-dimensional, tabular, spreadsheet format) and some are hierarchial (tree-structure) files, such as Petroleum Information's Well History Control System, where many files (e.g., formation tops) can be built per each well's unique API number. Expert systems are presently plagued by the inadequacy of user interfaces that are suppose to tie the myriad of differently structured databases, the inference engine, the graphics and mathematics programs, and the user together. Learning curves will be long unless time and resources are devoted for a central person or group or project or contractor who will be responsible for managing, documenting, structuring, and normalizing the data into compatible formats (relational databases). Currently the Branch of Petroleum Geology uses INGRES as one of its primary relationaldatabase management software. See Date (1983 and 1986) and Fleming and von Halle (1989) for discussions of database design and management.

As with any new computer application, setting up a new expert system with valid rules will be more labor-intensive initially but much less labor-intensive in the intermediate- and long-term. Eventually, if many geologists try to implement expert systems in resource assessment without a master plan or strategy, one problem or limitation that may arise is the agreement on standardized geologic terms, models, and "systems" (see Magoon, 1988b, 1992), i.e., a problem of accepting good operational definitions.

Determination of "geologic zip code" (as described above) or tract/cluster boundaries may be difficult and ambiguous unless the same scientist or group of scientists, for the sake of conformity, determines the boundaries for all "geologic zip codes". The gathering of adequate subsurface data in frontier or partially drilled petroleum provinces is a major concern -- special rules will need to be written for areas of sparse data. Not all seismic data is public. Some data may be too expensive. All boreholes do not have source-rock (e.g., geochemical Rock Eval) information. Magnetic-telluric data may be too limited geographically, and its interpretation may not be reliable. The list of data limitations could be very long.

Major concerns regarding data accuracy and standardization of multiple databases are real and need to be addressed. This standardization problem is particularly cogent when several layers of data are brought together in one view, such as done in three-dimensional modeling. The training of end-users in order to maintain compatibility among databases is, of course, another concern, but one which is manageable. Some province geologists who are unfamiliar with hands-on computer applications may resist the "conversion of their data" to a standardized/computerized form. The unglamorous task of collecting and digitizing data simply takes time!

Pellerin (1990) relates, "GIS integrates hardware, software and data..... And integration is the primary stumbling block for federal agencies, which use a mind-boggling array of different hardware and software for equally diverse applications. Like it or not, it appears that federal standards for operating systems, user interfaces, networking, programming languages, data, and virtually all other aspects of computing are in the future, and they will affect GIS technology substantially."

The application of expert systems to petroleum resource appraisal (play analysis) should be initiated and tested in a restricted geographic area where there is a known occurrence of petroleum and where extrapolation of what is learned can be easily achieved and then translated to surrounding less- or non-productive areas. A small test area will also allow practice and proficiency in writing **VALID RULES** and decision-tree logic structures; disagreement could arise over what is valid per the particular geologic setting (but, that is to be expected in science). Lastly, heuristic searches/logic are important in order to limit the combinatorial explosions that are possible.

HYPOTHETICAL EXAMPLE OF A PROTOTYPE RULE-BASED SYSTEM

Northern Arizona is a good example of a moderately-small test area for developing an expert system to assess hydrocarbon potential; i.e., it is smaller than the entire petroleum province by the same name currently used by the U.S. Geological Survey. This area is that part of the Colorado Plateau north of about 35^{o} N. latitude and between west longitudes 109^{o} to almost 114^{o} (Grand Wash fault). There is a wide diversity of structural features and stratigraphic pinchouts. The Black Mesa structural (Laramide) basin overprints the Devonian Oraibi trough. Northern Arizona is a good area because the land-use is diversified (...and an interesting GIS example/problem) having five Indian Reservations plus Bureau of Land Management, state, private, and wilderness lands. Furthermore, four speculative and proven hydrocarbon plays have been identified in this physiographic province (Butler, 1988) and many more have been identified bordering the defined test area.

Although there are many interesting stratigraphic problems to be resolved, the structural geology of northern Arizona's Colorado Plateau is relatively uncomplicated and moderately-well understood (see Baars, 1983; Dott and Batten, 1971; Frazier and Schwimmer, 1987; Hunt, 1956; Kelley, 1955; Mallory, 1972; Nations and Stump, 1981; Thornbury, 1965; and, Wilson, 1962). The 15 "geologic zip codes" include: Shivwits Plateau, Coconino Plateau, Kaibab Plateau, Grand Canyon, Kaibito Plateau, Black Mesa basin, Oraibi Trough, Defiance Uplift, Painted Desert, Paradox basin (Blanding basin southern margin), San Francisco Volcanic Field, Mogollon Slope, Tyende Saddle, northern flank of the Holbrook basin, and Kaibab Arch. Some of these areas overlap, but I foresee no complications with this; in fact, it may provide a beneficial continuity.

Other qualitative and quantitative petroleum "assessments" -- to use the term in its broadest sense -- have been conducted in the suggested test area; for example, see: Barwin (1969); Barwin, King, and Hassenfratz (1971); Beikman, Peterson, Huber, and Butler (1986); Brown (1956); Brown and Lauth (1958 and 1961); Conley (1974); Conley and Giardina (1979); Cram (1971); Crawford (1963); Kiersch (1956); McKenny and Masters (1968); Nations, Doss, and Ybarra (1983a,b); Oil and Gas Journal (1979); O'Sullivan (1969); Peirce (1982); Peirce, Keith, and Wilt (1970); Pye (1961, 1967); Ryder (1983); Turner (1968); and, Wardlaw and Harris (1984).

Production of non-combustible gas (helium) plus both conventional (2 million BBLS and 15 million MCF) and unconventional (20 million BBLS from igneous rocks) oil and gas occurs in northeastern Arizona in the Four Corners area. The proposed test area has experienced moderate exploration in the northeastern part to inadequate exploration elsewhere. Tectonic and structural elements are fairly well defined and the stratigraphy is relatively less complex than in surrounding areas.

If this test area proves to be too large, perhaps a better starting place might be the Ute Mountain Ute Indian Reservation in southwestern Colorado and northwestern New Mexico. The U.S. Geological Survey has conducted special studies, including an oil and gas resource assessment (Butler, 1987), seismic, mapping, hydrologic, mineral and other investigations. A further alternative in reducing the prototype expert system might be to select only one of the "geologic zip codes" noted above.

Any expert system software requires a powerful rule editor because the rules will be constantly modified, added, and deleted as the expert geologist refines his/her thinking as the system grows. The level or certainty of belief that a rule is true (relevancy factor) may also be adjusted. Assuming all databases have been obtained and are in a compatible format, an integrated expert system might be structured in the following manner:

PROBLEM: Assess the undiscovered, economically-recoverable, conventional oil accumulations in YYYYY area which has 12 "geologic zip codes". RF is the relevancy factor, or the "belief factor" of Cheong (1990), which is assigned to each answer. In this hypothetical example, RFs are "just numbers" between 0.0 and 1.0 used for illustrative purposes only. This problem is not intended to be real or to be complete.

STEP 1: Write an expert system that evaluates and characterizes ALL **potential reservoirs** of "geologic zip code" XXXXXX. Databases M, N, P, X, Y, Z, AA, FF, JJ, QQ, RR, and VV will be searched and queried (these are relational normalized databases).

A. Write questions that ask .... for reservoir XYZFM, what is the exploration status and known facts about this formation, i.e., what is the...

probability that this formation is present in the subsurface? If...
1. 0.00 then go to...
2. 0.01-0.24 then go to...
3. 0.25-0.49 then go to...
4. 0.50-0.74 then go to...
5. 0.75-0.94 then go to...
6. 0.95-1.00 then go to...

geographic size of the area being assessed? If...
1. up to 249 square miles, then go to...
2. 250-499 square miles, then go to...
3. 500-999 square miles, then go to...
4. 1,000-1,499 square miles, then go to...
5. 1,500-2,499 square miles, then go to...
6. 2,500-4,999 square miles, then go to...
7. 5,000-9,999 square miles, then go to...
8. 10,000-14,999 square miles, then go to...
9. 15,000 or more square miles, then go to...

percent of the area being assessed that contains the specific reservoir or potential reservoir in the subsurface? If...
1. 1-24, then go to...
2. 25-49, then go to...
3. 50-74, then go to...
4. 75-100, then go to...
5. unknown, then go to...

status of exploration by drilling in this part of the province? If...
1. essentially unexplored; drilling density = 200 square miles or more per borehole,

then go to...

2. inadequately explored; drilling density = 50-199 square miles per borehole, then go to...
3. moderately explored; drilling density = 16-49 square miles per borehole, then go to...
4. maturely explored; drilling density = 2-15 square miles per borehole, then go to...
5. very maturely explored; drilling density = up to 2 square miles per borehole, then go to...

percent of boreholes bottoming in depth range below surface. If...

1. 500-999 feet:
   a. 0-19 % ... RF= xx, and go to...
   b. 20-39 % ... RF= xx, and go to...
   c. 40-59 % ... RF= xx, and go to...
   d. 60-79 % ... RF= xx, and go to...
   e. 80-100 % ... RF= xx, and go to...
2. 1,000-4,999 feet:
   a. 0-19 % ... RF= ww, and go to...
   b. 20-39 % ... RF= ww, and go to...
   c. 40-59 % ... RF= ww, and go to...
   d. 60-79 % ... RF= ww, and go to...
   e. 80-100 % ... RF= ww, and go to...
3. 5,000-9,999 feet:
   a. 0-19 % ... RF= qq, and go to...
   b. 20-39 % ... RF= qq, and go to...
   c. 40-59 % ... RF= qq, and go to...
   d. 60-79 % ... RF= qq, and go to...
   e. 80-100 % ... RF= qq, and go to...
4. 10,000-14,999 feet:
   a. 0-19 % ... RF= ss, and go to...
   b. 20-39 % ... RF= ss, and go to...
   c. 40-59 % ... RF= ss, and go to...
   d. 60-79 % ... RF= ss, and go to...
   e. 80-100 % ... RF= ss, and go to...
5. 15,000-19,999 feet:
   a. 0-19 % ... RF= yy, and go to...
   b. 20-39 % ... RF= yy, and go to...
   c. 40-59 % ... RF= yy, and go to...
   d. 60-79 % ... RF= yy, and go to...
   e. 80-100 % ... RF= yy, and go to...
6. 20,000 feet or more:
   a. 0-19 % ... RF = zz, and go to...
   b. 20-39 % ... RF= zz, and go to...
   c. 40-59 % ... RF= zz, and go to...
   d. 60-79 % ... RF= zz, and go to...
   e. 80-100 % ... RF= zz, and go to...

production status of the reservoir? If...

1. currently producing oil, then go to...
2. depleted and abandoned, then go to...
3. none, this is a conceptual play, then go to...

<u>age</u> of the reservoir? If...
1. Precambrian, then go to...
2. lower Paleozoic, then go to...
3. middle Paleozoic, then go to...
4. upper Paleozoic, then go to...
5. Triassic or Jurassic, then go to...
6. Cretaceous, then go to...
7. Cenozoic, then go to...

<u>type of hydrocarbon</u> expected? If...
1. mostly oil, then go to...
2. oil and associated gas, then go to...
3. non-associated gas, then go to...
4. biogenic gas, then go to...
5. unknown, then go to...

<u>lithology</u> of the reservoir? If...
1. mostly clastic rocks..if yes, then RF=0.8, and go to...
2. mostly carbonate rocks.. if yes, then RF=.9, and go to...
3. a mixture of clastics & carbonates, RF=0.6, and go to...
4. algal bioherm, reef, stromatolitic.. RF=1.0, and go to...
5. not sedimentary rock...RF=0.25, and go to...
6. unknown...RF=1.0, and go to...
7. homogeneous well-sorted quartz sandstone... RF=1.0, and go to...
8. dirty sandstone with poor permeability... RF=0.3, and go to...
9. etc., etc., etc.

<u>porosity</u> of the reservoir? If...
1. 0-2 %...then RF=0.1, and go to...
2. 3-7 %...then RF=0.4, and go to...
3. 8-15 %...then RF=0.7, and go to...
4. 16-25 %...then RF=0.95, and go to...
5. unknown...then RF=0.5, and go to...
6. highly variable, ranging from tight to highly porous...then RF=0.6, and go to...

<u>depth</u> of the reservoir? If...
1. less than 1000 ft., then go to...
2. 1000 to 5000 ft., then go to...
3. 5000 to 10,000 ft., then go to...
4. 10,000 to 15,000 ft., then go to...
5. 15,000 to 20,000 ft., then go to...
6. over 20,000 ft., then go to...

past production history of the reservoir (barrels equivalent)? If...

1. none...then RF=0.5 [neither an attribute or a condemnation], and go to...
2. 100-999 BBLS...then RF=0.55, and go to...
3. 1,000-4,999 BBLS...then RF=0.60, and go to...
4. 5,000-9,999 BBLS...then RF=0.65, and go to...
5. 10,000-99,999 BBLS..then RF=0.7, and go to...
6. 100,000-999,999 BBLS...then RF=0.8, and go to...
7. 1,000,000-9,999,999 BBLS...then RF=.9, and go to...
8. 10,000,000-99,999,999 BBLS...then RF=.98, and go to...
9. 100,000,000-199,999,999 BBLS...then RF= .99, and go to...
10. 200,000,000-500,000,000 BBLS...then RF= 1.00, and go to...

thickness of the reservoir facies? If...

1. 1-9 feet...then RF=0.3, and go to...
2. 10-49 feet...then RF=0.4, and go to...
3. 50-99 feet...then RF=0.8, and go to...
4. 100-199 feet...then RF=0.85, and go to...
5. 200-499 feet...RF=0.90, and go to...
6. 500-999 feet...RF=0.95, and go to...
7. 1,000 feet or greater...RF=1.00, and go to...
8. unknown...then RF=0.50, and go to...

B. Write questions that ask other pertinent reservoir attribute questions, such as analogs, known hydrocarbon seeps and any existing evidence of hydrocarbons, depositional environment, etc....

J. Repeat this query process for every known or potential reservoir in this area of the province

M. Write rules that decide if this is an excellent, good, fair, poor, unconventional, or non-reservoir for each of the various forms of hydrocarbons

STEP 2: Write an expert system that evaluates and characterizes the potential **source rocks** of "zip code" XXXXXX. Relational databases CCC, EE, and KK will be queried and searched.

A. Write questions that ask... for source rock LMNFM, what is the

probability that this source rock exists in this area?

If...

1. 0.00, then go to...
2. 0.01-0.24, then go to...
3. 0.25-0.49, then go to...
4. 0.50-0.74, then go to...
5. 0.75-0.94, then go to...
6. 0.95-1.00, then go to...

thermal maturity? If...

1. less than 0.60 Ro% ...then RF=0.2, and go to...
2. 0.60-1.30 Ro% ...then RF=1.0, and go to...
3. 1.31-2.90 Ro %...then RF=0.3, and go to...
4. 3.00-5.00 Ro% ...then RF=0.05, and go to...
5. >5.00 Ro% ...then RF=0.0, and go to...
6. unknown ...then RF=0.5, and go to...

type of organic matter (Tissot and Welte, 1984)? If...

1. I (amorphous), then go to...
2. II (herbaceous), then go to...
3. III (woody), then go to...
4. unknown, then go to...
5. mixed types, then go to...

total organic carbon in clastic sedimentary rocks? If...

1. 0.00-0.50 %,...then RF=0.05, and go to...
2. 0.51-1.00 % ...RF=0.20, and go to...
3. 1.01-2.00 % ...RF=0.35, and go to...
4. 2.01-3.00 % ...RF=0.65, and go to...
5. 3.01-4.00 % ...RF=0.85, and go to...
6. 4.01-8.00 % ...RF=0.95, and go to...
7. 8.01 % or greater ...RF=1.0, and go to...
8. unknown ....RF=0.50, and go to...

B. Write questions asking about pertinent source rock characteristics, such as age and depth of burial...

C., D., E. Write questions...

F. Repeat this query process for every known or potential source rock in this part of the province

STEP 3: Write an expert system that evaluates the quality of stratigraphic and/or structural **traps**.

STEP 4: Write an expert system that evaluates and characterizes the **basin history** -- sedimentological, thermal, subsidence/uplift, structural complexity, etc., etc. Databases P, Q, R, S, and T will be searched and rules 842 through 2,155 will be fired.

A. Write questions that ask about basin classification...(Kingston and others, 1983a,b; Klemme, 1986).
B. Write questions that ask about geophysical data, such as gravity and magnetic...
C. Write questions that ask...

STEP 43: Write an expert system which includes rules that integrate relationships between empirical associations of geology and hydrocarbon accumulations; the goal is to **integrate all of the expert systems** (reservoir rocks, source rocks, traps, migration, etc.) and make sense from the relevancy factors (or judgmental beliefs, fuzzy logic, weight factors, or confidence levels).

STEP 44: have the system write the rationale for areas that have high probability distributions.

N.B. -- this expert system may have 3,000 or more questions that must be asked of the various databases, and it may have more than 1,000 rules that link and address the significance of the answers to these questions. Also, note that there are many ways to structure the questions and rules. For example, one could use a strategy where...

```
IF xxxxx = YES, AND,
   wwwww = YES, AND,
   yyyyy = YES, AND,
   zzzzz = NO,...

  THEN Scuddzy Formation = VERY POOR RESERVOIR, or...
  THEN geologic "zip code 'FFFFF'" = a potential oil play larger
    than one million barrels.
```

Another example might be...

```
IF reservoir XYZFM is present,
AND, age is Cretaceous,
AND, type of hydrocarbon expected is mostly oil,
AND, evidence of hydrocarbons is oil shows in several boreholes,
AND, lithology is algal bioherm/mound,
AND, porosity is 10-15 percent,
AND, average thickness is 50-99 feet,
AND, depth is 10,000-15,000 feet,
AND, areal extent is 1,000 square miles,
THEN, conclude that this potential reservoir will meet the
  criteria for a good reservoir in a hydrocarbon play
```

On any given scientific subject there is usually some disagreement among the experts on how to interpret the data. Thus, a well-written set of rules should enhance the quality of the expert system by allowing for such differences of opinion, i.e., it should provide alternative conclusions.

DISCUSSION AND CONCLUSIONS

The computer has revolutionized society more than any other invention since the Industrial Revolution; it enables us to integrate knowledge at very high speed. The significance of the development of expert systems has not been trivial. The use of neural networks and expert systems to make human decisions (and study the human brain) is the result of a natural and probably an inevitable evolution in science. Such systems today are a major asset to the business and scientific communities of industrialized countries of the world.

The 1980s was a time during which there was an explosion in the accumulation of digitzed/machineable data -- and consequently, a need to manage and interpret it. Today, this deluge of information is overwhelming the scientific community -- geologists included. In scientific circles the syndrome is known as "information anxiety" or "paralysis from analysis". Over 50,000 journals publish over a million scientific articles annually worldwide. Thus, one can easily support the argument that the time has come when resource assessors need to be able to efficiently search out the petroleum assessment information and integrate the universal data system using the existing expertise and computer knowledge/programs of the computer industry and Geological Survey scientists. The goal is toward applications that the petroleum industry and academia have already been developing, refining, and using successfully to find petroleum.

Although the success ratio of drilling (new fields per new wildcat boreholes) is at an all time high in the United States, the amount of petroleum resources discovered in these fields is near or at an all time low (Menard, 1981). Menard and Sharman (1975) and Menard (1981) further concluded that purely random exploratory drilling using computer simulation was actually far more successful than the actual search for petroleum by non-random drilling. Given this fact, one can judge the incredible uncertainty about the methodology used in estimating undiscovered resources, particularly when exploration based on modern scientific knowledge apparently may have little or no positive impact on finding new oil and gas reserves.

By adopting the use of expert systems, resource assessors can accomplish the following job functions: capture knowledge from experts and pass it along to those who will eventually research the same problems, demand compatibility among geologists, organize spatial databases and the decision-making process, assess risk, and confidently determine the potential of hydrocarbon accumulation. Adoption is not a question of "if" it will happen, but rather "when" it will happen.

Knowledge-based computing employing artificial intelligence is no longer considered "science fiction". Through user interface programs, such as INGRES, the end user (assessor) of an expert system provides facts about a geologic problem to the system's inference engine, which in turn taps the appropriate knowledge bases and then returns a solution. Petroleum exploration, and hence petroleum resource appraisal, has been recognized by the experts as an "expert systems task". In this report I have shown that sophisticated generic computer software is commercially available to accomodate the individual geologist's rules. Programs and rules for expert systems have successfully been developed in the U.S. Geological Survey (Miller, 1986a) and in academia (Bezdek and others, 1990; Cheong, 1990; and, Morgan and others, 1988) to assess the hydrocarbon potential on the scale from hydrocarbon plays to major world petroleum provinces. However, greater emphasis on the use of these computing approaches is crucial to developing a long-term strategy for recurrent national petroleum assessments.

The components of artificial intelligence, expert systems, neural networks, and GIS (Geographic Information Systems) are successful, practical, labor-saving, "real world" tools waiting for new applications (Miller, 1986a and 1989). Much of the expert systems development to date in the U.S. Geological Survey effort to appraise oil and gas resources has been in the area of GIS rather than in defining new petroleum plays.

Today's expert system software can reason, answer questions, "learn" (or be trained, i.e., neural nets) from past experience (iterative parallel processing of data), and even handle contradictions. Software that can do this is certainly equivalent to a very smart "technological assistant". The GIS can manipulate and produce geologic maps that represent numerical and logical databases. The threshold for entry into this exciting computer environment continues to drop as more, and friendlier, expert systems become available; as responsible (and under-staffed) scientists of the U.S. Geological Survey, we need to take advantage of the powerful applications afforded by expert systems.

Expert systems that predict petroleum source-rock potential have been available to the public for several years (Fowler, 1987). If a resource assessor could merge source-rock systems with reservoir-rock systems and basin-history systems, the end result would be an extremely valuable addition to our appraisal toolbox. It is suggested here that the petroleum system of Magoon (1987, 1988a,b, and 1992) can provide the basic architectural structure for writing empirical association rules of the qualitative part of the assessment expert systems. The level of certainty (subjective belief factors) have been built into the petroleum system. The last phase, i.e., the quantitative part, of the assessment has already been developed (and made available as microcomputer disks to the public) by Crovelli (1983, 1984, 1986, 1987, and 1988) and Crovelli and Balay (1984, 1986, 1988, 1990, and 1992).

An easier exchange of technical data and information is needed among Survey researchers who have their own "private" databases. There can be more "team effort" in resource assessment. This effort must incorporate the "smart", cost-effective, automated, knowledge-based environments of the 1990s with the hundreds of scattered databases and files within the Geological Survey.

A small, simple, prototype expert system can be developed for a small petroliferous geologic province (maybe a training area for neural networks), using: 1) a new array of searchable databases, 2) NEXPERT OBJECT software (which can talk to many different databases simultaneously), and 3) valid rules. Ultimately, this prototype can be expanded so that our resource assessors and the U.S. Geological Survey will benefit by being able to rapidly generate clear, meaningful, high-quality, and insightful assessment products. These critical products could be three-dimensional models, documents, and maps for an industry which must find the oil and gas essential to our national interests.

Scientists of the U.S. Geological Survey must keep up with the rapidly-evolving computer technology that is used to scan, capture, edit, vectorize/rasterize, analyze, plot, and display spatially-referenced layered data, i.e., combinations of geographic, cultural, and scientific data. By using structured knowledge and the commercially-available expert system shells, such as NEXPERT OBJECT, the resource assessor can work faster with less project money and with improved quality, compatibility, and consistency over the long term. Expert systems will not replace people; they will, however, relieve people from repetitive tasks, reduce the tedium of always starting over, and capture expert sources of knowledge making it available to a wider range of users.

Expert systems are easy to de-bug and update. Rules can be changed easily; adding, editing, and deleting information is simple because no complex computer language is needed by the user. Geologists can concentrate on the geology and not be overwhelmed by all the computer "mumbo-jumbo". Most importantly, each hydrocarbon play will be fully documented in terms of the assumptions, weight factors, and reasons for the final assessment (see Fritz, 1985).

A petroleum appraisal test project, limited to economically-recoverable conventional hydrocarbons, could be initiated by a small team of multidisciplinary scientists for a small geographic area, e.g., northern Arizona's Colorado Plateau (or a portion thereof), to incorporate the geologic data and advanced technology (software and hardware) available today. A successful application will undoubtedly prove to be an invaluable tool and opportunity to help policy-makers better understand the Nation's long-term energy situation and to help them make better-informed decisions.

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APPENDIX A

WHAT MAKES UP AN EXPERT SYSTEM AND HOW DOES IT WORK?

The following is taken from Schaub (1989).

"Expert systems are not futuristic science-fiction products that threaten to replace human workers or provide incomprehensibly complex solutions to commonsense problems. Instead, they are business tools that help to enhance the quality and availability of knowledge required by decision-making professionals in a wide range of industries.

If they are designed and implemented correctly, expert systems provide business users with high-powered complements to their conventional programs such as databases, word processors, and spreadsheet analysis.

Expert systems differ from conventional applications software in the following ways:

- The sophistication of the user interface.
- The existence of a 'knowledge base,' or system of related concepts that enable the computer to approximate human judgment.
- The expert system shell, or interpreter.

It's the shell that actually processes the information entered by a user, relates it to the concepts contained in the knowledge base; and provides an assessment, judgment, or solution to a particular problem or question.

Note that, in principle, any conventional programming language can be used to build a knowledge base; you don't need so-called artificial intelligence languages such as Lisp or Prolog. The shell simplifies the process of creating a knowledge base.

INTERFACE DESIGNS. Traditionally, interface designs for expert systems have hinged on graphical capabilities and unconventional methods of entering data into the system. For example, many expert systems used a mouse for data entry well before the Mac became accepted in corporate America.

Graphical interfaces can supply information in any number of forms; simple text 'dressed up' in windows, pop-up menus, or actual graphical objects designed to represent things like statistical information or flow of logic.

Now, much of this style has been integrated into the conventional applications, but they're of particular use in expert systems. An expert system may express an idea, solution, or explanation using more complex conventions than rows of numbers, pie charts, or brief messages such as 'Out of space on drive B:'.

Practical examples include the drawing of a map by an expert system that provides directions or geographic analysis or the expression of financial relationships through complex charts organized dynamically to emphasize a particular point.

The user interface does not intrinsically limit the capabilities of the expert system to 'reason'. It only enhances the ability of the user and computer to gain a better and more complete understanding of the assessments.

KNOWLEDGE BASE. The knowledge base is the library of 'rules' the expert system uses when making a decision or offering a solution to a problem. In general, there's a system designed specifically to manipulate information in the particular form the knowledge base has. Knowledge bases are traditionally described as large systems of 'if-then' statements, but this description is misleading.

Knowledge bases may not contain definitive rules at all but may contain many other objects: associative relationships between different concepts, statistical information about the probability of certain solutions, or simply large databases of facts that can be compared to one another based on simple conventions intrinsic to the expert system.

As an example, an expert system designed to manage portfolios would have to include both hard financial concepts and equations and softer information, such as rules of thumb concerning appropriate times to buy and sell based on the intuitive feel of a specific expert investor's reading of 'technical' trends.

The rules may categorically favor certain investments, such as high-tech firms. And the developer may have encoded some concept of legal limitations in the expert system.

CREATING THE KNOWLEDGE BASE. The way the information gets into the knowledge base is dependent on the specific expert system. Generally, it's coded by hand, like a traditional program, by 'knowledge engineers' who perform structured interviews of experts in the particular field. There are other ways emerging, too. Far from hand-coding are neural networks, which have an intrinsic capability to memorize and 'learn' from patterns reinforced by trainers/experts in a specific field.

The main purpose of the knowledge base is to provide the guts of the expert system -- the connections among ideas, concepts, and statistical probabilities that allow the reasoning part of the system to perform an accurate evaluation of a potential problem, asset, or investment.

SO, HOW ABOUT THE SHELL? An expert system shell provides a layer between the user interface and computer operating system to manage the input and output of data. It also manipulates the information provided by the user in conjunction with the knowledge base to arrive at a particular conclusion.

The structure of the shell is very similar to that of an interpreter or a front end to a database program but richer and more capable of taking the facts, assertions, and conditions contained in the knowledge base and applying them to the input data.

The shell is often sold as an end-product, allowing the purchaser to encode a knowledge base from scratch, the same way a user would purchase a database system to store information provided by his company. On the other hand, knowledge bases can be sold as products -- where a shell or interpreter may be an incidental part of the package -- in the same way a user might buy data, such as the complete works of William Shakespeare or a body of data relevant to the user's business. In that case, the user can immediately take advantage of the existing library of judgments provided by the system.

SYSTEM SOFTWARE: HELP OR HINDRANCE? The computer's operating system plays an important role in the implementation of an expert system. The operating system provides the basic capabilities of the machine to the expert system, including file management, some user interface support, memory management, and interfaces to other products that might want to share information that is contained in the expert system. The operating system's resources and utilities may intrinsically provide needed capabilities (for example, graphic or mouse support, database management) that, therefore, ease the need for additional programming. In some cases, the operating system may even provide conventions for interfacing the expert system to other programs.

The disadvantage of using the operating system's facilities is the limited control the developer has over the facilities and likely performance degradation. I believe, as an example, OS/2 and the Presentation Manager will provide much better interface support than DOS, with less plumbing work for the expert system developer.

USING AND MISUSING THE EXPERT SYSTEM. The purpose of the expert system is to enhance, or enable, judgment on the part of a human being, not to replace human judgment altogether. Expert systems can provide a relatively naive user with a lucid and powerful assessment of a problem where an expert is either unavailable or where it isn't practical to involve an expert in the decision.

Additionally, expert systems -- without being formal training systems -- can help users learn concepts and methods of decision analysis through the process of solving problems <u>in conjunction with</u> the computer, a valuable asset in any business situation. Over time, the user of a properly implemented expert system has the opportunity to absorb the expert's rules and intuitive decision-making skills."

<u>EXPERT SYSTEMS BREED "KNOWLEDGE ENGINEERS"</u>

The following is taken from Charland (1988).

"In the mid-1970s, Boeing Aerospace found itself in a corporate predicament. Two of its leading aircraft designs were obsolescent. There was an immediate need to train young engineers in the development of new systems.

But just as the firm's designs needed updating, a number of its leading engineers were retiring. How could Boeing change its product line and personnel at the same time?

Management decided to assign each of the retiring tool-design engineers as a mentor to a young engineer. Each pair worked at a computer-aided-design station. As the senior engineers taught the novices, their design were stored in computer memory.

The company discovered an unforeseen benefit. Their computers had created an entire library of design information. Now they could use the expertise of their senior engineers long after the individuals had retired.

Today, the Boeing experience is commonplace in the field of expert systems. Computers are used for much more than calculating figures and storing data. They transmit the stored knowledge and problem-solving skills of expert professionals as well.

Jeff Richardson is a leader in the emerging field of expert systems. He heads the Center for Applied Artificial Intelligence at the University of Colorado's College of Business in Boulder.

Richardson sees several forms of expert systems developing, for different markets.

Many large organizations have developed computer-supported systems for internal operations such as selecting transportation systems or trouble-shooting maintenance.

The Campbell Company has an expert system for cooking soup. Other expert systems provide skills and knowledge to masses of individuals with common information needs. There is an expert system to tutor students in beginning algebra, and another to help with tax returns.

Noetics Inc. of Englewood, CO, has developed an expert system for preparing wills. Many of the most popular applications are in subspecialties of law.

Richardson finds that the most narrowly defined expert systems function best. 'You need a knowledge base that's just the same,' he says.

Reid Merrill Brunson, a Denver-based management consulting firm, is developing a system for testing job applicants in customer service and sales. The firm has 33 years accumulated data on traits and aptitudes of 14,000 sales professionals. In the past, they have shared this information through consultation and written reports. Now the computer system will make test data available to hiring managers across the country, at the touch of a button.

A third market lies in software development. A number of companies are creating Expert Systems Development Programs, or 'shells' for noncomputer specialists.

Jackie Nairn is a high-tech marketing professional who recently completed a master's thesis on expert systems. She finds two kinds of shells emerging, one for large organizations and one for specialized tasks such as tax-form preparation. 'The most successful systems are solving simple problems,' Nairn says.

The new job roles in expert systems are as varied as in other areas of computer science. They range from software developers to market support positions.

One of the key jobs is 'knowledge engineer'. That is the person who helps expert specialists communicate their knowledge to computer technicians.

Some knowledge engineers have strong technical skills themselves, such as programming in the advanced List Processor, or LISP landguage. All are conversant with the technical challenges of designing expert systems.

Knowledge engineers also must be good listeners, to pick the brains and problem-solving skills of specialists.

Richardson finds that the best people have a strong background in cognitive psychology as well as computer science. They can appreciate how human beings and computers process knowledge.

The Colorado Institute for Artificial Intelligence has additional information on jobs and training in expert systems. Its address is Campus Box 419, University of Colorado, Boulder 80309.

'Understanding Expert Systems' by Mike Van Horn is a good introductory book on the field."

WHY EXPERT SYSTEMS IN PETROLEUM EXPLORATION?

The following is taken from Fang, Shultz, and Chen (1986).

"The tremendous advances of the last 30 years in computer technology have evolved through four generations. The fourth generation, still active, belongs to supercomputers; however, the next, fifth-generation computers are revolutionarily different -- encompassing the functions of knowledge (or symbolic) processing, but not data (or numerical processing, which has been associated with all previous generations of computers).

Understandably, geologists were slow initially in making use of the computers in their work because the nature of geological research (except for a few areas such as X-ray crystallography, geostatistics, etc.) involves little if any exact computation, but instead requires interpretations based on incomplete and imprecise data. Thus, the number-crunching computers found few applications in geology. However, there has been a recent surge in the use of microcomputers, mostly for word processing and graphics applications. Those who read the AAPG Explorer (especially the July 1985 issue which also introduces expert systems) are aware of an explosive interest shown by geologists in the application of microcomputers to all phases of oil exploration.

This naturally brings up the question of what we can do with expert systems in the multifaceted endeavor of oil exploration. When reviewing the steps and phases required in oil exploration, leading to a prospect delineation, these phases may be tied into four basic questions, which must be raised in delineating favorable zones of petroleum accumulation. It is clear by now that an exploration effort may be characterized as an "expert" task because:

- Many exploration phases and tasks require subjective interpretation based on incomplete and imprecise data.
- The degree of confidence of an interpretation varies depending on the strength of evidence.
- Direct field observations as well as indirect subsurface measurements provide only a list of probable alternatives.
- Human decision is involved at nearly every step or task.
- Dealing with anything but facts implies uncertainty. Expert systems can make allowance for propagation of subjective certainty factors associated with such expressions as 'I strongly believe that...', or 'The field evidence suggests that...'"

APPENDIX B

OVERVIEW OF THE PLAY ANALYSIS RESOURCE ASSESSMENT METHOD

The following is taken from White (1981).

"The exploration process is simulated through the integration of two independent models: a geology model, which is based on a probabilistic assessment of the most important geologic parameters in a province, and an exploration model, which simulates the search for oil and gas in the province. The geologic model generates a list of prospects (potential drilling targets) and a resource appraisal of the oil and gas in place using subjective probability distributions developed by experts familiar with the geology of the area. The exploration model simulates both the economic evaluation of prospects by an explorer and the drilling decision, generating a sequence of discoveries that form an inventory of pools to be evaluated for development.

These two models are integrated in a Monte Carlo simulator of exploratory activity over an extended time period. Each Monte Carlo pass begins by the geologic model sampling from probability distributions for the important geologic parameters to simulate a possible state of geologic nature for the province. This state of geologic nature is composed of a particular number of prospects, some of which are simulated as actual deposits of oil and gas and some as dry. After simulating their expected size, these prospects are ranked according to expected volume to form a simulated target list for the discovery process.

The discovery process is then represented, on a year-by-year basis, as the sequential evaluation of prospects on the target list. The status of the prospects (as either having a deposit or being dry) is unknown to the simulated explorer. If the expected economic value of a particular prospect justifies drilling an exploratory well, the simulated decision is to test it and determine whether it contains hydrocarbons. This procedure continues each year in the Monte Carlo pass or until all prospects have been tested. The learning process in exploration is simulated by using the drilling results each year to update the simulated explorer's perceived state of geologic nature. The output of the exploration model each year is a list of dry wells and discovered deposits of oil and gas. The discovered deposits are added to an inventory of pools to be considered for development. A large number of Monte Carlo passes are made to generate frequency distributions for the important output variables, such as total oil and gas resources in place, discovered reserves, and production."