BASIN ANALOG APPROACH ANSWERS CHARACTERIZATION CHALLENGES OF UNCONVENTIONAL GAS POTENTIAL IN FRONTIER BASINS

A Thesis

by

KALWANT SINGH

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial of fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2006

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee, Stephen A. Holditch
Committee Members, Walter B. Ayers
Eric J. Bickel
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ABSTRACT

Basin Analog Approach Answers Characterization Challenges of Unconventional Gas Potential in Frontier Basins.

(December 2006)

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Chair of Advisory Committee: Dr. Stephen A. Holditch

To continue increasing the energy supply to meet global demand in the coming decades, the energy industry needs creative thinking that leads to the development of new energy sources. Unconventional gas resources, especially those in frontier basins, will play an important role in fulfilling future world energy needs. We must identify and quantify potential unconventional gas resources in basins around the world to plan for their development. Basin analog assessment is one technique that can be used to identify and quantify unconventional gas resources that is less expensive and less time consuming.

We have developed a basin analog methodology that is useful for rapidly and consistently evaluating the unconventional hydrocarbon resource potential in exploratory basins. We developed software, Basin Analog System (BAS), to perform and accelerate the process of identifying analog basins. Also, we built a database that includes geologic and petroleum systems information of intensely studied North America basins that contain well characterized conventional and unconventional hydrocarbon resources. We have selected 25 basins in North America that have a history of producing

unconventional gas resources. These are “reference” basins that are used to predict resources in frontier or exploratory basins. The software assists us in ranking reference basins that are most analogous to the target basin for the primary purpose of evaluating the potential unconventional resources in the target basin. The methodology allows us to numerically rank all the reference basins relative to the target basin. The accuracy of the results depends on the descriptions of geologic and petroleum systems. We validated the software to make sure it is functioning correctly and to test the validity of the process and the database.

Finding a reference basin that is analogous to a frontier basin can provide insights into potential unconventional gas resources of the frontier basin. Our method will help industry predict the unconventional hydrocarbon resource potential of frontier basins, guide exploration strategy, infer reservoir characteristics, and make preliminary decisions concerning the best engineering practices as wells are drilled, completed, stimulated and produced.

DEDICATION

This thesis would be incomplete without a mention of the support given me by my big brother, Deev, and my mother to whom this thesis is dedicated. They kept my spirits up when the muses failed me. Without their lifting me up when this thesis seemed interminable, I doubt it should ever have been completed.

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CHAPTER I

INTRODUCTION

This chapter is a review of the problem we are solving and the approach we used to build the software. Based on this review, we present specific objectives, and discuss the overall organization of this thesis.

1.1 Unconventional Resources

"Unconventional resources" are best defined using the resource triangle concept **(Fig. 1.1)**. The concept of the resource triangle is that "oil and gas resources are distributed log normally in nature," [1] just like any other natural resource. The top part of the resource triangle consists of conventional resources that are easy to develop but small in size. The lower part of the triangle illustrates the unconventional resources, including tight gas sands, coal-bed methane (CBM), shale gas and heavy oil. These resources account for very large volumes of hydrocarbon in-place, but these unconventional reservoirs are difficult and expensive to develop. Improved technology and better resource assessment are important in our quest to produce unconventional resources economically. [1,2,3,4]

Unconventional resources already play an important role in the United States (US). The US has been producing oil and gas from tight gas, shale gas, coal-bed methane, and heavy oil reservoirs.

This thesis follows the style and format of the *Society of Petroleum Engineering Journal.*

For many decades, outside the US, many companies are beginning to consider the development of unconventional reservoirs. Asia, for example, will need production from unconventional gas source to secure energy demand in the next 30 years. [4] In summary, unconventional resources will be an important energy source to meet future world energy demands. One of improved methodology that we offer to better evaluate these unconventional resources (especially those in frontier basins) is a basin analog approach.

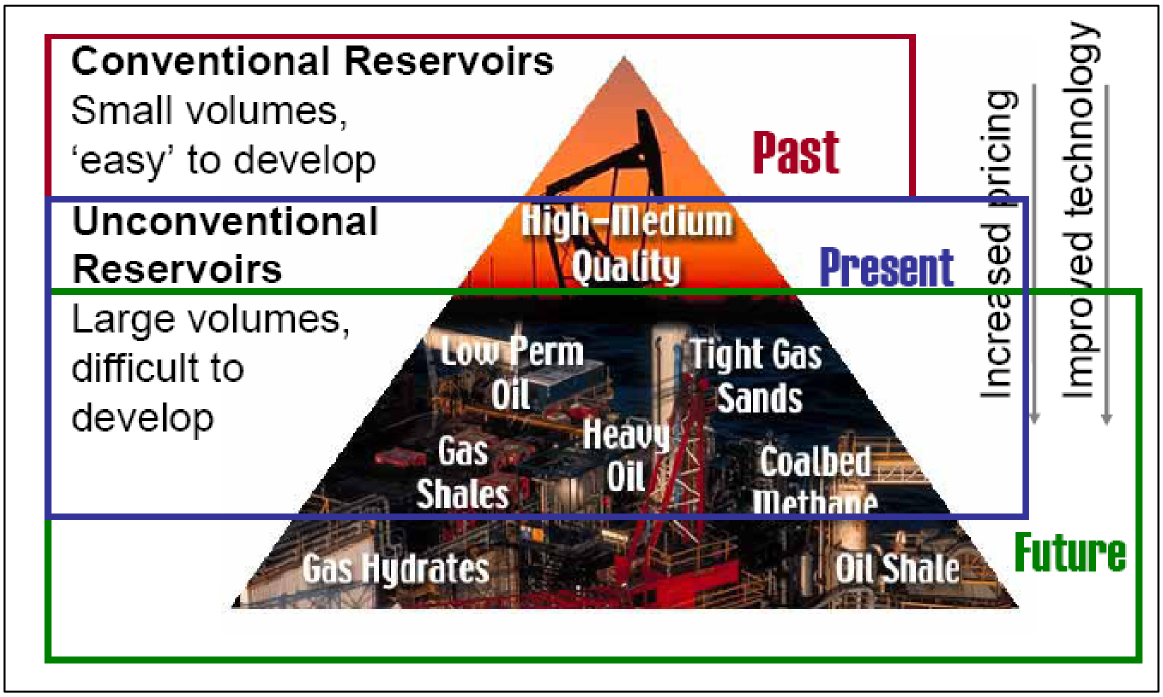

Fig. 1.1—Resource triangle concept [5]

1.2 The Basin Analog Method of Evaluation

The basin analog approach is not new to geoscientists. For over fifty years, basin analog processes have been used in the oil and gas industry. [6,7,8] However, there is no published methodology that allows a non-expert geoscientist to identify analogous basins.

Current practices are based on an expert's "subjective opinions and experience." Any specific expert would need a substantial effort to analyze data from a target basin and match those data with an analog basin. Moreover, without an established methodology, it is feasible that different experts with different levels of experience would select different analog basins, given the same information. We found no published guidelines or step-by-step procedures in the public domain that can be followed to identify an analog basin. Therefore, we developed our own methodology.

In this research, we developed a method that can be used to consistently identify analog basins. We built a database that contains both geologic and petroleum systems information of basins in North America that contain both conventional and unconventional resources. We call these basins "reference" basins. Also, we built a system to match a frontier (or target) basin to its closest analog in the North America reference basin database. Typically, we will have sufficient information about the geology of the reference basin, and we will have data concerning the conventional reservoirs in the target basin. The system assists the user in ranking reference basins that are most analogous to the target basin. Ultimately, we want to use the analog basin to assess the potential of the unconventional resources in the target basin. The method allows us to find reference basins that are similar to the target basin, then to rank the reference basins to determine the one that is most similar to the target basin. We developed a numerical ranking system for evaluating the analog basins.

In North America, more than 25 basins have produced substantial volumes of both conventional and unconventional oil and gas. These are our reference basins. Out side of North America, there are literally hundreds of basins that may hold substantial volumes of unconventional resources. However, very little data have been published on unconventional reservoirs in these basins. We anticipate that once we match up the target basin with its closest North America analog basin, we can help operators better evaluate potential production of unconventional oil and gas from target basins.

1.3 The Objectives of the Research

To accelerate the process of finding analog basins, we developed software to provide logical and consistent results and we built a database for 25 basins to validate the software. Specifically, the research proposed in this project set out to accomplish the following objectives:

(1) develop the methodology needed to identify analog basins;

(2) develop software and a database that can capture characteristics of conventional and unconventional geologic and petroleum systems in North America;

(3) define various basins according to their petroleum systems characteristics to include:

- stratigraphic, depositional systems, structural, thermal and reservoir diagenetic histories;
- source rocks, seals, and timing of hydrocarbon generation and migration;

(4) validate the methodology and the software using data in the public domain.

1.4 Organization of This Thesis

This thesis is divided into seven chapters. In Chapter II, I review basin analog practices in the petroleum industry. In Chapter III, I discuss the basin analog system (BAS) developed in this project. Chapter IV focuses on the design of the basin analog system software. In Chapter V, I demonstrate implementation of BAS. Chapter VI, presents the methodology, software validation, and usefulness of the basin analog system, and finally, Chapter VII contains the conclusions and recommendations.

CHAPTER II

LITERATURE REVIEW OF PETROLEUM INDUSTRY BASIN ANALOG PRACTICES

2.1 Basin Analog Practices

Many basins in the world have been under development for more than a century. We have a wealth of information concerning the petroleum systems within those basins. There are even more basins around the world that are relatively unexplored, especially when it comes to the understanding of the low quality, unconventional oil and gas deposits. One way to understand a basin where low drilling and exploration activity has resulted in limited data about the basin is to compare the basin with an analog basin that has been extensively explored and developed. If the analogy is correct, then statistical information from the better explored basin can be used to improve one's understanding and expectations for the under-explored basin. For these and other reasons, basin analog practices have been used by geologists for many decades.

Historically, basin analog practices have been performed by expert geoscientists using their experiences and subjective opinions to find basins that are analogues to the target basins. [9-12] Experts expend substantial effort to perform this task. Importantly, one expert's opinion can differ significantly from the opinions of other experts. I couldn't find any publish literature or step-by-step guidelines in public domain that could standardize the procedure and be followed to identify an analog basin. Therefore, without an established methodology, it is probable that experts with different levels of expertise and experience would select different analog basins given the same information.

2.2 Basin Classification

Basin classification is a logical starting point when searching for a basin analog model because the basin type reflects tectonic history, sedimentary fills burial history, and HC generation migration, and trapping. To select analog basins, it is necessary to understand how basins are classified. [6-8,13-15] The published literature indicates that there are many aspects one must consider to classify a basin, such as basin type, [8] structural styles and hydrocarbon traps, [14] stratigraphy, lithology, depositional environment, and structural and tectonic setting, [7] production size, [13] and perhaps, other aspects, such as locations.

Basin classification schemes evolved from genetic interpretations (Halbouty et al.,[13] Klemme,[15] Kingston et al.[6,7]) with the advent of plate tectonic theory to deterministic models with increased understanding of organic geochemistry (Ungerer et al.[16] and Tissot[17]). The newer more quantitative approaches to the analysis improve the ability to estimate the volume of petroleum generated and trapped in a particular type of basin.

Halbouty et al.[13] listed giant oil and gas fields in the world. The defined "giant" fields as fields that have recoverable oil of 500 million barrels or more or a minimum of 3.5 trillion cubic feet (Tcf) of recoverable gas. The geologic factors examined in this study were trap size, timing of trap development, hydrocarbon sources, marine content of total sedimentary section, reservoir rock, evaporates, cap rock, unconformities, geologic age, and geothermal gradient. They concluded that those geologic factors explained the unusual occurrences of giant fields in most productive provinces, and their existence in only a few of the world's sedimentary basins.

Klemme[15] stated “a basin classification when linked to the variability of petroleum characteristics may provide a worthwhile exercise in appraising the petroleum potential of new frontier basins or developing further production in newly developing basins.” He classified basins into 8 types which are interior simple, composite complex, rift, downwrap, pull-apart, subduction, median, and delta. Klemme classified the basins based on tectonic location, crustal zones, basin shape, principle traps, and basin size.

Tissot[17] claimed that temperature is the most sensitive parameter in hydrocarbon generation. He mentions that temperature history is essential for evaluating petroleum prospects. Maturation indices such as vitrinite reflectance and Thermal Alteration Index (TAI) are functions of the thermal history through rather complex kinetics. It is also important to simultaneously interpret kerogen type and maturation to avoid difficult conversions form one index to another.

CHAPTER III

BASIN ANALOG SYSTEM (BAS)

The use of analog basins to better understand new frontier basins has been used by geologists for many years. It is logical to take what we have learned in one basin and apply the appropriate technology to at least begin our evaluation and development of a new basin. In this research, we developed a methodology and software that can help engineers and geoscientist obtain consistent results when searching for analog basins. We named the software “Basin Analog System” (BAS). This chapter will describe the idea, challenges, approach, and the methodology developed during this project.

3.1 The Idea

In North America, there are more than 30 basins where oil and/or gas have been produced from unconventional reservoirs for many decades. Twenty five of the thirty basins produce large volumes of unconventional natural gas. By “unconventional” reservoirs, **(Fig. 1.1)**, I refer primarily to tight gas, coalbed, shale and heavy oil reservoirs. In all of the basins where unconventional reservoirs have produced, we also have substantial data about conventional, high permeability oil and gas reservoirs.

Thus, in most of the 25 basins, we can do a reasonable job of quantifying oil and gas resource in different segments of the resource triangle. As such, it maybe useful to investigate whether the amount of conventional oil and gas at the top of the triangle, can be used to estimate the amount of oil and gas in the base of the triangle, in the unconventional reservoirs.

Many basins outside of North America also contain unconventional resources, as predicted by the resource triangle and the concept of all natural resources being distributed log normally in nature. However, in most target basins of the world, unconventional resources have not been drilled or developed. In most cases, the conventional reservoirs are still being developed, and there has been no reason to assess the unconventional resources. Thus, there may be large volumes of unconventional resources in some target basins, but very little data have been collected or published on these resources.

So, if we can find a North America basin that is analogous to the target basin outside North America, and we can enter the available data from the target basin, we can use the analog basin to (1) predict hydrocarbon resource potential of the target basin, (2) guide exploration and infer reservoir characteristics, (3) make preliminary decision concerning best engineering practices (e.g., drilling program, completion method, stimulation method, etc.). **Fig. 3.1** illustrates this idea.

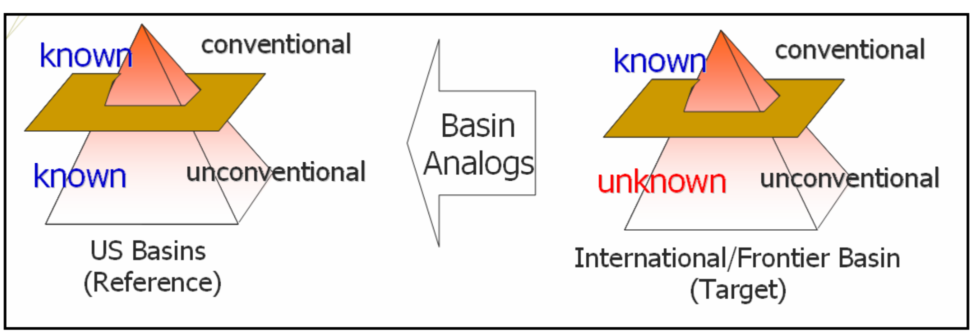

Fig. 3.1—Basin analog concept

In North America, we have lot of information on both the conventional and unconventional reservoirs in many of our basins, and much of this information is available in public literature. Outside North America, we usually have information on the conventional reservoirs, but limited information for the unconventional reservoirs. Using the information from the conventional reservoirs in the target basin, we can determine the best analog basin in North America, and then use analogy and statistics to infer what might be found if the target basin.

Of course, there are exceptions to most assumptions. For example, we know a lot about some unconventional resources outside of North America, such as the heavy oil fields in Venezuela and Indonesia. Also, there has been some work done in tight gas sand in Europe, South America, China and other places. Many areas of the world have abundant coal resources, so some coalbed methane exploration has occurred outside of North America during the past decade. In fact, much of the data from these “current” unconventional oil and gas development activities outside of North America can help us validate our methodology, eventually.

3.2 Challenges

To test the basin analog approach, we developed a methodology and software. We began our work by reviewing literature to find what has been published to help us perform basin analogy work. However, we did not find much on the subject and nothing quantitative. Most of the basin analog papers discussed the results in terms of geologic and geophysics characteristics. [9,10,16,17] None of the papers discussed the methodology they use to find an analog basin to a specific target basin. It appears that the experts simply rely on their experience to qualitatively select analog basins.

Besides the problem with a lack of published, qualitative solutions to this basin analog problem, we also had to select the basins we wanted to evaluate as reference basins. There are a large number of basins in North America that contain both conventional and unconventional resources. To characterize these basins, we had to develop a method using publically available data that could be evaluated quantitatively. Also, we had to decide which basins should be selected, and which basin should be evaluated first.

3.3 Approach and Methodology

The first step in developing the Basin Analog System was to determine which parameters we needed to evaluate to quantitatively find a basin analog. We identified 32 parameters that we think are important parameters to evaluate a basin. These parameters were categorized and weighted based on their relative importance.

Once we decided which parameters to use, we selected the North America basins that have conventional and unconventional gas and will be reference basins. We used maps from GRI/GTI [18-20] as a basis for selecting these reference basins. Also, we selected an international or frontier basin as our target basin for testing the results. We selected Neuquen basin in Argentina for the target basin, based on suggestion by one of our research sponsors, Burlington Resources.

The next step was to summarize the geologic and petroleum systems characteristics of the reference and target basins using public literature. Several electronic databases, such as American Association of Petroleum Geologists (AAPG) datapages, Society of Petroleum Engineers (SPE) e-Library, United States Geological Survey (USGS), and Society of Exploration Geophysicists (SEG) are our main sources for this task.

While summarizing the geology and petroleum systems characteristics, we developed the methodology and the software to identify the reference basins that are analogous to the target basin. The selection process is discussed thoroughly in Section 3.3.4 in this thesis. The final step was to validate the results (discussed in Chapter VI). **Fig. 3.2** presents the flowchart of the methodology we used to develop the Basin Analog System.

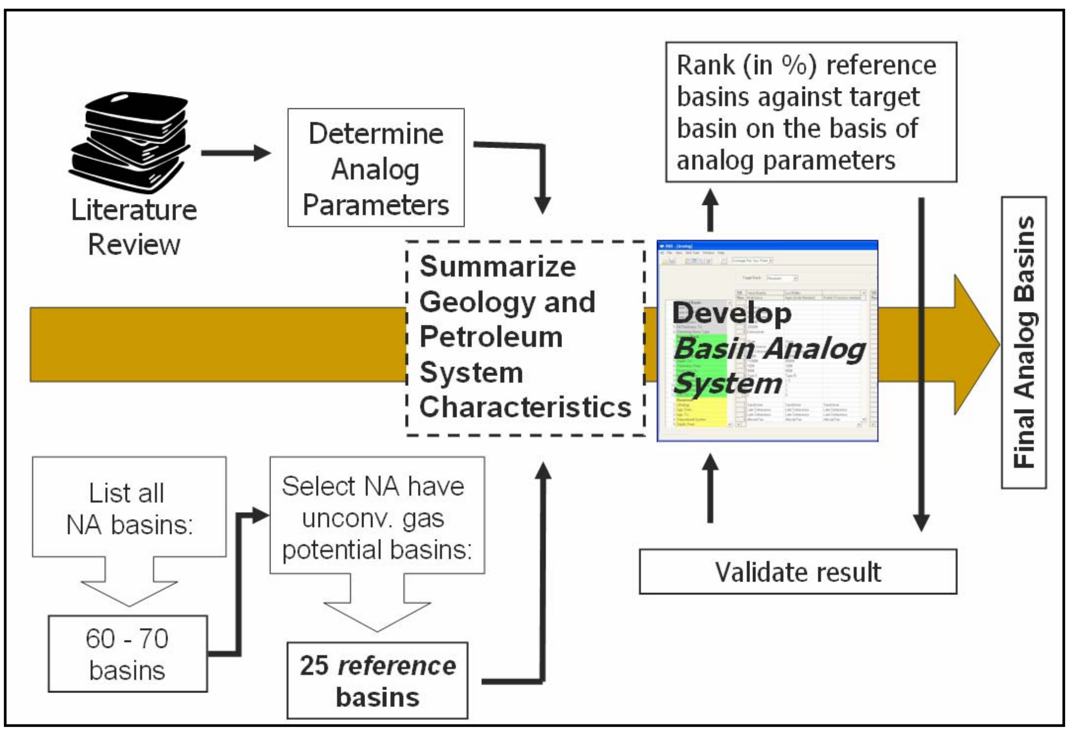

Fig. 3.2—Basin analog approach

3.3.1 Analog Parameters

We determined the analog parameters by reviewing the basin classification [6-11] literature. Also, we determined the importance of each of the parameters to the selection process. The importance helped us develop weighting factors in the quantification process.

We identified 32 parameters that we used in analog analysis **(Table 3.1)**. Those parameters are classified into three categories, which are (1) general basin parameters, (2) source rock parameters, and (3) reservoir rock parameters. General basin parameters are parameters such as basin type, basin area, fill thickness, and deforming stress type. Source rock parameters are parameters that are properties of a source rock. These parameters include source rock type, age, thickness, depth, kerogen type, vitrinite reflectance, and total organic contents. Reservoir rock parameters are parameters that associated with hydrocarbon reservoirs. We have identified reservoir rock parameters **(Table 3.1)**.

For each analog parameter, we used weighting factors to reflect their relative importance. There are two types of weighting for each parameter. General weighting is scaled from 0 to 100, and depends on the degree of importance. The other weighting is called the second weighting factor. Not all of the parameters need this second weighting factor. The parameters that have quantitative classes (e.g., porosity, permeability) need this weightings and we did not assign this weighting to the parameters that have qualitative classes (e.g., lithology, fluid type) (see **Table 3.1**). The second weighting concept is explained in Section 3.3.4 (also, see **Fig. 3.5**).

We determined the classes for each of analog parameters. The term “classes” here means the pre-assigned quantitative or qualitative values or descriptions for each parameter. All of these classes are tabulated in Appendix B. For example, the classes for lithology are sandstone, carbonate, tight sand, coal, and shale, and porosity has classes of 1%, 2%, 3%, …, 40%. **Table 3.2** shows the classes for some analog parameters. In developing the software, we gave flexibility to the user to add more analog parameters and to edit or modify them, if necessary.

Among the analog parameters we considered 5 parameters to be critical parameters. There are lithology, fluid type, kerogen type, vitrinite reflectance, and seals. We picked these critical parameters based on our best knowledge that these parameters are the minimum parameters that have to be common to both the target and the analog basin. The purpose for using critical parameters was to avoid obtaining false analogs. For example, a sandstone reservoir will not be analogous to a carbonate reservoir. Also, an oil reservoir would not be an analog to a gas reservoir. Thus, in the mathematical model we developed, it checks these critical parameters first and make sure that they are common before looking at other parameters. If any of these 5 critical parameters does not match, then the model will decide that the petroleum system and the basin that being compared are not analogous.

3.3.2 Reference Basin Selection

North America has more than 60 major basins that have unconventional resources potential. We use maps from Gas Research Institute (GRI), [18-20] now called the Gas Technology Institute (GTI) **(Fig. 3.3)** to identify 25 basins that have a history of producing unconventional resources **(Table 3.3),** and where sufficient data concerning unconventional gas resources are available. GRI/GTI published maps for basins in North America that have coalbed methane, tight gas, and gas shale resources. The 25 basins we selected have significant volumes of those 3 unconventional gas resources.

Table 3.1—PARAMETERS USED TO EVALUATE ANALOG BASINS

No.	Category	Weighting Factor	Second WF	Parameter	Critical
1	General Basin	30	FALSE	Basin Type	FALSE
2		60	TRUE	Basin Area	FALSE
3		50	TRUE	Fill Thickness	FALSE
4		70	FALSE	Deforming Stress Type	FALSE
5	Source Rock	80	FALSE	Rock Type	FALSE
6		50	FALSE	Age	FALSE
7		50	TRUE	Depth	FALSE
8		70	TRUE	Thickness	FALSE
9		100	FALSE	Kerogen Type	TRUE
10		100	TRUE	Vitrinite reflectance (%)	TRUE
11		80	TRUE	Total Organic Content (%)	FALSE
12	Reservoir Rock	100	FALSE	Lithology	TRUE
13		30	FALSE	Age	FALSE
14		60	FALSE	Depositional System	FALSE
15		50	TRUE	Depth	FALSE
16		70	TRUE	Thickness	FALSE
17		80	TRUE	Pressure	FALSE
18		80	FALSE	Pressure Regime	FALSE
19		90	TRUE	Porosity	FALSE
20		90	TRUE	Permeability	FALSE
21		70	TRUE	Water Saturation	FALSE
22		50	TRUE	Migration Distance	FALSE
23		50	FALSE	Migration Direction	FALSE
24		100	FALSE	Seals	TRUE
25		90	FALSE	Traps Type	FALSE
26		100	FALSE	Fluid Type	TRUE
27		50	TRUE	Oil Gravity (API)	FALSE
28		10	TRUE	Sulfur content	FALSE
29		10	TRUE	CO2 content	FALSE
30		10	TRUE	H2S content	FALSE
31		10	TRUE	Heavy gas (C2-C5)	FALSE
32		10	TRUE	EUR	FALSE

Table 3.2—EXAMPLE OF ANALOG PARAMETER'S CLASSES

No.	Parameter	Classes
1	Basin Type	Foreland
2		ForeArc
3		BackArc
4		Rift
5		Srike Slip
6		IntraArc
1	Fill Thickness	< 1000ft
2		1000ft
3		5000ft
4		10000ft
5		15000ft
6		20000ft
7		25000ft
8		30000ft
9		35000ft
10		40000ft
11		45000ft
12		50000ft
13		55000ft
14		60000ft
1	Deforming Stress	Extensional
2		Compressive
3		Lateral

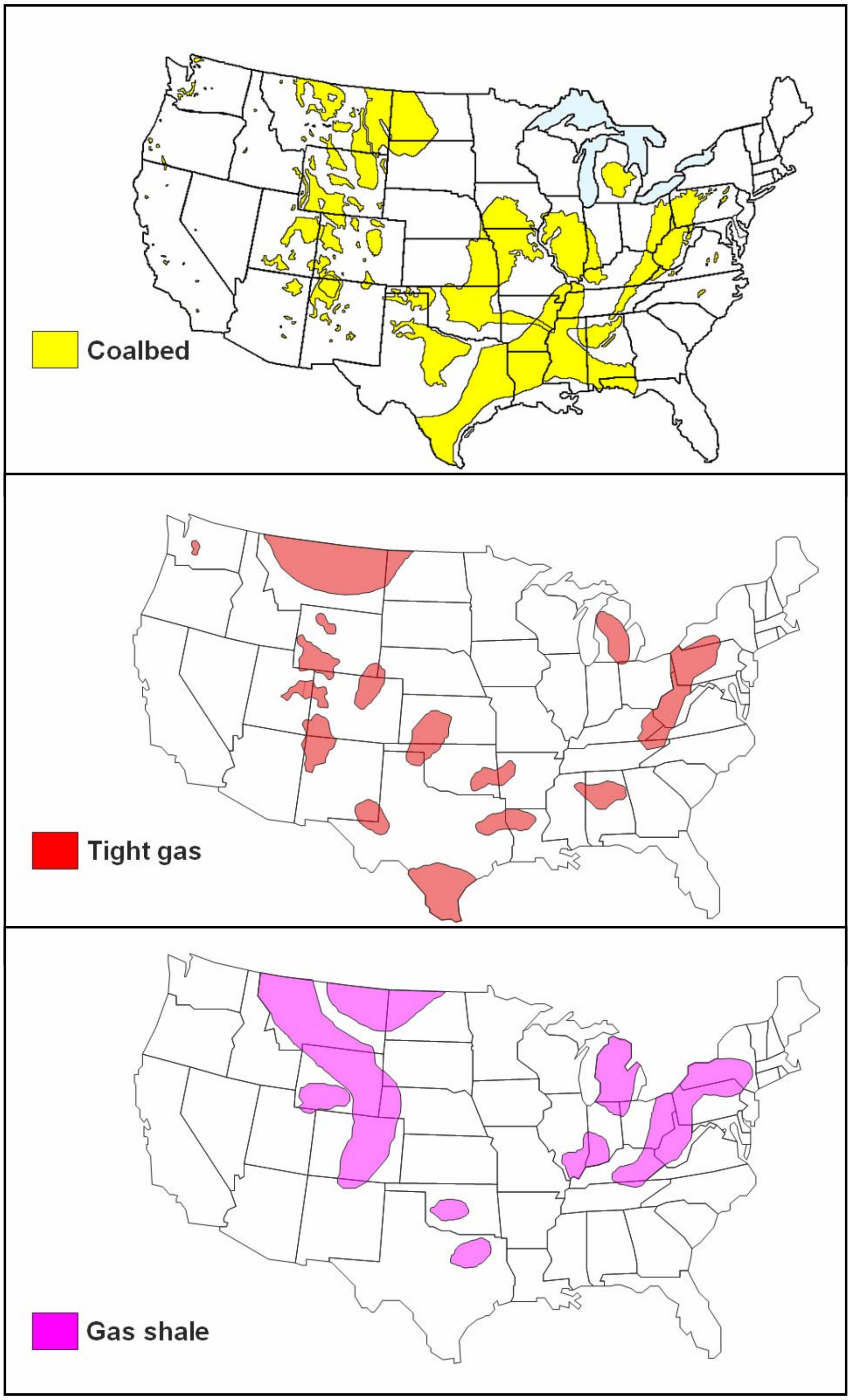

Fig. 3.3—Twenty-five North American reference basins that contain unconventional gas resources[18-20]

Table 3.3—NORTH AMERICA BASINS

No.	Reference basin name
1	Permian
2	San Juan
3	Uinta
4	Anadarko
5	Appalachian
6	Arkoma
7	Big Horn
8	Black Warrior
9	Cherokee
10	Denver
11	East Texas
12	Forest City
13	Fort Worth
14	Greater Green River
15	Illinois
16	Louisiana Mississippi Salt
17	Michigan
18	Paradox
19	Piceance
20	Powder River
21	Raton
22	Texas Gulf Coast
23	Williston
24	Wind River
25	Western Canada Sedimentary

3.3.3 Geology and Petroleum Systems Summary

In this research, we used information from the published literature to describe the geology and petroleum systems for the reference basins, and the target basin. Our main sources for published literature were the American Association of Petroleum Geologists (AAPG) datapages, Society of Petroleum Engineers (SPE) e-Library, the United States Geological Survey (USGS) 1995 National Assessment of US Oil and Gas Resources, the

USGS website, the Society of Exploration Geophysicists (SEG), and information found on the internet. We consider this geology and petroleum systems summary task as a very important part in our project. We realize that we need accurate descriptions of the reference basins if our methodology is to be valuable.

3.3.4 Basin and Petroleum Systems Analog Identification

We identify the analog basins by comparing each available parameter shown in **Table 3.2** in the target basin to the parameters in the reference basins. This process is illustrated in **Fig. 3.4**. First, we look at the first parameter, basin type. We will assign a value of 1 if the target basin matches and 0 if it does not match the reference basin. If it matches, then the value 1 is multiplied by the weighting factor, WF_1. The weighting factors are used to gauge the importance of each parameter. As we gain more experience with BAS, it is feasible that the value of the weighting factors will be adjusted to provide more accurate analogs. In **Fig. 3.4**, the basin type parameter for the Appalachian and San Juan basins match with the Neuquen basin, which is a foreland basin. Therefore, both the Appalachian and San Juan are assigned the value (1 x WF_1). The deforming stress type of the San Juan basin does not match with the Neuquen basin, so the San Juan basin receives zero (0) points for that particular parameter, but Appalachian receives a value of 1 x WF_6.

Some quantitative parameters can not be described using only 1 or 0 such as basin area, fill thickness, porosity, and permeability. To properly use these parameters to determine analogs, we have to establish ranges and bins for each parameter. To evaluate those parameters, we divide them into two parts and differentiate them by beginning range (indicated by *parameter: from*) and ending range (indicated by *parameter: to*). Using a range lets us handle parameter values from a wide variety of formations within each basin. In **Fig. 3.5**, Basin A has porosity ranging from 20 – 25%, while Basin B has a porosity range of 12 – 25%. If we pre-assigned the classes for parameter porosity in fix classes with 5% range (as shown in bottom-left of **Fig. 3.5**), we can fit the porosity of Basin A in one of this classes, but we cannot assign Basin B's porosity to any of this classes properly. Thus, dividing the parameter porosity into *porosity:from* and *porosity:to* (**Fig. 3.5**, bottom-right) solves this issue.

Another concept that we adopted for the quantitative parameters was to incorporate a secondary weighting factor. Suppose a formation in a target basin has a porosity of 20% and the formation in reference basin has a porosity of 21%. These two porosities are not perfectly match but very close. So we handle this issue by using weighted points less then one. We call this weighted concept as the second weighting factor. **Fig. 3.6** illustrates this concept. In that illustration, the target basin that has a porosity of 15% is being compared to the reference basin that has a porosity of 5%. There are 5 pre-assigned porosity classes (i.e., 0%, 5%, 10%, 15%, and 20%). Within those pre-assigned classes, the distance from 5% to 15% is 2 classes. Thus, to quantitative weight this classes that are not perfectly matched, we subtract the total number pre-assigned classes by the distance of classes being compared then divide them by the total number pre-assigned classes (i.e., [5-2]/5). This process resulted value of 0.6 for the example in **Fig. 3.6**. The procedure results in a higher value when the two value are close and a lower value when the two parameters are not close. The next step is multiplying the second weighted factor (i.e., 0.6) by the main weighting factor of parameter porosity.

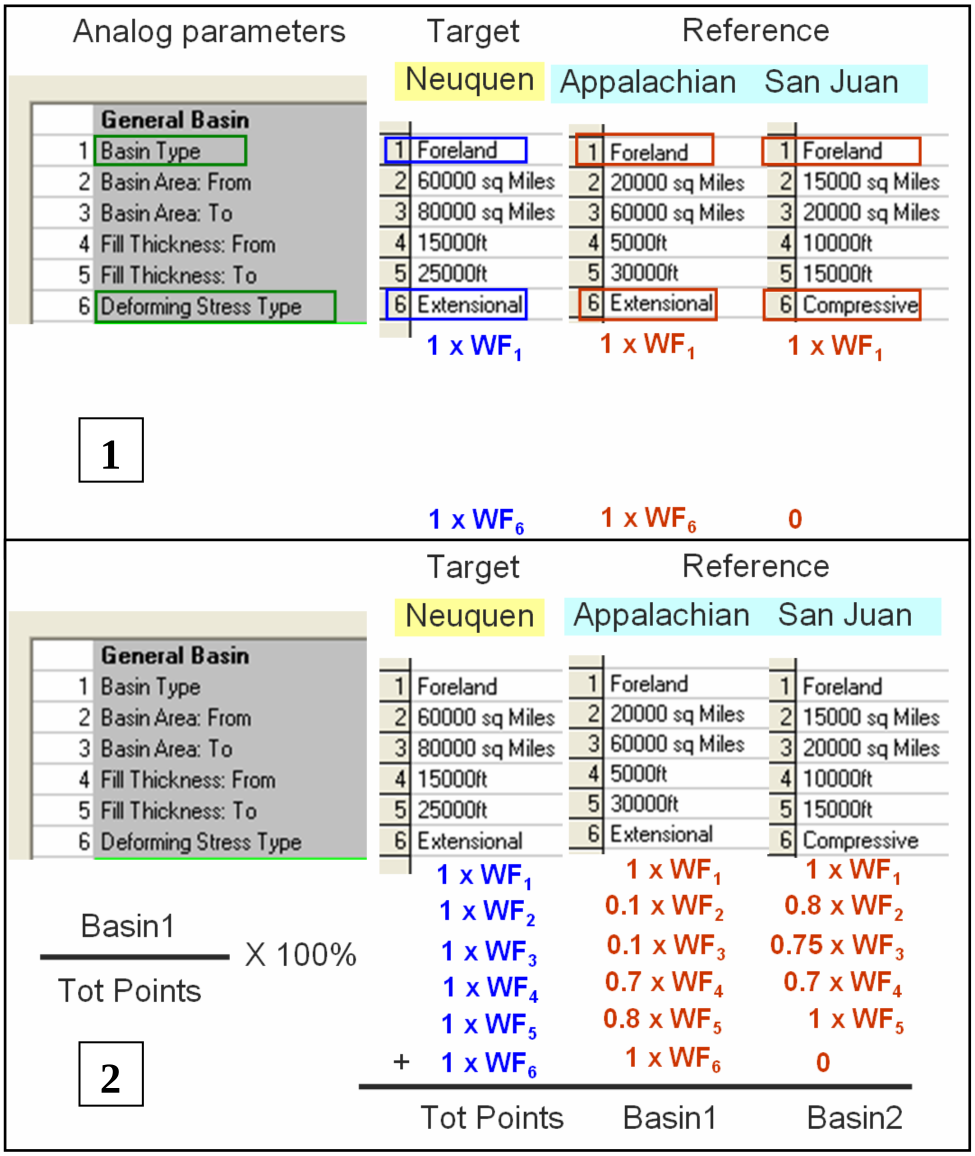

Fig. 3.4—Parameter comparison process to identify analog

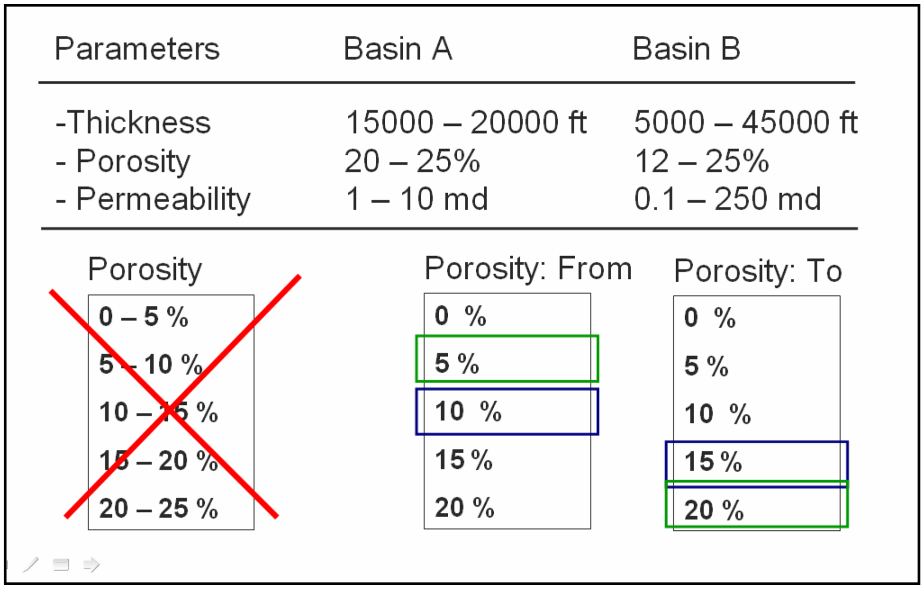

Fig. 3.5—Flexible parameter classes

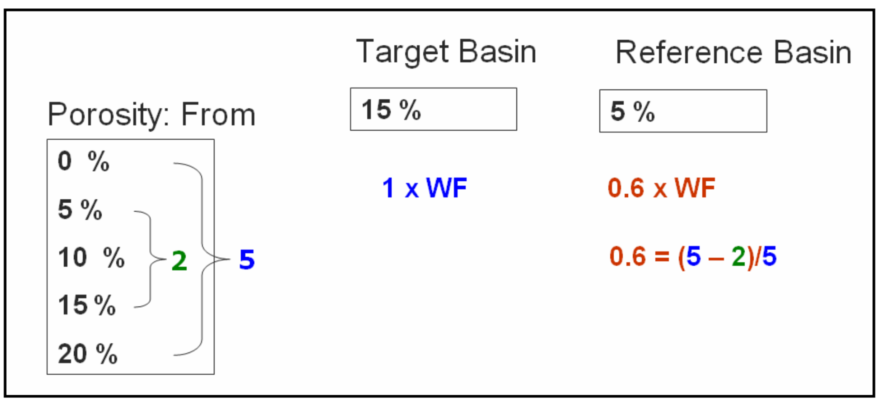

Fig. 3.6—Second weighting concept

The discussion above covers only the general basin parameter category where each basin has only one general set of data to describe the basin. However, each basin will have more then one source rock parameter category and multiple reservoir parameter categories. To assess the basin and to determine analog basins where multiple petroleum systems are involved, we used the approach shown in **Fig. 3.7**.

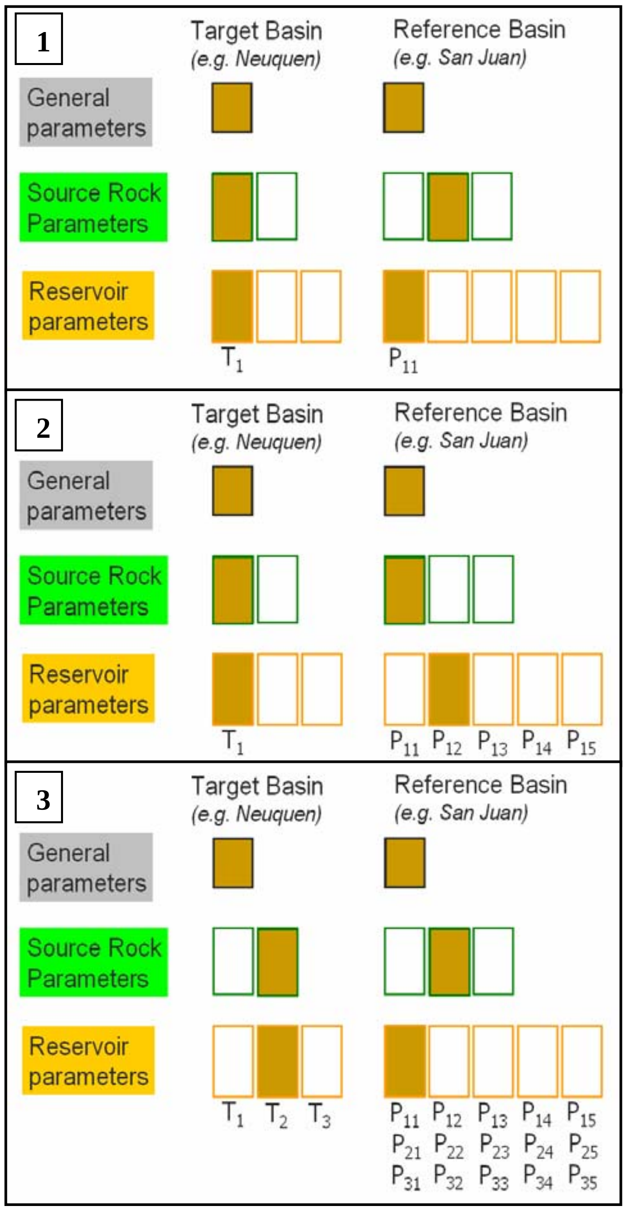

Fig. 3.7—Handling multiple petroleum systems/source rocks and reservoirs

In **Fig. 3.7**, the target basin has 3 potential reservoir formations and 2 potential source rocks, while the reference basin has 5 reservoir formations and 3 source rocks. This condition is more complicated to evaluate. We handle this issue by comparing the two basins at the reservoir formation level. For each reservoir formation, we can determine which source rock generated the hydrocarbon that eventually filled the reservoir rock. In the other words, we know the source of the hydrocarbon in each reservoir. We then combine the reservoir formation, its source rock, and the general information as a set. We called this combination as a "petroleum system" set. The first part of **Fig. 3.7**, the shaded area, illustrates the first petroleum system of the target basin being compared to the first petroleum system of the reference basin.

Once we evaluated all the analog parameters for those sets, we moved to the second petroleum system in reference basin and compare it with the first petroleum system of the target basin (see second part of **Fig. 3.7**). This process will continue until all petroleum systems in the reference basin have been compared to the first petroleum system in the target basin. We then start comparing the second petroleum system in the target basin to the first petroleum system in the reference basin (see third part of **Fig. 3.7**). We will continue the process until all petroleum systems in both the target basin and the reference basin have been compared one to the other. For the example in **Fig. 3.7**, it takes 15 comparisons to evaluate each of these three petroleum systems in the target basin to each of these five petroleum systems of the reference basin.

We evaluated each analog parameter in every comparison. Each comparison produced one point for the petroleum system of the target basin and one point for the petroleum system of the reference basin. In Fig 3.7, the points for the target basin are indicated by T_m, where m refers to the petroleum system. The points for the reference basin are indicated by P_{mn}, where n refers to the petroleum system of the reference basin and m is the petroleum system of the target basin that was being compared to produce that particular point (see the third part of **Fig. 3.7**).

Each point in every comparison will be collected and processed. We use three different methods in processing these points. The first method is to average the points, where we determine the arithmetic average of the points from the reference basins (i.e., avg[P_{11},P_{12},…,P_{mn}]) and divide them by the average of points from target basins (i.e., avg[T_1, T_2, …, T_n]) then multiply by 100 to obtain the value as a percentage. The left part of Fig. 3.8 shows the average points calculation for the example shown in Fig 3.7.

The second method is to determine the best match of a petroleum system in the target basin to a petroleum system in a reference basin. The term best match petroleum system means that the method will only process the highest point from all the petroleum system comparison. The right part of **Fig. 3.8** shows that from the 15 points obtained, turn out that the third petroleum system of the reference basin (P_{23}) was the highest numerical value when compared to the second petroleum system set of the target basin. We then divide this point by the second petroleum system of the target basin (T_2) and multiply by 100 to obtain the value in percentage.

Method 1 – Average points	**Method 2 – Best Match, Petroleum System**
$$\frac{\mathrm{Avg}\begin{pmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{21} & P_{22} & P_{23} & P_{24} & P_{25} \\ P_{31} & P_{32} & P_{33} & P_{34} & P_{35} \end{pmatrix}}{\mathrm{Avg}(T_1 \quad T_2 \quad T_3)} \times 100\%$$	$$\mathrm{Max}\begin{pmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{21} & P_{22} & P_{23} & P_{24} & P_{25} \\ P_{31} & P_{32} & P_{33} & P_{34} & P_{35} \end{pmatrix} = P_{23}$$ $$\frac{P_{23}}{T_2} \times 100\%$$

Fig. 3.8—Methods in processing analog parameters' points

The third method is similar to the second method, but instead of processing the highest point, we look for a specific resource type (e.g., coalbed, tight gas, sandstone, shale, etc.). We specify from the beginning what type of resource or petroleum systems we want to find from our target basin. For example, we have a coalbed reservoir the target basin. Then this method will only process coalbed formations from the reference basins.

Finally all these processed points are shown as a percentage for the entire basin, and are ranked as shown in **Fig. 3.9** for Average Points method and **Fig. 3.10** for Best Match Petroleum System method.

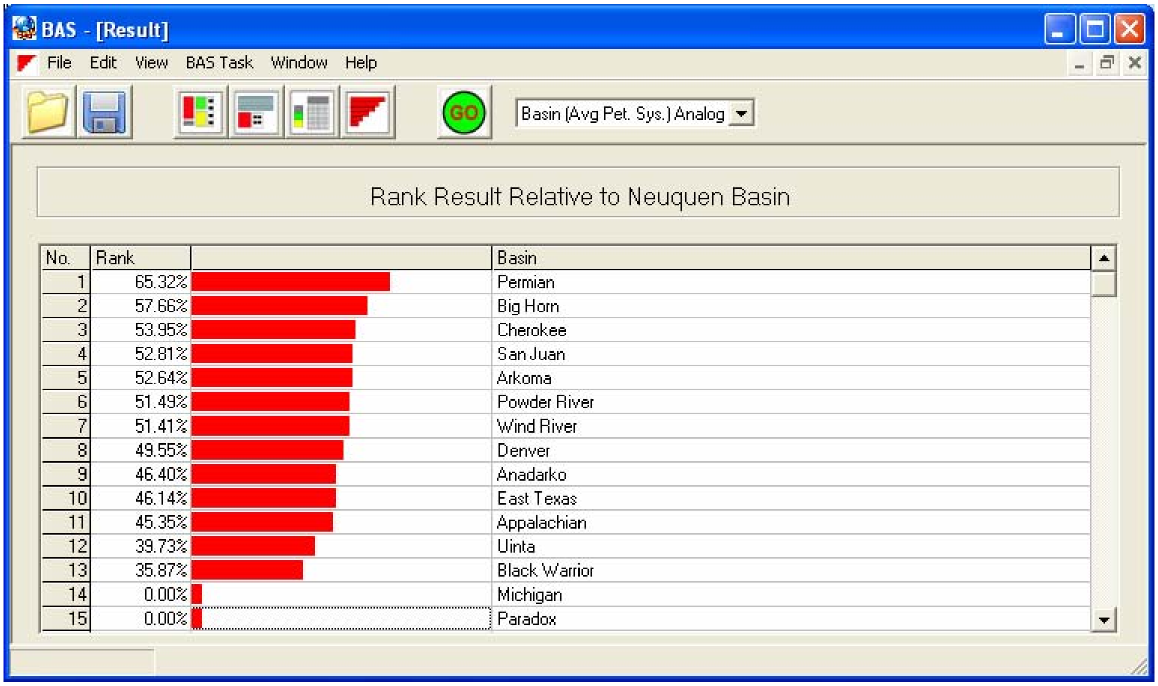

Fig. 3.9—Example result for Neuquen basin

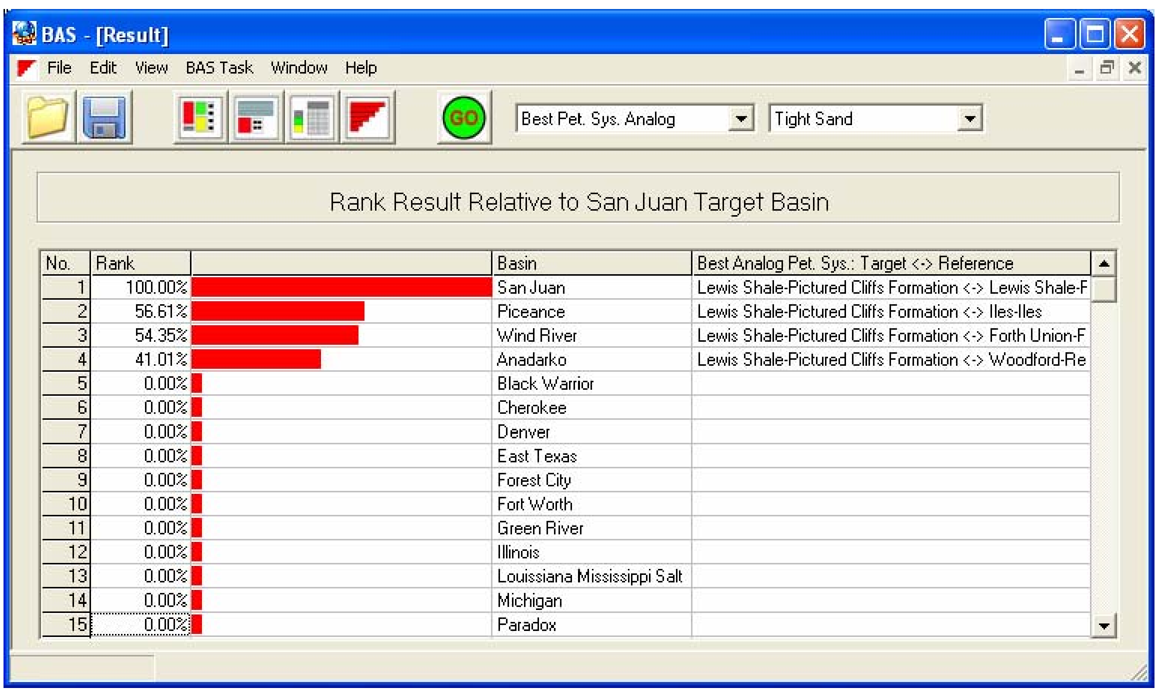

Fig. 3.10—Example result for San Juan basin – tight gas resource

CHAPTER IV

THE DESIGN OF BASIN ANALOG SYSTEM SOFTWARE

This chapter presents the design of the Basin Analog System, to include the features, the software, the system components and their functions, and the system architecture.

4.1 The Main Features

The BAS software will be used to consistently identify analog basins. The software will be able to rank the North America reference basins against a target frontier basin on the basis of analog parameters. The detailed features of BAS are described as follows.

(1) There are 25 reference basins and one target basin in the current version of the BAS software. The software will be able to carry many more reference and target basins. There is a user interface available within the software for users to input data for more reference or target basins including the source rocks and reservoir rocks of each basin. The association of each reservoir rock to its source rock must be specified.

(2) BAS allows the user to modify analog parameters. We have used 32 analog parameters that are classified into *general*, *source rock* and *reservoir rock* categories. Each analog parameter has a weighting factor and classes assigned to describe the parameters. If a user has specific information for certain basins, the software will let the user modify the parameters, variables, and weighting factors to better solve the problem.

However, the user should be very careful and confident of the changes made to the software.

(3) The geology and petroleum system characterization was performed using public information. BAS has a spreadsheet like window that allows the user to see and check the information. It allows the user to modify the information (e.g., porosity range, source rock's vitrinite reflectance, etc.) if the user has more reliable information regarding a particular basin. For the new reference or target basin, the user can input the characterization information to the database through this interface.

(4) BAS is capable of identifying analog basins. The degree to which the target basin is analogous to the reference basin will be shown in percentage for each basin. These reference basins will be ranked from the most analogous to the least analogous.

4.2 The Components of BAS

To achieve the main features described in section 4.1, the software has been divided into the following 4 components. Each window is linked to the database to obtain information, input information, or to modify the information. Each component is also integrated one to the other. The structure of each component is illustrated in **Fig. 4.1**.

(1) Basin List is a component containing the names of all reference and target basins that have been described in the database. Each basin usually has multiple source rocks and multiple reservoir rocks. These source rocks and reservoir rocks are in the basin list, as well as the association of each reservoir rock to its source rock. The information in the basin list was obtained from the database.

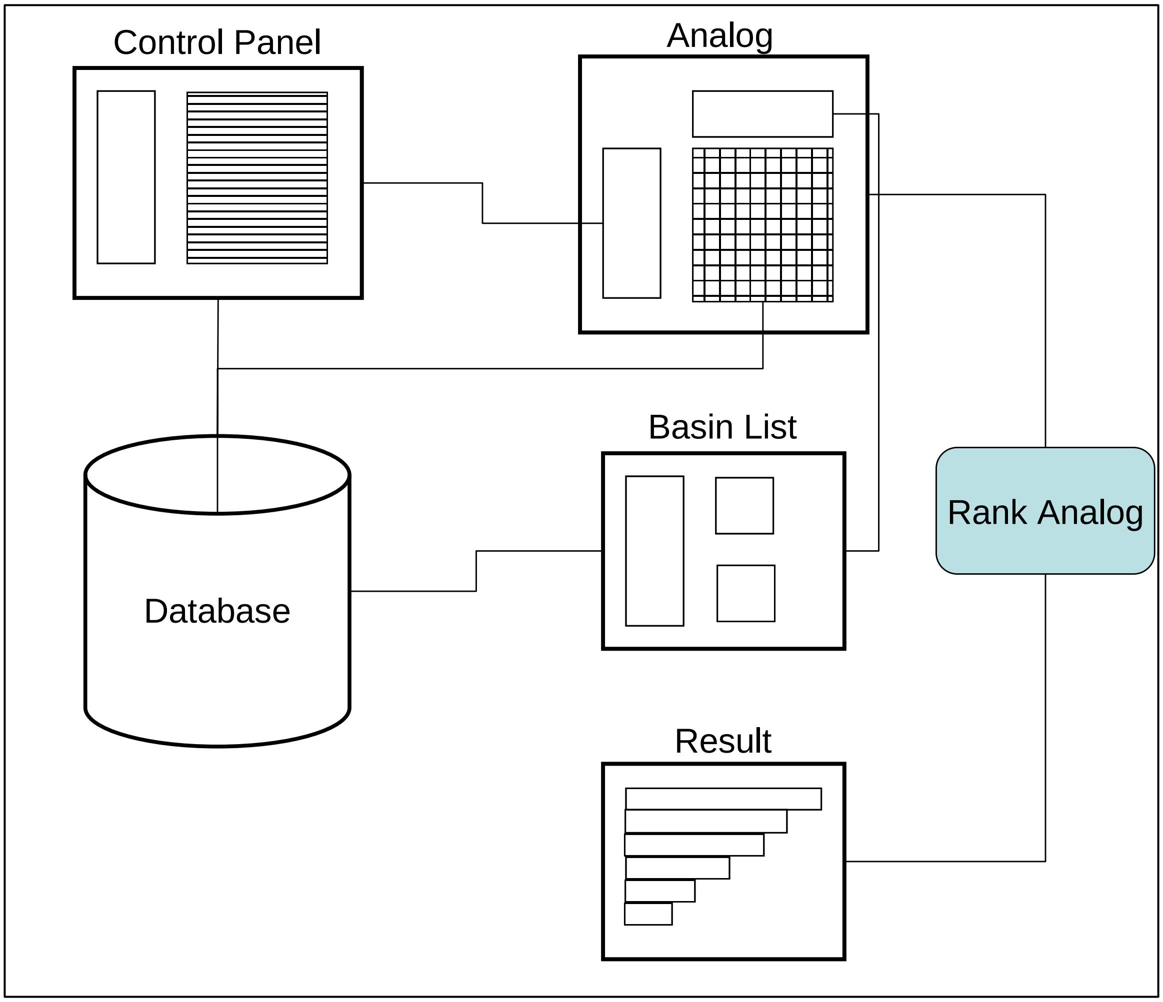

Fig. 4.1—The modular structure of BAS components showing integration one to the other

(2) Control Panel is the component containing the information about the analog parameters. This component displays information about the analog parameters. The analog parameters information includes the weighting factor, secondary weighting factor, critical parameter indication, the analog parameter itself and the variables of each analog

parameter. The Control Panel component is the place for the user to control the analog parameters, to edit and modify the weighting factors and to input other information related to the analog parameters.

(3) Analog is the component containing petroleum system and geology characterization information for each basin. It is divided into three columns where the first column displays all of the analog parameter, the second column show the characterization information for target basin displaying for each source rock and reservoir rock in spreadsheet format. The last column is similar to the second column, but the information is for the reference basin.

(4) Rank Analog is the component where the mathematical computations take place for ranking the analog basins. This component contains the methodology that we have developed and takes all the information from the analog component, processes the information, and produces the results.

(5) Result is the component that displays the results of the analog computations. The results are displayed in a table where the first column is the rank number, followed by analog degree in percentage and scaled bar for comparison, and the last column is the basin name.

Each component in the Basin Analog System has a link to the database and the components all work together to solve the problem.

4.3 BAS Architecture

BAS is an object oriented program (OOP). Section 5.1.2 presents more information on OOP. As an OOP, BAS was design with the possibility of eliminating redundant code and being able to communicate with other software modules without having to start writing code from scratch.

BAS is divided into two main parts, which are data collection and data processing. **Fig. 4.2** illustrates the system architecture. The program starts by obtaining both reference basin and target basin names using the *GetBasinName* procedure. This first procedure will also reserve memory from the computer to be allocated later for other purposes. The amount of memory allocated depends on how many basins are in the database. The information from this procedure will go to Basin List component.

The next procedure is *GetAnalogParameter*. This procedure is used to obtain analog parameters, all the weighting factors and the variables associated with the parameters. That information is assign to the Control Panel component. The *GetBasinVar* procedure is used to acquire information on the source rocks and reservoir rocks of each basin and store them into the Basin List component. The petroleum system and geology characterization information of each basin is acquired using the *GetBasinChar* procedure. This petroleum system and geology characterization information will then be displayed in the Analog component. Two main functions in data collection are the Database functions and the Modification functions. Each procedure in data collection and data processing part needs the Database functions for pulling information from database and the Modification functions for adding, editing and deleting information and storing them back into database.

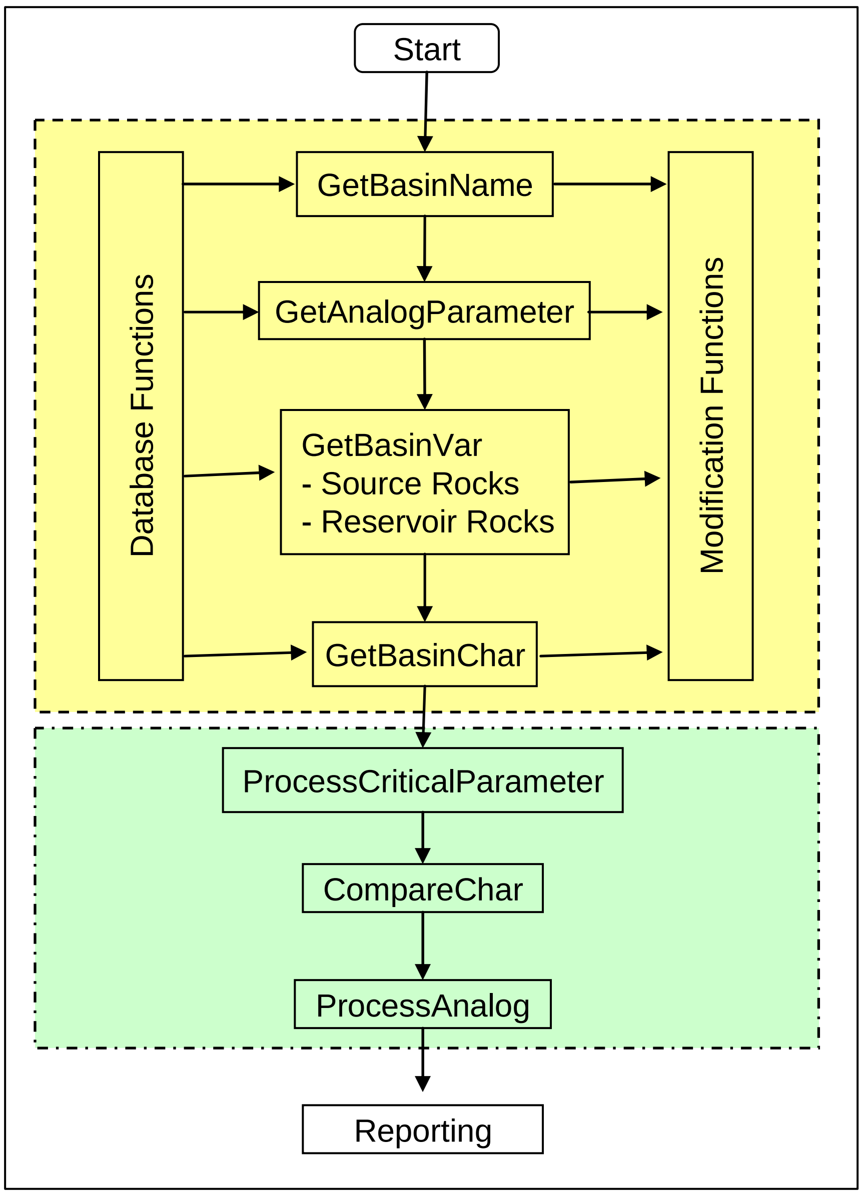

Fig. 4.2—BAS architecture

The second part in this software plays an important role in determining the analog basin. The *ProcessCriticalParameter* procedure is used to make sure that each reference basins that is being compared to the target basin has common critical parameters. Characterization information comparison on the basis of analog parameters is processed through the *CompareChar* procedure. This procedure will communicate with the *ProcessAnalog* to determine the degree of how each reference basin is analogous to the target basin. Finally, the *Reporting* procedure will gather all information from the previous procedures to rank and list the reference basins and display them in tabulation format.

CHAPTER V

THE IMPLEMENTATION OF BAS

This chapter discusses the implementation of BAS, including hardware, software, object-oriented programming, database design, and user interface construction.

5.1 Hardware, Software, and Object-Oriented Programming (OOP)

5.1.1 Hardware and Software

We used an IBM-compatible PC as our development platform. The main reasons are that BAS needs to be linked with a database that is compatible with Microsoft Windows application, and we expect most users have IBM-compatible PCs as it is the most widely used computer in the petroleum engineering community.

The software that we have used to develop our BAS software is the Microsoft Visual Basic 6.0 application development package from Microsoft Corp. Microsoft Visual Basic 6.0 provides the developer with the flexibility and power required to support complex application [21]. Microsoft Visual Studio 6.0 has the following main features:

(1) it supports Object-Oriented Programming (OOP);

(2) it can manipulate various commercially available databases such as Microsoft Access, MsSQL server, and even flat ASCII files;

(3) it can easily integrated with various Ms Office package such as Excel and Word;

(4) it provide comfort in editing and manipulating; and

(5) it is a graphical development environment.

5.1.2 Object-Oriented Programming (OOP)

Over past few years, Object-Oriented Programming (OOP) has become popular in the software development community. OOP, like function programming or logical programming, incorporates a metaphor in which computation is viewed in terms divorced from the details of actual computation. [22-24]

OOP is a type of programming that provides a way of modularizing programs by establishing partitioned memory areas for both data and procedures that can be used as templates for spawning copies of such modules on demand. [25] In general, procedure structured programming uses variables that may be local to a particular procedure, and these procedures typically pass arguments such as strings and numbers between them. In OOP, variables are no longer local just to the procedures that are called methods. The methods make it possible for the messages to be sent and received by objects. Objects are entities that combine the properties of procedures and data.

One of the advantages of object-oriented systems is that the protocol for handling various objects stays essentially the same as the language becomes extended. OOP has the following features:

(1) the possibility of eliminating redundant code that is most appealing;

(2) the protection that objects have from being invaded by code from other parts of the program;

(3) being able to build programs out of standard working parts that communicate with one another, rather than having to start writing code from scratch; and

(4) the ability to have as many instances of object as one likes to present without any interference.

The basic component of OOP is the object, which includes two parts: classes and instances. A class is a description of one or more similar objects. For example, “AnalogParameter” is a class and “Parameter 1” or “WeightingFactor 1” may be one of its instances. In our software, the structure of OOP is hierarchy as illustrated in **Fig. 5.1** where a class consists of several instances.

5.2 Database

BAS requires not only in-depth knowledge about basin analog procedures, but also substantial volumes of data regarding the geology and petroleum system characterization for each basin. The software works by pulling stored data from the database, processing the data, performing necessary modifications, and storing the data back to the database. This process is done repetitively and simultaneously; therefore, selecting the right database type and designing the database structure is the key to achieve robust performance.

5.2.1 Database Type

Software development integration and user-friendly aspects of the software were the main considerations in selecting the database type. We selected Microsoft Access 2003 as the database in our software. It has two main advantages which are (1) it is easy to integrate capability with the application development, and (2) it is readily available in most current computer system that use the Windows operating systems. Strong integration with the application development is important to maintain robust connection.

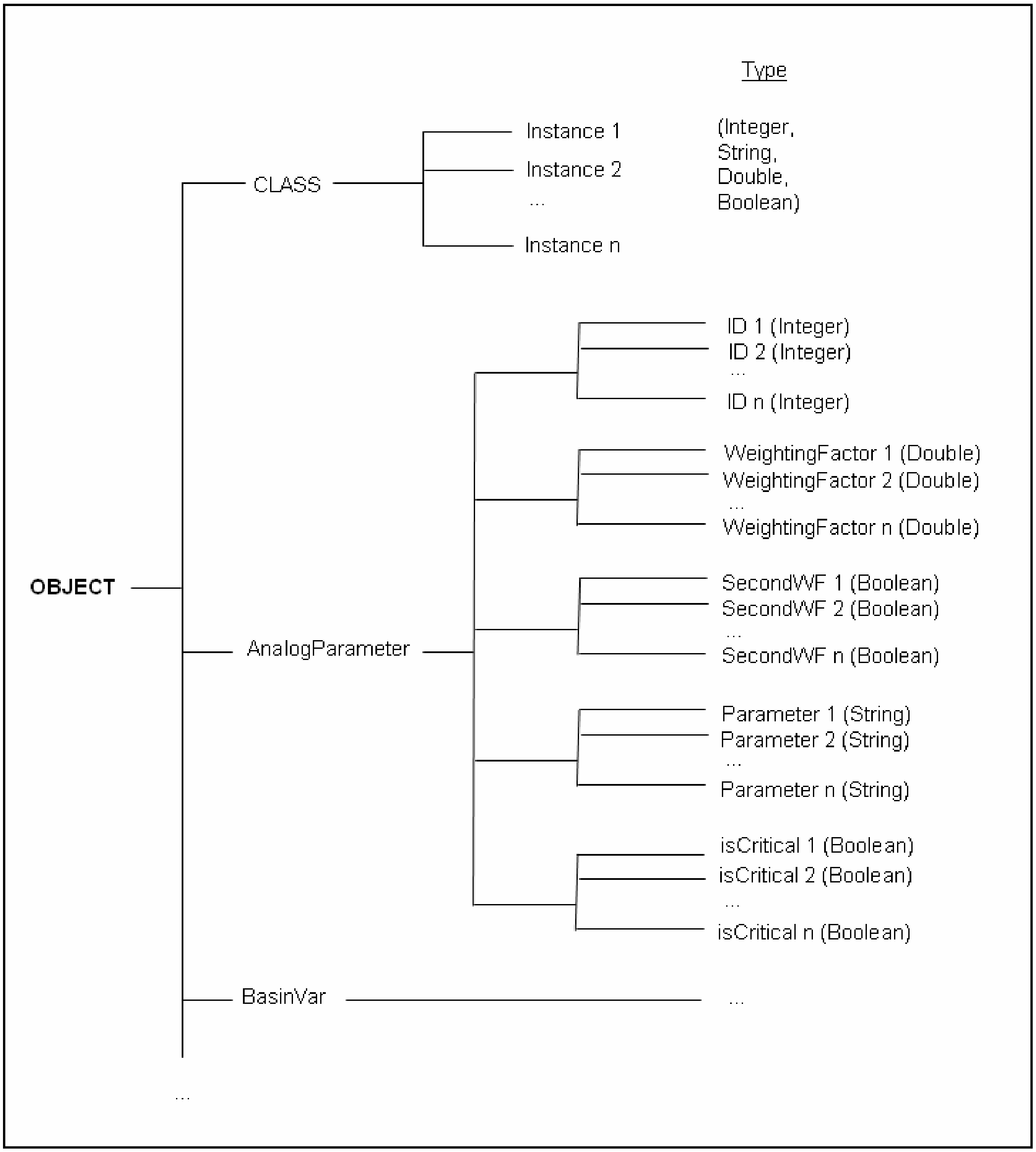

Fig. 5.1—Object-oriented modeling

The other important features of Microsoft Access 2003 are as follows.

(1) It is packaged with Microsoft Office Professional and equipped with graphical user interface.

(2) It is has the capability for skilled software developers to develop powerful and complex database systems and relatively unskilled programmers or non-programmers can use it to build simple databases without have to deal with features they don't understand.

(3) It supports substantial object-oriented techniques.

(4) The cut and paste functionality can make it a useful tool for connecting between other databases (for example, Oracle and Microsoft SQL Server during data or database conversions). It also comes with various import and export features that allow integration with Windows and other platform applications.

5.2.2 Database Structure

Geological and petroleum reservoir characteristics of the basins we are evaluating represents a very large amount of information to review, store and evaluate. Constructing a database to make it compact is the key to avoiding redundant data and keeping the database size as small as possible. This practice will improve data manipulation so it can retrieve information rapidly. **Fig. 5.2** illustrates the database structure we used in the BAS. We created nine tables within the database and each table has a relationship with the other tables. In each table, we structure the fields where each table has primary unique identifier, we name that identifiers as "ID". This identifier (ID) will then be related to at least one field in the other tables (see **Fig. 5.2**). This method of using an ID makes the database more compact and avoids redundant data in the tables. Instead of inputting the basin name like "Permian" or "San Juan" in BasinChar table, we input the ID of Basins table, as well as the analog parameters and analog parameter variables. Thus, the word "Permian" or "Basin Type" or "Foreland" is not written over and over redundantly and this saves memory since the BasinChar table itself may eventually contain thousands of rows. All of the tables and fields and their definitions are presented in Appendix A.

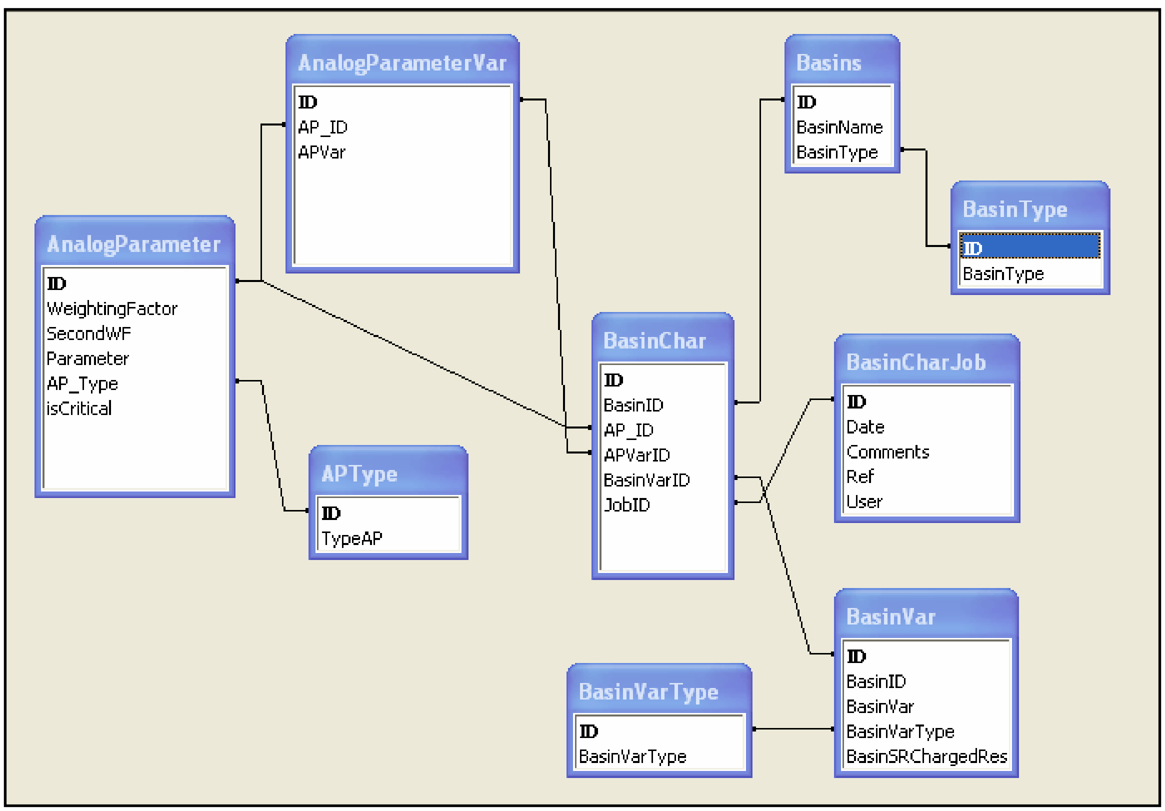

Fig. 5.2—The Database Structure Showing Relationship of One Table to The Other

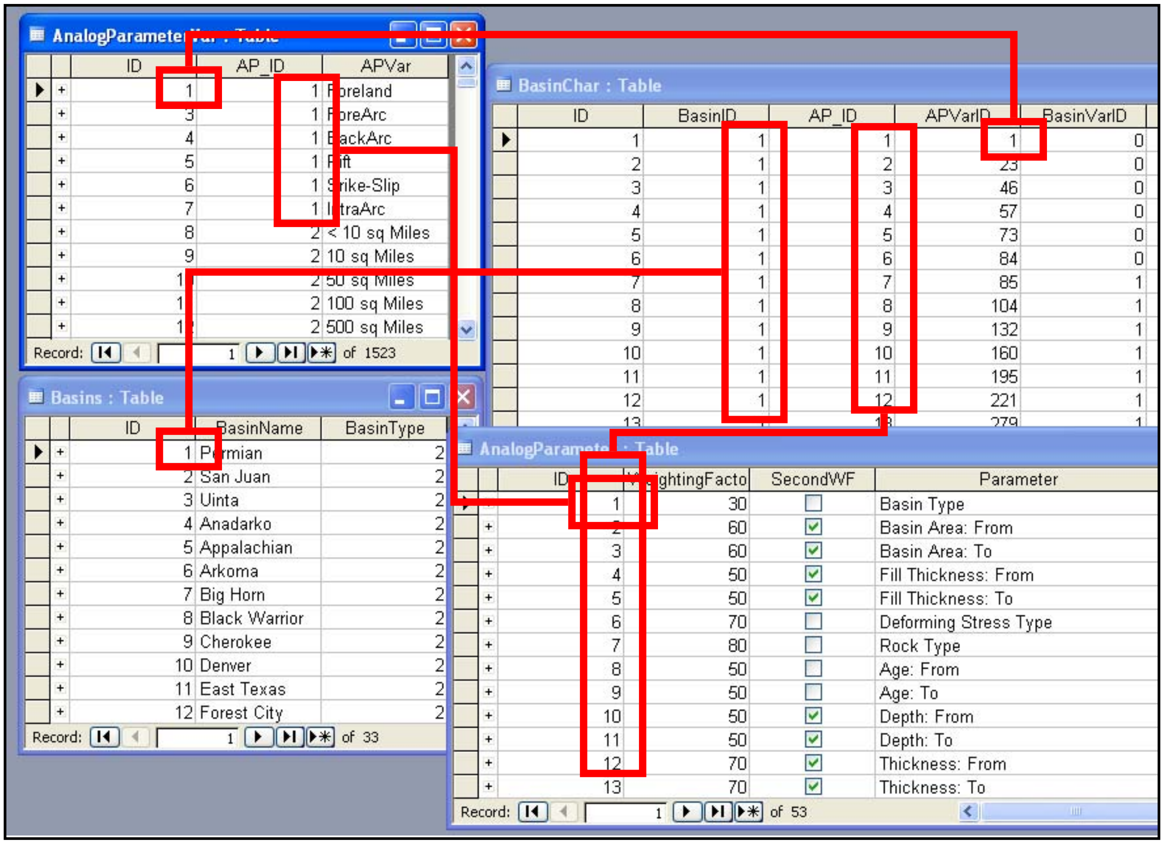

Fig. 5.3—Identifier Relationship Illustrating How to Compact A Table By Inputting Only IDs From Other Tables That Contain The Data Instead of Inputting The Data Itself

5.3 User Interface Construction

BAS has a very friendly user interface. The basic principles that were used to construct the user interface are (1) to minimize the work required from the user, and (2) ensure that the user can interface with the software from anywhere in the program.

5.3.1 The Structure of the User Interface System

The user interface system consists of a series of windows, formatted forms, menu bars, and pop-up menus. **Table 5.1** summarizes the functions of all windows.

Table 5.1—THE WINDOWS AND THEIR FUNCTIONS IN BAS

Window	Function
Basin List	The window used to show all the basin names, their source rocks and reservoir rocks and the associations of each reservoir to its source rock
Control Panel	The window that shows analog parameters, their weighting factors, the classes for each parameter, and also with the edit buttons.
Analog	The main window used to show characterization information of both target and reference basins
Result	The window that displays analog results ranked and indicated with bar chart
Analog Edit	The window used to modify and input characterization information to the database for the selected basins and analog parameters

5.3.2 I/O System

There are 2 ways to input data in BAS.

(1) The user inputs data from the main user interface (see **Fig. 5.4**). These data will be stored in the database.

(2) The user directly opens the database and inputs all data into the database either manually or using an import feature in the database. This method requires advanced skills in database management, and in the BAS software itself. It is recommended if user already has a large amount of data in some format (e.g., excel spreadsheet).

BAS was designed in such a way that it will still work even with an incomplete data set. Generally, it is not possible to find data for every analog parameter from public literature. For such cases, BAS will evaluate and compare only the data that are available for the target basin. However, there are minimum data that have to be input to allow BAS to work. These minimum data sets are the data for critical analog parameters (i.e., lithology, fluid type, kerogen, vitrinite reflectance, and seals). As with any other software application, limited data will reduce accuracy.

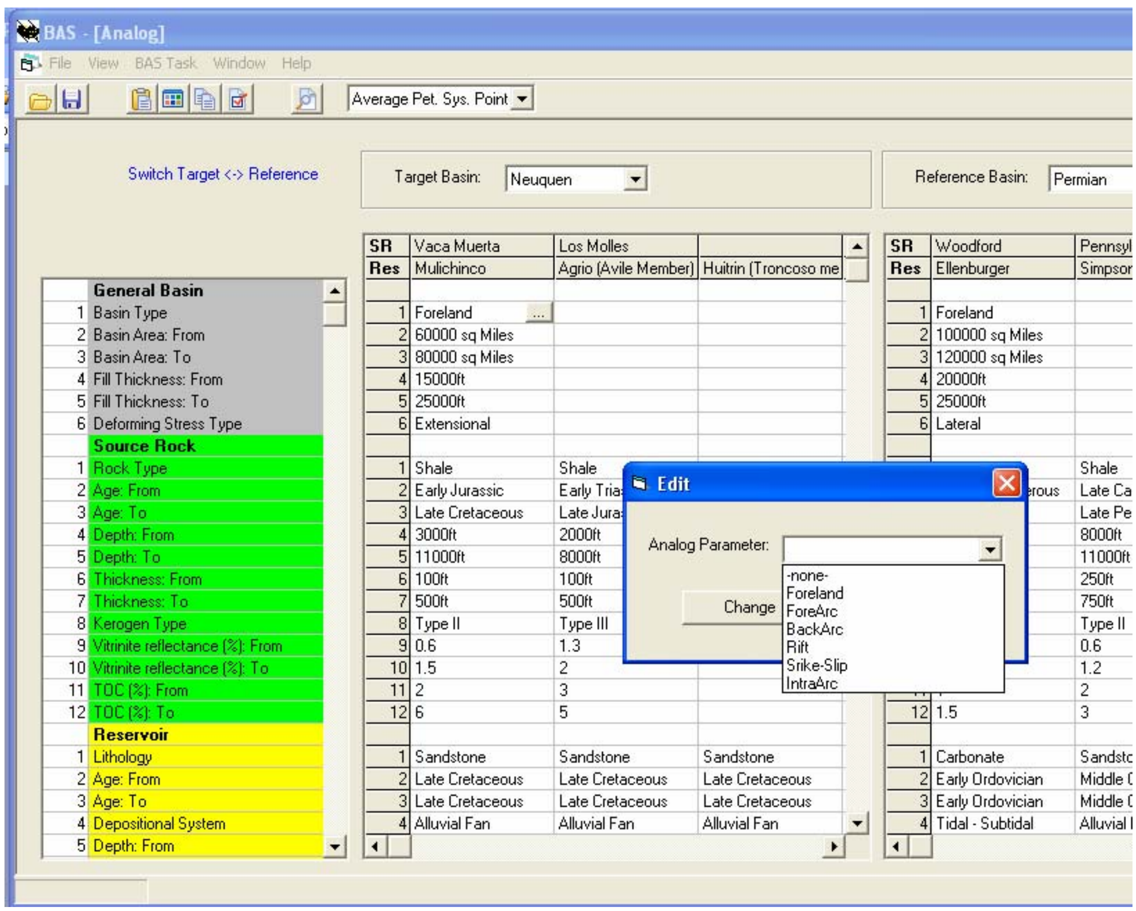

Fig. 5.4—Input data form in the main user interface

CHAPTER VI

SOFTWARE AND METHODOLOGY VALIDATION

6.1 Software Validation

It is important to test out the software to ensure it produces valid results. We need to validate the software to make sure that it gives us both accurate and consistent results. The process we have chosen is to use one of our reference basins as a target basin to be certain the software matches the data properly. We have used data from several of the reference basins to be sure the model selects the correct basin as an analog. We have also used partial data sets to investigate how much data must be entered to obtain a valid analog.

6.1.1 Validation Check Using Permian Basin

We used data from the Permian Basin as the target basin while still keeping the Permian in the reference basin list. We then ran the software and checked the results. The expectation was that the Permian would produce a 100% match with Permian Basin in the reference list because the exact same data are in both data sets. The result, as illustrated in **Fig. 6.1**, showed that Permian does provide a 100% match in the reference basin list when the Permian basin data are used as the target basin. You can also see that other basins that scored high on the list were the Piceance, Big Horn, and San Juan basins.

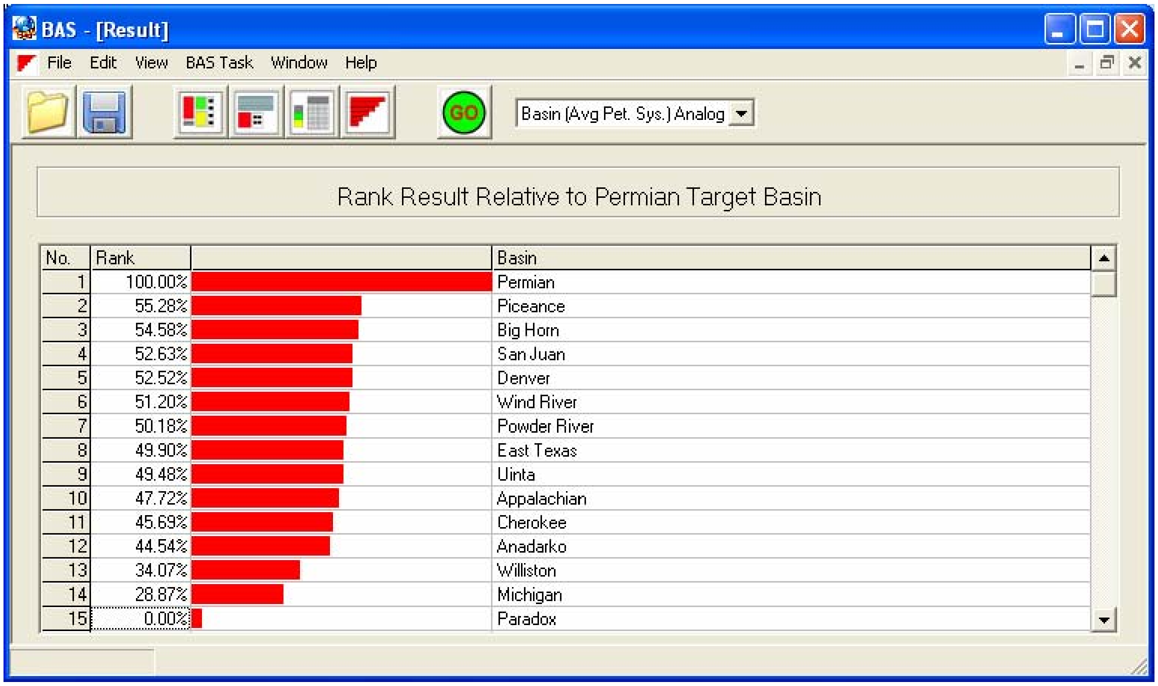

Fig. 6.1—Software validation results for Permian basin as target.

6.1.2 Validation Check Using San Juan and Appalachian Basin Data Sets

We analyzed both the San Juan and Appalachian basins as we did the Permian Basin. Again, for each case, we used the data from San Juan or the Appalachian basin as input as if it were the target basin. We then let the program run to be sure it selected the correct basin as the analog. **Fig. 6.2** and **Fig. 6.3** illustrate the results for the San Juan and Appalachian basins, respectively. As expected, when the input data from a basin such as the San Juan is used as the target basin, the software chose the San Juan as the analog basin.

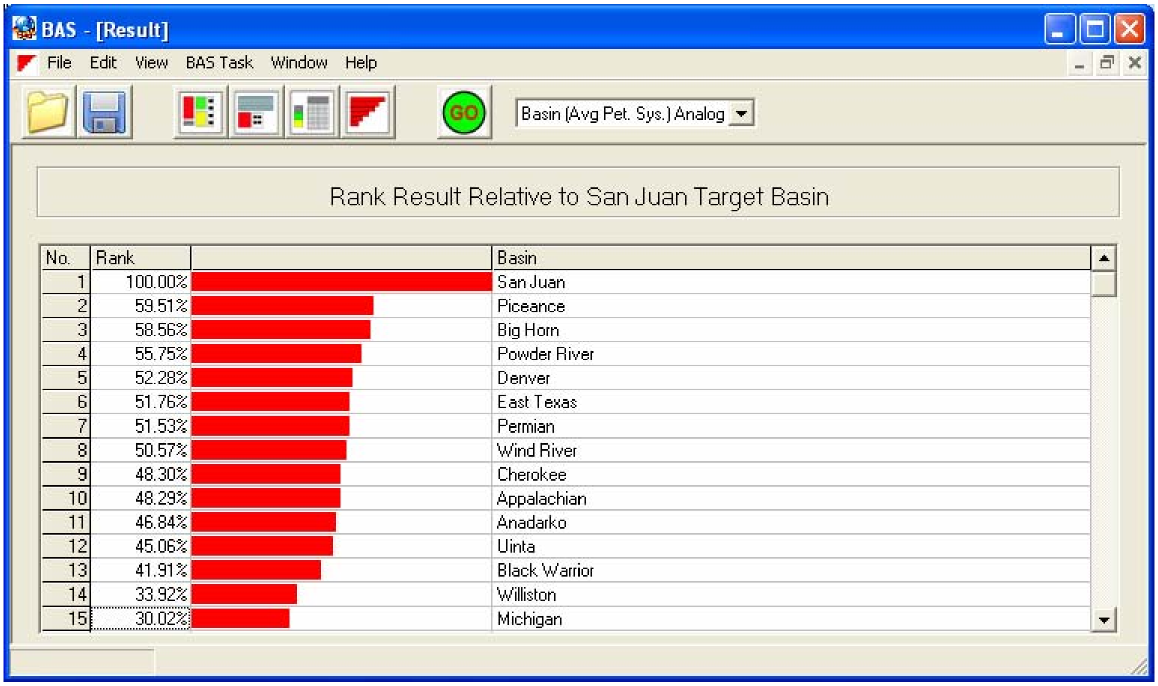

Fig. 6.2—Software validation results for San Juan basin as target.

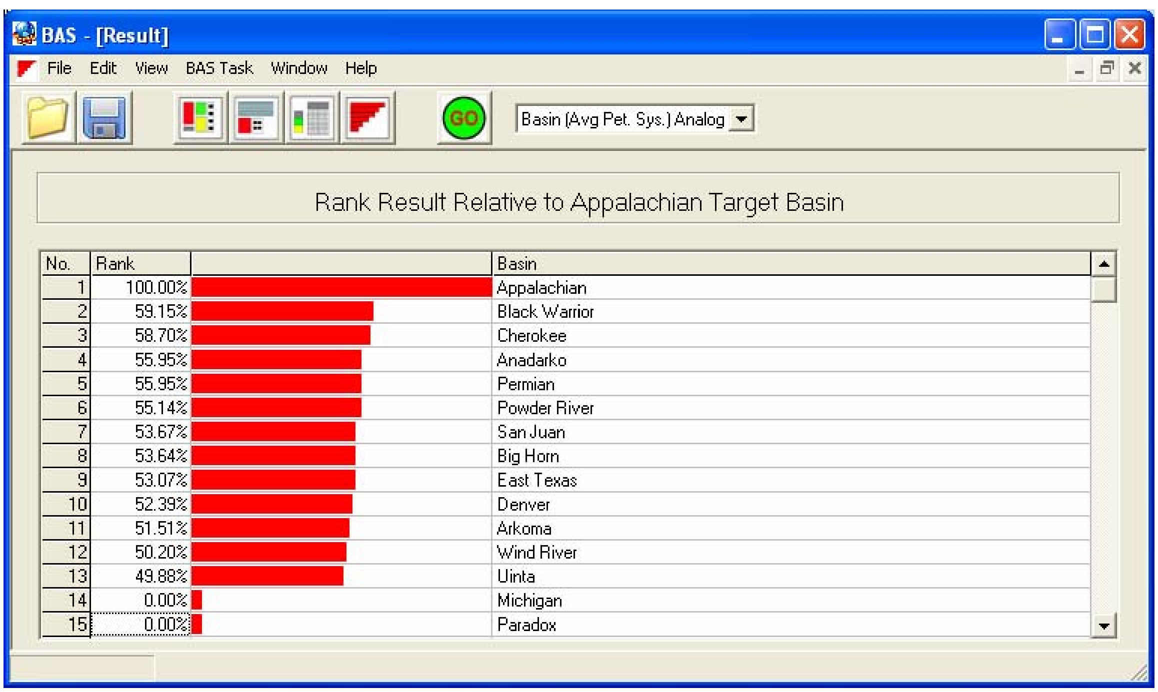

Fig. 6.3—Software validation results for Appalachian basin as target.

6.1.3 Validation Check Using Only Conventional Petroleum System of San Juan Basin

For another check of the software, we input only the data for the conventional reservoirs in the San Juan basin as the target basin. We removed all the data for the unconventional reservoirs in the San Juan basin from the target basin data set while still keeping all of the conventional and unconventional data from the San Juan basin in the reference basin data set. The result, as illustrated in **Fig. 6.4**, showed that the software still chose the San Juan basin as the analog basin, but as one could expect, the match parameter was less then 100%. The match was only 89%, which is actually very acceptable.

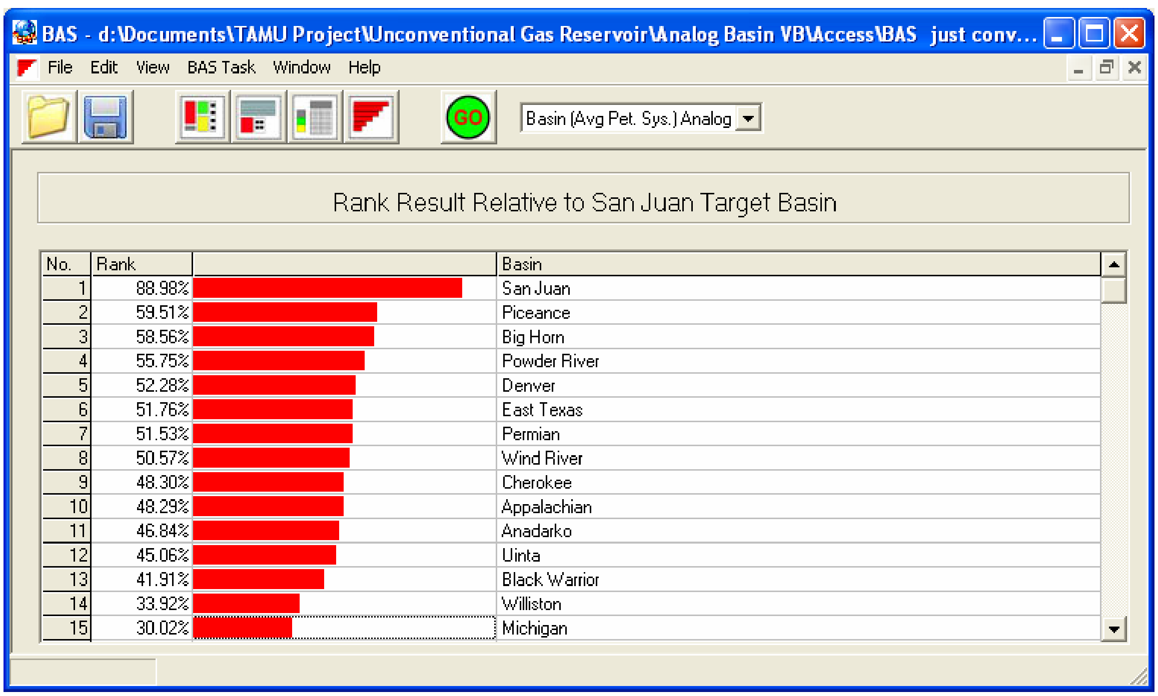

Fig. 6.4—Software validation results for San Juan basin as target compared to only conventional resources of San Juan basin.

6.1.4 Validation Check Using Modified Data of San Juan Basin

For another check of the software, we introduced variation in the input data used as the target basin to determine how robust the prediction would be for choosing an analog. We used the San Juan basin data as the target basin. First, we changed the porosity data of all reservoirs in the San Juan basin in the target basin list, while keeping the data for the San Juan basin in the reference basin list at its original values. The result shows that it is still analogous to the San Juan basin as much as 94.57% **(Fig. 6.5)**. We then further modified the data and checked the result. Modifying porosity and permeability data for all reservoirs in the San Juan basin resulted in a value that was 89.17% analogous to original San Juan basin **(Fig.6.6)**. When we modified porosity, permeability, depth, thickness, and pressure, the software still chose the San Juan but the measurement fell to 73.14% **(Fig. 6.7)**.

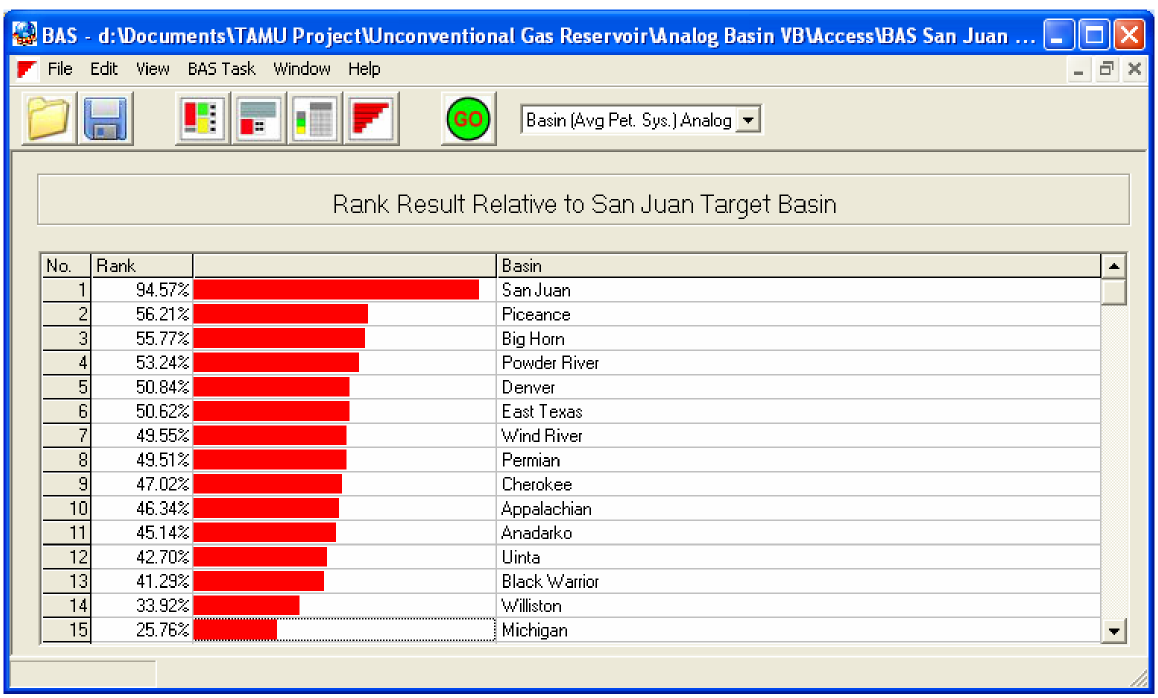

Fig. 6.5—Results for San Juan basin with modified porosity data.

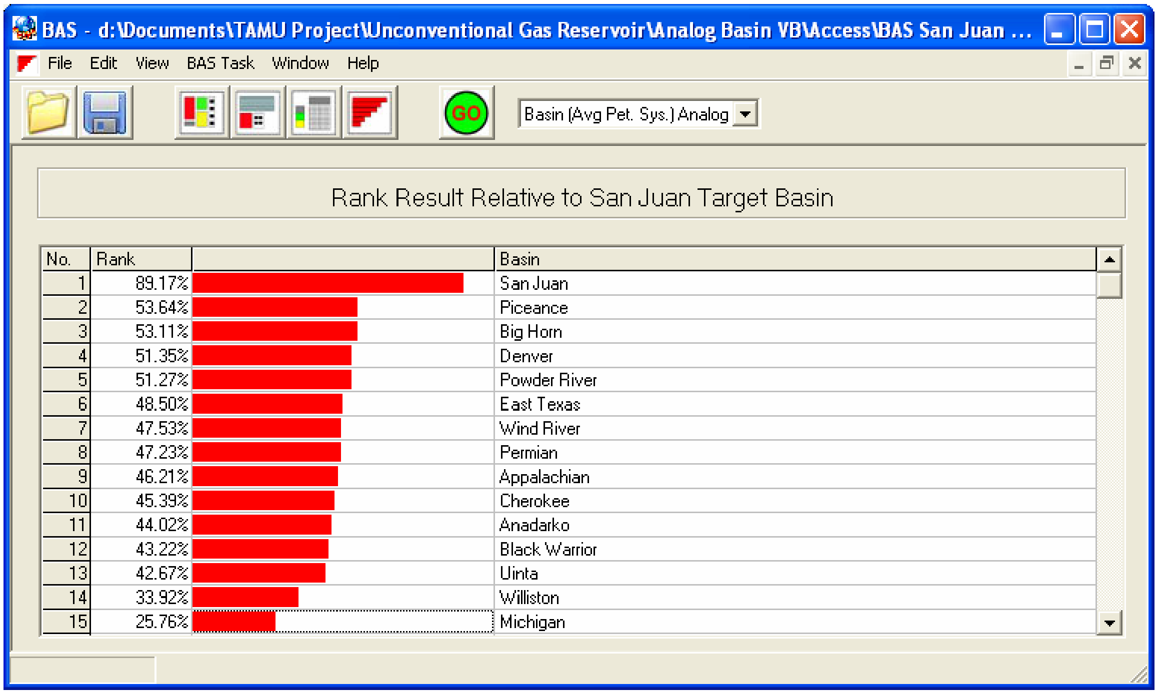

Fig. 6.6—Results for San Juan basin with modified porosity and permeability data.

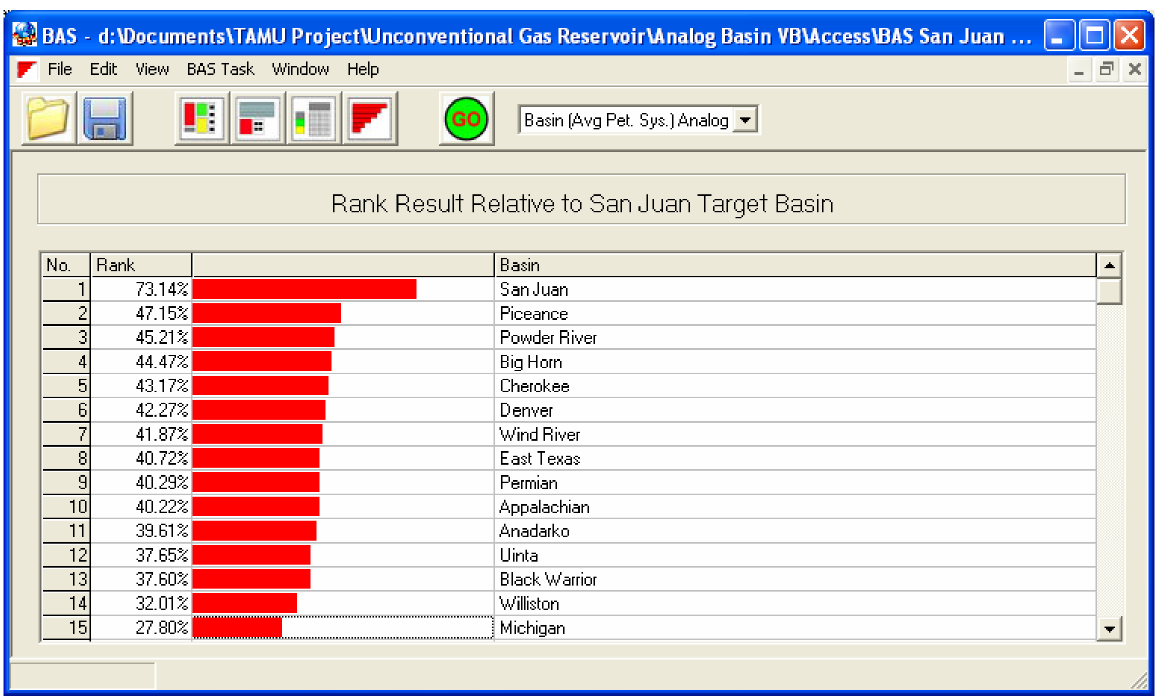

Fig. 6.7—Results for San Juan basin with modified porosity, permeability, depth, thickness, and pressure data.

6.2 Methodology Validation

Methodology validation is an important part of this work. We have to make sure that our methodology works and provides acceptable results. As stated in the literature review, we could not find any published method that we could use to validate our methodology and results.

To help us evaluate our methodology, we sent out a questionnaire to several expert geoscientists. In the questionnaires, we asked questions regarding basin analog procedures, and we asked the experts, according their experiences, what basins they know in North America that are analogous to other basins. The questionnaire is presented in Appendix C.

We picked 6 basins (San Juan, Appalachian, East Texas, Arkoma, Piceance, and Powder River) and asked the geoscientists to tell us their opinion concerning the analog for each of those 6 basins. The response for the San Juan basin is presented in **Table 6.1**. **Fig. 6.8** shows how the experts responded for then San Juan basin analog. It shows that 6 out of 8 respondents picked the Piceance basin as the analog of San Juan, and 4 respondents picked the Green River, Raton, or Uinta basin as an analog to San Juan. **Fig. 6.9** shows the graphical representation of what experts identified as the relative analog (in percentage) to the San Juan basin compared to our software results. The first analog, which is Piceance basin, has a good match between the experts' selection and the BAS software results. The second and third analogs, Raton and Green River basins, do not match with BAS since we don't have the data for both basins. The BAS results for the fourth and the rest of the analogs still do not match with experts' responses. This could have been caused by lack of information in some of these basins or need for some adjustment in the weighting factors or other reasons. However, further validation is necessary and we are still working on getting the data input for the rest of the basins. The results of all of the 6 basins are presented in Appendix D.

Table 6.1—VALIDATION QUESTIONNAIRES RESPONSES FOR SAN JUAN BASIN

		San Juan										
No	**BasinName**	**% Analog**									**Count**	**AVG**
1	Anadarko	60									1	10
2	Appalachian										0	0
3	Arkoma					25					1	4.16667
4	Big Horn										0	0
5	Black Warrior		30								1	5
6	Cherokee										0	0
7	Denver										0	0
8	East Texas	40									1	6.66667
9	Forest City										0	0
10	Fort Worth										0	0
11	Green River			40			50		60	40	4	31.6667
12	Illinois										0	0
13	Louissiana Mississippi Salt										0	0
14	Michigan										0	0
15	Paradox										0	0
16	Permian	80									1	13.3333
17	Piceance			60	25	50	80		70	60	6	57.5
18	Powder River										0	0
19	Raton		80		25	75	40				4	36.6667
20	San Juan										0	0
21	Texas Gulf Coast										0	0
22	Uinta		50		50				50	40	4	31.6667
23	Western Canada Sedimentary			30							1	5
24	Williston										0	0
25	Wind River										0	0
		Benjamin Jacobson	Paul Basinski (CBM)	Paul Basinski (TGS)	Charles M Boyer II	Andrew R. Scott	Joel Degenstein	Mark Larsen	SLB Team	Steve Calkins		

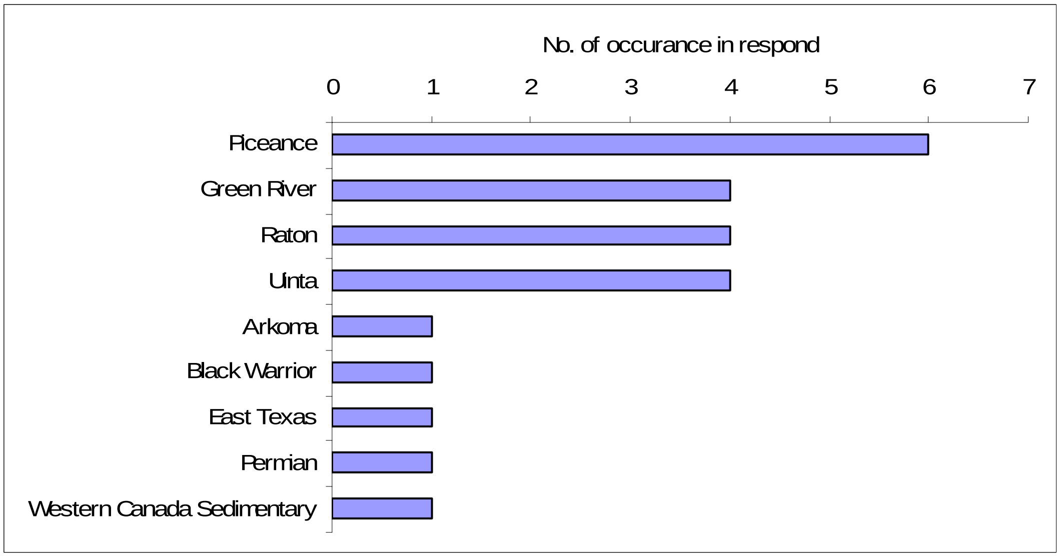

Fig. 6.8—Expert responses for San Juan basin analog.

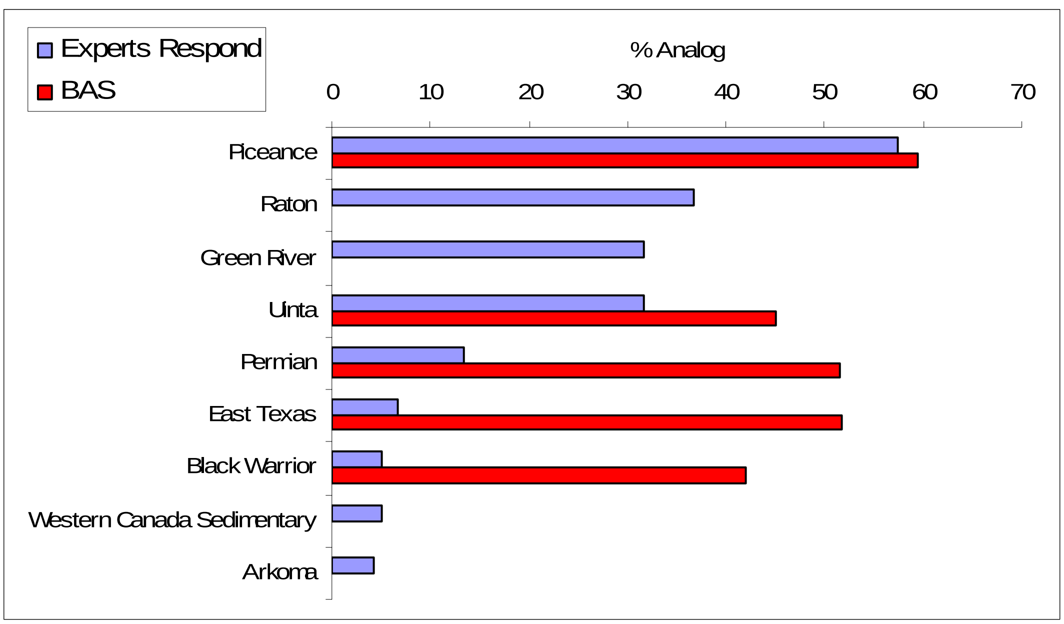

Fig. 6.9—Comparison of expert responses and BAS results for San Juan basin.

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

Unconventional resources are becoming very important to the future energy supply around the globe. Among several ways to identify these resources, the basin analog approach is one which is not time consuming and not costly, compared to other methods.

The idea of the basin analog approach is to find basins in North America, where we know the conventional and unconventional resources, and where there North America basins are analogous to the frontier basin, where we normally only know the conventional resources information. We started this work by determining analog parameters. Then we selected the reference basins, summarized geology and petroleum systems information of those basins, and developed a methodology and software to compare basins.

We developed the Basin Analog System interface in Microsoft Visual Basic 6.0 development software and stored geology and petroleum systems characterization in a database created in Microsoft Access 2003. They were written in an object-oriented programming. BAS is expected to identify analog basins by listing and ranking the reference basins against the target basin on the basis of analog parameters, using our developed mathematical method.

Software validation was perform by taking out one of reference basins and put it in the target basin slot while still keeping it in the reference list. The result of this task shows that the target basin is 100% match with itself in the reference list.

7.2 Conclusions

On the basis of the research results presented in this thesis, we offer the following conclusions.

(1) We have successfully developed BAS, a basin analog methodology that is useful for rapidly and consistently evaluating unconventional hydrocarbon resource potential. Basin analogy is one of the less expensive and less time consuming techniques that can be used for preliminary identification of unconventional gas resources.

(2) We developed the software and database of 25 selected basins in North America to perform and accelerate the process of identifying analog basins and generate consistent results.

(3) The Basin Analog System interface was develop in Microsoft Visual Basic 6.0 development software, and the database was created in Microsoft Access 2003. They were designed in an object oriented programming that allowed elimination redundant code and communication with other software modules without having to start writing code from scratch.

(4) Geologic and petroleum systems information was collected from published literatures. Information for fifteen out of twenty-five basins was collected and stored in the database.

(5) The accuracy of the results depends on the descriptions of geologic and petroleum systems in those basins. We used our best effort to find accurate information to make sure our techniques can be applied properly.

(6) The first stage of software validation shows consistent result. If a basin is selected as the target basin while the same basin is also in the reference basins list, the

result shows that the basin is 100% analog to itself. The other basins in the reference basins list are less then 100% analog. However, further validation of Basin Analog System is being conducted.

7.3 Recommendations

In this present form, BAS achieves essentially all the objectives and expectation mentioned in Chapters I and IV. However, there are several areas where this program can be improved. We would like to briefly discuss some of these areas. We recommended that future work:

(1) expand the approach, not only to find analogous basins or petroleum systems, but also, to find the best engineering practices in the analogous reservoirs. For example, find the proven, successful drilling and stimulation methods for a particular type of reservoir;

(2) further characterize the geology and petroleum systems of the reference basins, not only using public literature, but also, using industry data; and

(3) incorporate expert-system features such as neural network to be able to acquire better weighting factors.

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APPENDIX A

DATABASE TABLES AND FIELDS AND THEIR DEFINITIONS

Table A.1 Fields of AnalogParameter table

Table A.2 Fields of AnalogParameterVar table

Table A.3 Fields of APType table

Table A.4 Fields of BasinChar table

Table A.5 Fields of Basins table

Table A.6 Fields of BasinType table

Table A.7 Fields of BasinVar table

Table A.8 Fields of BasinVarType table

Table A.1 Fields of AnalogParameter table

Field Name	Data Type	Description
ID	AutoNumber	Data identifier
WeightingFactor	Number	Weighting factor of each analog parameter
SecondWF	Yes/No	Secondary weighting factor
Parameter	Text	The analog parameter
AP_Type	Number	Analog parameter type, linked to field ID of table APType
isCritical	AutoNumber	Critical parameter indication

Table A.2 Fields of AnalogParameterVar table

Field Name	Data Type	Description
ID	AutoNumber	Data identifier
AP_ID	Number	Analog Parameter ID, linked to field ID of table AnalogParameter
APVar	Text	The analog parameter variables

Table A.3 Fields of APType table

Field Name	Data Type	Description
ID	AutoNumber	Data identifier
TypeAP	Text	Analog parameter category, linked to field AP_Type of table AnalogParameter

Table A.4 Fields of BasinChar table

Field Name	Data Type	Description
ID	AutoNumber	Data identifier
BasinID	Number	Basin identifier, linked to table Basins field ID
AP_ID	Number	Analog parameter identifier, linked to field ID of table AnalogParameter
APVarID	Number	Analog parameter variable identifier, linked to field ID of table AnalogParameterVar
BasinVarID	Number	Basin variable identifier, linked to field ID of table BasinVar

Table A.5 Fields of Basins table

Field Name	Data Type	Description
ID	AutoNumber	Data identifier
BasinName	Text	Name of Basins
BasinType	Number	Basin type (i.e., target, reference), linked to field ID of table BasinType

Table A.6 Fields of BasinType table

Field Name	Data Type	Description
ID	AutoNumber	Data identifier
BasinType	Text	Type of basin (i.e., target, reference)

Table A.7 Fields of BasinVar table

Field Name	Data Type	Description
ID	AutoNumber	Data identifier
BasinID	Number	Basin identifier, linked to field ID of table Basins
BasinVar	Text	Source rocks and reservoir formations name of the basin
BasinVarType	Number	Type of basin variable (i.e., source rock or reservoir formation), linked to field ID of table BasinVarType
BasinSRChargedRes	Number	Indication of which reservoir formation being charge by which source rock, linked to field ID of table BasinVar

Table A.8 Fields of BasinVarType table

Field Name	Data Type	Description
ID	AutoNumber	Data identifier
BasinVarType	Text	Source Rock or Reservoir

APPENDIX B

ANALOG PARAMETERS AND THEIR CLASSES

Table B.1 General Basin Category

Table B.2 Source Rock Category

Table B.3 Reservoir Category

Table B.1 General Basin Category

No.	Classes	Analog Parameter
1	Foreland	Basin Type
2	ForeArc	
3	BackArc	
4	Rift	
5	Srike-Slip	
6	IntraArc	
1	< 10 sq Miles	Basin Area
2	10 sq Miles	
3	50 sq Miles	
4	100 sq Miles	
5	500 sq Miles	
6	1000 sq Miles	
7	2500 sq Miles	
8	5000 sq Miles	
9	7500 sq Miles	
10	10000 sq Miles	
11	15000 sq Miles	
12	20000 sq Miles	
13	40000 sq Miles	
14	60000 sq Miles	
15	80000 sq Miles	
16	100000 sq Miles	
17	120000 sq Miles	
18	140000 sq Miles	
19	160000 sq Miles	
20	180000 sq Miles	
21	200000 sq Miles	
22	> 200000 sq Miles	
1	< 1000ft	Fill Thickness
2	1000ft	
3	5000ft	
4	10000ft	
5	15000ft	
6	20000ft	
7	25000ft	
8	30000ft	
9	35000ft	
10	40000ft	
11	45000ft	
12	50000ft	
13	55000ft	
14	60000ft	
15	> 60000ft	
1	Extensional	Deforming Stress Type
2	Compressive	
3	Lateral	

Table B.2 Source Rock Category

No.	Classes	Analog Parameter
1	Shale	Rock Type
2	Carbonate	
3	Coal	
1	Quaternary	Age
2	Late Tertiary	
3	Middle Tertiary	
4	Early Tertiary	
5	Late Cretaceous	
6	Middle Cretaceous	
7	Early Cretaceous	
8	Late Jurassic	
9	Middle Jurassic	
10	Early Jurassic	
11	Late Triassic	
12	Middle Triassic	
13	Early Triassic	
14	Late Permian	
15	Middle Permian	
16	Early Permian	
17	Late Carboniferous	
18	Middle Carboniferous	
19	Early Carboniferous	
20	Late Devonian	
21	Middle Devonian	
22	Early Devonian	
23	Late Silurian	
24	Middle Silurian	
25	Early Silurian	
26	Late Ordovician	
27	Middle Ordovician	
28	Early Ordovician	
29	Late Cambrian	
30	Middle Cambrian	
31	Early Cambrian	

No.	Classes	Analog Parameter
1	< 500ft	
2	500ft	
3	1000ft	
4	2000ft	
5	3000ft	
6	4000ft	
7	5000ft	
8	6000ft	
9	7000ft	
10	8000ft	
11	9000ft	
12	10000ft	
13	11000ft	
14	12000ft	
15	13000ft	
16	14000ft	
17	15000ft	Depth
18	16000ft	
19	17000ft	
20	18000ft	
21	19000ft	
22	20000ft	
23	21000ft	
24	22000ft	
25	23000ft	
26	24000ft	
27	25000ft	
28	26000ft	
29	27000ft	
30	28000ft	
31	29000ft	
32	30000ft	
33	>30000ft	

No.	Classes	Analog Parameter
1	<50ft	Thickness (Source Rock)
2	50ft	
3	100ft	
4	250ft	
5	500ft	
6	750ft	
7	1000ft	
8	1250ft	
9	1500ft	
10	1750ft	
11	2000ft	
12	2250ft	
13	2500ft	
14	2750ft	
15	3000ft	
16	3250ft	
17	3500ft	
18	3750ft	
19	4000ft	
20	4250ft	
21	4500ft	
22	4750ft	
23	5000ft	
24	5250ft	
25	5500ft	
26	5750ft	
27	6000ft	
28	6250ft	
29	6500ft	
30	6750ft	
31	7000ft	
32	7000ft	
33	7250ft	
34	7500ft	
35	7750ft	
36	8000ft	
37	8250ft	
38	8500ft	
39	8750ft	
40	9000ft	

No.	Classes	Analog Parameter
1	Type I	Kerogen Type
2	Type II	
3	Type III	
1	0.3	Vitrinite reflectance (%)
2	0.4	
3	0.5	
4	0.6	
5	0.7	
6	0.8	
7	0.9	
8	1	
9	1.1	
10	1.2	
11	1.3	
12	1.4	
13	1.5	
14	1.6	
15	1.7	
16	1.8	
17	1.9	
18	2	
19	2.1	
20	2.2	
21	2.3	
22	2.4	
23	2.5	

No.	Classes	Analog Parameter
1	0.2	TOC (%)
2	0.5	
3	1	
4	1.5	
5	2	
6	2.5	
7	3	
8	3.5	
9	4	
10	4.5	
11	5	
12	5.5	
13	6	
14	6.5	
15	7	
16	7.5	
17	8	
18	8.5	
19	9	
20	9.5	
21	10	
22	10.5	
23	11	
24	11.5	
25	12	
26	12.5	
27	13	
28	13.5	
29	14	
30	14.5	
31	15	
32	15.5	
33	16	
34	16.5	
35	17	
36	17.5	
37	18	

Table B.3 Reservoir Category

No.	Classes	Analog Parameter
1	Sandstone	Lithology
2	Carbonate	
3	Shale	
4	Coal	
5	Tight Sand	
1	Quaternary	Age
2	Late Tertiary	
3	Middle Tertiary	
4	Early Tertiary	
5	Late Cretaceous	
6	Middle Cretaceous	
7	Early Cretaceous	
8	Late Jurassic	
9	Middle Jurassic	
10	Early Jurassic	
11	Late Triassic	
12	Middle Triassic	
13	Early Triassic	
14	Late Permian	
15	Middle Permian	
16	Early Permian	
17	Late Carboniferous	
18	Middle Carboniferous	
19	Early Carboniferous	
20	Late Devonian	
21	Middle Devonian	
22	Early Devonian	
23	Late Silurian	
24	Middle Silurian	
25	Early Silurian	
26	Late Ordovician	
27	Middle Ordovician	
28	Early Ordovician	
29	Late Cambrian	
30	Middle Cambrian	
31	Early Cambrian	

No.	Classes	Analog Parameter
1	Alluvial Fan	Depositional System
2	Fluvial	
3	Fluvial - Meandering	
4	Fluvial - Breided	
5	Fluvial - Anastamosed	
6	Deltaic	
7	Deltaic - Wave dominated	
8	Deltaic - Tide dominated	
9	Deltaic - Fluvial/River dominated	
10	Eolian	
11	Lacustrine	
12	Strainplain	
13	Barrier Island	
14	Submarine Fan/Turbidite	
15	Carbonate	
16	Carbonate - Ramp	
17	Carbonate - Reef/Platform	
18	Carbonate - Mounts	
19	Tidal	
20	Tidal - Subtidal	
21	Tidal - intertidal	
22	Tidal - Supratidal	

No.	Classes	Analog Parameter
1	< 500ft	Depth
2	500ft	
3	1000ft	
4	2000ft	
5	3000ft	
6	4000ft	
7	5000ft	
8	6000ft	
9	7000ft	
10	8000ft	
11	9000ft	
12	10000ft	
13	11000ft	
14	12000ft	
15	13000ft	
16	14000ft	
17	15000ft	
18	16000ft	
19	17000ft	
20	18000ft	
21	19000ft	
22	20000ft	
23	21000ft	
24	22000ft	
25	23000ft	
26	24000ft	
27	25000ft	
28	26000ft	
29	27000ft	
30	28000ft	
31	29000ft	
32	30000ft	
33	>30000ft	

No.	Classes	Analog Parameter
1	<50ft	Thickness (Reservoir Gross Thickness)
2	50ft	
3	100ft	
4	250ft	
5	500ft	
6	750ft	
7	1000ft	
8	1250ft	
9	1500ft	
10	1750ft	
11	2000ft	
12	2250ft	
13	2500ft	
14	2750ft	
15	3000ft	
16	3250ft	
17	3500ft	
18	3750ft	
19	4000ft	
20	4250ft	
21	4500ft	
22	4750ft	
23	5000ft	
24	5250ft	
25	5500ft	
26	5750ft	
27	6000ft	
28	6250ft	
29	6500ft	
30	6750ft	
31	7000ft	
32	7000ft	
33	7250ft	
34	7500ft	
35	7750ft	
36	8000ft	
37	8250ft	
38	8500ft	
39	8750ft	
40	9000ft	
41	9250ft	
42	9500ft	
43	9750ft	
44	10000ft	
45	10250ft	
46	10500ft	
47	10750ft	
48	11000ft	
49	11250ft	
50	11500ft	
51	11750ft	
52	12000ft	
53	>12000ft	

No.	Classes	Analog Parameter
1	<500 psi	
2	500 psi	
3	1000 psi	
4	1500 psi	
5	2000 psi	
6	2500 psi	
7	3000 psi	
8	3500 psi	
9	4000 psi	
10	4500 psi	
11	5000 psi	
12	5500 psi	
13	6000 psi	
14	6500 psi	
15	7000 psi	
16	7500 psi	
17	8000 psi	
18	8500 psi	
19	9000 psi	
20	9500 psi	
21	10000 psi	Pressure
22	10500 psi	
23	11000 psi	
24	11500 psi	
25	12000 psi	
26	12500 psi	
27	13000 psi	
28	13500 psi	
29	14000 psi	
30	14500 psi	
31	15000 psi	
32	15500 psi	
33	16000 psi	
34	16500 psi	
35	17000 psi	
36	17500 psi	
37	18000 psi	
38	18500 psi	
39	19000 psi	
40	19500 psi	
41	20000 psi	
42	> 20000 psi	

No.	Classes	Analog Parameter
1	Over pressure	Pressure Regime
2	Normal pressure	
3	Under pressure	
1	< 1	Porosity
2	1	
3	3	
4	5	
5	7.5	
6	10	
7	12.5	
8	15	
9	17.5	
10	20	
11	22.5	
12	25	
13	27.5	
14	30	
15	33	
16	35	
17	38	
18	40	
19	> 40	
1	<0.1 md	Permeability
2	0.1 md	
3	0.5 md	
4	1 md	
5	5 md	
6	10 md	
7	50 md	
8	100 md	
9	250 md	
10	500 md	
11	750 md	
12	1000 md	
13	2000 md	
14	3000 md	
15	4000 md	
16	5000 md	
1	< 0.1	Water Saturation
2	0.1	
3	0.2	
4	0.3	
5	0.4	
6	0.5	
7	0.6	
8	0.7	
9	0.8	
10	0.9	
11	1	

No.	Classes	Analog Parameter
1	<50ft	Migration Distance
2	50ft	
3	100ft	
4	250ft	
5	500ft	
6	750ft	
7	1000ft	
8	1250ft	
9	1500ft	
10	1750ft	
11	2000ft	
12	2250ft	
13	2500ft	
14	2750ft	
15	3000ft	
16	3250ft	
17	3500ft	
18	3750ft	
19	4000ft	
20	5000ft	
21	6000ft	
22	7000ft	
23	8000ft	
24	9000ft	
25	10000ft	
26	>10000ft	
1	Vertical	Migration Direction
2	Lateral	
1	Shale	Seals
2	Carbonate	
3	Evaporite	
4	No Seal	
1	Structure Fault	Traps Type
2	Structure Anticlinal	
3	Stratigraphy	
4	Combination	
5	No Trap	
1	Oil	Fluid Type
2	Gas	
3	Condensate	

No.	Classes	Analog Parameter
1	< 10	
2	12	
3	14	
4	16	
5	18	
6	20	
7	22	
8	24	
9	26	
10	28	
11	30	
12	32	
13	34	
14	36	
15	38	
16	40	
17	42	Oil Gravity (API)
18	44	
19	46	
20	48	
21	50	
22	52	
23	54	
24	56	
25	58	
26	60	
27	62	
28	64	
29	66	
30	68	
31	70	
32	>70	

No.	Classes	Analog Parameter
1	< 1%	
2	1%	
3	2%	
4	4%	
5	6%	
6	8%	
7	10%	
8	12%	
9	14%	
10	16%	
11	18%	
12	20%	
13	22%	
14	24%	
15	26%	
16	28%	
17	30%	
18	32%	
19	34%	
20	36%	
21	38%	
22	40%	
23	42%	
24	44%	
25	46%	
26	48%	Sulfur content
27	50%	
28	52%	
29	54%	
30	56%	
31	58%	
32	60%	
33	62%	
34	64%	
35	68%	
36	70%	
37	72%	
38	74%	
39	76%	
40	78%	
41	80%	
42	82%	
43	84%	
44	86%	
45	88%	
46	90%	
47	92%	
48	94%	
49	96%	
50	98%	
51	100%	

No.	Classes	Analog Parameter
1	< 1%	
2	1%	
3	2%	
4	4%	
5	6%	
6	8%	
7	10%	
8	12%	
9	14%	
10	16%	
11	18%	
12	20%	
13	22%	
14	24%	
15	26%	
16	28%	
17	30%	
18	32%	
19	34%	
20	36%	
21	38%	
22	40%	
23	42%	
24	44%	
25	46%	
26	48%	CO2 content
27	50%	
28	52%	
29	54%	
30	56%	
31	58%	
32	60%	
33	62%	
34	64%	
35	68%	
36	70%	
37	72%	
38	74%	
39	76%	
40	78%	
41	80%	
42	82%	
43	84%	
44	86%	
45	88%	
46	90%	
47	92%	
48	94%	
49	96%	
50	98%	
51	100%	

No.	Classes	Analog Parameter
1	< 1%	H2S content
2	1%	
3	2%	
4	4%	
5	6%	
6	8%	
7	10%	
8	12%	
9	14%	
10	16%	
11	18%	
12	20%	
13	22%	
14	24%	
15	26%	
16	28%	
17	30%	
18	32%	
19	34%	
20	36%	
21	38%	
22	40%	
23	42%	
24	44%	
25	46%	
26	48%	
27	50%	
28	52%	
29	54%	
30	56%	
31	58%	
32	60%	
33	62%	
34	64%	
35	68%	
36	70%	
37	72%	
38	74%	
39	76%	
40	78%	
41	80%	
42	82%	
43	84%	
44	86%	
45	88%	
46	90%	
47	92%	
48	94%	
49	96%	
50	98%	
51	100%	

No.	Classes	Analog Parameter
1	< 1%	
2	1%	
3	2%	
4	4%	
5	6%	
6	8%	
7	10%	
8	12%	
9	14%	
10	16%	
11	18%	
12	20%	
13	22%	
14	24%	
15	26%	
16	28%	
17	30%	
18	32%	
19	34%	
20	36%	
21	38%	
22	40%	
23	42%	
24	44%	
25	46%	
26	48%	Heavy gas (C2-C5)
27	50%	
28	52%	
29	54%	
30	56%	
31	58%	
32	60%	
33	62%	
34	64%	
35	68%	
36	70%	
37	72%	
38	74%	
39	76%	
40	78%	
41	80%	
42	82%	
43	84%	
44	86%	
45	88%	
46	90%	
47	92%	
48	94%	
49	96%	
50	98%	
51	100%	

No.	Classes	Analog Parameter
1	< 1%	EUR
2	1%	
3	2%	
4	4%	
5	6%	
6	8%	
7	10%	
8	12%	
9	14%	
10	16%	
11	18%	
12	20%	
13	22%	
14	24%	
15	26%	
16	28%	
17	30%	
18	32%	
19	34%	
20	36%	
21	38%	
22	40%	
23	42%	
24	44%	
25	46%	
26	48%	
27	50%	
28	52%	
29	54%	
30	56%	
31	58%	
32	60%	
33	62%	
34	64%	
35	68%	
36	70%	
37	72%	
38	74%	
39	76%	
40	78%	
41	80%	
42	82%	
43	84%	
44	86%	
45	88%	
46	90%	
47	92%	
48	94%	
49	96%	
50	98%	
51	100%	

APPENDIX C

VALIDATION QUESTIONNAIRE

Questionnaire

«« Basin Analogs in Frontier Exploration for Unconventional Reservoirs »»

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Statement of the Problem and Objectives

Meeting the growing global energy demand for the coming decades requires creative thinking that leads to the development of new energy sources. The U.S. is in a mature stage of hydrocarbon development – we are rapidly depleting the conventional, high-permeability reservoirs. Thus, to meet growing energy demands, we have developed the technology required to produce natural gas from unconventional, low-permeability reservoirs, such as tight sands, shales, and coal beds, which hold vast natural gas resources. These unconventional gas resources will continue to play an important role in fulfilling the U.S. energy needs. Outside North America, natural gas production has been limited, with a few exceptions, to conventional reservoirs – unconventional reservoirs are virtually an untapped resource. However, as conventional oil and gas resources are depleted worldwide, unconventional gas resources will assume greater importance in petroleum basins, worldwide.

To address future energy demands, we must assess unconventional gas resources in international basins, as well as in under-explored North American basins, and we must determine the best technology for specific resource recovery. Many techniques can be used to identify and quantify unconventional gas resources, including seismic surveys, drilling programs, and basin analog assessments. Seismic surveys and drilling programs can be expensive, and they require considerable lead time, but they provide concrete answers to resource questions. On the other hand, a basin analog approach can be used to (1) rapidly assess the gas resource potential, (2) direct seismic acquisition, drilling, and testing efforts to the most prospective parts of basins, and (3) indicate the optimal drilling, stimulation, and testing programs for preliminary resource assessment. Our objective is to develop a computer-based method to compare and identify analog basins, and thus, facilitate international exploration and development of unconventional gas resources.

Basin Analog System (BAS)

A frontier basin is defined as any basin where there has been very little exploration for a specific resource. Historically, explorationists have used an analog approach in the early stages of assessment of frontier basins. They gathered what data were available for the frontier basin and compared these data to known basins, either those described in the literature or those basin previously worked by the explorationist. To facilitate exploration for unconventional gas resources in frontier basins, we are developing computer-based software (**B**asin **A**nalog **S**ystem, or BAS) anchored in the analog basin approach.

Unconventional gas resources have been well characterized in most North American basins, and thus these basins serve as "reference" basins in the BAS database. Twenty-five unconventional gas reference basins have been identified in North America, and geologic and engineering data are being entered into the database. The various geologic and reservoir parameters are weighted by relative importance using multipliers. The frontier basins of interest, or "target" basins, are mostly outside North America. To find the "reference" basin most analogous to a "target" frontier basin, all available data for the target basin are input in BAS. Then, the computer program searches the reference basins database and ranks the individual petroleum systems and the reference basins relative to the target or frontier basin.

We hope that the oil and gas industry will find BAS a useful complement to existing exploration tools, and we solicit your input as an industry professional in helping us develop the most reliable and efficient instrument possible.

This Questionnaire

This survey aims to validate geoscience and engineering assumptions in BAS software by soliciting feedback from oil and gas industry professionals. We estimate that response to the questions will require 20-30 minutes. The questionnaire is divided into 3 parts. In Part A, we request information concerning your background. In Part B, we ask you to rank, order, or score some petroleum parameters based on their importance in determining analogs for specific petroleum systems, such as tight sandstones, fractured shales, and coal beds. Sedimentary basins may have multiple or no petroleum systems. This information will help us assess the weighting factors that we assign to various parameters. Finally, in Part C, we ask you to compare and rank 6 North American basins, based on your knowledge and experience.

We request that you complete and return the questionnaire by July 24, 2006 using one of the following methods:

(1) as an e-mail attachment to: Kalwant.singh@pe.tamu.edu
(2) by FAX to: (979) 845-1307, **or**
(3) in the attached, address envelop

Thanks in advance for your participation.

Sincerely, Kalwant Singh

Part A: General Information

1. Your name and the name of your company (optional):

   Name:
   Company:

   This information will not be released. I will assign a letter (A, B, ….) to each company to refer to the answers.

2. If you prefer to not name your company, please indicate the following.
   My company is a
   - ☐ major operator.
   - ☐ large independent operator.
   - ☐ small independent operator.
   - ☐ consulting company.
   - ☐ service company.
   - ☐ governmental or educational agency.
   - ☐ Other. Type: ____

3. My company is involved in (check all that apply):
   - ☐ Tight gas
   - ☐ Shale gas
   - ☐ CBM
   - ☐ Heavy Oil
   - ☐ Other: ____

4. My expertise:
   - ☐ Geologist
   - ☐ Geophysicist
   - ☐ Engineer
   - ☐ Other ____

My Industry experience: ____ years.

5. My company is involved in the following basin and petroleum systems assessments for unconventional resources.

   Countries

   a. U.S. and Canada (North America)

      Basins

1.	4.
2.	5.
3.	6.

   b. International

      Country:

      1. ____

      Basins

      1.
      2.

      2. ____

      Basins

      1.
      2.

6. Do you use an analog approach when evaluating petroleum systems and frontier basins? Please briefly explain.

Part B: Parameters Important for Determining Analog <u>Petroleum Systems.</u>
Please score the following parameters *from 0 – 100, depending on that parameter's importance in determining reservoir performance and analogous reservoirs, with a score 100 being very important and 0 being not important at all (More than one factor may have the same value). Your responses will help us assess the weighting factors used in our petroleum systems assessments.*

		Scores for Different Types of Reservoirs		
No.	**Parameter**	**Tight Sand**	**Shale Gas**	**Coalbed Methane**
1	Basin Type (foreland, forearc, backarc, rift, etc.)			
2	Basin Area			
3	Deforming Stress Type (extensional, compressive, lateral)			
5	Source Rock Kerogen Type			
6	Vitrinite reflectance (%) of Source Rock			
7	Source Rock Total Organic Content (%)*			
	Source Rock Age			
8	Source Rock Thickness			
9	Reservoir Thickness			
	Reservoir Age			
10	Reservoir Depth			
12	Depositional System (fluvial, alluvial fan, deltaic, tidal, etc.)			
13	Formation Pressure			
14	Pressure Regime (normal pressure, over-pressure, underpressure)			
15	Insitu Stress			
16	Insitu Stress Magnitude			
17	Insitu Stress Orientation (relative to natural fractures)			
18	Natural fracture description/characteristics			
19	Reservoir Porosity			
20	Reservoir Permeability			
21	Hydrologic Setting			
22	Reservoir Water Saturation			
23	Hydrocarbon Migration Distance & Direction			
24	Seals (shale, carbonate, evaporite)			
25	Trap Type (structure, stratigraphy, combination, etc.)			
26	Fluid Type (oil, gas, condensate)			
27	Oil API			
28	Gas Chemical Composition (CH_4, C_2-C_5, CO_2, H_2S, etc.)			
29	Gas Content (scf/ton)			
Below, Include And Rank Other Factors That You Believe Are Important				
28				
29				
30				

* Refers to typical shale & carbonate source rocks

Part C: Analog Basins

Basin characterization results from summarizing the component petroleum systems of each basin. To validate our software and assumption, we will test BAS results for selected North American basins against results of professional geoscientists and engineers. Thus, we will use your answer in this part to validate the methodology used to characterize and identify analog basins.

For the following ***target*** basins, select and list the numbers (in descending order) of the top 3 analog basins from the ***North American Reference*** basins list.

Example:

Permian	
1	***2***
2	***5***
3	***7***

In this example: San Juan, Appalachian, and Big Horn are chosen as most analogous to the Permian Basin, with greatest similarity between the San Juan and Permian Basins.

(This example is intended to show how to fill this questionnaire and is not considered to be correct.)

Target Basins

San Juan	
1	
2	
3	

Appalachian	
1	
2	
3	

East Texas	
1	
2	
3	

Arkoma	
1	
2	
3	

Piceance	
1	
2	
3	

Powder River	
1	
2	
3	

North American Reference Basins

North America Basins List			
1	Permian	14	Green River
2	San Juan	15	Illinois
3	Uinta	16	Louisiana Mississippi Salt
4	Anadarko	17	Michigan
5	Appalachian	18	Paradox
6	Arkoma	19	Piceance
7	Big Horn	20	Powder River
8	Black Warrior	21	Raton
9	Cherokee	22	Texas Gulf Coast
10	Denver	23	Williston
11	East Texas	24	Wind River
12	Forest City	25	Western Canada Sedimentary
13	Fort Worth		

APPENDIX D

QUESTIONNAIRE RESPONSES

Table D.1 Responses for San Juan Basin

Table D.2 Responses for Appalachian Basin

Table D.3 Responses for East Texas Basin

Table D.4 Responses for Arkoma Basin

Table D.5 Responses for Piceance Basin

Table D.6 Responses for Powder River Basin

Fig. D.1 Experts' Responses for San Juan Basin Analog

Fig. D.2 Experts' Responses for Appalachian Basin Analog

Fig. D.3 Experts' Responses for East Texas Basin Analog

Fig. D.4 Experts' Responses for Arkoma Basin Analog

Fig. D.5 Experts' Responses for Piceance Basin Analog

Fig. D.6 Experts' Responses for Powder River Basin Analog

Fig. D.7 Comparison of Experts Response and BAS Result for San Juan Basin

Fig. D.8 Comparison of Experts Response and BAS Result for Appalachian Basin

Fig. D.9 Comparison of Experts Response and BAS Result for East Texas Basin

Fig. D.10 Comparison of Experts Response and BAS Result for Arkoma Basin

Fig. D.11 Comparison of Experts Response and BAS Result for Piceance Basin

Fig. D.12 Comparison of Experts Response and BAS Result for Powder River Basin

Table D.1 Responses for San Juan Basin

		San Juan										
No	Basin Name	% Analog									Count	AVG
		Benjamin Jacobson	Paul Basinski (CBM)	Paul Basinski (TGS)	Charles M Boyer II	Andrew R. Scott	Joel Degenstein	Mark Larsen	SLB Team	Steve Calkins		
1	Anadarko	60									1	10
2	Appalachian										0	0
3	Arkoma					25					1	4.17
4	Big Horn										0	0
5	Black Warrior		30								1	5
6	Cherokee										0	0
7	Denver										0	0
8	East Texas	40									1	6.67
9	Forest City										0	0
10	Fort Worth										0	0
11	Green River			40			50		60	40	4	31.7
12	Illinois										0	0
13	Louissiana Mississippi Salt										0	0
14	Michigan										0	0
15	Paradox										0	0
16	Permian	80									1	13.3
17	Piceance			60	25	50	80		70	60	6	57.5
18	Powder River										0	0
19	Raton		80		25	75	40				4	36.7
20	San Juan										0	0
21	Texas Gulf Coast										0	0
22	Uinta		50		50				50	40	4	31.7
23	Western Canada Sedimentary			30							1	5
24	Williston										0	0
25	Wind River										0	0

Table D.2 Responses for Appalachian Basin

	Appalachian							
Basin Name	% Analog						Count	AVG
	Charles M Boyer II	Andrew R. Scott	Joel Degenstein	Mark Larsen	SLB Team	Steve Calkins		
Anadarko							1	0.2
Appalachian							1	0.4
Arkoma	30			50		60	4	28.6
Big Horn							1	0.8
Black Warrior	60	50	25			40	5	36
Cherokee		25					2	6.2
Denver							1	1.4
East Texas							1	1.6
Forest City							1	1.8
Fort Worth				60		25	3	19
Green River							1	2.2
Illinois	40	75	65				4	38.4
Louissiana Mississippi Salt							1	2.6
Michigan			70				2	16.8
Paradox							1	3
Permian				28			2	8.8
Piceance							1	3.4
Powder River					40		2	11.6
Raton					30		2	9.8
San Juan							1	4
Texas Gulf Coast							1	4.2
Uinta							1	4.4
Western Canada Sedimentary							1	4.6
Williston							1	4.8
Wind River							1	5

Table D.3 Responses for East Texas Basin

		East Texas							
No	Basin Name	% Analog						Count	AVG
		Charles M Boyer II	Andrew R. Scott	Joel Degenstein	Mark Larsen	SLB Team	Steve Calkins		
1	Anadarko	40						2	10.25
2	Appalachian							1	0.5
3	Arkoma							1	0.75
4	Big Horn							1	1
5	Black Warrior							1	1.25
6	Cherokee							1	1.5
7	Denver							1	1.75
8	East Texas							1	2
9	Forest City		25					2	8.5
10	Fort Worth		50					2	15
11	Green River					50		2	15.25
12	Illinois							1	3
13	Louissiana Mississippi Salt			80			70	3	40.75
14	Michigan							1	3.5
15	Paradox							1	3.75
16	Permian	25						2	10.25
17	Piceance	20				40		3	19.25
18	Powder River							1	4.5
19	Raton							1	4.75
20	San Juan							1	5
21	Texas Gulf Coast		75	80			60	4	59
22	Uinta					40		2	15.5
23	Western Canada Sedimentary							1	5.75
24	Williston							1	6
25	Wind River							1	6.25

Table D.4 Responses for Arkoma Basin

		Arkoma										
No	Basin Name	% Analog									Count	AVG
1	Anadarko		40			65		70	70		4	61.3
2	Appalachian	70		30			50		30		4	45
3	Arkoma										0	0
4	Big Horn										0	0
5	Black Warrior			50	50	70					3	42.5
6	Cherokee				75	40			20		3	33.8
7	Denver										0	0
8	East Texas	60									1	15
9	Forest City										0	0
10	Fort Worth						65	70			2	33.8
11	Green River										0	0
12	Illinois	40									1	10
13	Louissiana Mississippi Salt										0	0
14	Michigan										0	0
15	Paradox										0	0
16	Permian						40				1	10
17	Piceance			10							1	2.5
18	Powder River										0	0
19	Raton										0	0
20	San Juan		20								1	5
21	Texas Gulf Coast										0	0
22	Uinta		50								1	12.5
23	Western Canada Sedimentary				25						1	6.25
24	Williston										0	0
25	Wind River										0	0
		Benjamin Jacobson	Paul Basinski	Charles M Boyer II	Andrew R. Scott	Joel Degenstein	Mark Larsen	SLB Team	Steve Calkins			

Table D.5 Responses for Piceance Basin

		Piceance							
No	Basin Name	% Analog						Count	AVG
		Charles M Boyer II	Andrew R. Scott	Joel Degenstein	Mark Larsen	SLB Team	Steve Calkins		
1	Anadarko							1	0.2
2	Appalachian							1	0.4
3	Arkoma							1	0.6
4	Big Horn		25					2	5.8
5	Black Warrior							1	1
6	Cherokee							1	1.2
7	Denver							1	1.4
8	East Texas							1	1.6
9	Forest City							1	1.8
10	Fort Worth							1	2
11	Green River	30		50		70	50	5	42.2
12	Illinois							1	2.4
13	Louissiana Mississippi Salt							1	2.6
14	Michigan							1	2.8
15	Paradox							1	3
16	Permian							1	3.2
17	Piceance							1	3.4
18	Powder River							1	3.6
19	Raton							1	3.8
20	San Juan	25		70		70	40	5	45
21	Texas Gulf Coast							1	4.2
22	Uinta		50	65		95	70	5	60.4
23	Western Canada Sedimentary		75					2	19.6
24	Williston							1	4.8
25	Wind River	40						2	13

Table D.6 Responses for Powder River Basin

		Powder River							
No	Basin Name	% Analog						Count	AVG
		Charles M Boyer II	Andrew R. Scott	Joel Degenstein	Mark Larsen	SLB Team	Steve Calkins		
1	Anadarko							1	0.2
2	Appalachian					40		2	8.4
3	Arkoma							1	0.6
4	Big Horn	30	25					3	11.8
5	Black Warrior					60		2	13
6	Cherokee							1	1.2
7	Denver						25	2	6.4
8	East Texas							1	1.6
9	Forest City							1	1.8
10	Fort Worth							1	2
11	Green River	10	50	70			50	5	38.2
12	Illinois							1	2.4
13	Louissiana Mississippi Salt							1	2.6
14	Michigan							1	2.8
15	Paradox							1	3
16	Permian							1	3.2
17	Piceance							1	3.4
18	Powder River							1	3.6
19	Raton			60		40		3	23.8
20	San Juan							1	4
21	Texas Gulf Coast	20						2	8.2
22	Uinta							1	4.4
23	Western Canada Sedimentary						60	2	16.6
24	Williston		75					2	19.8
25	Wind River			65				2	18

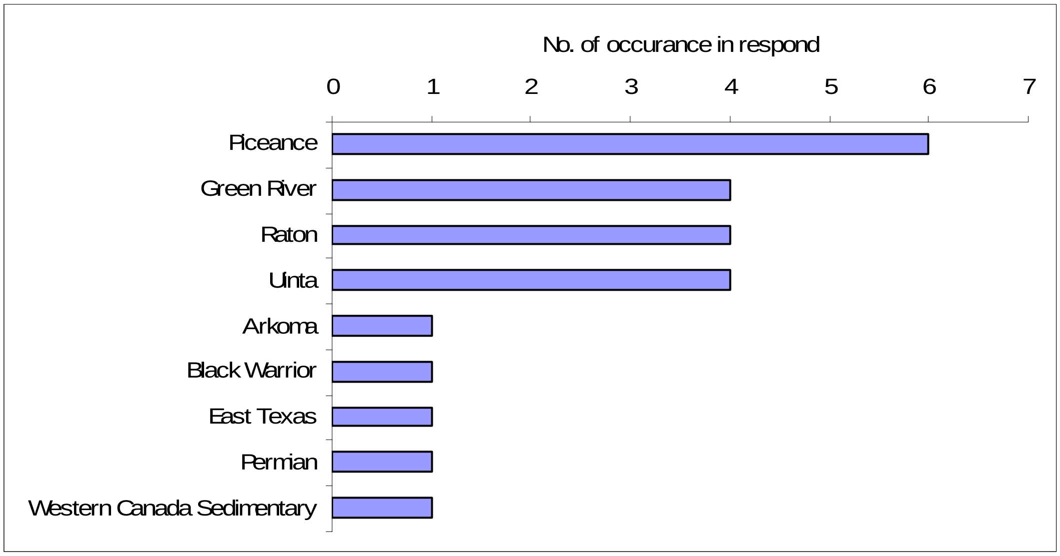

Fig. D.1 Experts' Responses for San Juan Basin Analog

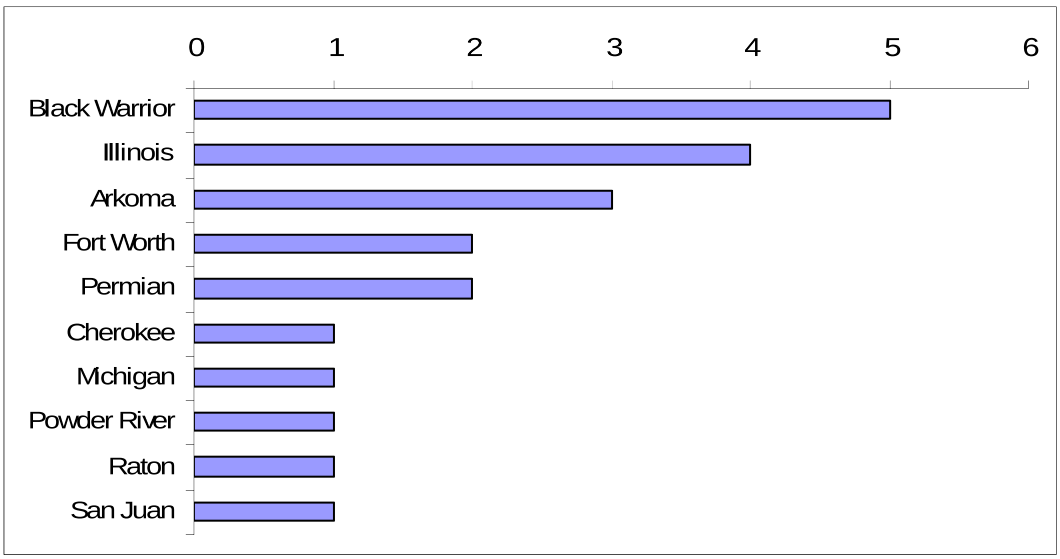

Fig. D.2 Experts' Responses for Appalachian Basin Analog

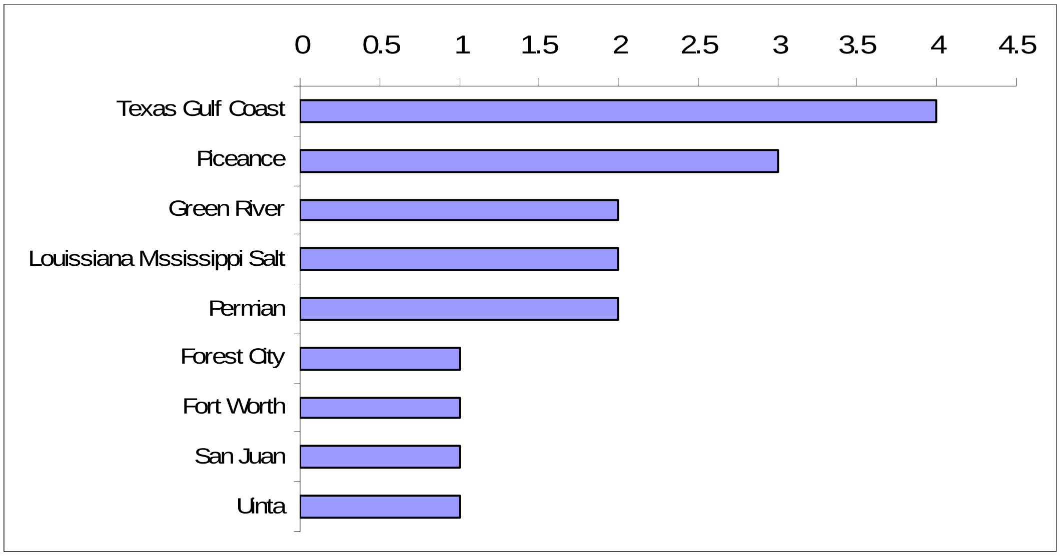

Fig. D.3 Experts' Responses for East Texas Basin Analog

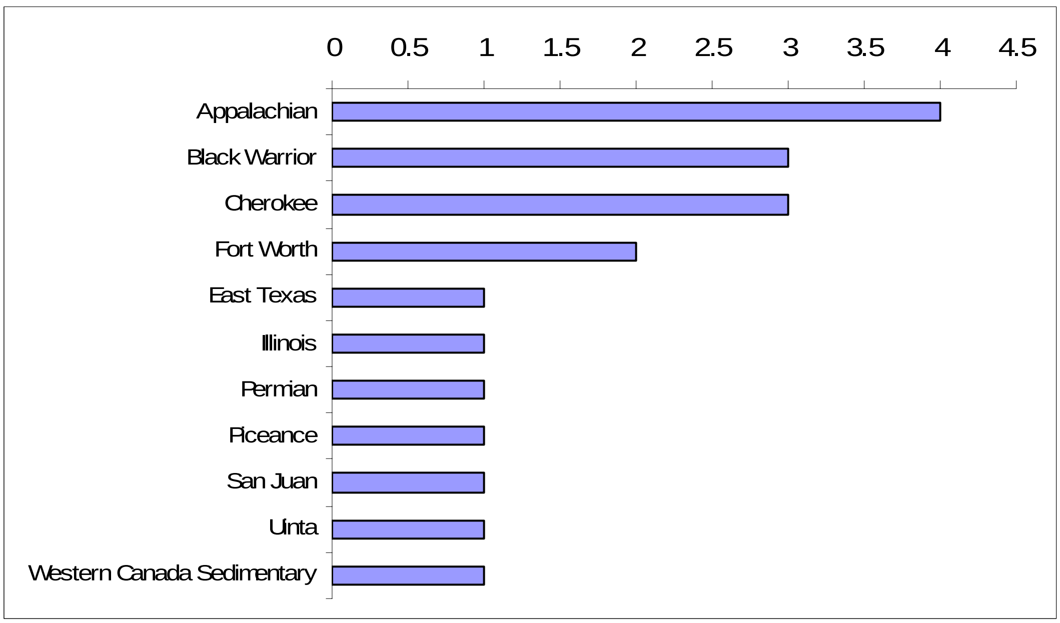

Fig. D.4 Experts' Responses for Arkoma Basin Analog

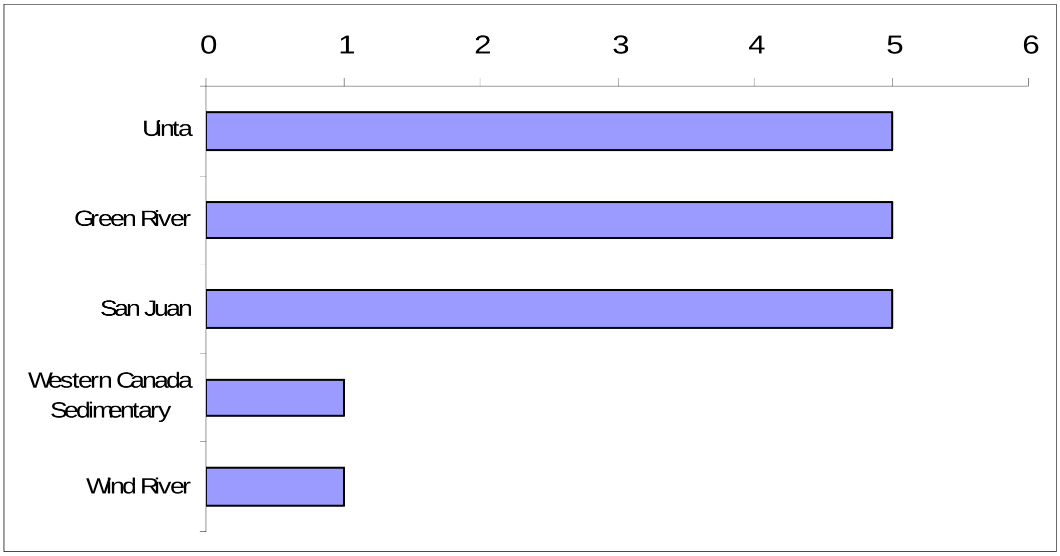

Fig. D.5 Experts' Responses for Piceance Basin Analog

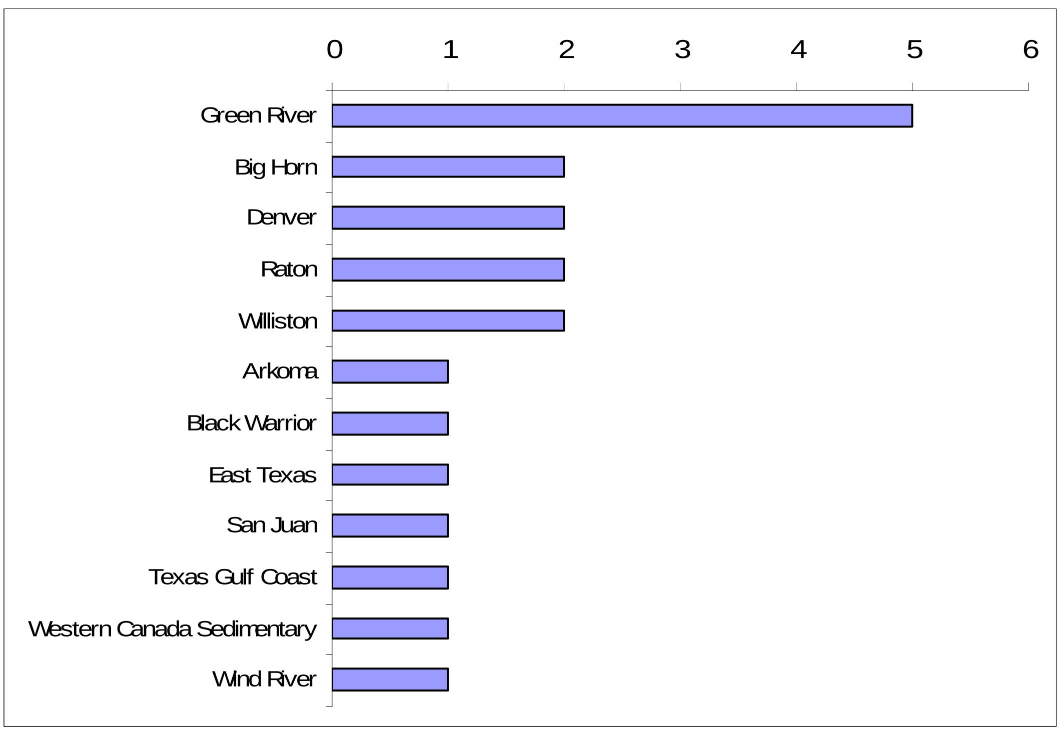

Fig. D.6 Experts' Responses for Powder River Basin Analog

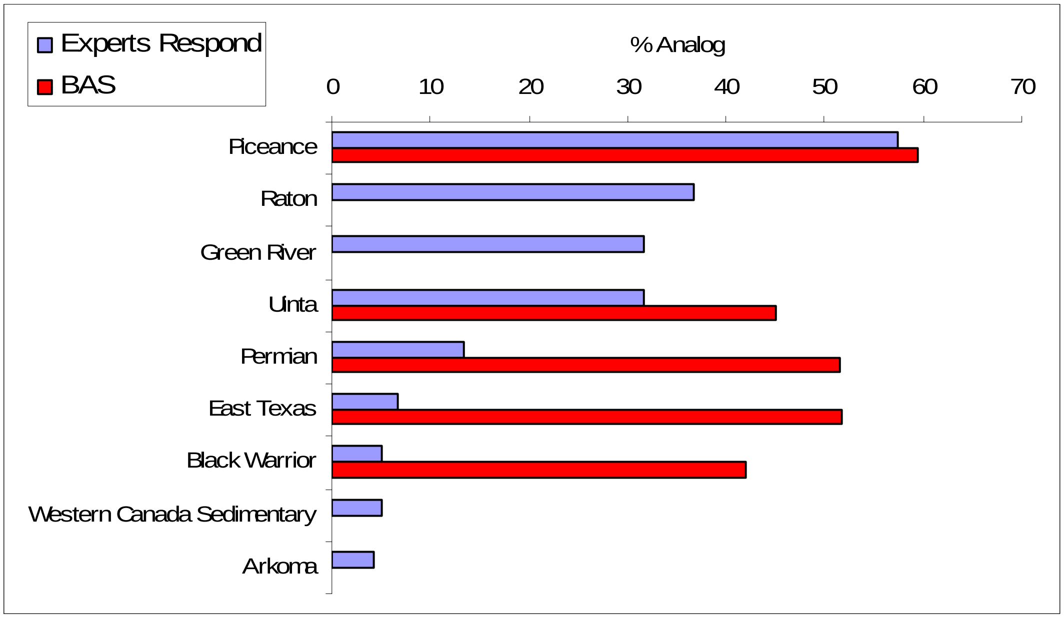

Fig. D.7 Comparison of Experts Responses and BAS Result for San Juan Basin

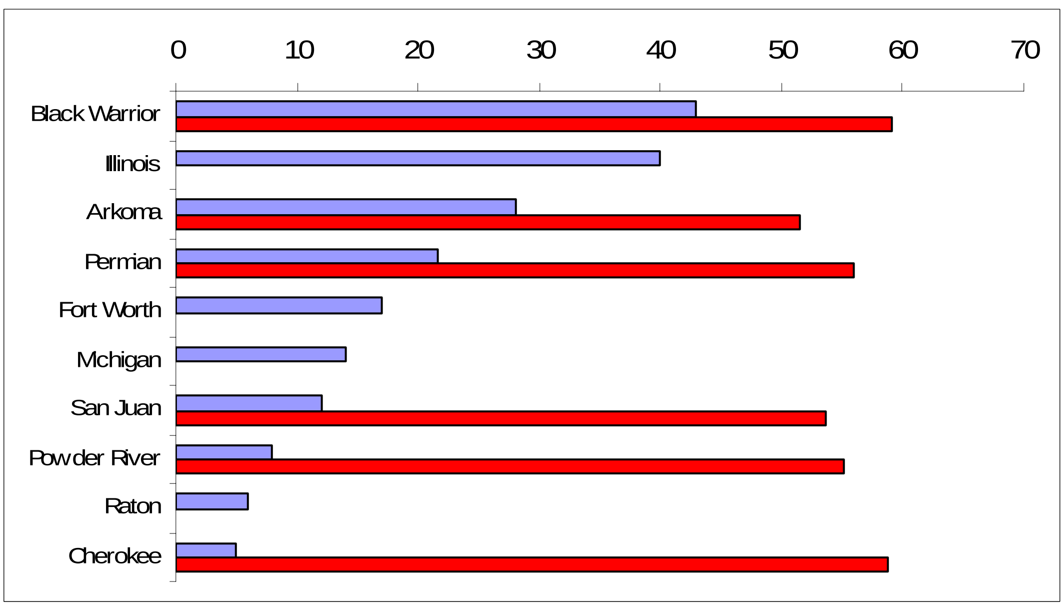

Fig. D.8 Comparison of Experts Responses and BAS Result for Appalachian Basin

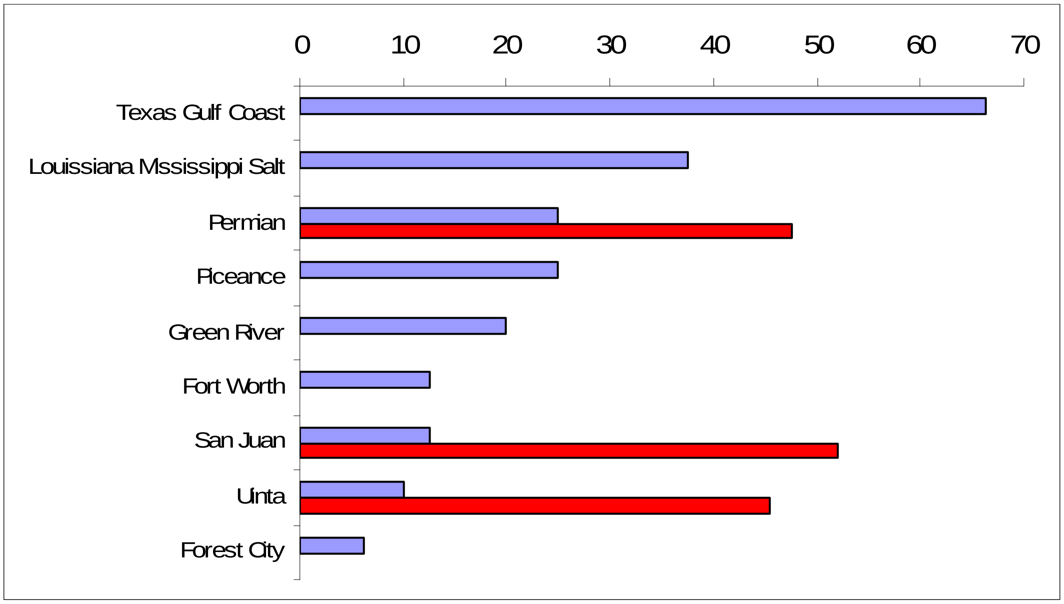

Fig. D.9 Comparison of Experts Responses and BAS Result for East Texas Basin

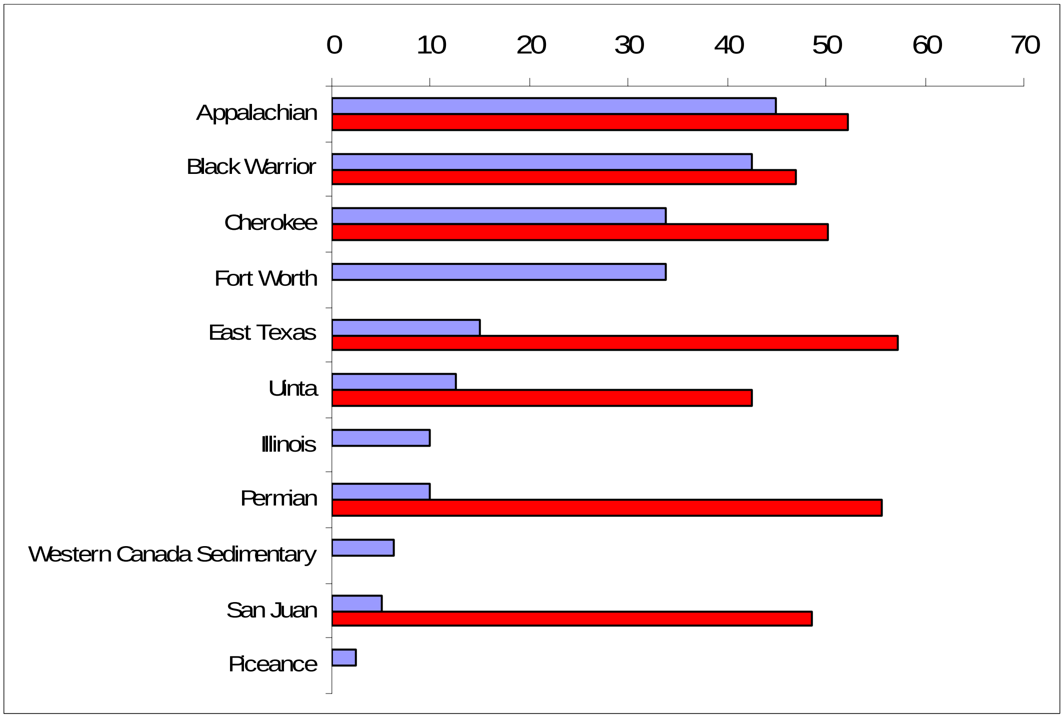

Fig. D.10 Comparison of Experts Responses and BAS Result for Arkoma Basin

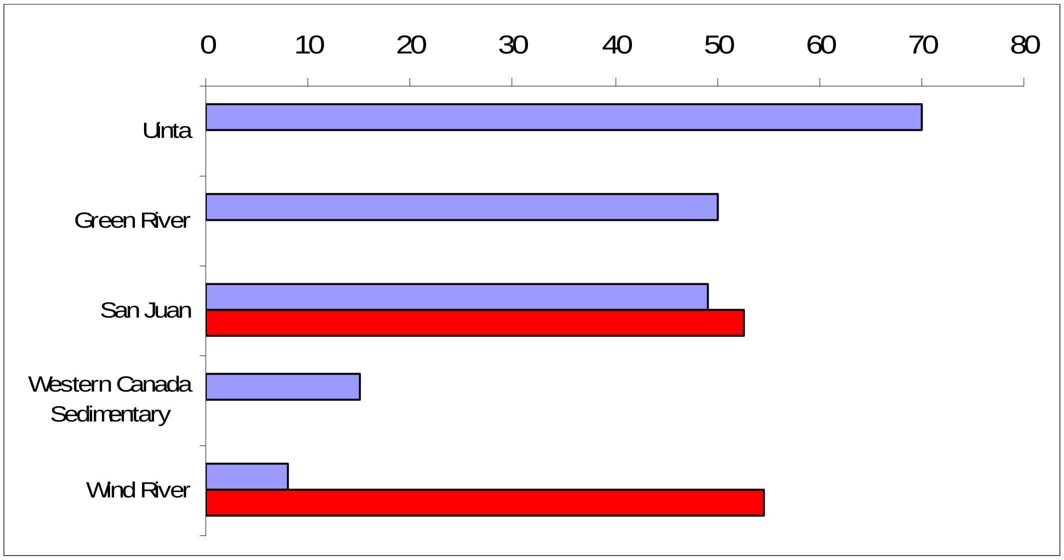

Fig. D.11 Comparison of Experts Responses and BAS Result for Piceance Basin

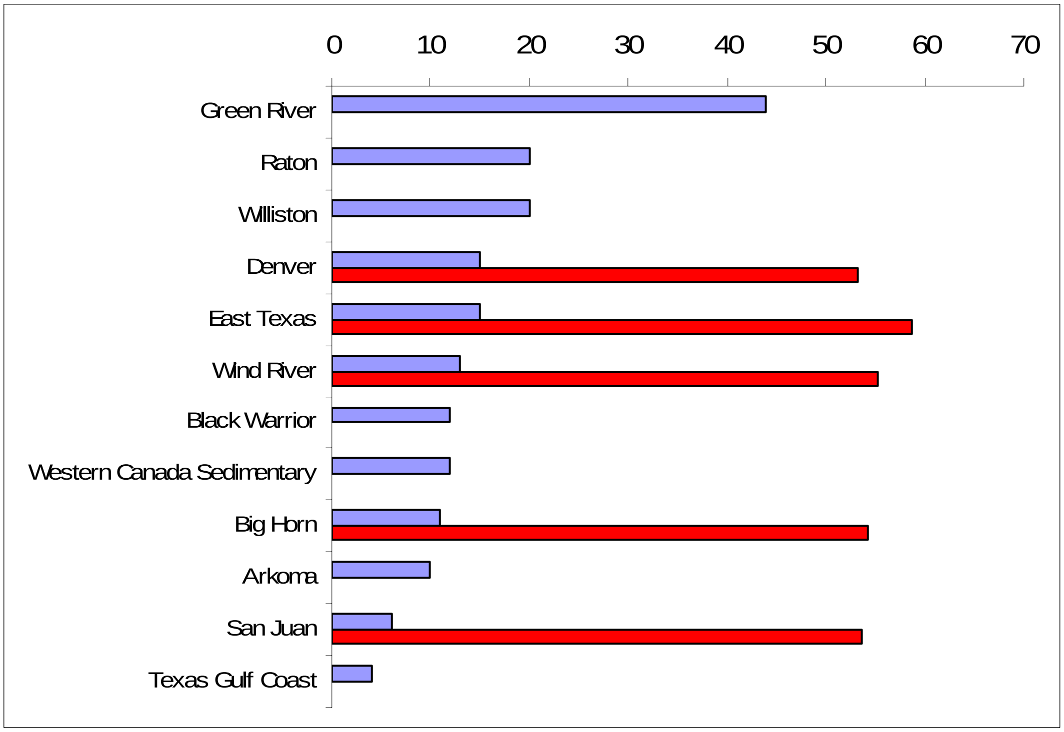

Fig. D.12 Comparison of Experts Responses and BAS Result for Powder River Basin

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