IMPROVED BASIN ANALOG SYSTEM TO CHARACTERIZE UNCONVENTIONAL GAS RESOURCE

A Thesis

by

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ABSTRACT

Unconventional resources will play an important role in filling the gap between supply and demand for future world energy. In North America, the impact of unconventional resources on energy supplies is growing continuously. However, around the world they have yet to serve as a major contributor to the energy supply, partly due to the scarcity of information about the exploration and development technologies required to produce them.

Basin analogy can be used to estimate the undiscovered petroleum potential in a target basin by finding a geological analog that has been explored enough that its resource potential is fully understood. In 2006, Singh developed a basin analog system BASIN (Basin Analog Systems INvestigation) in detail that could rapidly and consistently identify analogous reference basins for a target basin. My research focused on continuing that work, comprehensively improving the basin analog system in four areas: the basin analog method; the database; the software functionality; and the validation methods.

The updated system compares basins in terms of probability distributions of geological parameters. It compensates for data that are sparse or that do not represent basin-level geological parameters, and it expands the system's ability to compare widely varying quantitative parameters. Because the updated BASIN database contains more geologic and petroleum systems information on reference (existing) basins, it identifies analog basins more accurately and efficiently.

The updated BASIN software was developed by using component-based design and data visualization techniques that help users better manage large volumes of information to understand various data objects and their complicated relationships among various data objects.

Validation of the improved BASIN software confirms its accuracy: if a basin selected as the target basin appears in the reference basin list with other basins, the target basin is 100% analogous only to itself. Furthermore, when a target basin is analyzed by both BASIN and PRISE (Petroleum Resources Investigation and Summary Evaluation) software, results of the improved BASIN closely matched the PRISE results, which provides important support for using BASIN and PRISE together to quantitatively estimate the resource potential in frontier basins.

DEDICATION

This thesis is dedicated to my parents and my husband. No matter what difficulty I encounter, the love from family, in China and the United States, always gives me courage to move forward.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude and appreciation to my advisor and committee chair, Dr. Stephen A. Holditch. Because of his kind assistance, I had the precious opportunity of studying the petroleum engineering field. His broad knowledge and foresight always guided me throughout the course of this research.

I would also like to thank Dr. Walter B. Ayers and Dr. Yuefeng Sun for providing detailed guidance and support during my research progress.

Finally, I would like to thank the Crisman Institute in the Harold Vance Department of Petroleum Engineering at Texas A&M University for sponsoring my research during my endeavor for an M.S. degree in petroleum engineering.

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1 INTRODUCTION

This chapter provides a general review of my research area from three perspectives: the background of basin analog study, the progress and issues in the current basin analog system, and the efforts I made to improve the system.

1.1 Unconventional Resource Evaluation

Unconventional resources will play an important role in filling the gap between supply and demand for future world energy. Particularly in the USA, and to some degrees also in Canada, the impact of unconventional resources on energy supplies is growing (Jochen, 2011). However, even with unconventional resources currently playing a major role in the national energy picture in North America, in the rest of the world they have yet to become a major contributor to the energy supply, partly due to the scarcity of information about the exploration and development technologies required to produce unconventional resources (Holditch et al., 2007). Also, in many producing areas, still ample supplies of conventional oil and gas remain.

Unconventional resources are defined as those oil and gas accumulations that, owing to their special reservoir rock properties (such as low matrix permeability, presence of natural fractures), charge (adsorbed gas in self-sourced reservoirs, methane clathrates), and/or fluids characteristics (high viscosity), are economically exploitable only by using advanced technologies, massive stimulation treatments, and/or special recovery processes (Martin et al. 2010). Unconventional resources include tight gas sands (TGS), coalbed methane (CBM), shale gas (SG), and heavy oil.

The difference between unconventional resources and conventional resources is best illustrated using the resource triangle concept (Gray, 1977; Masters, 1979; Holditch, 2004). The resource triangle suggests that hydrocarbon resources are distributed log-normally in nature. Resource distributions in the triangle reflect their abundance and, reservoir quality and the technology required for recovery. The base of the triangle represents large volumes of unconventional, low-quality hydrocarbon resources, in contrast to the apex of the triangle, which indicates the small volumes of conventional, high-quality resources (Fig. 1.1). Improved technology and better resource assessment are important to produce unconventional resources economically.

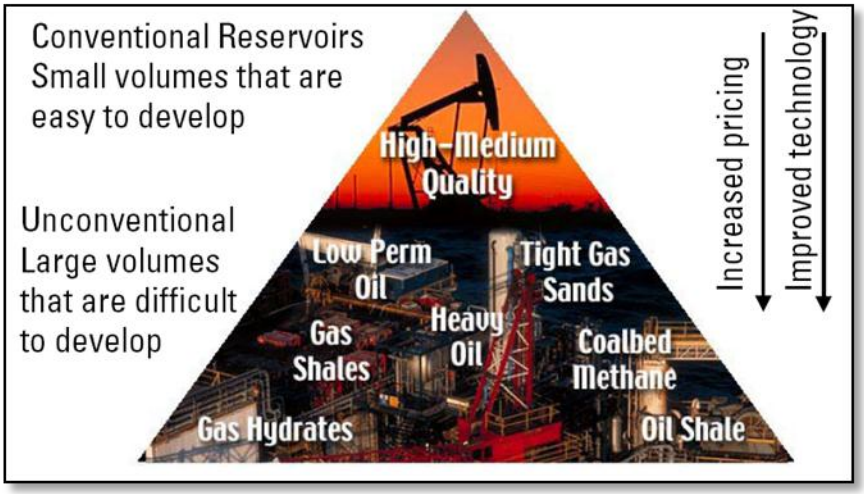


Fig. 1.1— Resource Triangle (Holditch, 2004).

At present, most of the expertise in UGR (unconventional gas reservoir) development resides in the North America. There is an urgent need to make the expertise and technology required for drilling, completion, and stimulation more accessible to the engineers for developing UGRs outside of North America. Therefore, a complex, multicomponent software package called UGRA (Unconventional Gas Reservoirs Advisory) system has been designed to provide advice, recommendations, and/or best practices for a broad array of issues that describe a large and interconnected set of solutions required to develop an UGR (Cheng, 2012). The UGRA system smoothly and efficiently integrates all components with optimized functions (Table 1.1), and the imbedded connections among these components allow them to work seamlessly together (Fig. 1.2) (Cheng, 2012).

Table 1.1— Components of UGRA System (Cheng, 2012)

Abbreviation	Full Name	Function
BASIN	Basin Analog Systems INvestigations	Identify analog basins.
FAST	Formation Analog Selection Tool	Identify and rank analog formations.
PRISE	Petroleum Resource Investigation Summary and Evaluation	1. Demonstrate the resource evaluation of 25 North American basins; 2. Perform the calculations to estimate the resource volume for frontier basins.
TGS	Tight Gas Sand Advisory System	Implement engineering computations to provide advice concerning drilling, completing, and stimulating unconventional gas reservoirs.
CBM	Coal Bed Methane Advisory System	
SG	Shale Gas Advisory System	
OPTII	Fracture OPTimization II	Optimize hydraulic fracturing.
PMT	ProMAT™	A single phase, single well analytical production model.
RBK	eRedBook™	An essential information source for Halliburton services, products, and API standards.

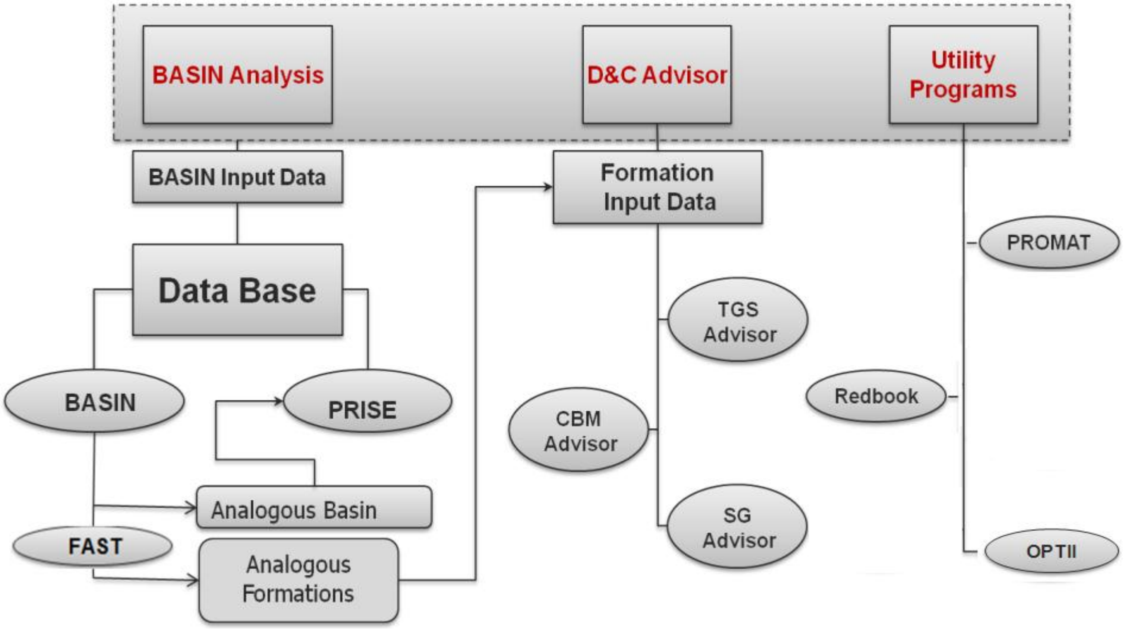


Fig. 1.2—UGRA system architecture (Cheng et al., 2010b).

1.2 Overview of Basin Analog Method and Software

Basin analogy is commonly used in the field of geosciences, where geologists seek to determine the similarity between two basins under the assumption that greater amounts of knowledge lead to better accuracy (McCormick et al., 1999). As a supplementary analysis, the geological analog is helpful to characterize the less accessible reservoirs and complement the field model.

Every geoscientist knows how to do basin analogy (Perrodon and Zabek, 1990; Bridge et al., 2000; Sivils, 2004; Bhattacharya and Tye, 2004); however, the basin analog practice of each geologist requires substantial effort and depends on his or her experience. Frequently, subjective opinions are used to find basins that are analogous to the target basin, and no step-by-step guidelines had been published until 2005 (Singh, 2006). Although a digital analog knowledge system (Sun et al., 2004; C&C Reservoirs, 2011) was developed to compare frontier basins with productive counterparts of similar tectono-stratigraphic settings, the search for analogs was basically a classification process to generate basins that are in the same category with the target basin in terms of general geological factors, and still needed the users to compare each basin summary in a standardized format. Also, the classification method cannot differentiate the importance of various factors in deciding the analog results. In addition, basin analogs have not been used to directly assist in the exploration and development applications of petroleum engineering. Some works have indicated that the undiscovered petroleum potential of a target basin could be predicated by finding a geological analog that has been sufficiently explored and fully realized for its resource potential (Morton, 1998; USGS Bighorn Basin Province Assessment Team, 2010; Abangan, 2011; CNPC, 2011), but no method has been established for such analytical evaluations. They also lack of validation and quantitative support.

In 2006, Singh designed a detailed basin analog method that was capable of identifying analogous North American reference basins for the newly discovered target basins or “frontier basins.” This method was developed in new software called BASIN (Basin Analog Systems INvestigation), in Visual Basic 6.0 that compiles the database to accelerate the process of identifying analog basins. However, there are some issues in the original BAS from the accuracy of basin analog method to the usability of the software and completeness of the database.

In my efforts to continue the development of the basin analog system, I improved the basin analog method that extracts and compares the characterized parameter distributions at the basin scale, which can not only solve the incomplete analog problem, but can also achieve more accurate results. I also updated the database by adding data on the 25 North American basins. With the updated database and method, I redeveloped the BASIN software in Visual Basic.Net to improve its extensibility and user-friendliness that supports easily-accessible interface and graphical representation and allows users more control and comprehension of the basin analog practice. Tests and case studies show that the improved basin analog system can assist in estimating unconventional gas potential in frontier basins, worldwide.

1.3 Significance of BASIN

The BASIN software can consistently identify analog basins with the objective of: (1) predicting hydrocarbon resource potential of the target basin, (2) guiding exploration and inferring reservoir characteristics, (3) making preliminary decisions concerning best engineering practices for the drilling program, completion method, and stimulation method (Singh, 2006). Fig. 1.3 illustrates this idea.

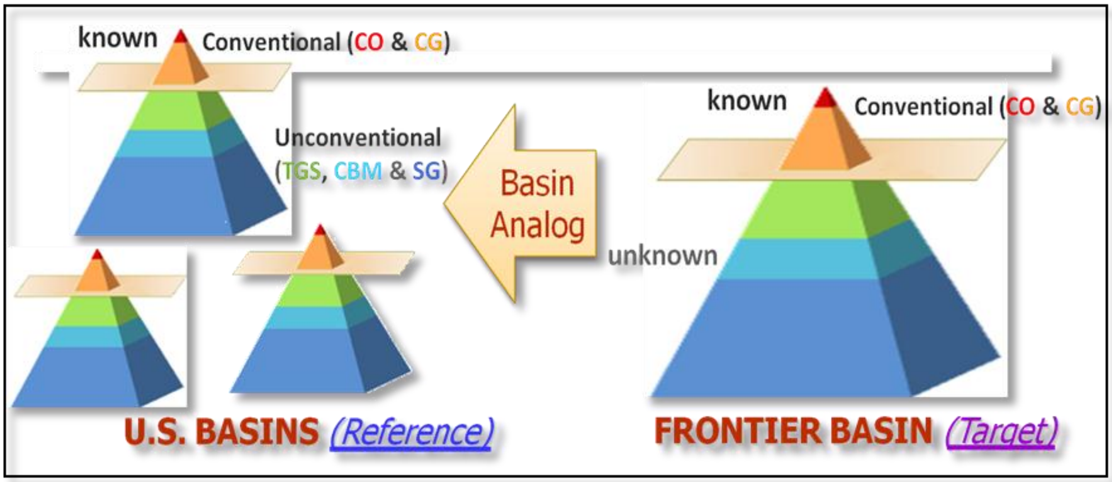


Fig. 1.3—Idea of BASIN (Modified from Singh 2008)

To achieve the objectives, the BASIN software is combined with PRISE in the UGRA system to estimate unconventional resource potential in frontier basins. The PRISE software contains information about the resources (conventional gas, conventional oil, shale gas, coalbed methane, and tight gas sand) for each of the North American reference basins. Fig. 1.4 illustrated the workflow of a typical application that uses BASIN and PRISE to estimate TRR (technically recoverable resources) for a target basin: first, the geologic and engineering data for the target basin is input into the BASIN software, BASIN generates the list of reference basins ranked by their similarity to the target basin. Then, PRISE provides TRR distribution information on the analogous basins in the list. This list of the TRR distributions of the analog basins, combined with additional input information (depending on the specific estimation method), provides the necessary data for the TRR estimation methods to output different types of unconventional TRR for the target basin in the result (Martin et al., 2010; Cheng et al., 2011a).

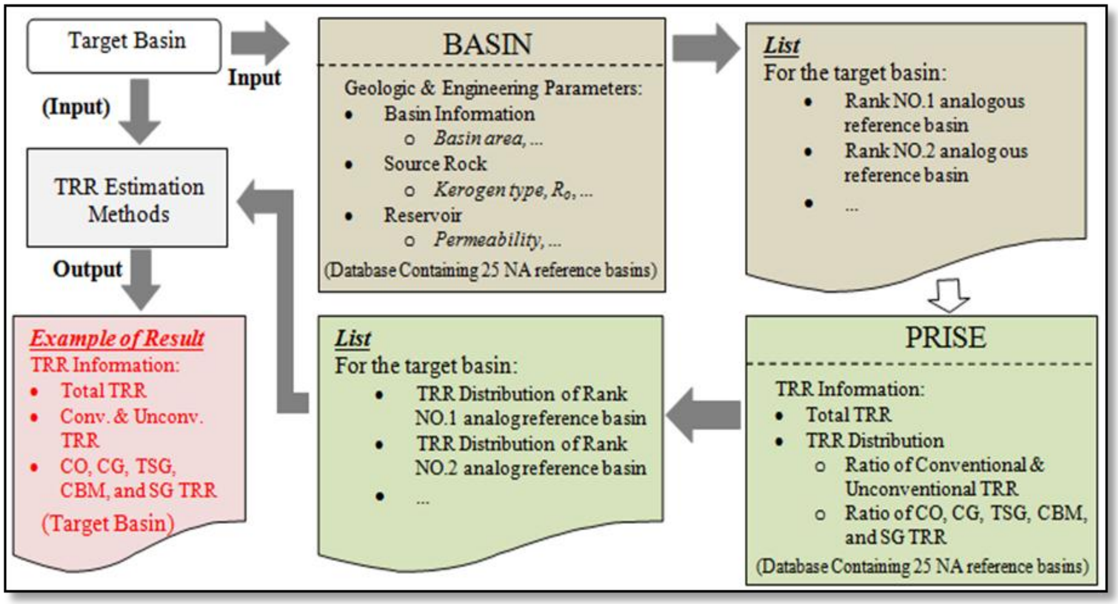


Fig. 1.4—Workflow of BASIN and PRISE in estimating TRR for the target basin (Cheng et al., 2011a).

1.4 The Objectives of This Research

To improve the BASIN software, I updated the basin analog method and database for 25 basins to provide more accurate results from basin analog analysis and better support its usage for evaluating unconventional resource potential in frontier basins. Specifically, the research proposed in this project set out to accomplish the following objectives.

1 To improve the basin analog methodology for comparing frontier (target) basins with North American reference basins that we have characterized, I

reviewed the Singh's (2006) thesis and BASIN software (Singh et al., 2008) and improved its methodology for solving the problem.

   a. I analyzed the analog method proposed in the thesis, and checked the source code for the basin analog function in the BASIN software.

   b. I identified the potential issues and problems of the basin analog approach used in the BASIN software.

2 To identify the optimal approach for basin analog, I:

   a. reviewed the literature to find the candidate solutions for the issues and problems;

   b. compared and evaluated the possible solutions, and selected the optimal solution that is practical and effective; and

   c. tested the consistency and accuracy of the improved basin analog approach.

3 To better manage the large volume of data for the BASIN database and interpret the results, I made the BASIN software more user-friendly. It now:

   a. supports selecting worldwide basins from maps of different regions and countries;

   b. provides formatted reports for basin information and basin analog results; and

   c. generates data visualization to reflect various evaluations.

4 To keep up with the recent developments in the North American basins and conduct basin analog searches based on more complete data, it was necessary

to update the database that was originally built in 2006, which included

a. updating the design of the database so that it can be shared by the three applications BASIN and PRISE from the UGRA suite of software; and

b. designing and developing the software to populate the database from the spreadsheets of 25 North American basins.

1.5 Organization of This Thesis

This thesis is divided into six chapters. In Chapter II, I review the original basin analog method developed by Singh and analyze its issues. Chapter III focuses on the improvement of the basin analog method. Chapter IV provides details about the design and implementation of the improved BASIN database and software. Chapter V presents the software and method validation, and finally, Chapter VI contains the conclusions and recommendations.

2 BASIN ANALOG METHOD

A basin analog method quickly and effectively provides the analogous reference basins for the target basin so that we can use what we have learned in the reference basins to infer unknown information in the target basin. The original basin analog method developed by Singh in 2006 covered the analog parameters, reference basin selection, geologic and petroleum systems data, and basin analog identification process. Since it was the basis of my improvement work, this chapter will describe the original method in detail and analyze its issues.

2.1 Problem Definition and Analysis

The problem of identifying the reference basins (the North American basins having significant unconventional gas resources development) that are analogous to the target basin (the underexplored frontier basin) is defined as:

Condition. We have a set of basins $B_S = \{B_i | i \geq 0\} = \{B_0\} \cup B_R$ and $B_R = \{B_i | i \geq 1\}$, where

- B_0 is the target basin, and B_i is a reference basin if $i \geq 1$
- $\forall B_i \in B_S$, $B_i = [s_1, \dots, s_j, \dots]$, where s_j refers to any petroleum system in the basin B_i
- $\forall B_i \in B_S, \forall s_j \in B_i, s_j = [p_{j1}, p_{j2}, \dots, p_{jk}, \dots]^T$, where p_{kj} refers to the value (which can be null) of s_j for the geologic or petroleum system parameter k.

Result. For the target basin B_0, output the list of reference basins $L = \{B_i | i \geq 1\}$, which are ranked by their similarity degree to B_0 from high to low.

This definition indicates that the basin analog results will depend on the four factors: selection of parameters, selection of reference basins, data for petroleum systems and their parameter values in the reference basins and target basin, and a basin analog identification method. Therefore, I analyzed the original basin analog method in terms of these factors.

2.2 The Original Basin Analog Method

For the original basin analog method, Singh identified 67 parameters to evaluate a basin. These parameters were categorized and weighted based on their relative importance. Then, based on available maps from GRI/GTI (GRI, 1999; GRI, 2000; GTI, 2001), 25 North American basins that have conventional and unconventional gas were selected as reference basins. To summarize the geologic and petroleum systems characteristics of the reference and target basins, public records from several electronic databases (AAPG datapages, SPE e-Library, USGS, and SEG) were compiled into a database. To identify the analogous North American reference basins, each of the these 25 reference basins is tested against the target (or frontier) basin, and similarity between the target basin and its reference basin is calculated by comparing each pair of petroleum systems (one each from the target basin and the reference basin) and integrating the results of all the petroleum systems pairs.

2.2.1 Analog Parameters

Table 2.1 shows the identified parameters in analog analysis. Those parameters are classified into three categories: (1) general basin parameters, (2) source rock parameters; and (3) reservoir rock parameters. In addition, each of the analog parameters was designed to have two features: weighting factor and class.

The concept of weighting factor was used to reflect the parameter's relative importance and quantify the analog process. 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. The class factor only applied to the parameters that have quantitative classes (such as porosity or permeability).

The term "classes" means the pre-assigned quantitative or qualitative values or descriptions for each parameter. For example, the classes for lithology are sandstone, carbonate, tight sand, coal, and shale, and porosity has classes of 1%, 2%, 3%, …, 40% (see Table 2.2). This design gave flexibility to add more analog parameters and edit or modify them, if necessary.

Table 2.1—Parameters Used To Evaluate Analog Basins (Singh et al., 2008)

NO	Category	Weighting Factor	Second WF	Parameter	Critical
1	General Basin	30	FALSE	Basin Type	FALSE
2		60	TRUE	Basin Area Min	FALSE
3		60	TRUE	Basin Area Max	FALSE
4		50	TRUE	Fill Thickness Min	FALSE
5		50	TRUE	Fill Thickness Max	FALSE
6		70	FALSE	Deforming Stress Type	FALSE
7	Source Rock	80	FALSE	Rock Type	FALSE
8		50	FALSE	Age Min	FALSE
9		50	FALSE	Age Max	FALSE
10		50	TRUE	Depth Min	FALSE
11		50	TRUE	Depth Max	FALSE
12		70	TRUE	Thickness Min	FALSE
13		70	TRUE	Thickness Max	FALSE
14		100	FALSE	Kerogen Type	TRUE
15		100	TRUE	Vitrinite reflectance Min	TRUE
16		100	TRUE	Vitrinite reflectance Max	TRUE
17		80	TRUE	Total Organic Content Min	FALSE
18		80	TRUE	Total Organic Content Min	FALSE
19	Reservoir Rock	100	FALSE	Lithology	TRUE
20		30	FALSE	Age Min	FALSE
21		30	FALSE	Age Max	FALSE
22		60	FALSE	Depositional System	FALSE
23		50	TRUE	Depth Min	FALSE
24		50	TRUE	Depth Max	FALSE
25		70	TRUE	Gross Thickness Min	FALSE
26		70	TRUE	Gross Thickness Max	FALSE
27		70	TRUE	Net Thickness Min	FALSE
28		70	TRUE	Net Thickness Max	FALSE
29		80	TRUE	Pressure Min	FALSE
30		80	TRUE	Pressure Max	FALSE
31		80	FALSE	Pressure Regime	FALSE
32		90	TRUE	Porosity Min	FALSE
33		90	TRUE	Porosity Max	FALSE
34		90	TRUE	Permeability Min	FALSE
35		90	TRUE	Permeability Max	FALSE
36		70	TRUE	Water Saturation Min	FALSE
337		70	TRUE	Water Saturation Max	FALSE
38		50	TRUE	Migration Distance Min	FALSE
39		50	TRUE	Migration Distance Max	FALSE
40		50	FALSE	Migration Direction	FALSE
41		100	FALSE	Seals	TRUE
42		90	FALSE	Traps Type	FALSE
43		100	FALSE	Fluid Type	TRUE
44		50	TRUE	Oil Gravity (API)	FALSE

Table 2.1 Continued—Parameters Used To Evaluate Analog Basins (Singh et al., 2008)

NO	Category	Weighting Factor	Second WF	Parameter	Critical
45	Reservoir Rock	50	TRUE	Oil Gravity (API) Max	FALSE
46		10	TRUE	Sulfur content Min	FALSE
47		10	TRUE	Sulfur content Max	FALSE
48		10	TRUE	CO2 content Min	FALSE
49		10	TRUE	CO2 content Max	FALSE
50		10	TRUE	H2S content Min	FALSE
51		10	TRUE	H2S content Max	FALSE
52		10	TRUE	Heavy gas (C2-C5) Min	FALSE
53		10	TRUE	Heavy gas (C2-C5) Max	FALSE
54		10	TRUE	Oil-in-place Min	FALSE
55		10	TRUE	Oil-in-place Max	FALSE
56		10	TRUE	Oil recoverable Min	FALSE
57		10	TRUE	Oil recoverable Max	FALSE
58		10	TRUE	Oil reserve Min	FALSE
59		10	TRUE	Oil reserve Max	FALSE
60		10	TRUE	Gas-in-place Min	FALSE
61		10	TRUE	Gas-in-place Max	FALSE
62		10	TRUE	Gas recoverable Min	FALSE
63		10	TRUE	Gas recoverable Max	FALSE
64		10	TRUE	EUR Min	FALSE
65		10	TRUE	EUR Max	FALSE

Table 2.2—Example Of Analog Parameter Classes (Singh, 2006)

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		45000ft
1	Deforming Stress	Extensional
2		Compressive
3		Lateral

In addition, five parameters were picked to be critical parameters. They were lithology, fluid type, kerogen type, vitrinite reflectance, and seals. These parameters were the minimum parameters that have to be common to both the target and the analog basin.

2.2.2 Reference Basin Selection

North America has more than 60 major basins that have unconventional resources potential. The original method used maps (Fig. 2.1) from Gas Research Institute (GRI), now called the Gas Technology Institute (GTI) (GRI, 1999; GRI, 2000; GTI, 2001) to identify 25 basins that have a history of producing unconventional resources (Table 2.3), and where sufficient data concerning unconventional gas resources are available. The selected 25 basins have significant volumes of those three unconventional gas resources.

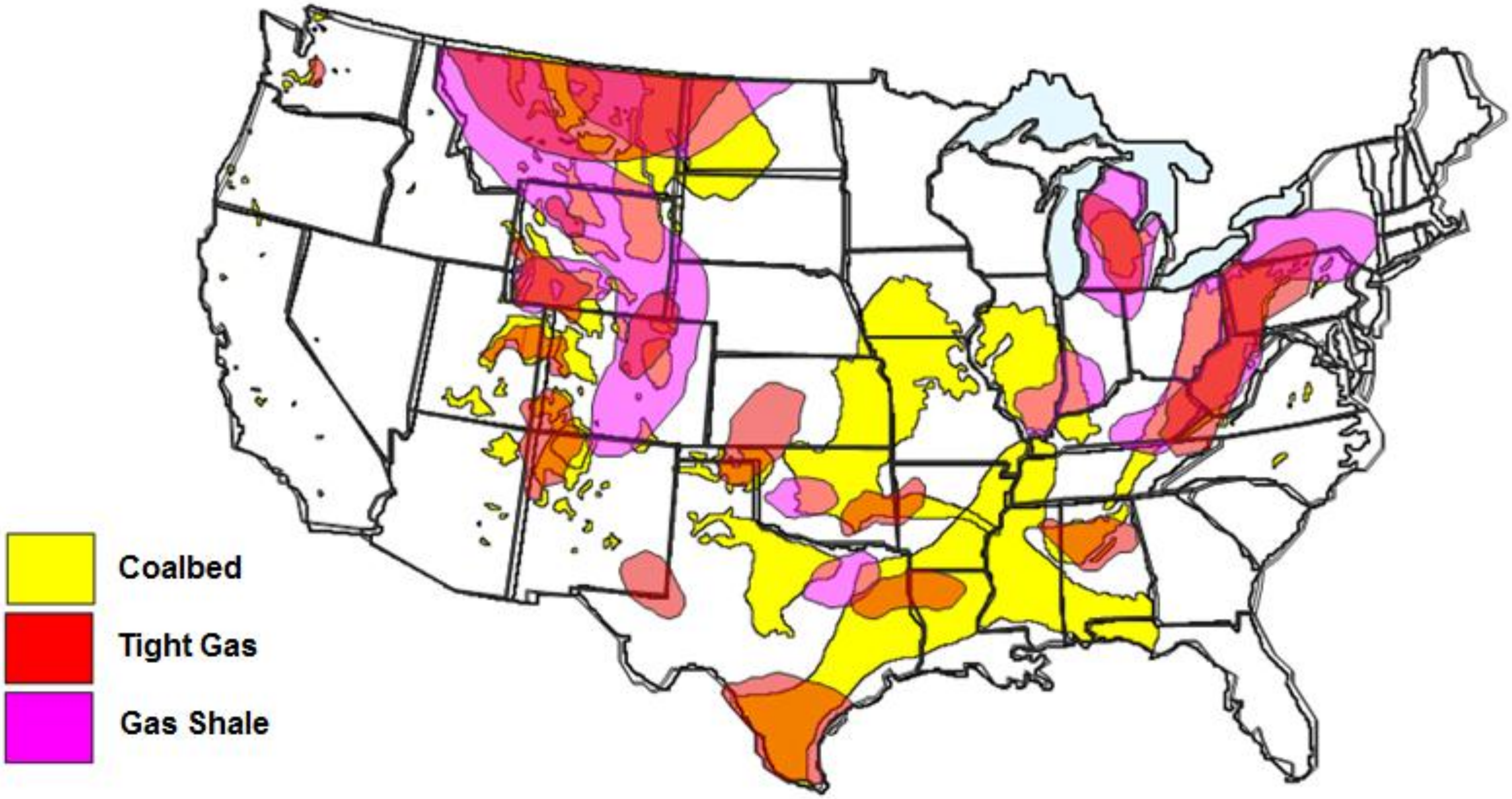


Fig 2.1—Twenty-five North American reference basins that contain unconventional gas resources. (GRI/GTI, 2000)

Table 2.3—North America Reference Basins (Singh, 2006)

Permian
San Juan
Uinta
Anadarko
Appalachian
Arkoma
Big Horn
Black Warrior
Cherokee
Denver
East Texas
Forest City
Fort Worth
Greater Green River
Illinois
Louisiana Mississippi Salt
Michigan
Paradox
Piceance
Powder River
Raton
Texas Gulf Coast
Williston
Wind River
Western Canada Sedimentary

2.2.3 Geology and Petroleum Systems Data

The data used in the basin analog method described petroleum systems with their geologic and engineering parameters in the reference basins and the target basin. The 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 elsewhere on the internet (Singh, 2006).

2.2.4 Basin Analog Identification Method

Fig. 2.2 illustrates the workflow of the original basin analog identification method: after the data were input for the target basin (B_0), each of the reference basins (B_i) was evaluated against the target basin at the petroleum system level by comparing each pair of the petroleum systems that are from the reference basin and target basin (that is, s_i and s_j), respectively. Each petroleum system consists of a reservoir formation and the potential source rock that generated the hydrocarbon to eventually fill the reservoir rock. At the reservoir formation level, the two petroleum systems were compared on each parameter. That produced one point for the petroleum system of the target basin ($P_{kij}\mathrm{P}_{kij}$) and one point for the petroleum system of the reference basin ($\mathrm{T}_{kij}T_{kij}$).

Each point in every comparison was collected and processed. The comparison on each parameter generates the points P_{kij} and T_{kij}. Then, the points on each parameter were accumulated to generate the point for the corresponding petroleum system in the reference or target basin. Last, all of the points at the petroleum system level in the reference basin and target basin were calculated to define the analog result between the reference basin and target basin [$A(B_i, B_0)$] by two methods. The first method averaged the points by the arithmetic average of the points from the reference basin divided by the average of points from the target basins. The second method determined the best match of a petroleum system in the target basin to a petroleum system in a reference basin. In other words, the method would only process the highest point of comparison from all the petroleum system comparisons.

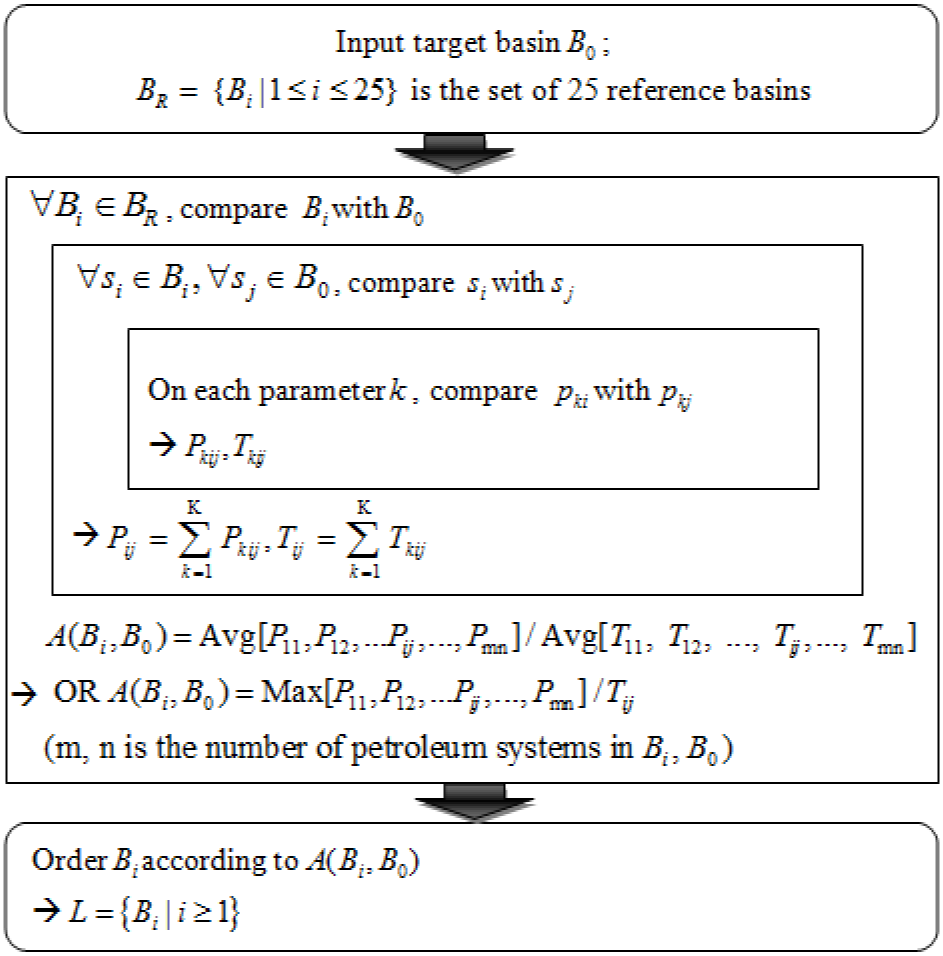


Fig 2.2—Workflow of the original basin analog identification method.

For the specific comparison on each parameter, the method differentiated the quantitative parameters from the other parameters. For the nonquantitative parameters, it assigned a value of 1 if the target basin matched and 0 if it did not match the reference basin. If it matched, then the value 1 was multiplied by the weighting factor. Fig. 2.3 provides an example of the approach to nonquantitative parameter comparison. For the quantitative parameters that could not be described using only 1 or 0 such as basin area, fill thickness, porosity, and permeability, the method established ranges and classes for each parameter: each quantitative parameter was actually divided into two parts that were differentiated by beginning range (indicated by parameter: from) and ending range (indicated by parameter: to). The beginning range and ending range were assigned to the corresponding classes, respectively.

For the quantitative parameters, the method incorporated a secondary weighting factor. This concept is illustrated in Fig. 2.4, where the porosity for a petroleum system of the target basin ranges from 15%, and for a petroleum system of the reference basin, it ranges from 5%. The example includes five pre-assigned porosity classes, c (0%, 5%, 10%, 15%, and 20%). Within those pre–assigned classes, the distance d from 5% to 15% is two classes. Thus, to weight this parameter, the method calculates $c - d/c$ [in this example, (5-2)/5]. This process results in a value of 0.6 for the example in Fig. 2.7. The procedure results in a higher value when the two values are close and a lower value when the two parameters are not close. The next step is multiplying the second weighted factor (0.6) by the main weighting factor of the parameter.

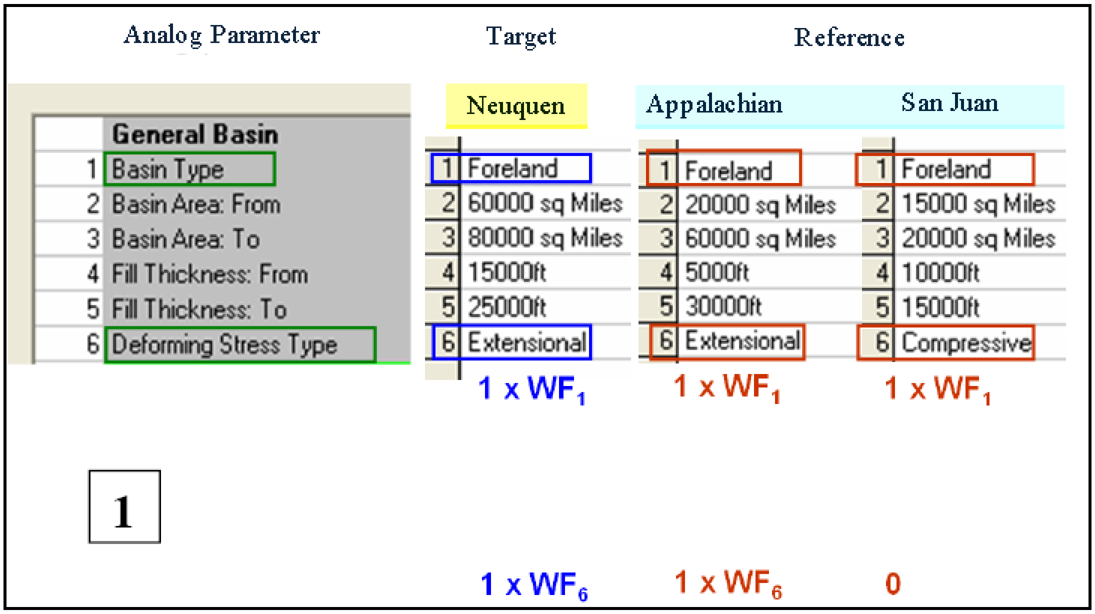


Fig 2.3—Example of non-quantitative parameter comparison (Singh, 2006).

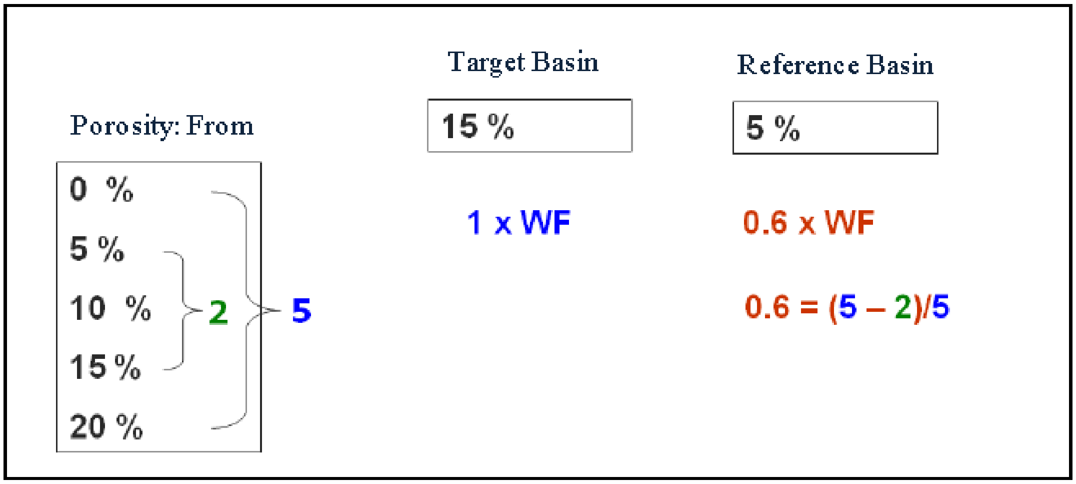


Fig 2.4—Example of quantitative parameter comparison (Singh, 2006).

2.3 Analysis of the Original Basin Analog Method

Although the original basin analog method provides the specific algorithm to identify the analogous reference basins for the target basin, some issues remain.

2.3.1 Incomplete Data

The data used for the basin analog method have been continuously investigated and updated from public literature, but not every petroleum system has complete data for all its parameters. This problem is inherently typical of unconventional basins: many unconventional petroleum systems are newly developed, or the unconventional basins, especially the frontier basins, are exploratory with many plays undeveloped or in the very early development stage, which means reliable characterization data are unavailable. In the original approach, the issue was addressed by simply ignoring the comparison between two petroleum systems when either of them did not have complete data. However, the solution missed comparisons of many petroleum systems even if the blank cells in the data matrix were sparse (see Fig. 2.5): for example, if the petroleum system s_i in the basin has data on all of the parameters except the parameter k, then this petroleum system could not be used for comparison.

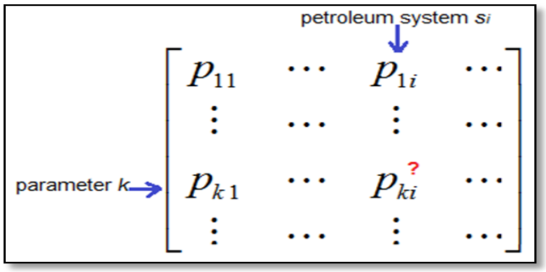


Fig 2.5—Data matrix of a basin.

2.3.2 Comparison Unit

It is difficult to directly compare two basins which are basically in the format of a matrix (Fig. 2.6).

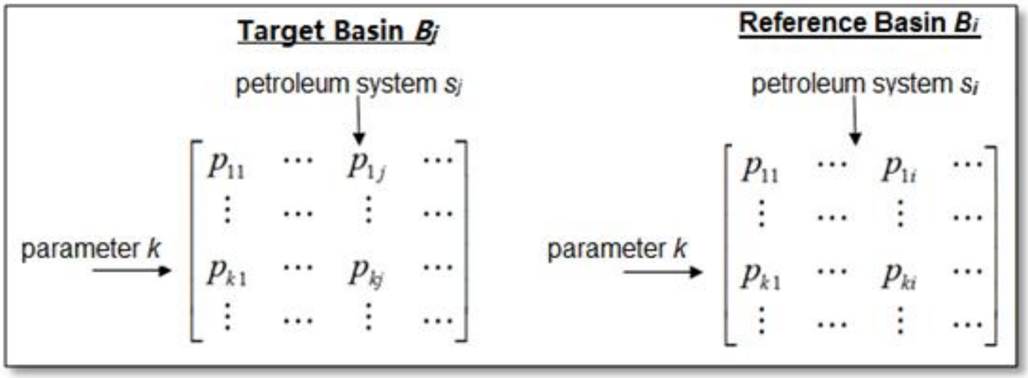


Fig 2.6—An example of basin comparison (Cheng et al., 2011b).

As introduced in Section 2.2.4, the analog result between the reference basin and target basin is based on all of the points at the petroleum system level by means of two methods. However, neither of these two equations can accurately reflect the integral basin characterization. The reasons are discussed as follows

- The first method:

$$A(B_i, B_0) = \mathrm{Avg}[P_{11}, P_{12}, \dots, P_{ij}, \dots, P_{mn}] / \mathrm{Avg}[T_{11}, T_{12}, \dots, T_{ij}, \dots, T_{mn}]$$

Assume that there are two reference basins and one target basin, as shown in Fig. 2.7, and the first reference basin is completely the same as the target basin while the second reference basin is partly analogous to the target basin. Obviously, it is incorrect to conclude that the two reference basins have the same degree of analogy to the target basin.

- The second method: $(B_i, B_0) = \mathrm{Max}\left[\mathrm{P}_{11}, \mathrm{P}_{12}, \ldots, \mathrm{P}_{ij}, \ldots, \mathrm{P}_{\mathrm{mn}}\right]/\mathrm{T}_{ij}$

This method is obviously inaccurate because usually a single petroleum system cannot reflect the entire basin’s characteristics.

2.3.3 Comparison on Quantitative Parameter

Values of quantitative parameters (such as vitrinite reflectance and permeability) are usually continuous, and different petroleum systems can have different value ranges. Although this issue was noticed in the original basin analog method, it only considered the minimal and maximum values of the quantitative parameters.

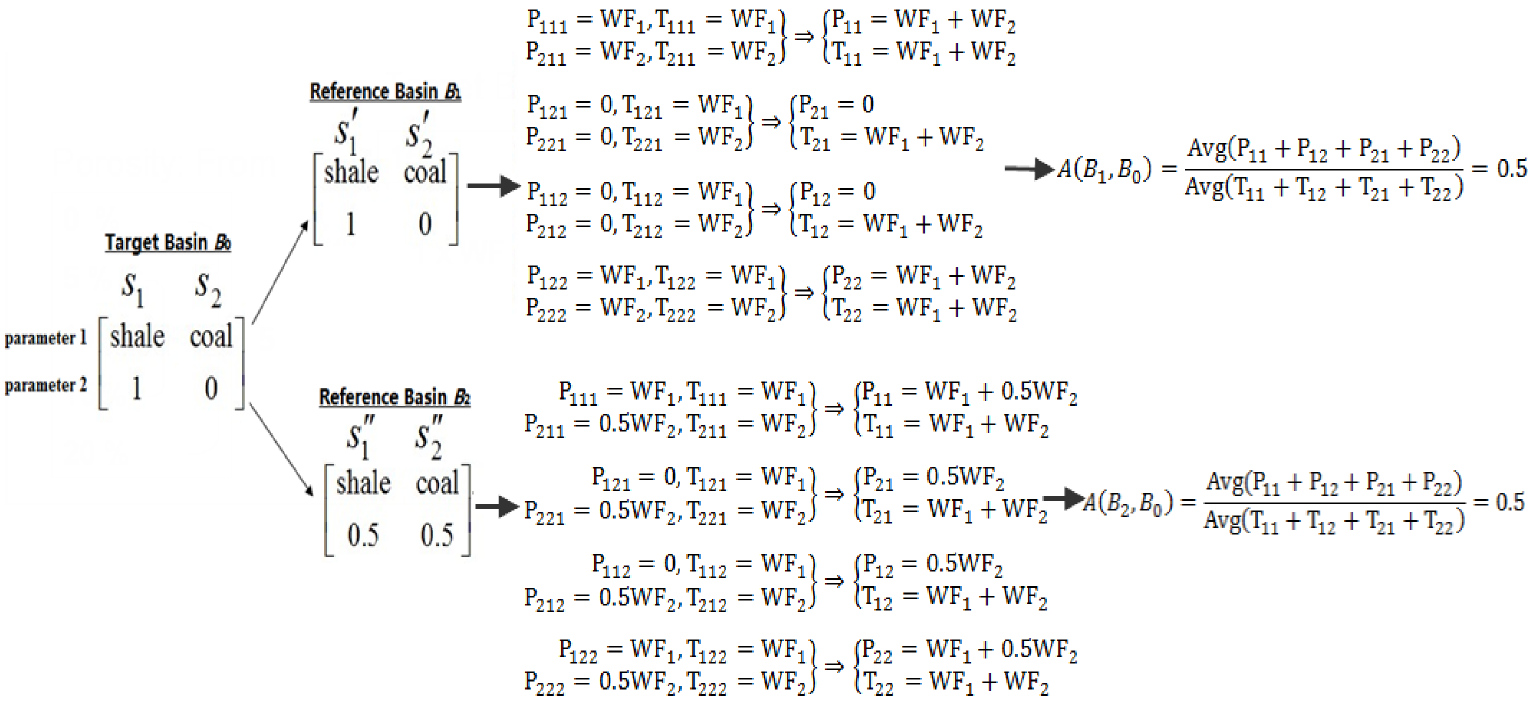


Fig 2.7—Comparison of two basins.

3 THE IMPROVED BASIN ANALOG METHOD

To solve the issues analyzed in Section 2.3, I updated the data for the geology and petroleum systems in the 25 North American reference basins. I then improved the basin analog approach that compares basins in terms of the distribution of each parameter at the basin level, which only solves the problems of incomplete analog and quantitative parameter comparison to achieve more accurate results, but also directly reflects and compares the characteristics of different basins on each parameter.

3.1 Updated Analog Parameters

After checking the data for the 25 North American reference basins, very limited data were observed on some parameters. Therefore, the parameters used for identifying analog basins were updated as in Fig. 3.1.

No.	Category / Parameter
	General Basin
1	Basin Type
2	Basin Area Min (mi2)
3	Basin Area Max (mi2)
4	Fill Thickness Min (ft)
5	Fill Thickness Max (ft)
6	Deforming Stress Type
7	Conventional Gas Cumulative Production (Tcf)
8	Conventional Oil Cumulative Production (Tcf)
	Source Rock
1	Rock Type
2	Age Min
3	Age Max
4	Depth Min (ft)
5	Depth Max (ft)
6	Thickness Min (ft)
7	Thickness Max (ft)
8	Kerogen Type
9	Vitrinite reflectance Min (%)
10	Vitrinite reflectance Max (%)
11	Total Organic Content Min (wt%)
12	Total Organic Content Max (wt%)

No.	Reservoir
1	Lithology
2	Age Min
3	Age Max
4	Depositional System
5	Present Depth Min (ft)
6	Present Depth Max (ft)
7	Gross Thickness Min (ft)
8	Gross Thickness Max (ft)
9	Net Thickness Min (ft)
10	Net Thickness Max (ft)
11	Pressure Min (psi)
12	Pressure Max (psi)
13	Pressure Regime (O,N,U)
14	Porosity Min (%)
15	Porosity Max (%)
16	Permeability Min (mD)
17	Permeability Max (mD)
18	Water Saturation Min (%)
19	Water Saturation Max (%)
20	Migration Distance Min (ft or mi)
21	Migration Distance Max (ft or mi)
22	Migration Direction (Vert., Hor.)
23	Seals
24	Traps Type
25	Fluid Type
26	Oil API Min (deg)
27	Oil API Max (deg)

No.	Reservoir (cont.)
28	Natural Fractures (Y,N)
29	Fracture type
30	Min Temperature (°F)
31	Max Temperature (°F)
32	Geothermal Gradient (°F/100ft)
33	Gas Gravity Min
34	Gas Gravity Max

BASIN Parameters

[54]

Fig. 3.1—54 BASIN geologic and petroleum system parameters (Holditch, 2010).

3.2 Reference Basins

The reference basins are the same 25 North American basins in Table 2.3.

3.3 Updated Geology and Petroleum Systems Data

With the significant progress in exploration and development progress of the North American UGR basins, more literature is continually published for characterizing the unconventional reservoirs in the reference basins, and data have been continuously searched into the database (Fig. 3.2).

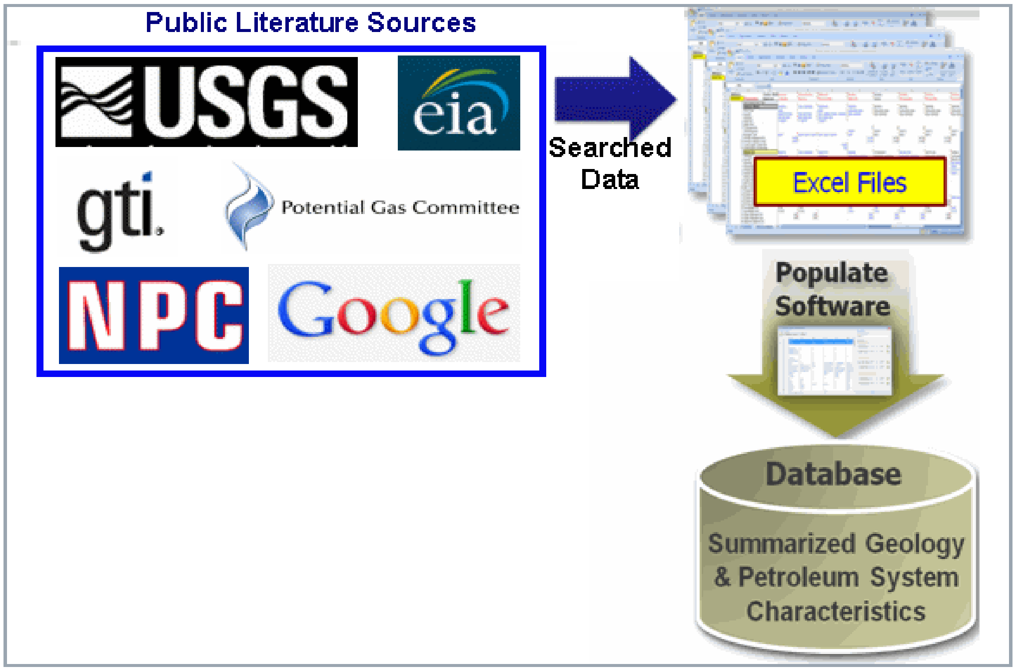


Fig. 3.2—Continuous quality improvement of system database.

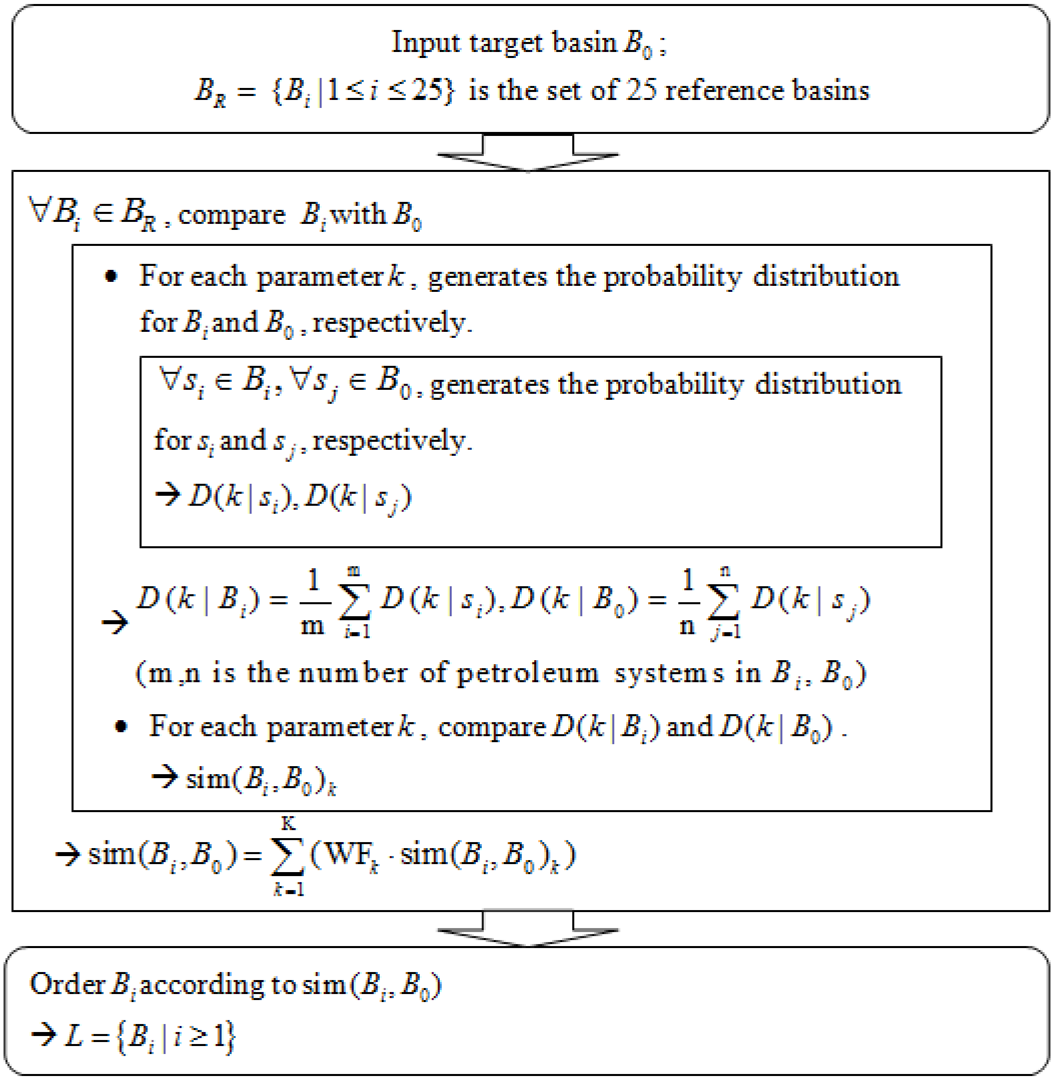
Out of consideration for convenience and quality control in the data input, the searched data are stored in spreadsheets. Then I developed the algorithm to load these data into the database. Techniques used for the software development will be described in Chapter 4.

3.4 Improved Basin Analog Identification Method

While the analog parameters and data were being updated, the issues of the original basin analog method had still not been solved. Therefore, I improved the basin analog identification method to the problems of incomplete data, unequal comparison units, and comparison of widely varying quantitative parameters.

Fig. 3.3 illustrates the process of the improved basin analog identification method. After the data are input for the target basin, we compare each of the reference basins with the target basin. First, the system integrates the probability distributions for all the petroleum systems of a reference and a target basin. Then it generates the basin-level probability distributions for each parameter for the reference $D(k|B_i)$ and target basins$D(k|B_0)$. Next, it compares the probability distributions for the two basins to quantify their similarity on each parameter [$\text{sim}(B_i,B_0)_k$]. Finally, it calculates the similarity between the two basins [$\text{sim}(B_i,B_0)_k$] by multiplying the parameter similarities by their individual weighting factors and summing the products.

In the improved method, the parameter's probability distribution is an important concept that is used to indicate the frequency that each possible value or range of the parameter appears. Before the discussion about my approaches to generating and comparing the probability distributions, let us differentiate two types of parameters.



Input target basin B_0;

$B_R = \{B_i \mid 1 \le i \le 25\}$ is the set of 25 reference basins

$\forall B_i \in B_R$, compare B_i with B_0

- For each parameter k, generates the probability distribution for B_i and B_0, respectively.

$\forall s_i \in B_i, \forall s_j \in B_0$, generates the probability distribution for s_i and s_j, respectively.

$\rightarrow D(k \mid s_i), D(k \mid s_j)$

$$\rightarrow D(k \mid B_i) = \frac{1}{\mathrm{m}} \sum_{i=1}^{\mathrm{m}} D(k \mid s_i), D(k \mid B_0) = \frac{1}{\mathrm{n}} \sum_{j=1}^{\mathrm{n}} D(k \mid s_j)$$

(m ,n is the number of petroleum systems in B_i, B_0)

- For each parameter k, compare $D(k \mid B_i)$ and $D(k \mid B_0)$.

$\rightarrow \mathrm{sim}(B_i, B_0)_k$

$$\rightarrow \mathrm{sim}(B_i, B_0) = \sum_{k=1}^{\mathrm{K}} (\mathrm{WF}_k \cdot \mathrm{sim}(B_i, B_0)_k)$$

Order B_i according to $\mathrm{sim}(B_i, B_0)$

$\rightarrow L = \{B_i \mid i \ge 1\}$

Fig. 3.3—Workflow of the improved basin analog identification method.

Qualitative/Descriptive Parameters. Qualitative/descriptive parameters are those parameters that can be observed but not measured, such as lithology. Because we cannot apply secondary weighting to qualitative/descriptive parameters, they are assigned "False" for the "Second WF" (Table 2.1). A petroleum system usually just has a single value on a qualitative parameter.

Quantitative/Numeric Parameters. Quantitative/numeric parameters can be measured with numbers, and the comparisons are more complex. Parameters of this type are indicated by the value of “True” for “Second WF” (such as basin area, fill thickness, and vitrinite reflectance) in Table 2.1. Commonly, a petroleum system has a range of values for a quantitative parameter.

Therefore, to process the two different types of parameters, a discrete probability distribution is calculated for the qualitative parameter and a continuous probability distribution is calculated for the quantitative parameter. To generate the probability distribution at the petroleum system level, the rule is simplified as follows:

- $D(k|s_i) = D(k = x|s_i) = 1$, where x is the value of s_i on parameter k

  (parameter k is qualitative)
- $D(k|s_i) = D(x_{\text{min}} \leq k \leq x_{\text{max}}|s_i) = 1$

  $D(k|s_i) = D(x_{min} \leq k \leq x_{max}|s_i) = 1$, where $[x_{\text{min}}, x_{\text{max}}]$ is the range of s_i on parameter k

  (parameter k is quantitative)

Fig. 3.4 provides examples of using this rule to generate a parameter’s probability distribution for any petroleum system. After the distribution is generated for every petroleum system in a basin, all of these distributions are accumulated for the basin-leveled probability distribution

- $D(k|B_i) = D(k = x|B_i) = \frac{1}{m}\sum_{i=1}^{m} D(k = x|s_i)$, where m is the number of petroleum systems in B_i (if parameter k is qualitative).

- $D(k|B_i) = D(a \leq k \leq b|B_i)=\sum_{i=1}^{m}(D(a \leq k \leq b|s_i) \cdot D(s_i|B_i))$

  $= \sum_{i=1}^{m}(D(a \leq k \leq b|s_i) \cdot \frac{1}{m})= \frac{1}{m}\sum_{i=1}^{m} D(a \leq k \leq b|s_i)$, and

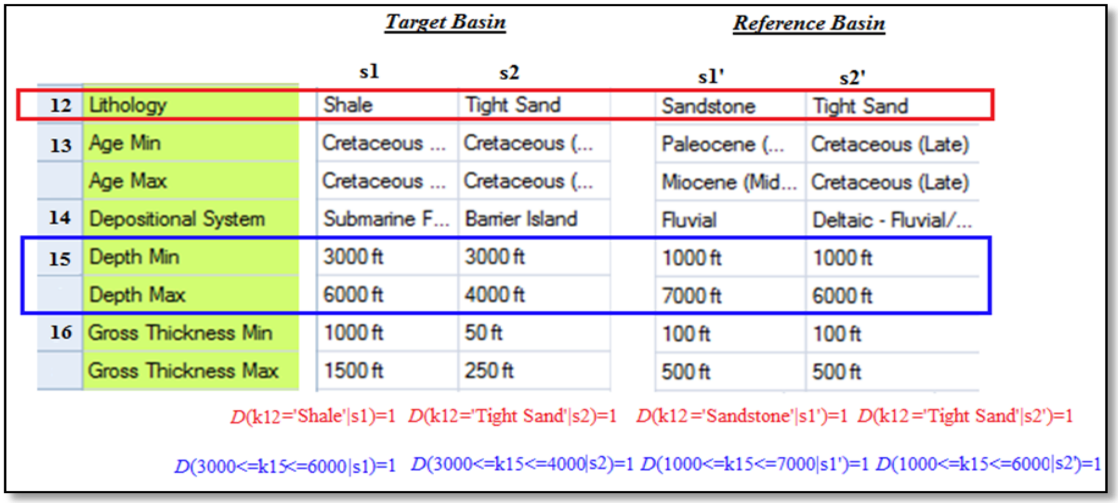
  $= D(a \leq k \leq b|s_i)$

  $= D(a \leq k \leq b|x_{min} \leq k \leq x_{max} D(a \leq k \leq b|x_{\min} \leq k \leq x_{\max})$

  $\cdot D(x_{\min} \leq k \leq x_{\max}|s_i)$

  $= \frac{b-a}{x_{max}-x_{min}}(\frac{b-a}{x_{\max}-x_{\min}}) \cdot D(x_{\min} \leq k \leq x_{\max}|s_i)$, where $[a, b]$ is a class of the values of parameter k and m is the number of petroleum systems in B_i (if parameter k quantitative).

Fig. 3.5 and Fig. 3.6 provide examples of using these equations to calculate the basin-level probability distributions of qualitative parameters (such as lithology) and quantitative parameters (such as depth), respectively.

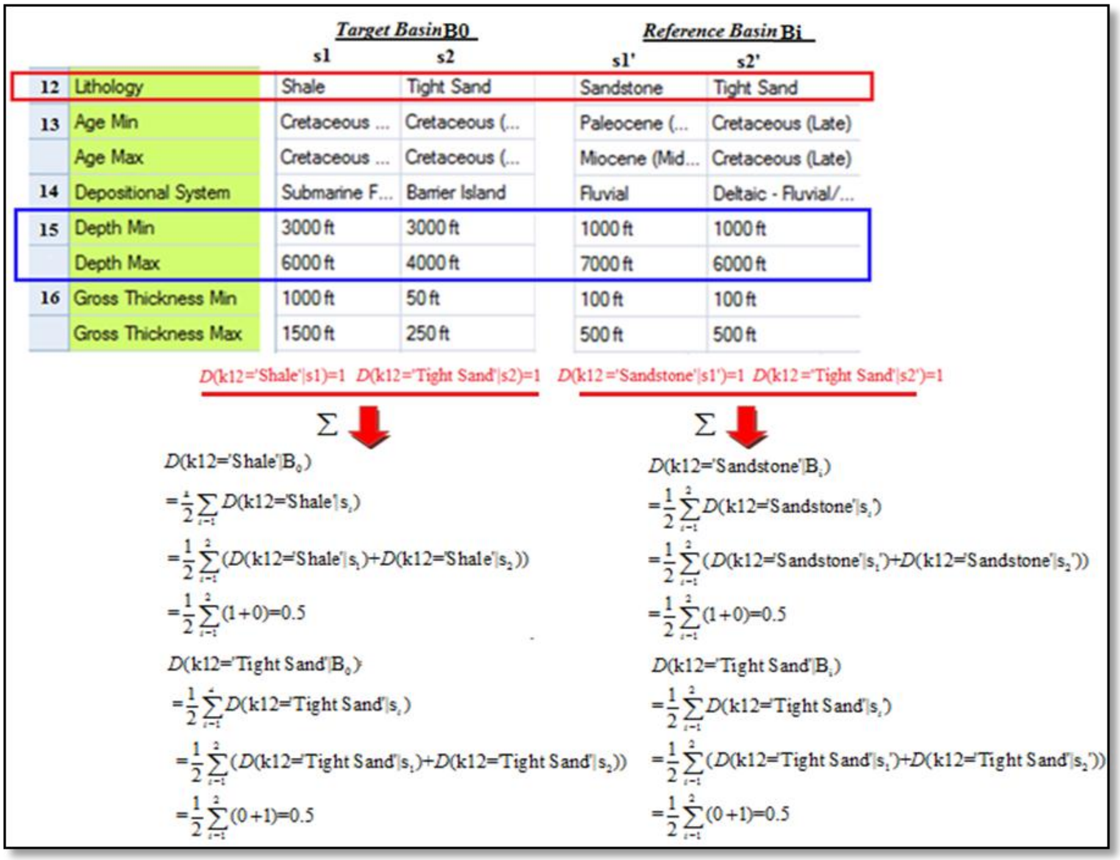


		Target Basin		Reference Basin	
		s1	s2	s1'	s2'
12	Lithology	Shale	Tight Sand	Sandstone	Tight Sand
13	Age Min	Cretaceous ...	Cretaceous (...	Paleocene (...	Cretaceous (Late)
	Age Max	Cretaceous ...	Cretaceous (...	Miocene (Mid...	Cretaceous (Late)
14	Depositional System	Submarine F...	Barrier Island	Fluvial	Deltaic - Fluvial/...
15	Depth Min	3000 ft	3000 ft	1000 ft	1000 ft
	Depth Max	6000 ft	4000 ft	7000 ft	6000 ft
16	Gross Thickness Min	1000 ft	50 ft	100 ft	100 ft
	Gross Thickness Max	1500 ft	250 ft	500 ft	500 ft

$D(\text{k12='Shale'}|\text{s1})=1$ $D(\text{k12='Tight Sand'}|\text{s2})=1$ $D(\text{k12='Sandstone'}|\text{s1'})=1$ $D(\text{k12='Tight Sand'}|\text{s2'})=1$

$D(3000<=\text{k15}<=6000|\text{s1})=1$ $D(3000<=\text{k15}<=4000|\text{s2})=1$ $D(1000<=\text{k15}<=7000|\text{s1'})=1$ $D(1000<=\text{k15}<=6000|\text{s2'})=1$

Fig. 3.4—Probability distribution at petroleum system level.



		Target Basin B0		Reference Basin Bi	
		s1	s2	s1'	s2'
12	Lithology	Shale	Tight Sand	Sandstone	Tight Sand
13	Age Min	Cretaceous ...	Cretaceous (...	Paleocene (...	Cretaceous (Late)
	Age Max	Cretaceous ...	Cretaceous (...	Miocene (Mid...	Cretaceous (Late)
14	Depositional System	Submarine F...	Barrier Island	Fluvial	Deltaic - Fluvial/...
15	Depth Min	3000 ft	3000 ft	1000 ft	1000 ft
	Depth Max	6000 ft	4000 ft	7000 ft	6000 ft
16	Gross Thickness Min	1000 ft	50 ft	100 ft	100 ft
	Gross Thickness Max	1500 ft	250 ft	500 ft	500 ft

$D(\text{k12='Shale'}|\text{s1})=1$ $D(\text{k12='Tight Sand'}|\text{s2})=1$ $D(\text{k12='Sandstone'}|\text{s1'})=1$ $D(\text{k12='Tight Sand'}|\text{s2'})=1$

Σ

$$D(\text{k12='Shale'}|\text{B}_0)$$
$$=\frac{1}{2}\sum_{i=1}^{2} D(\text{k12='Shale'}|\text{s}_i)$$
$$=\frac{1}{2}\sum_{i=1}^{2}(D(\text{k12='Shale'}|\text{s}_1)+D(\text{k12='Shale'}|\text{s}_2))$$
$$=\frac{1}{2}\sum_{i=1}^{2}(1+0)=0.5$$

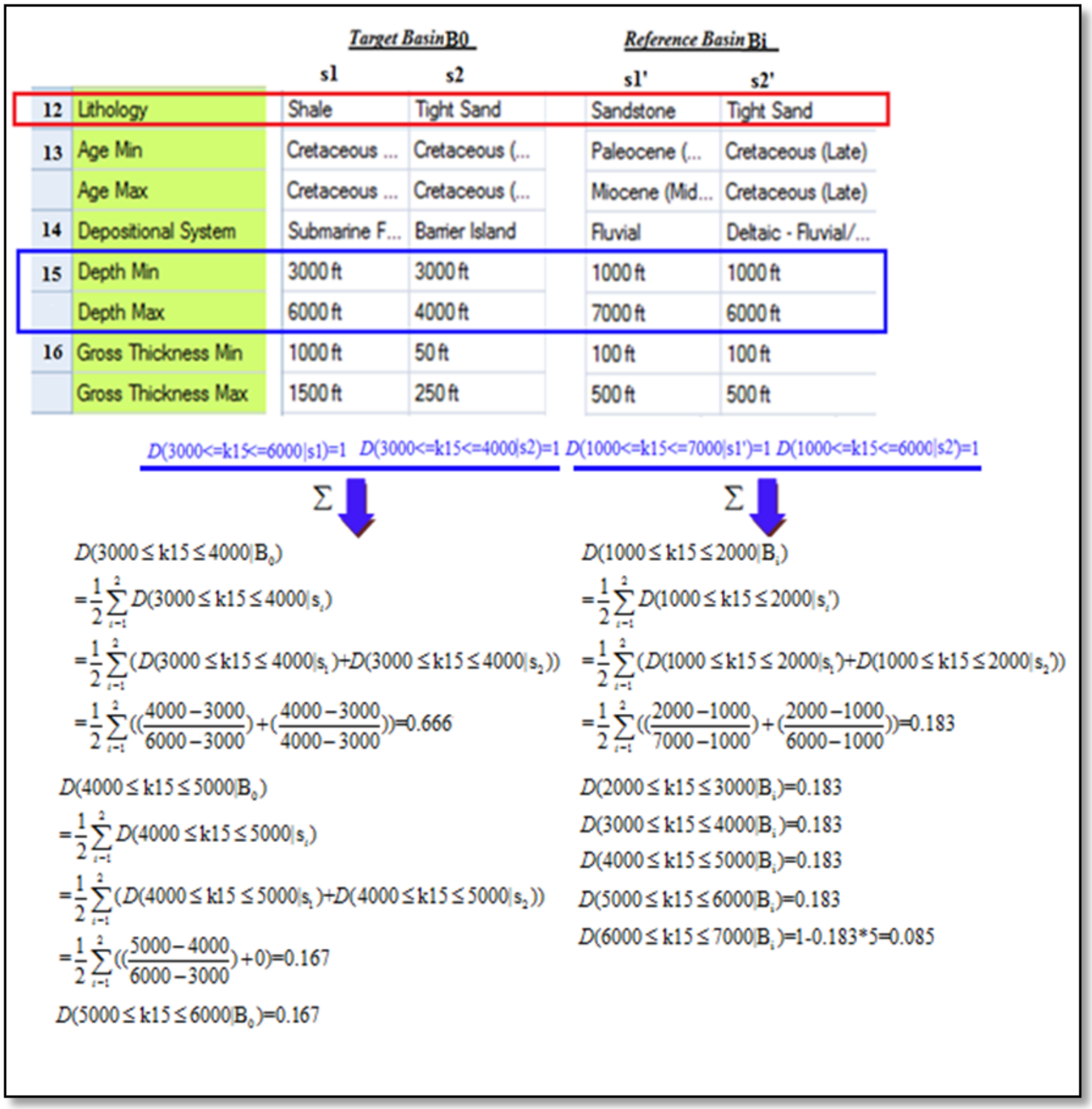
$$D(\text{k12='Tight Sand'}|\text{B}_0)$$
$$=\frac{1}{2}\sum_{i=1}^{2} D(\text{k12='Tight Sand'}|\text{s}_i)$$
$$=\frac{1}{2}\sum_{i=1}^{2}(D(\text{k12='Tight Sand'}|\text{s}_1)+D(\text{k12='Tight Sand'}|\text{s}_2))$$
$$=\frac{1}{2}\sum_{i=1}^{2}(0+1)=0.5$$

Σ

$$D(\text{k12='Sandstone'}|\text{B}_i)$$
$$=\frac{1}{2}\sum_{i=1}^{2} D(\text{k12='Sandstone'}|\text{s}_i')$$
$$=\frac{1}{2}\sum_{i=1}^{2}(D(\text{k12='Sandstone'}|\text{s}_1')+D(\text{k12='Sandstone'}|\text{s}_2'))$$
$$=\frac{1}{2}\sum_{i=1}^{2}(1+0)=0.5$$

$$D(\text{k12='Tight Sand'}|\text{B}_i)$$
$$=\frac{1}{2}\sum_{i=1}^{2} D(\text{k12='Tight Sand'}|\text{s}_i')$$
$$=\frac{1}{2}\sum_{i=1}^{2}(D(\text{k12='Tight Sand'}|\text{s}_1')+D(\text{k12='Tight Sand'}|\text{s}_2'))$$
$$=\frac{1}{2}\sum_{i=1}^{2}(0+1)=0.5$$

Fig. 3.5—Example of generating probability distribution of qualitative parameter.



		Target Basin B0		Reference Basin Bi	
		s1	s2	s1'	s2'
12	Lithology	Shale	Tight Sand	Sandstone	Tight Sand
13	Age Min	Cretaceous ...	Cretaceous (...	Paleocene (...	Cretaceous (Late)
	Age Max	Cretaceous ...	Cretaceous (...	Miocene (Mid...	Cretaceous (Late)
14	Depositional System	Submarine F...	Barrier Island	Fluvial	Deltaic - Fluvial/...
15	Depth Min	3000 ft	3000 ft	1000 ft	1000 ft
	Depth Max	6000 ft	4000 ft	7000 ft	6000 ft
16	Gross Thickness Min	1000 ft	50 ft	100 ft	100 ft
	Gross Thickness Max	1500 ft	250 ft	500 ft	500 ft

$D(3000<=k15<=6000|s1)=1$ $D(3000<=k15<=4000|s2)=1$ $D(1000<=k15<=7000|s1')=1$ $D(1000<=k15<=6000|s2')=1$

Σ

$$D(3000 \le k15 \le 4000 | B_0)$$
$$= \frac{1}{2}\sum_{i=1}^{2} D(3000 \le k15 \le 4000 | s_i)$$
$$= \frac{1}{2}\sum_{i=1}^{2} (D(3000 \le k15 \le 4000 | s_1) + D(3000 \le k15 \le 4000 | s_2))$$
$$= \frac{1}{2}\sum_{i=1}^{2} ((\frac{4000-3000}{6000-3000}) + (\frac{4000-3000}{4000-3000})) = 0.666$$

$$D(4000 \le k15 \le 5000 | B_0)$$
$$= \frac{1}{2}\sum_{i=1}^{2} D(4000 \le k15 \le 5000 | s_i)$$
$$= \frac{1}{2}\sum_{i=1}^{2} (D(4000 \le k15 \le 5000 | s_1) + D(4000 \le k15 \le 5000 | s_2))$$
$$= \frac{1}{2}\sum_{i=1}^{2} ((\frac{5000-4000}{6000-3000}) + 0) = 0.167$$

$$D(5000 \le k15 \le 6000 | B_0) = 0.167$$

Σ

$$D(1000 \le k15 \le 2000 | B_i)$$
$$= \frac{1}{2}\sum_{i=1}^{2} D(1000 \le k15 \le 2000 | s_i')$$
$$= \frac{1}{2}\sum_{i=1}^{2} (D(1000 \le k15 \le 2000 | s_1') + D(1000 \le k15 \le 2000 | s_2'))$$
$$= \frac{1}{2}\sum_{i=1}^{2} ((\frac{2000-1000}{7000-1000}) + (\frac{2000-1000}{6000-1000})) = 0.183$$

$$D(2000 \le k15 \le 3000 | B_i) = 0.183$$
$$D(3000 \le k15 \le 4000 | B_i) = 0.183$$
$$D(4000 \le k15 \le 5000 | B_i) = 0.183$$
$$D(5000 \le k15 \le 6000 | B_i) = 0.183$$
$$D(6000 \le k15 \le 7000 | B_i) = 1 - 0.183*5 = 0.085$$

Fig. 3.6—Example of generating probability distribution of quantitative parameter.

To compare the distribution of a parameter in a reference basin [$D(k|B_i)$] against the distribution of the same parameter in the target basin [$D(k|B_0)$], I used the following method:

- $\text{sim}(B_i, B_0)_k = \sum \min\ [D(k = x|B_i), D(k = x|B_0)]$, where x is a value of parameter k in B_0 (if parameter k is qualitative).
- $\text{Sim}(B_i, B_0)_k = \sum \min[D(a \leq k \leq b|B_i), D(a \leq k \leq b|B_0)] \times [1 -$

  $\sum D(a' \leq k \leq b'|B_i)]$
  $\text{sim}(B_i, B_0)_k = \sum \min[D(a \leq k \leq b|B_i), D(a \leq k \leq b|B_0)] \times \sum[1 -$
  $D(a' \leq k \leq b'|B_i)]$, where $[a, b]$ is any class belonging to the intersection of the range of parameter k in B_0 and the range of parameter k in B_i, and $[a', b']$ is any class belonging to the range of parameter k in B_i but not the range of parameter k in B_0 (if parameter k is quantitative)

For example, in Fig. 3.5 the similarity between the distribution of lithology in the target basin and the distribution of lithology in the reference basin is

$$\text{sim}(B_i, B_0)_{\text{k12}} = \sum \min\ [D(\text{k12} = x|B_i), D(\text{k12} = x|B_0)]$$

$$= \min\ [D(\text{k12} = \text{'Shale'}|B_i), D(\text{k12} = \text{'Shale'}|B_0)]$$

$$+ \min\ [D(\text{k12} =\text{' TightSand'}|B_i), D(\text{k12} =\text{' TightSand'}|B_0)]$$

$$= \min[0{,}0.5] + \min\ [0.5{,}0.5]$$

$$= 0 + 0.5 = 0.5$$

Also in Fig. 3.6, the similarity between the distribution of depth in the target basin and the distribution of depth in the reference basin is

$$\mathrm{sim}(B_i,B_0)_{\mathrm{k15}} = \sum \min\left[D(\mathrm{a} \le \mathrm{k15} \le b|B_i), D(\mathrm{a} \le \mathrm{k15} \le b|B_0)\right]$$

$$\times [1 - \sum D(a' \le k \le b'|B_i)]$$

$$= \{\min\left[D(3000 \le \mathrm{k15} \le 4000|B_i), D(3000 \le \mathrm{k15} \le 4000|B_0)\right]$$

$$+\min\left[D(4000 \le \mathrm{k15} \le 5000|B_i), D(4000 \le \mathrm{k15} \le 5000|B_0)\right]$$

$$+\min\left[D(5000 \le \mathrm{k15} \le 6000|B_i), D(5000 \le \mathrm{k15} \le 6000|B_0)\right]\}$$

$$\times \{1 - [D(1000 \le \mathrm{k15} \le 2000|B_i)$$

$$+D(2000 \le \mathrm{k15} \le 3000|B_i) + D(6000 \le \mathrm{k15} \le 7000|B_i)]\}$$

$$= \{\min[0.183,0.666] + \min\ [0.183,0.167] + \min\ [0.183,0.167]\}$$

$$\times\ \{1 - [0.183 + 0.183 + 0.085]\}$$

$$= 0.275$$

Fig. 3.7 and Fig. 3.8 show examples of the probability distributions of kerogen type and porosity in a graph.

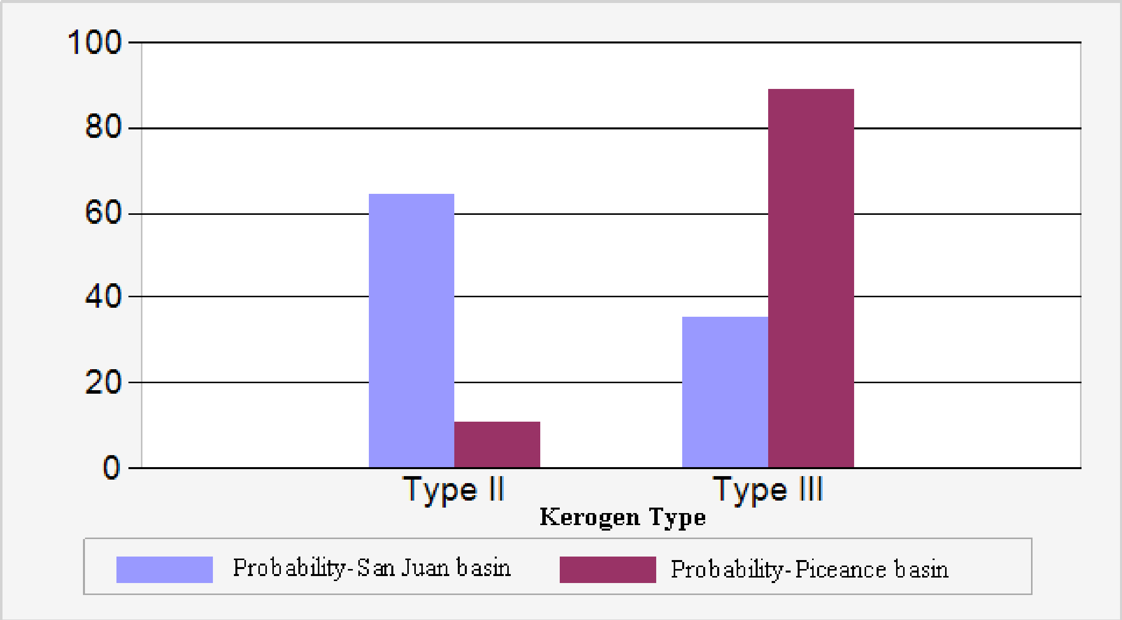


Fig. 3.7—Probability distributions of kerogen type in San Juan and Piceance basin.

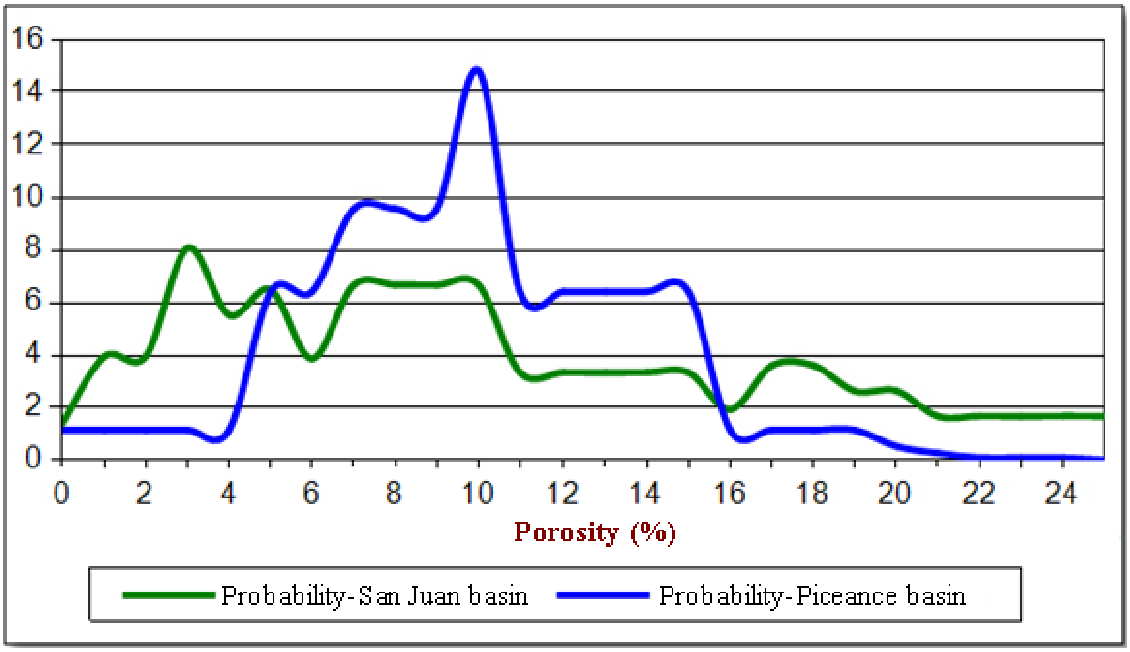


Fig. 3.8—Probability distributions of porosity in San Juan and Piceance basin.

4 DESIGN AND IMPLEMENTATION OF IMPROVED BASIN DATABASE AND SOFTWARE

This chapter discusses the design of BASIN software, including the features, the database, and the specific BASIN components and their functions. Then it describes the development of the improved software that includes hardware, software, and data visualization.

4.1 Design of Improved BASIN Software and Database

The improved BASIN software can be used to consistently and effectively identify analog basins. The software will be able to rank the North American reference basins against a target frontier basin on the basis of analog parameters.

4.1.1 Features of The Improved BASIN Software and Database

The detailed features of BASIN are described as follows.

1. Incorporated with the improved basin analog method, the improved BASIN software provides effective analog results.

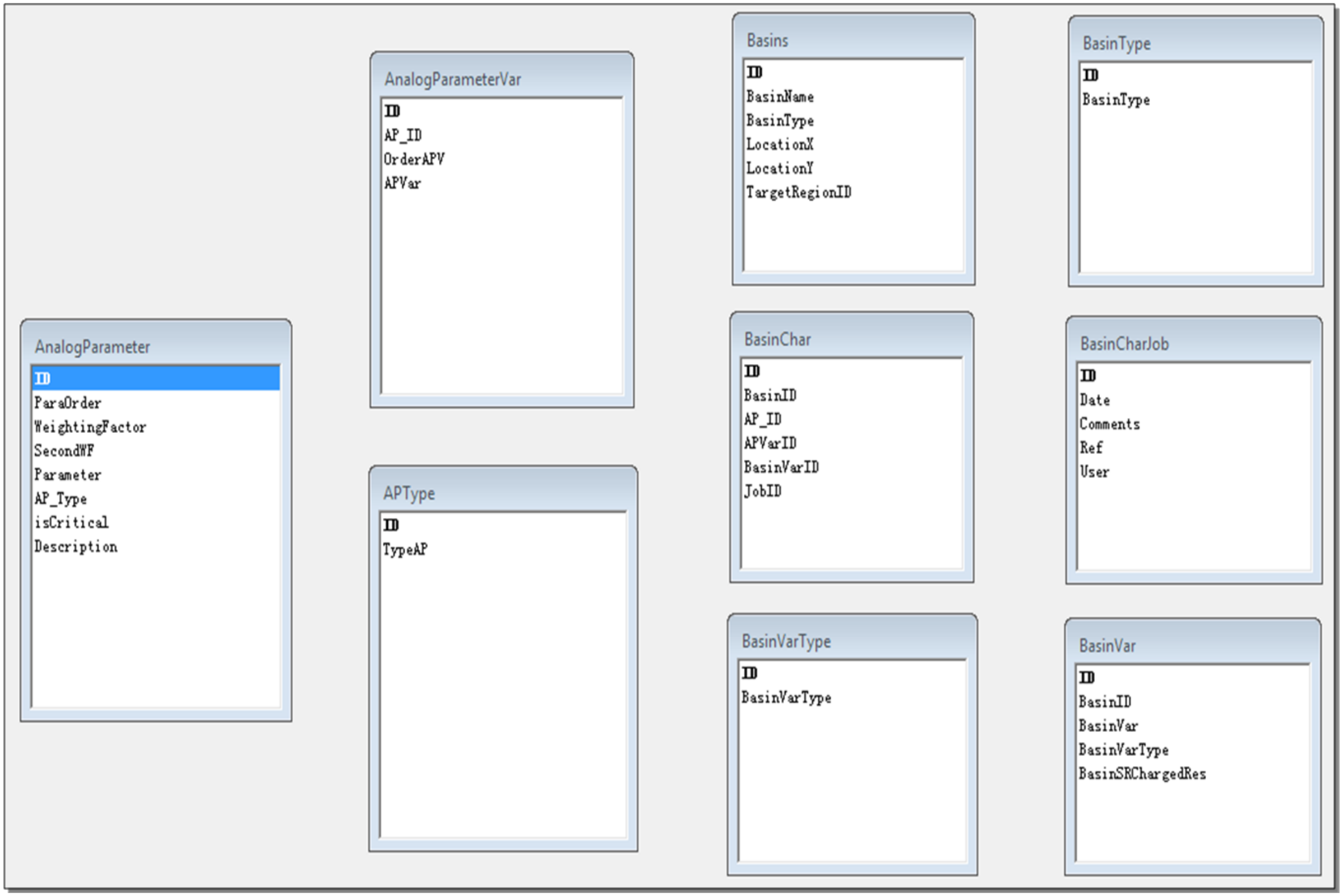
2. The BASIN database provides two approaches to populating the database: individual input from a data management interface and batch transfer from spreadsheets.

3. The BASIN software incorporates a component design for better management of data manipulation, basin analog analysis, and external links.

4. The BASIN software supports data visualization (maps, reports, and graphical distributions) that help organize and display information about various data objects and their complicated relationships.

4.1.2 Design of Database Population

As shown in Fig. 2.2, BASIN and petroleum resource investigation summary and evaluation (PRISE) applications share the same database in the UGA system, and they are combined together for a higher level of resource evaluations, such as the quantified prediction of technically recoverable resources in frontier basins (Cheng et al., 2011a). Therefore, the data used for evaluating the unconventional resources not only contains the properties of geologic and petroleum systems, but also, involves the information required to estimate the potential of different resources in the target basin (such as basin analog results and resource volumes of the reference basins). Fig. 4.1 shows the database structure designed by Cheng (2012). This design uses various keys to link different tables that makes the database more compact and avoids redundant data in the tables.



AnalogParameter
ID
ParaOrder
WeightingFactor
SecondWF
Parameter
AP_Type
isCritical
Description

AnalogParameterVar
ID
AP_ID
OrderAPV
APVar

APType
ID
TypeAP

Basins
ID
BasinName
BasinType
LocationX
LocationY
TargetRegionID

BasinChar
ID
BasinID
AP_ID
APVarID
BasinVarID
JobID

BasinVarType
ID
BasinVarType

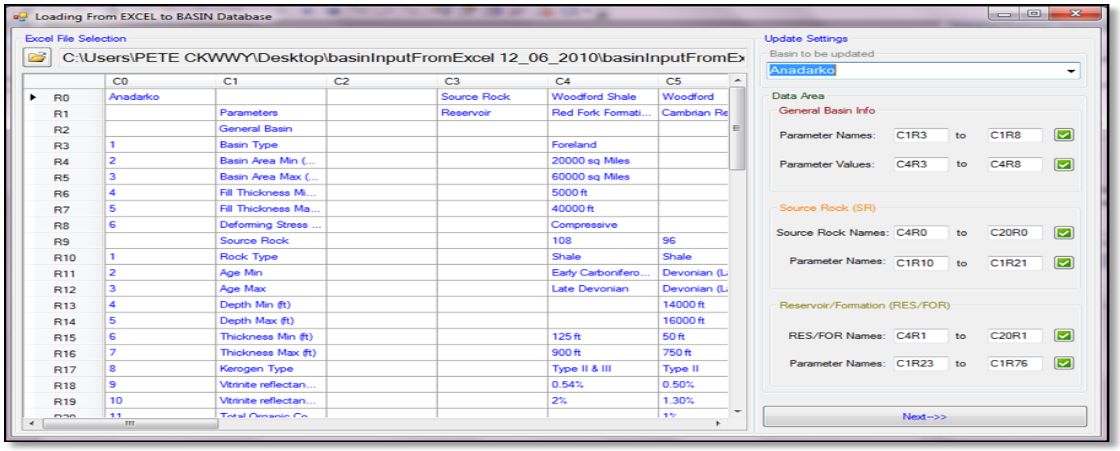
BasinType
ID
BasinType

BasinCharJob
ID
Date
Comments
Ref
User

BasinVar
ID
BasinID
BasinVar
BasinVarType
BasinSRChargedRes

Fig. 4.1—Architecture of the common database (Cheng, 2012).

To load data into the database, users can either input individual data from a data management interface (see section 4.1.3) or batch transfer data from spreadsheets. The first approach is more applicable when the accuracy of the input data needs to be guaranteed by users or there is only a small amount of data to be input, while the second approach is better when the spreadsheets exist. The data transfer software is designed to first find the ranges and values for three categories of parameters (general basin information, source rock, and reservoir/formation) and their values in a specific spreadsheet (Fig. 4.2). Next, it links the parameter names to a parameter defined in the database (Fig. 4.3). Here it applies fuzzy search technique in the text recognition so that it can find name strings that match a database-defined parameter approximately. For example, “Min Age” and “Max Age” of “Reservoir Variables” match the database “Age Min” and “Age Max.” Finally, it assigns the database-defined value/range that best fits the actual value in the spreadsheet to each parameter of every petroleum system (Fig. 4.4).



C:\Users\PETE CKWWY\Desktop\basinInputFromExcel 12_06_2010\basinInputFromEx

	C0	C1	C2	C3	C4	C5
R0	Anadarko			Source Rock	Woodford Shale	Woodford
R1		Parameters		Reservoir	Red Fork Formati...	Cambrian Re
R2		General Basin				
R3	1	Basin Type			Foreland	
R4	2	Basin Area Min (...			20000 sq Miles	
R5	3	Basin Area Max (...			60000 sq Miles	
R6	4	Fill Thickness Mi...			5000 ft	
R7	5	Fill Thickness Ma...			40000 ft	
R8	6	Deforming Stress ...			Compressive	
R9		Source Rock			108	96
R10	1	Rock Type			Shale	Shale
R11	2	Age Min			Early Carbonifero...	Devonian (L
R12	3	Age Max			Late Devonian	Devonian (L
R13	4	Depth Min (ft)				14000 ft
R14	5	Depth Max (ft)				16000 ft
R15	6	Thickness Min (ft)			125 ft	50 ft
R16	7	Thickness Max (ft)			900 ft	750 ft
R17	8	Kerogen Type			Type II & III	Type II
R18	9	Vitrinite reflectan...			0.54%	0.50%
R19	10	Vitrinite reflectan...			2%	1.30%

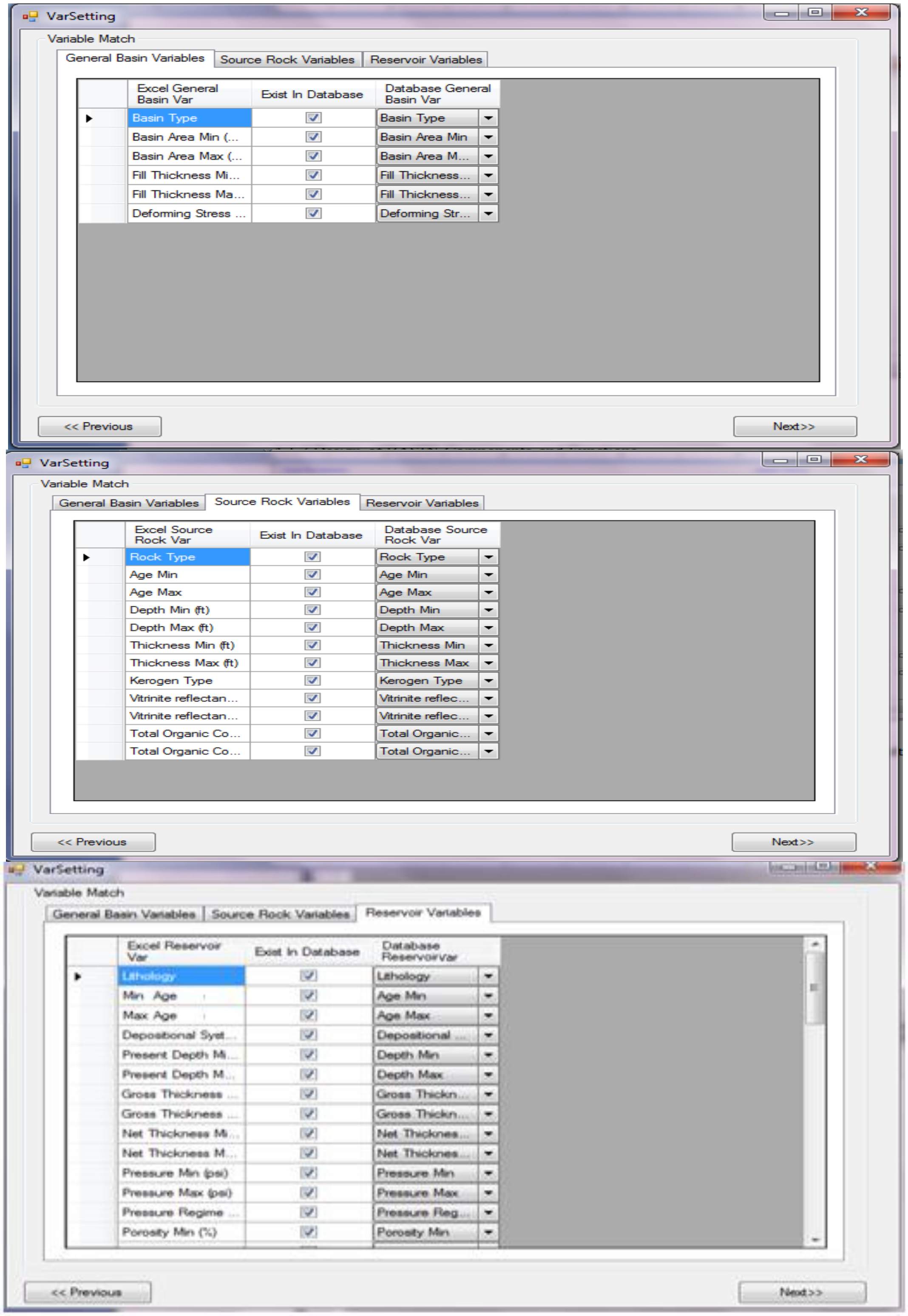
Basin to be updated: Anadarko

General Basin Info
Parameter Names: C1R3 to C1R8 ☑
Parameter Values: C4R3 to C4R8 ☑

Source Rock (SR)
Source Rock Names: C4R0 to C20R0 ☑
Parameter Names: C1R10 to C1R21 ☑

Reservoir/Formation (RES/FOR)
RES/FOR Names: C4R1 to C20R1 ☑
Parameter Names: C1R23 to C1R76 ☑

Fig. 4.2—Range identification of parameters and values from the spreadsheet to the database software.

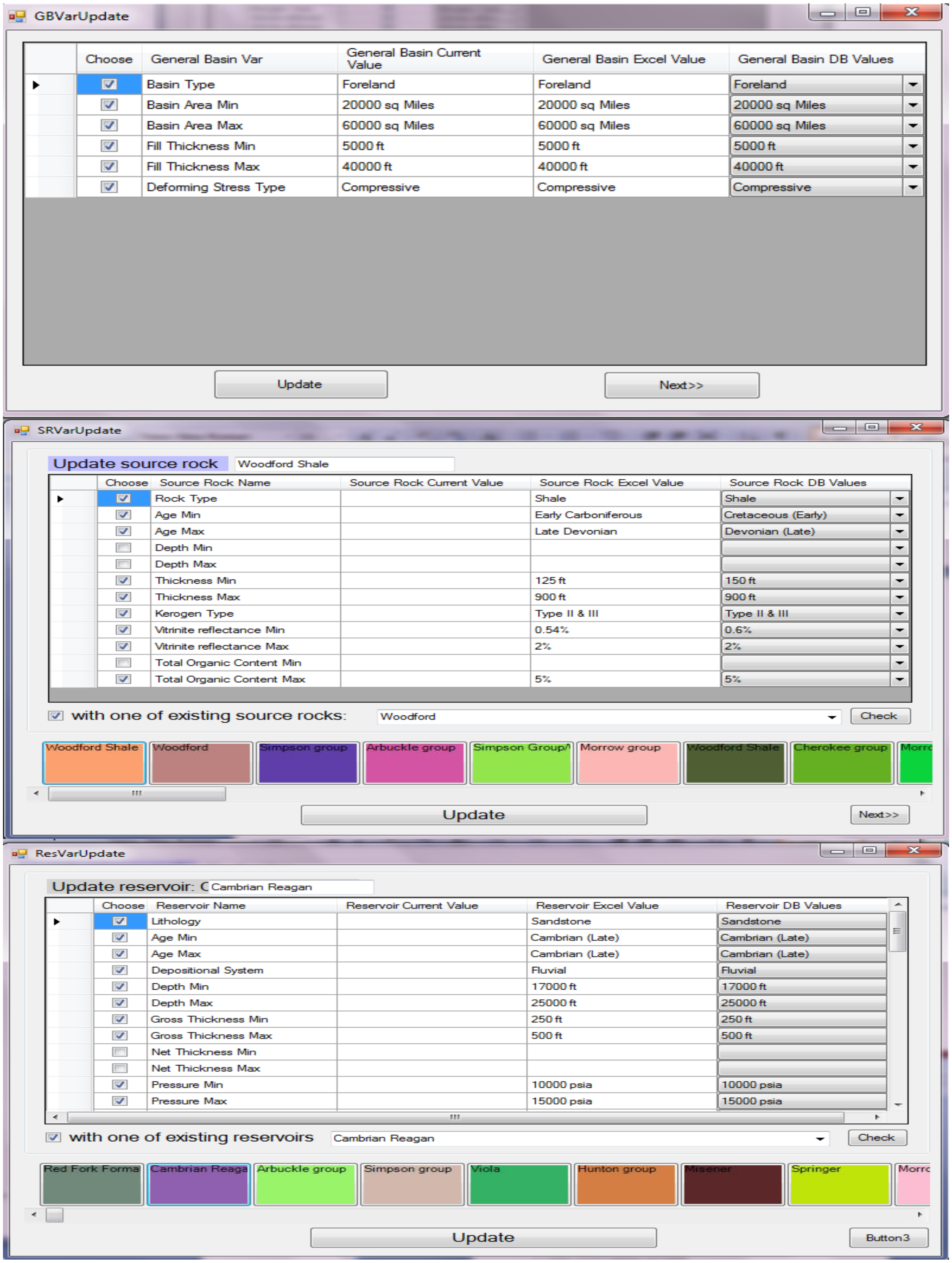


Excel General Basin Var	Exist In Database	Database General Basin Var
Basin Type	☑	Basin Type
Basin Area Min (...	☑	Basin Area Min
Basin Area Max (...	☑	Basin Area M...
Fill Thickness Mi...	☑	Fill Thickness...
Fill Thickness Ma...	☑	Fill Thickness...
Deforming Stress ...	☑	Deforming Str...

Excel Source Rock Var	Exist In Database	Database Source Rock Var
Rock Type	☑	Rock Type
Age Min	☑	Age Min
Age Max	☑	Age Max
Depth Min (ft)	☑	Depth Min
Depth Max (ft)	☑	Depth Max
Thickness Min (ft)	☑	Thickness Min
Thickness Max (ft)	☑	Thickness Max
Kerogen Type	☑	Kerogen Type
Vitrinite reflectan...	☑	Vitrinite reflec...
Vitrinite reflectan...	☑	Vitrinite reflec...
Total Organic Co...	☑	Total Organic...
Total Organic Co...	☑	Total Organic...

Excel Reservoir Var	Exist In Database	Database ReservoirVar
Lithology	☑	Lithology
Min Age	☑	Age Min
Max Age	☑	Age Max
Depositional Syst...	☑	Depositional ...
Present Depth Mi...	☑	Depth Min
Present Depth M...	☑	Depth Max
Gross Thickness ...	☑	Gross Thickn...
Gross Thickness ...	☑	Gross Thickn...
Net Thickness Mi...	☑	Net Thicknes...
Net Thickness M...	☑	Net Thicknes...
Pressure Min (psi)	☑	Pressure Min
Pressure Max (psi)	☑	Pressure Max
Pressure Regime ...	☑	Pressure Reg...
Porosity Min (%)	☑	Porosity Min

Fig. 4.3—Parameter recognition from the spreadsheet to database software.



Choose	General Basin Var	General Basin Current Value	General Basin Excel Value	General Basin DB Values
☑	Basin Type	Foreland	Foreland	Foreland
☑	Basin Area Min	20000 sq Miles	20000 sq Miles	20000 sq Miles
☑	Basin Area Max	60000 sq Miles	60000 sq Miles	60000 sq Miles
☑	Fill Thickness Min	5000 ft	5000 ft	5000 ft
☑	Fill Thickness Max	40000 ft	40000 ft	40000 ft
☑	Deforming Stress Type	Compressive	Compressive	Compressive

Update source rock: Woodford Shale

Choose	Source Rock Name	Source Rock Current Value	Source Rock Excel Value	Source Rock DB Values
☑	Rock Type		Shale	Shale
☑	Age Min		Early Carboniferous	Cretaceous (Early)
☑	Age Max		Late Devonian	Devonian (Late)
☐	Depth Min			
☐	Depth Max			
☑	Thickness Min		125 ft	150 ft
☑	Thickness Max		900 ft	900 ft
☑	Kerogen Type		Type II & III	Type II & III
☑	Vitrinite reflectance Min		0.54%	0.6%
☑	Vitrinite reflectance Max		2%	2%
☐	Total Organic Content Min			
☑	Total Organic Content Max		5%	5%

☑ with one of existing source rocks: Woodford [Check]

Update reservoir: C Cambrian Reagan

Choose	Reservoir Name	Reservoir Current Value	Reservoir Excel Value	Reservoir DB Values
☑	Lithology		Sandstone	Sandstone
☑	Age Min		Cambrian (Late)	Cambrian (Late)
☑	Age Max		Cambrian (Late)	Cambrian (Late)
☑	Depositional System		Fluvial	Fluvial
☑	Depth Min		17000 ft	17000 ft
☑	Depth Max		25000 ft	25000 ft
☑	Gross Thickness Min		250 ft	250 ft
☑	Gross Thickness Max		500 ft	500 ft
☐	Net Thickness Min			
☐	Net Thickness Max			
☑	Pressure Min		10000 psia	10000 psia
☑	Pressure Max		15000 psia	15000 psia

☑ with one of existing reservoirs Cambrian Reagan [Check]

Fig. 4.4—Value matching from the spreadsheet to database software.

4.1.3 Design of BASIN Components and Functions

An important approach in designing the BASIN software is component-based software engineering (CBSE), also known as component-based development (CBD). It emphasizes the separation of concerns in respect to the wide-ranging functionality available throughout a given software system. This practice aims to bring about an equally wide-ranging degree of benefits in both the short term and the long term for the software itself and for organizations that sponsor such software. Based on this concept, the BASIN software is designed to include two main components: database and basin analog.

1. Database component (Cheng et al., 2011c)

I designed an integrated management system so that it updates data from overview to details. In addition, the visualization tool allows users to more easily understand and operate the system. The operations follow the concept of WYSIWYG (what you see is what you get) so that operation effects can be instantly viewed.

Characteristics of the data in the database include

- The data correspond to different levels of resource evaluations.

  Fig. 4.5 shows the relationship between the resource evaluation applications and the data: BASIN and PRISE evaluate data at the basin level for basin analog analysis and basin resource prediction, respectively.

- The data exist in certain scientific relationships.

For the structure of resource evaluation data in Fig. 4.5, the relationships represent certain scientific, context-related meanings. For example, each basin has multiple petroleum systems, and each petroleum system is identified by a reservoir and its source rock. A source rock possibly generates hydrocarbons for multiple reservoirs.

- Updating of the data involves both the properties and relationships.

Because the data may change during continuous resource exploration or other practice, updating operations should include addition, deletion, and modification of the data for the various properties of the objects (indicated by the solid rectangles in the structure of resource evaluation data in Fig. 4.5) as well as the relationships among them.

Fig. 4.6 provides the significant features of the improved data management interface. In the control panel of the database component, functions for updating the different categories of data are divided into four groups (basin, petroleum system, data values, and parameters) of data management, which are generally determined by the data structure. Such division helps users obtain a general idea of the data domain and focus on areas of interest. Icons and/or background pictures are used to provide hints for users.

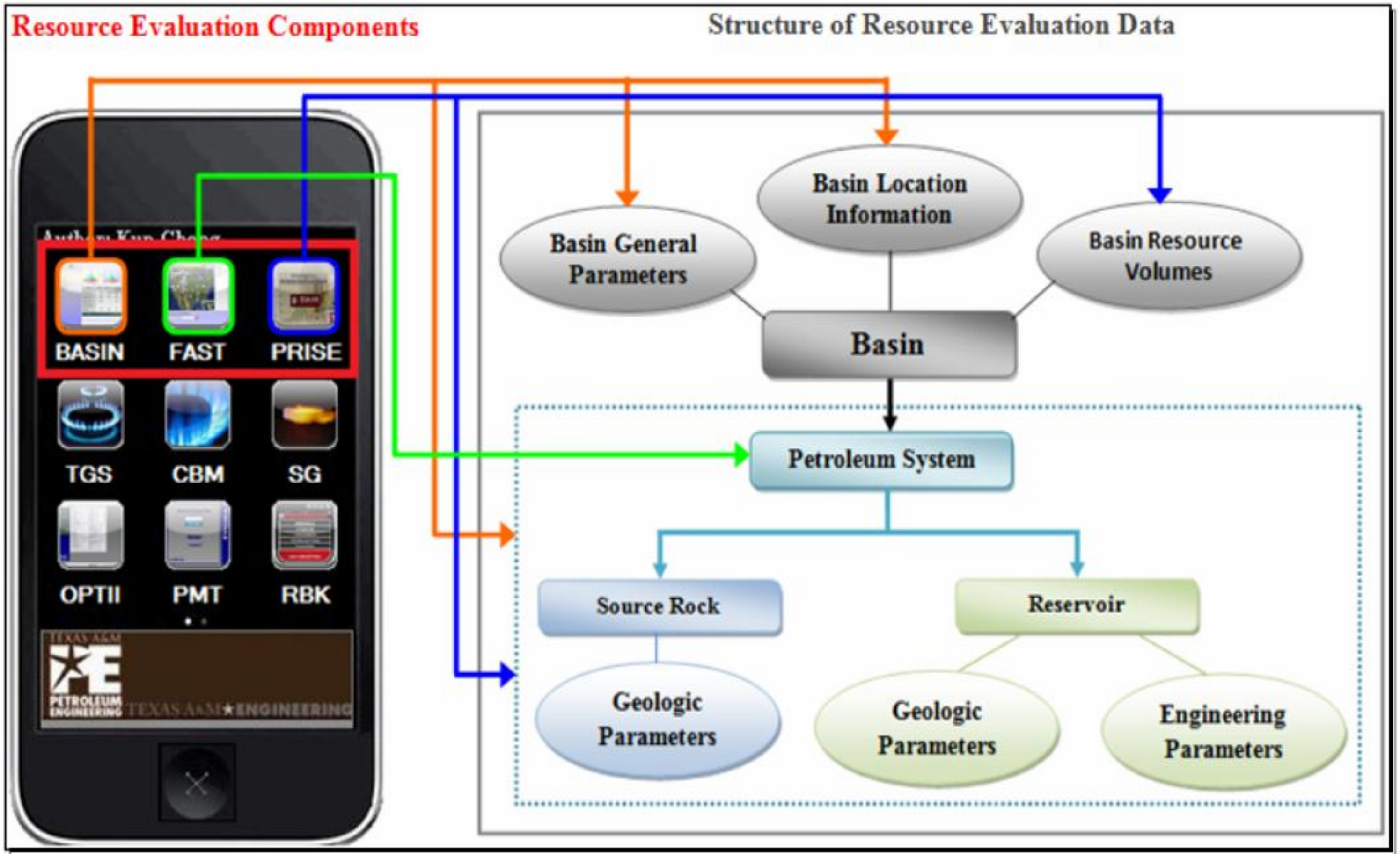


Fig. 4.5—Resource evaluation data and its structure (Cheng et al., 2011c).

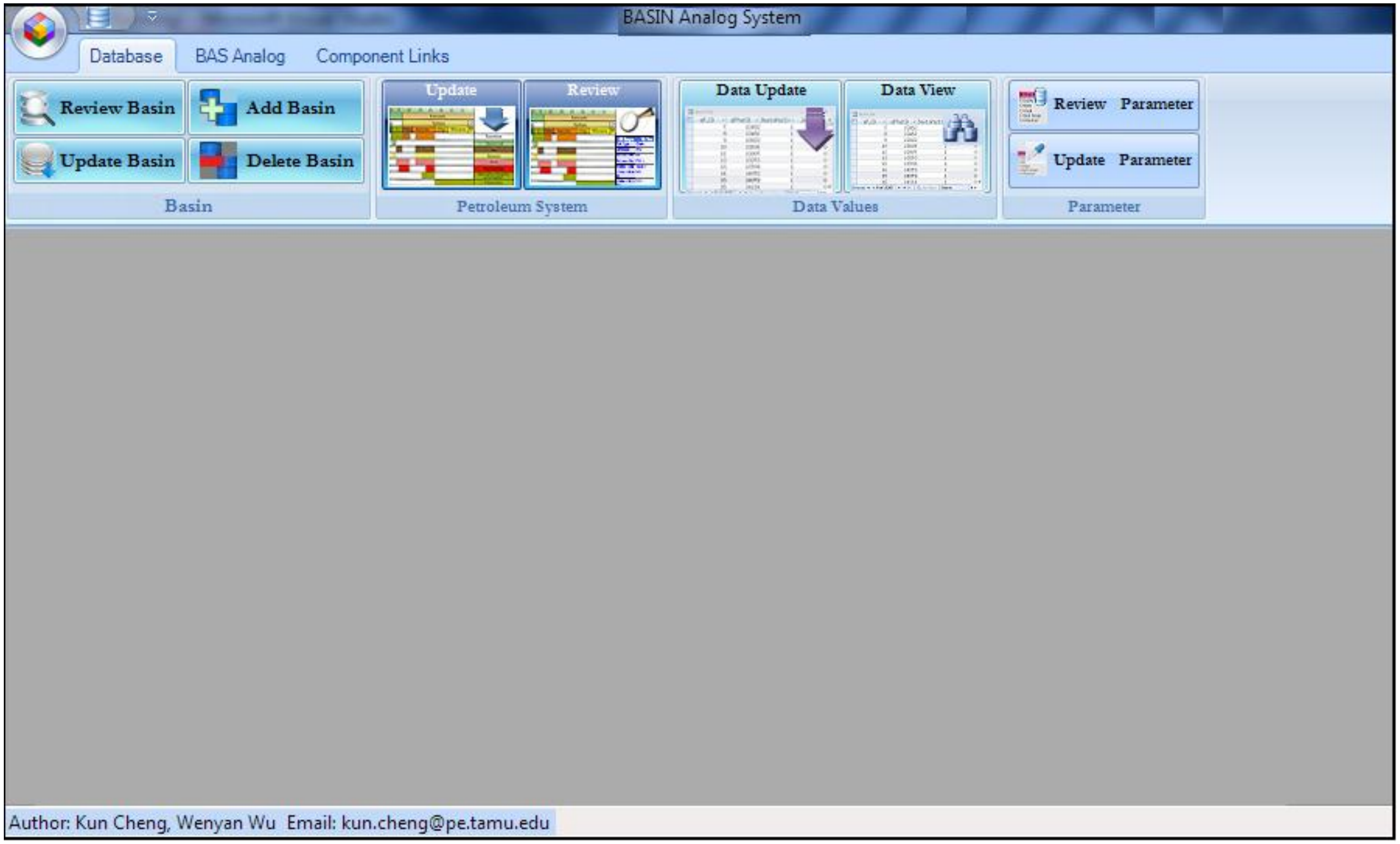
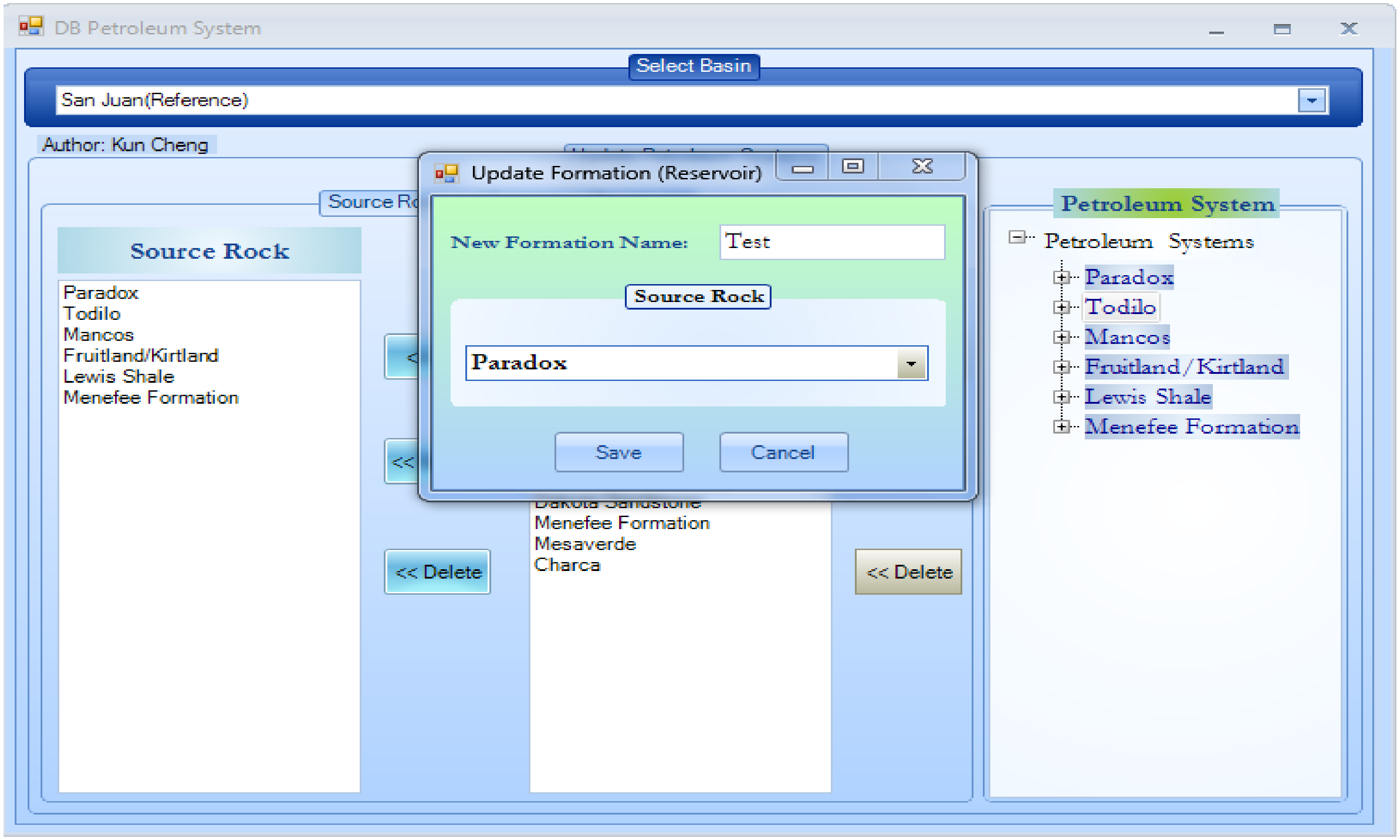


Fig. 4.6—Interface of managing evaluation data (Cheng et al., 2011c).

The “Basin” group is used to update the basin’s basic data and location information in the corresponding regional map. Users can click on a basin in the map, and then the data area will show its information, including name, category (for example, reference basin or target basin), and specific location in the map picture. If the exact location needs modification, the user can simply use the mouse to pick the desired point in the map and relocate it.

The “Petroleum System” group uses a tree tool to visualize the hierarchical relationships among systems. For example, the petroleum systems (the first level) for the selected basin (Fig. 4.6) include 3 source rocks (i.e., the nodes indicated by the blue rectangles) in the second level, and the reservoirs are connected to their corresponding source rocks (the nodes indicated by the green rectangles). The data area provides details when either a source rock or a reservoir node is clicked. Also the updating results can be directly reflected in the tree structure. Fig. 4.7 shows the updated petroleum systems after adding a new reservoir called “Test” where the source rock is “Lewis shale.”


DB Petroleum System

Select Basin: San Juan(Reference)

Author: Kun Cheng

Source Rock
- Paradox
- Todilo
- Mancos
- Fruitland/Kirtland
- Lewis Shale
- Menefee Formation

Update Formation (Reservoir)

New Formation Name: Test

Source Rock: Paradox

- Dakota Sandstone
- Menefee Formation
- Mesaverde
- Charca

Petroleum System
- Petroleum Systems
  - Paradox
  - Todilo
  - Mancos
  - Fruitland/Kirtland
  - Lewis Shale
  - Menefee Formation

Fig. 4.7—An example of managing data petroleum systems.

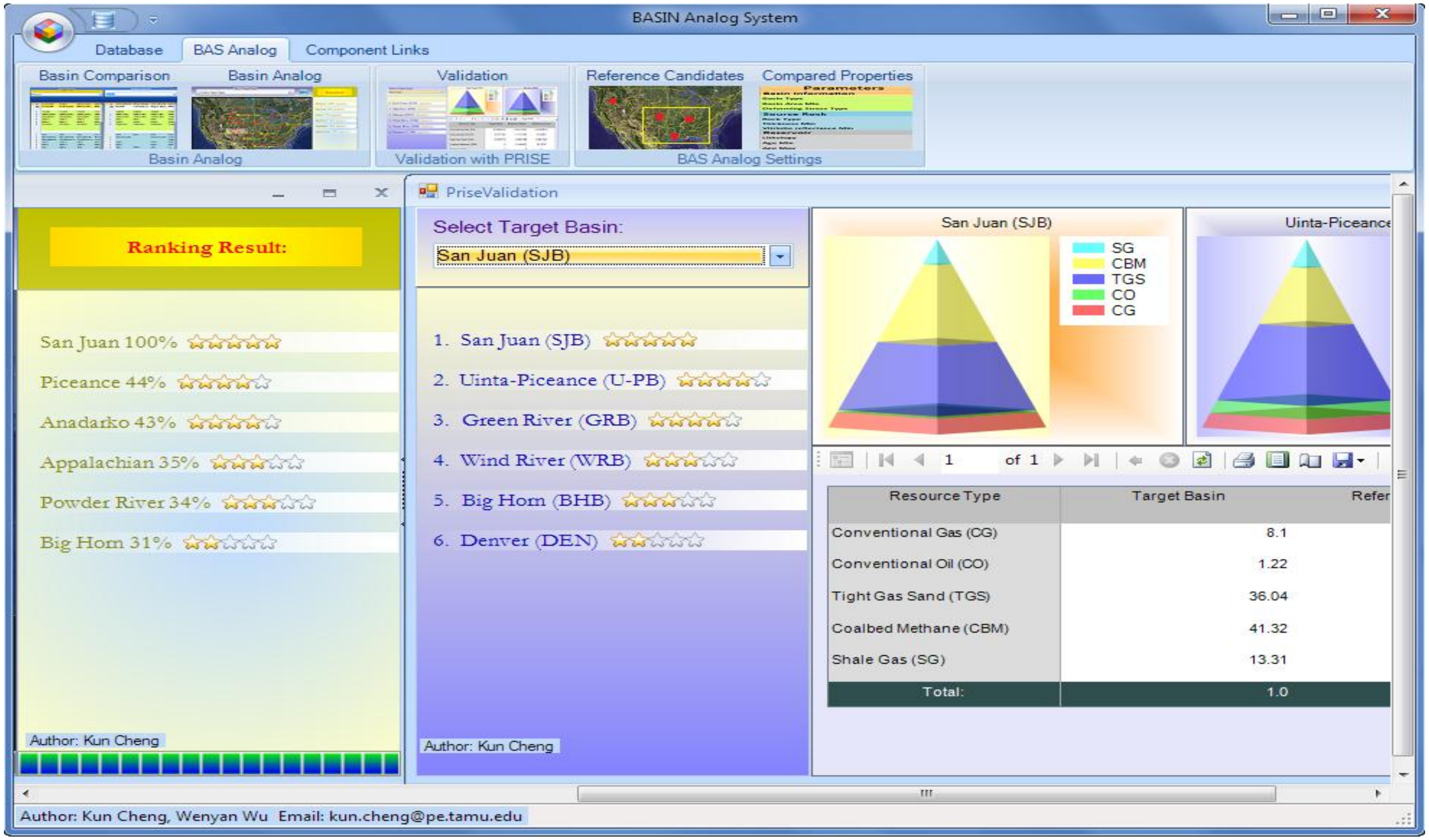
2. Basin analog component

The basin analog component provides multiple choices for conducting basin analog analysis, and its control panel has three groups (Basin Analog, Validation with PRISE, and Basin Analog Settings).

The “Basin Analog” function is used to identify the analogous reference basins for the selected target basin (Fig. 4.8). For the “Basin Comparison” function, users can visually compare the distribution in the target basin and the distribution in the reference basin by just clicking the parameter name (Fig. 4.9).

After running the “Basin Analog” function, validation with PRISE compares the basin analog results from BASIN with the analog results from PRISE (Fig. 4.8).

Users can select which reference basins and parameters will be used for basin analog (Fig. 4.8).



Ranking Result:

San Juan 100%
Piceance 44%
Anadarko 43%
Appalachian 35%
Powder River 34%
Big Horn 31%

Author: Kun Cheng

Select Target Basin:
San Juan (SJB)

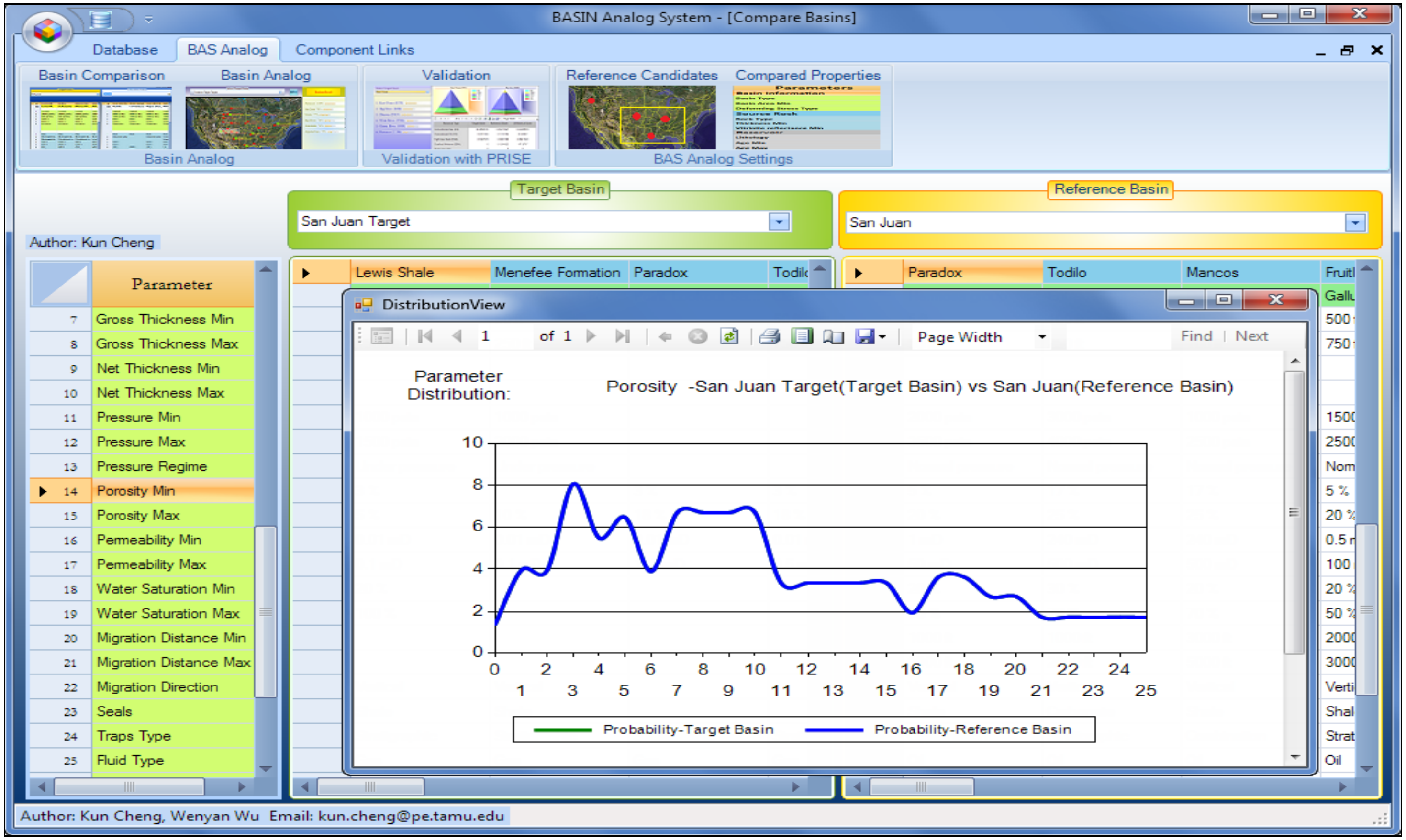
1. San Juan (SJB)
2. Uinta-Piceance (U-PB)
3. Green River (GRB)
4. Wind River (WRB)
5. Big Horn (BHB)
6. Denver (DEN)

Author: Kun Cheng

Resource Type	Target Basin	Refer
Conventional Gas (CG)	8.1	
Conventional Oil (CO)	1.22	
Tight Gas Sand (TGS)	36.04	
Coalbed Methane (CBM)	41.32	
Shale Gas (SG)	13.31	
Total:	1.0	

Author: Kun Cheng, Wenyan Wu Email: kun.cheng@pe.tamu.edu

Fig. 4.8—Interface for conducting basin analog analysis (Cheng et al., 2011c).



Author: Kun Cheng

Target Basin: San Juan Target

Reference Basin: San Juan

	Parameter
7	Gross Thickness Min
8	Gross Thickness Max
9	Net Thickness Min
10	Net Thickness Max
11	Pressure Min
12	Pressure Max
13	Pressure Regime
14	Porosity Min
15	Porosity Max
16	Permeability Min
17	Permeability Max
18	Water Saturation Min
19	Water Saturation Max
20	Migration Distance Min
21	Migration Distance Max
22	Migration Direction
23	Seals
24	Traps Type
25	Fluid Type

Porosity -San Juan Target(Target Basin) vs San Juan(Reference Basin)

Author: Kun Cheng, Wenyan Wu Email: kun.cheng@pe.tamu.edu

Fig. 4.9—An example comparing two basins on a parameter.

4.2 Hardware Development Platform

I used an IBM-compatible laptop as my hardware development platform. The main technical parameters for the laptop are: Intel® Core™ i5-520M CPU (2.40GHz base; 2.93GHz Max Turbo, 3MB Cache), 250GB, 7200RPM Serial ATA 2.5-in hard drive, 4GB DDR3 memory, and Windows 7 Professional 32–English. This configuration is common in current PCs and laptops. We also tested the software on the PCs with Window XP–Professional, where it also runs smoothly.

4.2.1 Software

The software that I used to develop the improved BASIN software is the Microsoft Visual Studio 2005, and the programming language is Visual Basic.NET (VB.NET). Compared to Visual Basic 6.0, which was used in the original BASIN software, VB .NET can be viewed as an evolution of the classic Visual Basic (VB), which is implemented on the .NET Framework. VB .NET has changed significantly in the semantics—from those of an object-based programming language running on a deterministic, reference-counted engine based on COM to a fully object-oriented language backed by the .NET Framework, which consists of a combination of the Common Language Runtime (a virtual machine using generational garbage collection and a just-in-time compilation engine) and a far larger class library.

For this development software, the main features that I used include:

1. Edit and continue;

2. Design-time expression evaluation;
3. My pseudo-namespace (overview, details);
4. Keywords (simplifying the use of objects that require the Dispose pattern to free resources); and
5. Data Source binding, easing database client/server development.

4.2.2 Data Visualization

Visualization is the graphical presentation of information. The main goal of data visualization is to communicate information clearly and effectively through graphical means. To convey ideas effectively, aesthetic form and functionality need to go hand in hand, providing insights into a rather sparse and complex data set by communicating its key aspects in a more intuitive way. An ideal visualization should not merely communicate clearly, but should stimulate viewer engagement and attention (Steele and Illinsky, 2010). Data visualization is closely related to information graphics, information visualization, scientific visualization, and statistical graphics.

In the BASIN software, visualization is generally used in two forms: scientific visualization and information visualization. The scientific visualization includes presentation graphics for models or simulations that are already known. The graphical display could lead to better understandings of the underlying concepts and methods in these models. This is particularly useful for engineers in frontier basins, where experience and practice with unconventional resources may be very limited. The information visualization is defined as the use of computer-supported, interactive, visual representation of abstract data to amplify cognition. The abstract characteristic of the data is what distinguishes information visualization from scientific visualization. Since the data visualization supports interactive manipulation of data items to be observed in compact graphical presentations, it allows users far more comprehension and control (Cheng et al., 2011c).

A typical application of the data visualization technique is to further understand the meanings of the resource triangle concept. We first apply the visualization to the PRISE resource volume data to reflect the distribution of various resources (CG, conventional gas; CO, conventional oil; SG, shale gas; CBM, coalbed methane; and TGS, tight gas sand) for each North American reference basin. For example, in Fig. 4.8 the resource triangles of the San Juan basin and the Uinta-Piceance basin validate the resource triangle concept. The basins are further compared on the basis of their distributions on the resource triangle. Then the comparison results from PRISE resource distribution are compared with the BASIN results. The BASIN results closely match the PRISE results, which suggests that the analogous basins have similar distributions on the resource triangle. Such a relationship is significant for prediction of resource potential in the frontier basin, because we can infer the resource distribution of the frontier basin from its analogous North American reference basins.

5 SOFTWARE AND METHOD VALIDATION

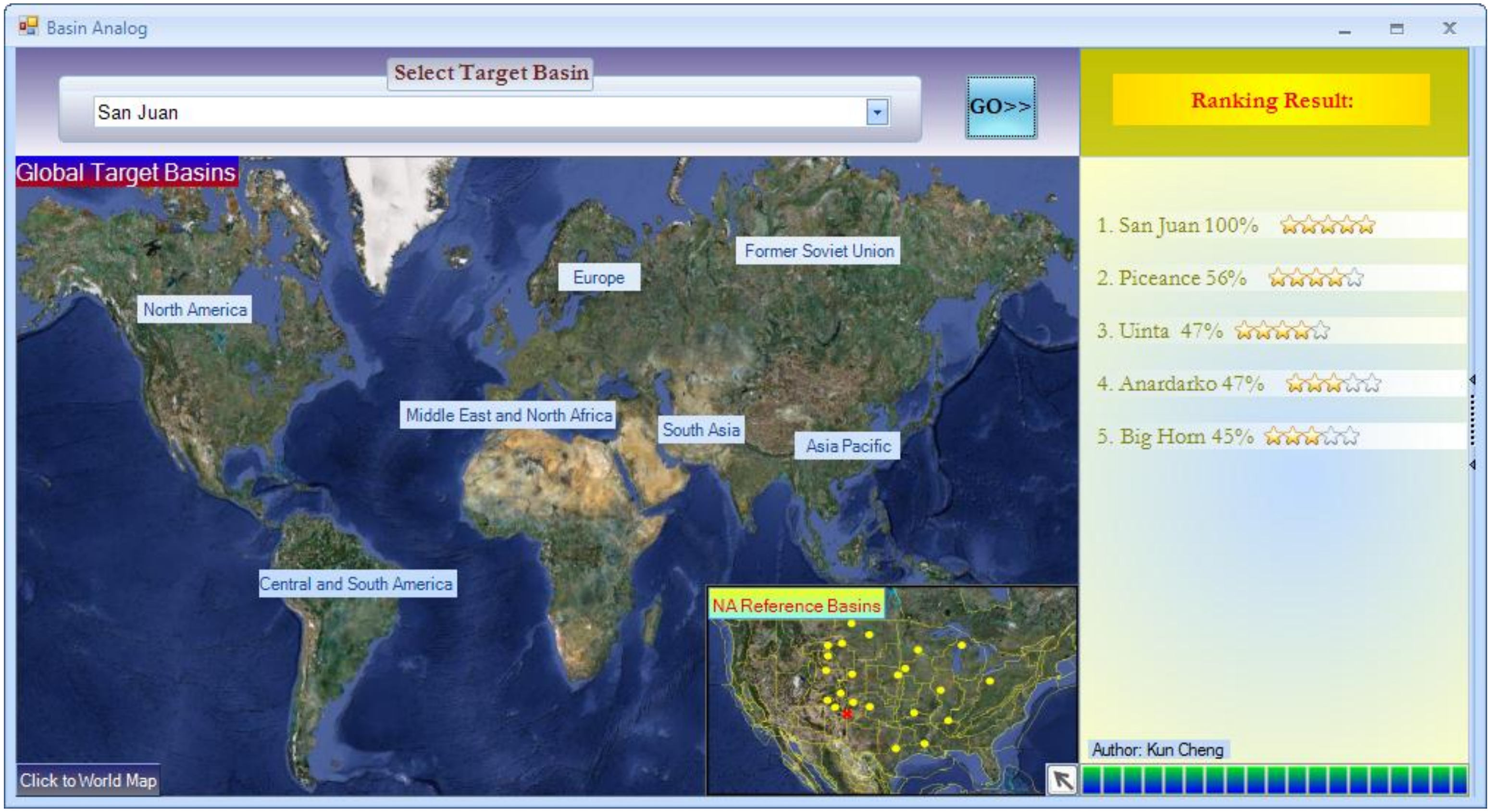
When the BASIN software was run on target basins, analog results demonstrated the consistency and correctness of the software. To further the effectiveness of the improved basin analog method, I compared the analog results from the improved BASIN with those from the PRISE quantified resources volume, and these two results matched closely.

5.1 Software Validation

It is important to test new software to ensure it produces valid results. The approach I chose was to use one of our reference basins as a target basin and check if the model selected the correct basin as an analog. I also used partially revised data sets to investigate whether the software could find analogous basins that do not exactly match the target basin.

5.1.1 Validation Check Using San Juan, Williston, Green River, East Texas and Paradox Basin

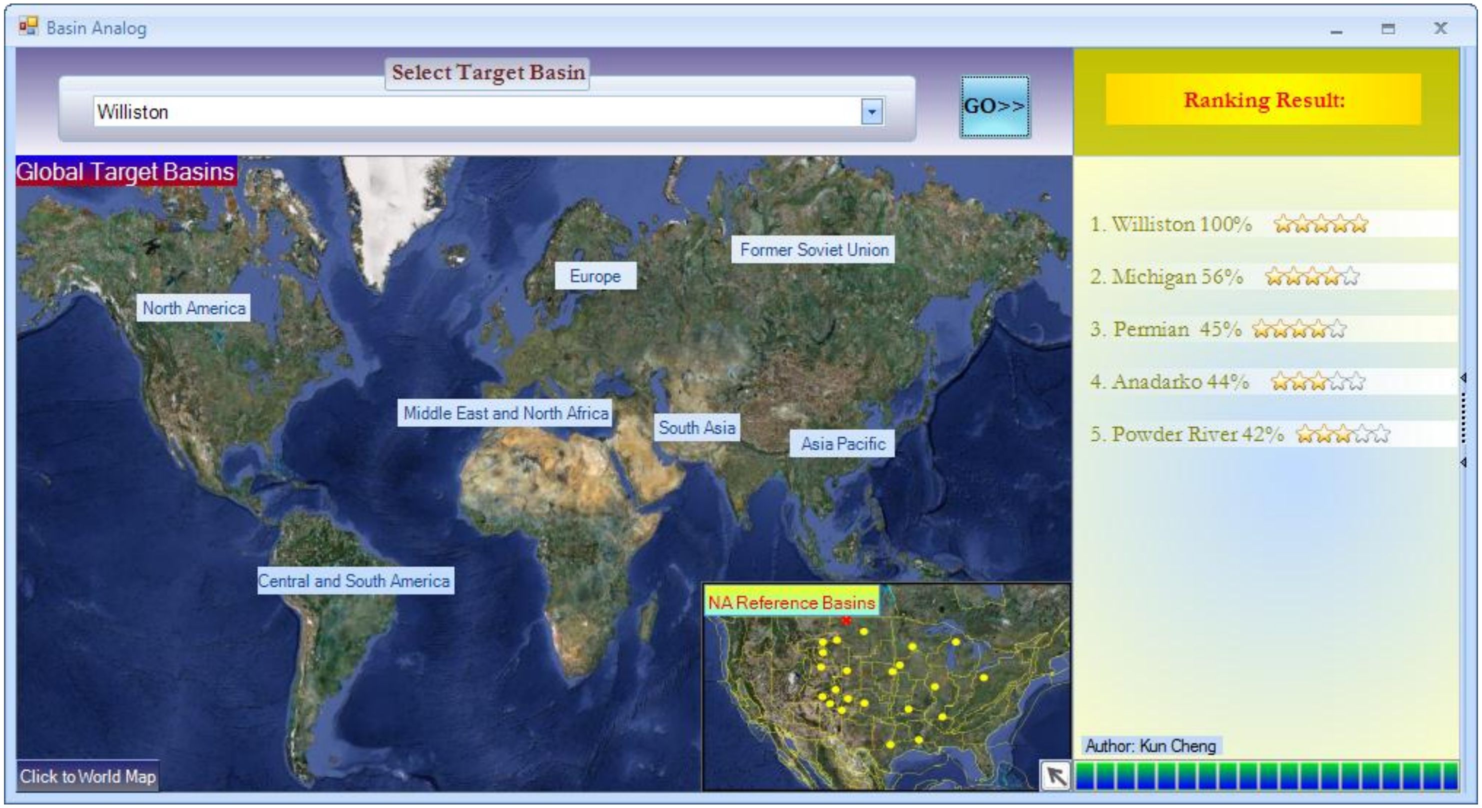
I used data from each of the San Juan, Williston, Green River, East Texas, and Paradox basins as the target basin while still keeping it in the reference basin list. I then ran the software and checked the results, expecting that BASIN would produce a 100% match with the same basin in the reference list because the exact same data are in both data sets. The result, as illustrated in Fig. 5.1 to Fig. 5.5, showed that each tested target basin does provide a 100% match in the reference basin list.



Select Target Basin: San Juan

1. San Juan 100% ★★★★★
2. Piceance 56% ★★★★☆
3. Uinta 47% ★★★★☆
4. Anardarko 47% ★★★☆☆
5. Big Horn 45% ★★★☆☆

Fig. 5.1—Software validation results for San Juan basin as target.

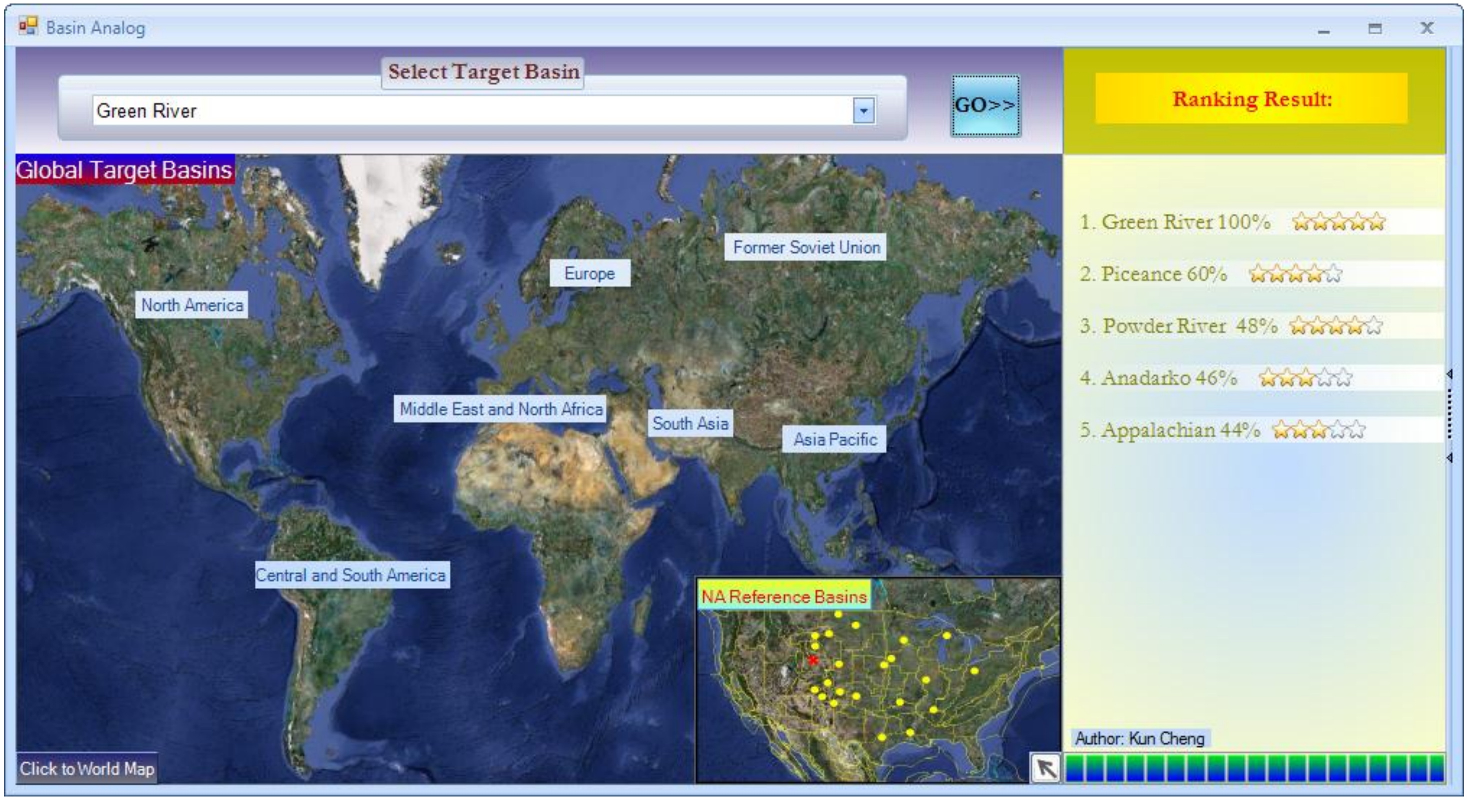


Williston

1. Williston 100% ★★★★★
2. Michigan 56% ★★★★☆
3. Permian 45% ★★★★☆
4. Anadarko 44% ★★★☆☆
5. Powder River 42% ★★★☆☆

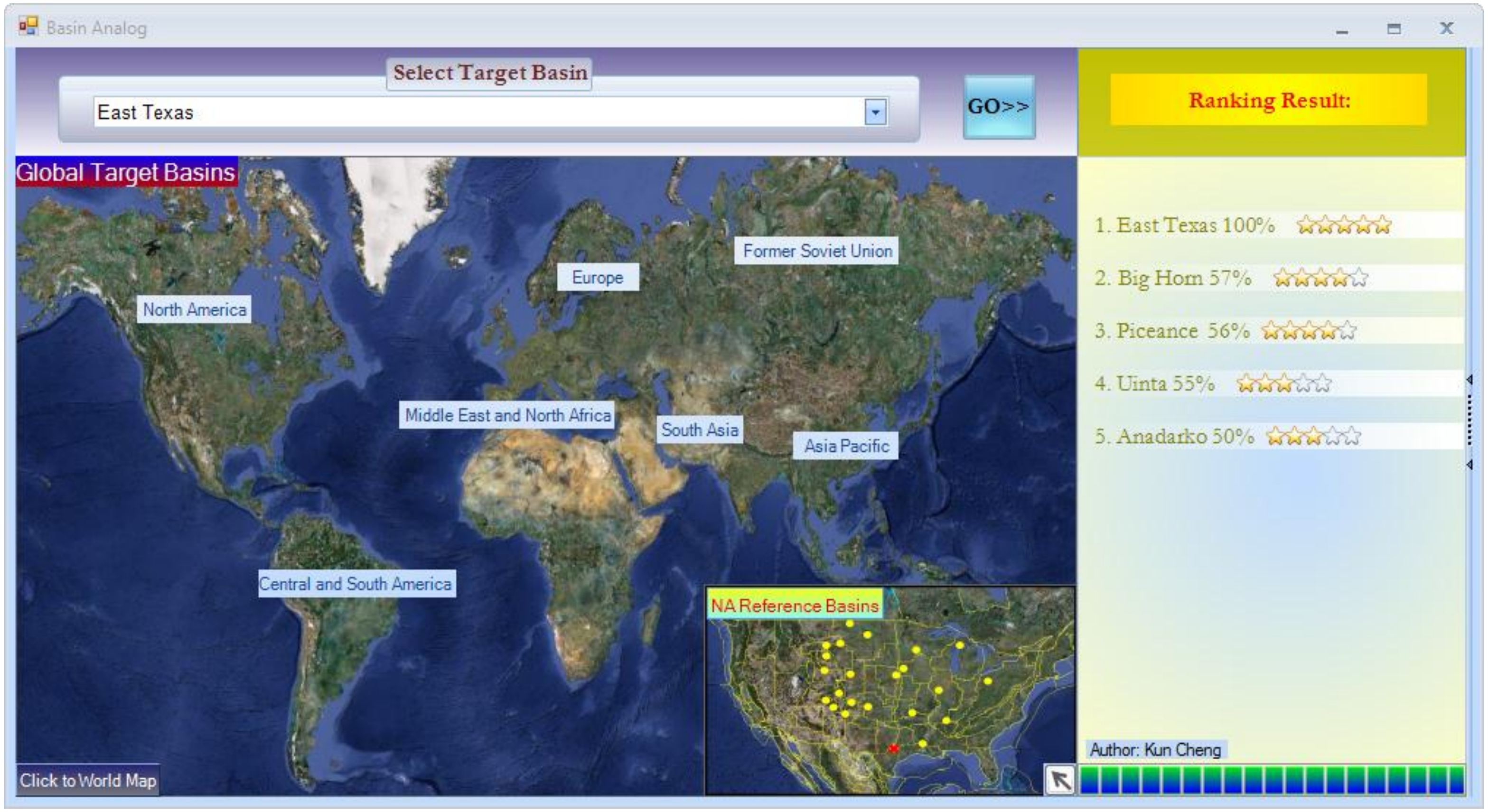
Author: Kun Cheng

Fig. 5.2—Software validation results for Williston basin as target.



1. Green River 100% ★★★★★
2. Piceance 60% ★★★★☆
3. Powder River 48% ★★★★☆
4. Anadarko 46% ★★★☆☆
5. Appalachian 44% ★★★☆☆

Fig. 5.3—Software validation results for Green River basin as target.

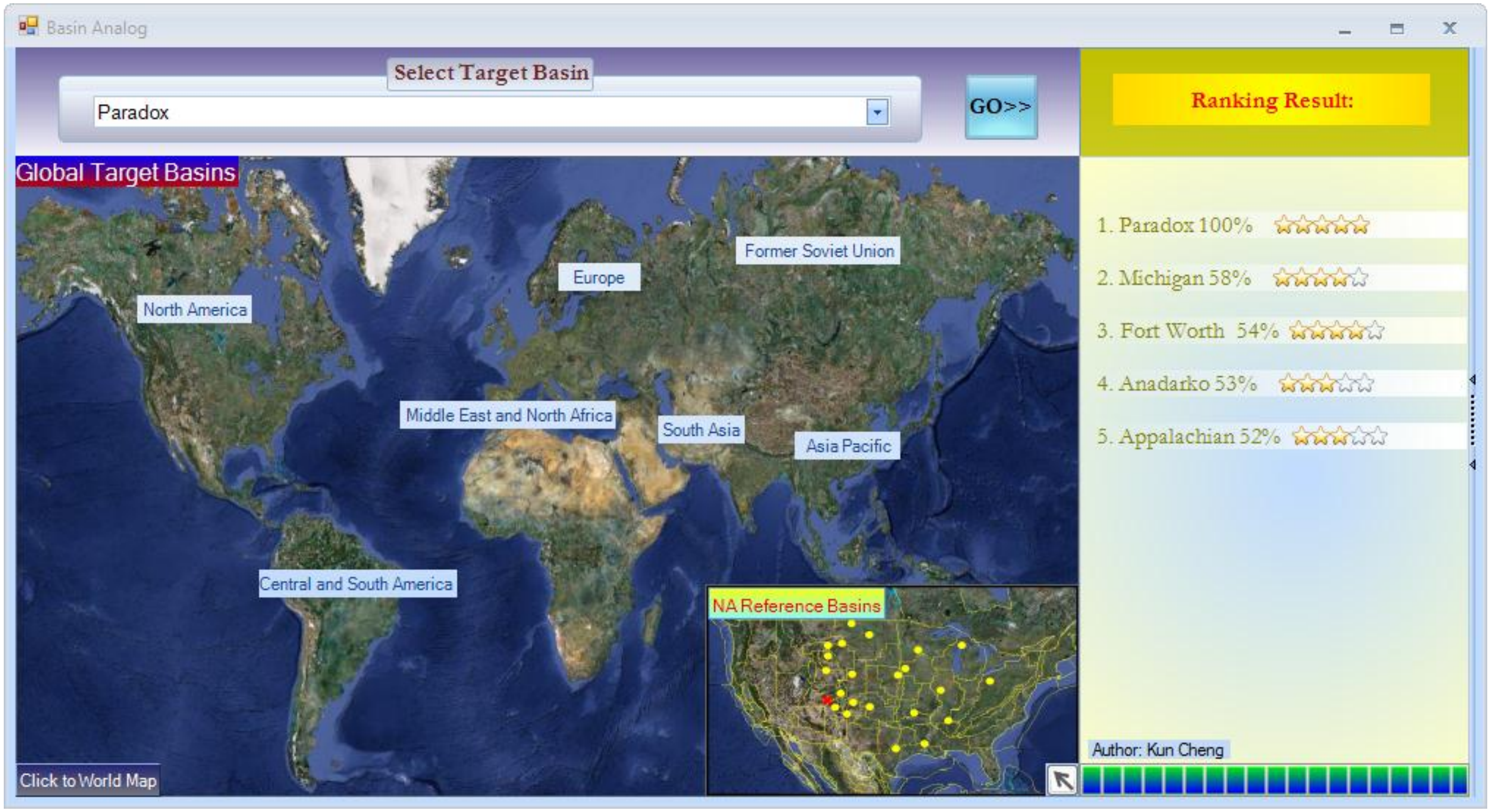


Select Target Basin: East Texas

Ranking Result:

1. East Texas 100% ★★★★★
2. Big Horn 57% ★★★★☆
3. Piceance 56% ★★★★☆
4. Uinta 55% ★★★☆☆
5. Anadarko 50% ★★★☆☆

Fig. 5.4—Software validation results for East Texas basin as target.



1. Paradox 100% ★★★★★
2. Michigan 58% ★★★★☆
3. Fort Worth 54% ★★★★☆
4. Anadarko 53% ★★★☆☆
5. Appalachian 52% ★★★☆☆

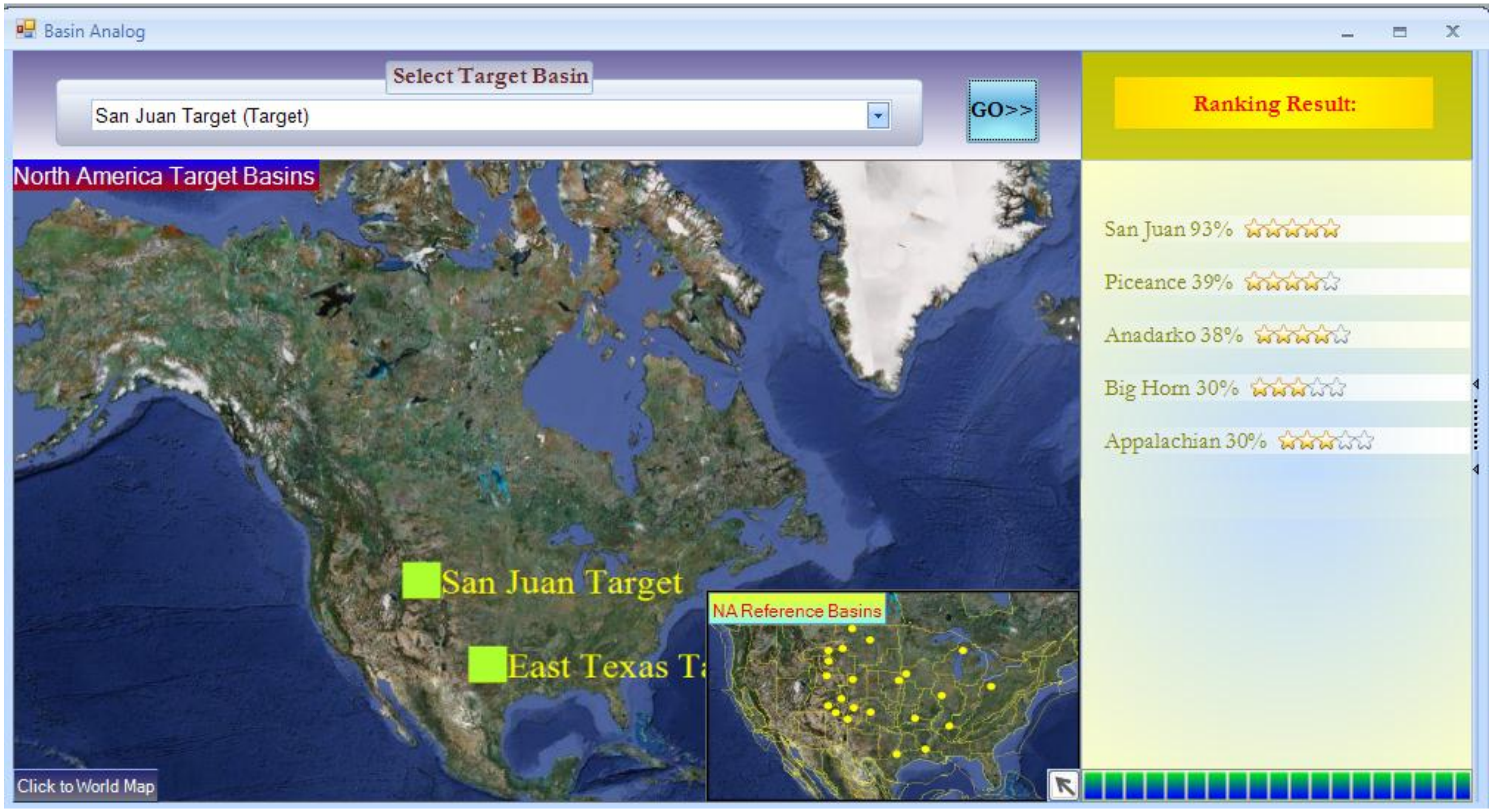
Fig. 5.5—Software validation results for Paradox basin as target.

5.1.2 Validation Check Using Modified 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 93% (Fig. 5.6). After modifying both porosity data for all reservoirs and vitrinite reflectance for all source rocks in the San Juan, the software still chose the San Juan with 90% similarity (Fig. 5.7).

5.2 Validation of Improved Basin Analog Method

The improved analog method is not only used to characterize the frontier basin by identifying its analogous North American basins, but also for the further objective of estimating the unconventional gas resources of the frontier basin. The estimation usage is based on the concept that analogous basins have similar distribution in the resource triangle.



Select Target Basin: San Juan Target (Target)

San Juan 93% ★★★★★

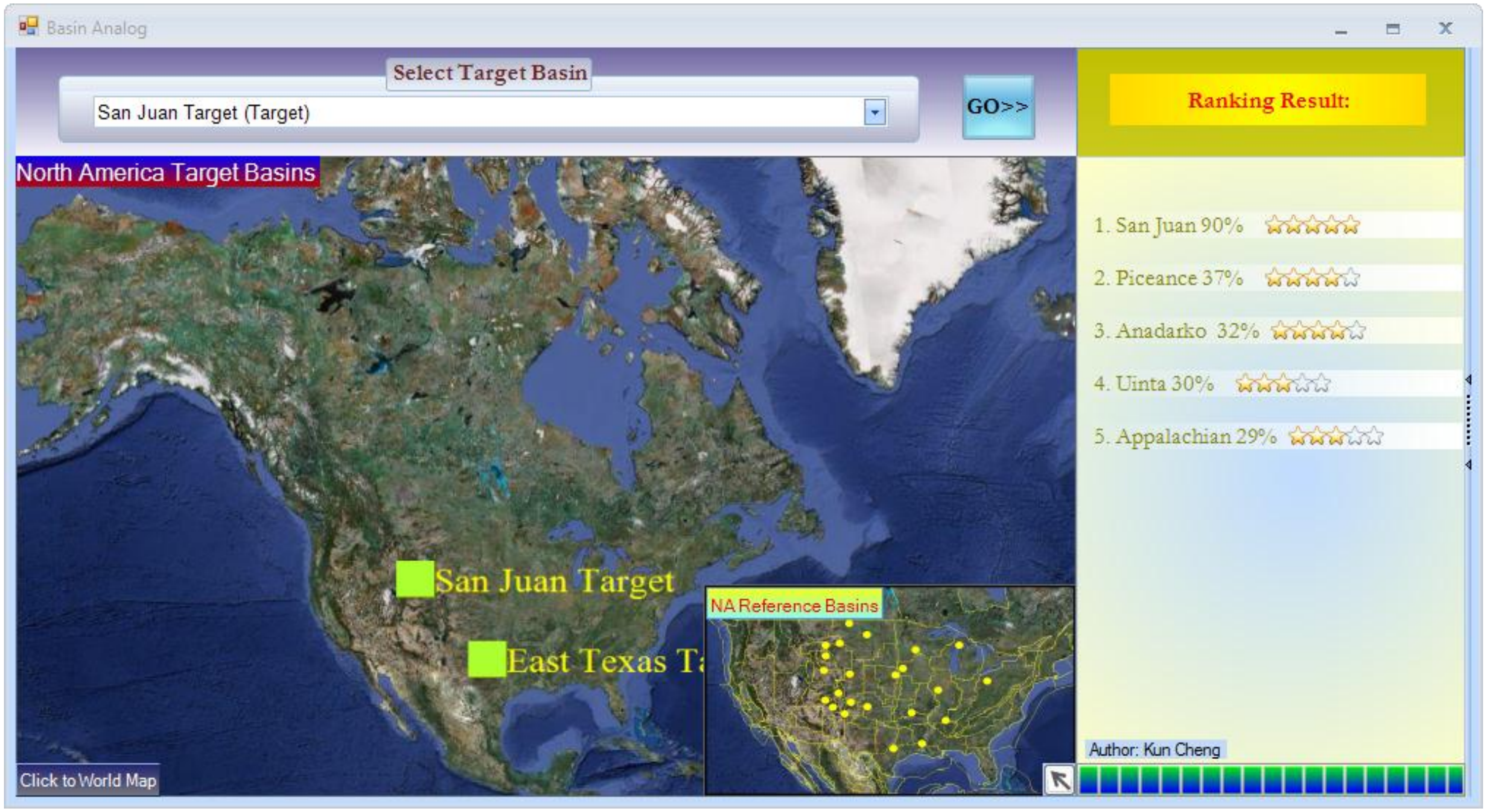
Piceance 39% ★★★★☆

Anadarko 38% ★★★★☆

Big Horn 30% ★★★☆☆

Appalachian 30% ★★★☆☆

Fig. 5.6—Results for San Juan basin with modified porosity as target.



Select Target Basin: San Juan Target (Target)

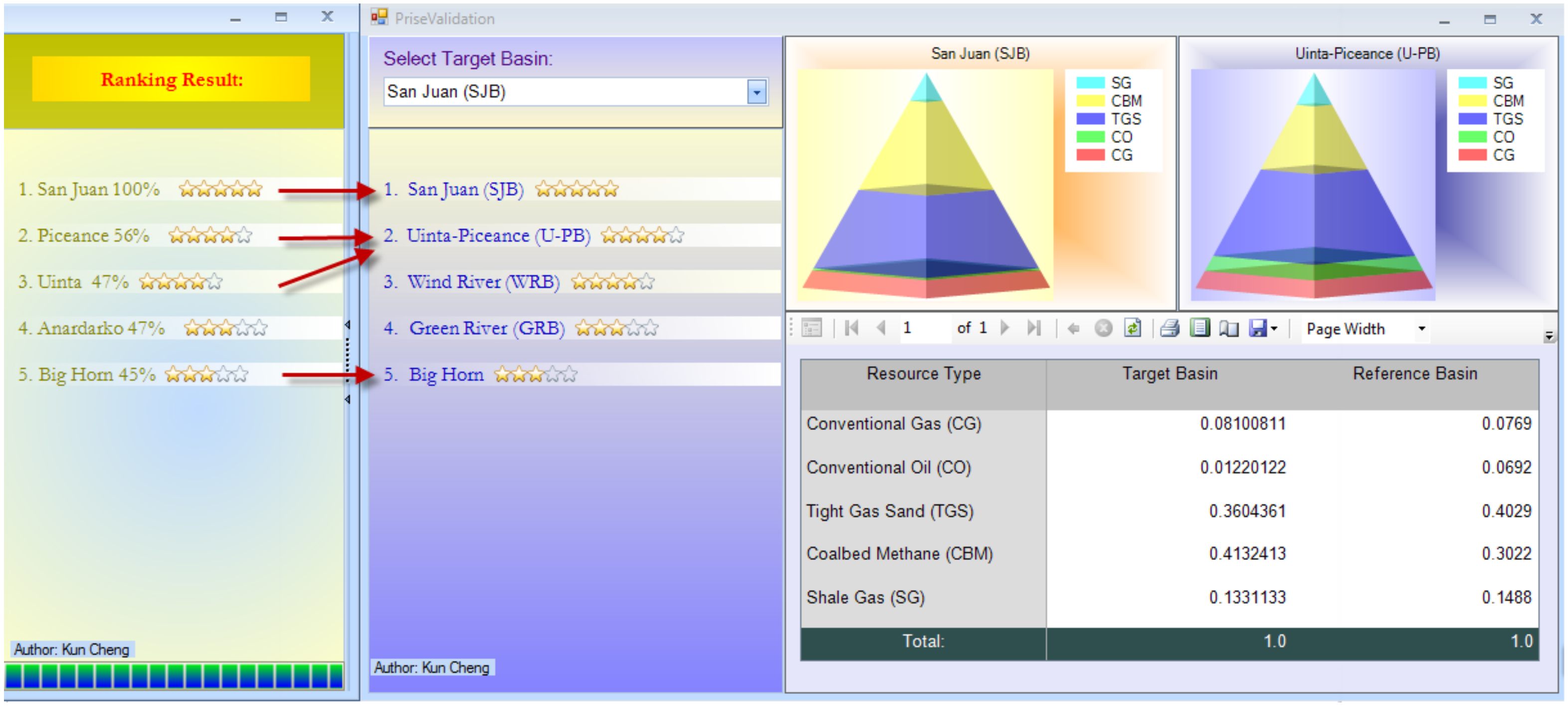
Ranking Result:

1. San Juan 90%
2. Piceance 37%
3. Anadarko 32%
4. Uinta 30%
5. Appalachian 29%

Fig. 5.7—Results for San Juan basin with modified porosity and vitrinite reflectance as target.

Based on this concept, Cheng (2010b) developed the method to compare the results of BASIN software with the analog results based on PRISE software. While the BASIN software uses the improved basin analog approach to identify and rank analogous basins for the target basin on the basis of their geology and petroleum systems characteristics, the PRISE software has detailed information on technically recoverable resources (TRR) distributions (CG, conventional gas; CO, conventional oil; SG, shale gas; CBM, coalbed methane; and TGS, tight gas sand) of the 25 North American basins. The method can calculate the similarity between any two of these reference basins based on their TRR distributions.

Each of the same five basins in Section 5.1.1 was selected as the target basin in the improved BASIN software and matched with the same reference basins in both BASIN and PRISE. Fig. 5.8 to Fig. 5.12 show the results for each basin as the target basin. Red arrows connect matching basins between the improved BASIN and PRISE, showing a close match. These results verify that analogous basins have similar resources distributions, which provides important support for quantitatively estimating the resource potential in frontier basins (Cheng et al., 2010b).



Ranking Result:

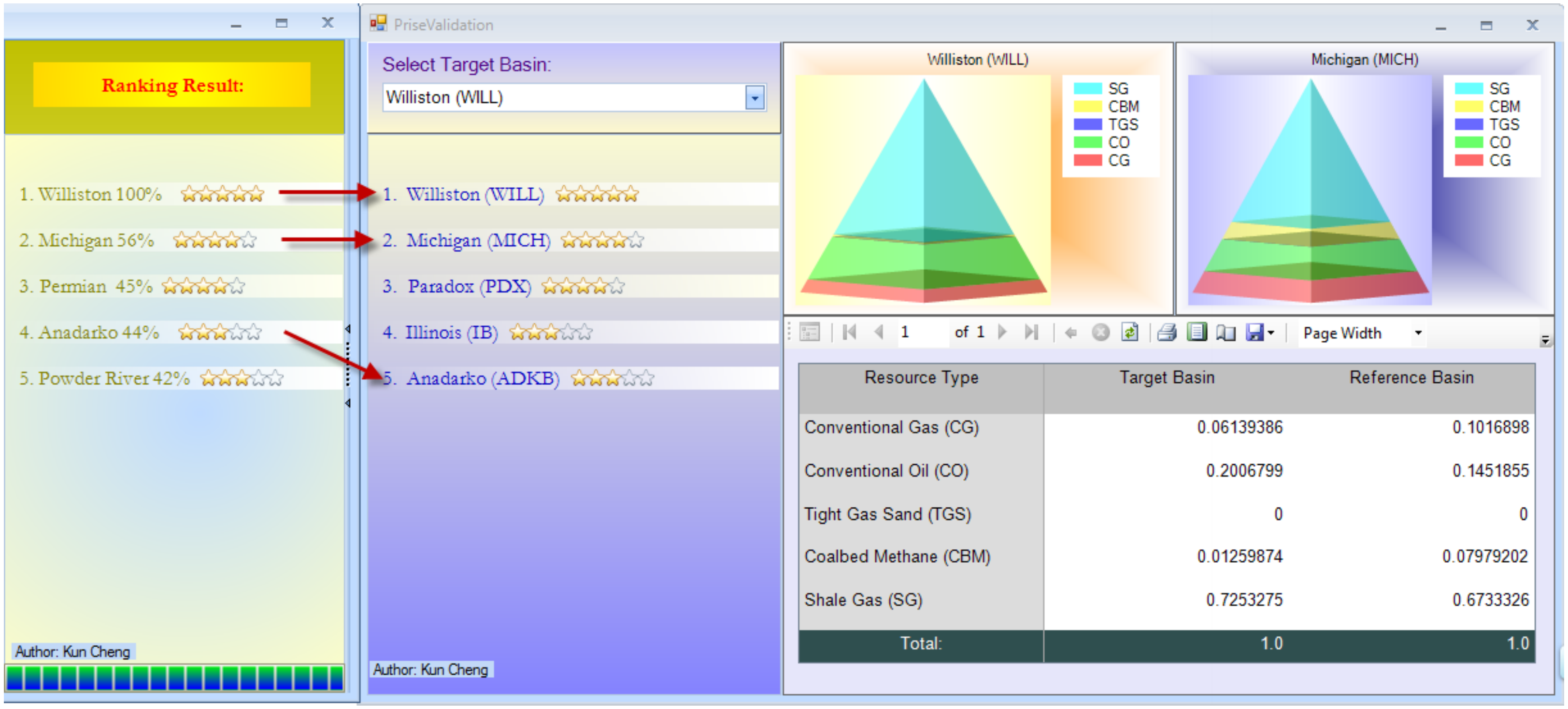
1. San Juan 100% ☆☆☆☆☆
2. Piceance 56% ☆☆☆☆☆
3. Uinta 47% ☆☆☆☆☆
4. Anardarko 47% ☆☆☆☆☆
5. Big Horn 45% ☆☆☆☆☆

Select Target Basin: San Juan (SJB)

1. San Juan (SJB) ☆☆☆☆☆
2. Uinta-Piceance (U-PB) ☆☆☆☆☆
3. Wind River (WRB) ☆☆☆☆☆
4. Green River (GRB) ☆☆☆☆☆
5. Big Horn ☆☆☆☆☆

Resource Type	Target Basin	Reference Basin
Conventional Gas (CG)	0.08100811	0.0769
Conventional Oil (CO)	0.01220122	0.0692
Tight Gas Sand (TGS)	0.3604361	0.4029
Coalbed Methane (CBM)	0.4132413	0.3022
Shale Gas (SG)	0.1331133	0.1488
Total:	1.0	1.0

Fig. 5.8—Comparison between improved BASIN and PRISE for San Juan basin as target.



Ranking Result:

1. Williston 100%
2. Michigan 56%
3. Permian 45%
4. Anadarko 44%
5. Powder River 42%

Author: Kun Cheng

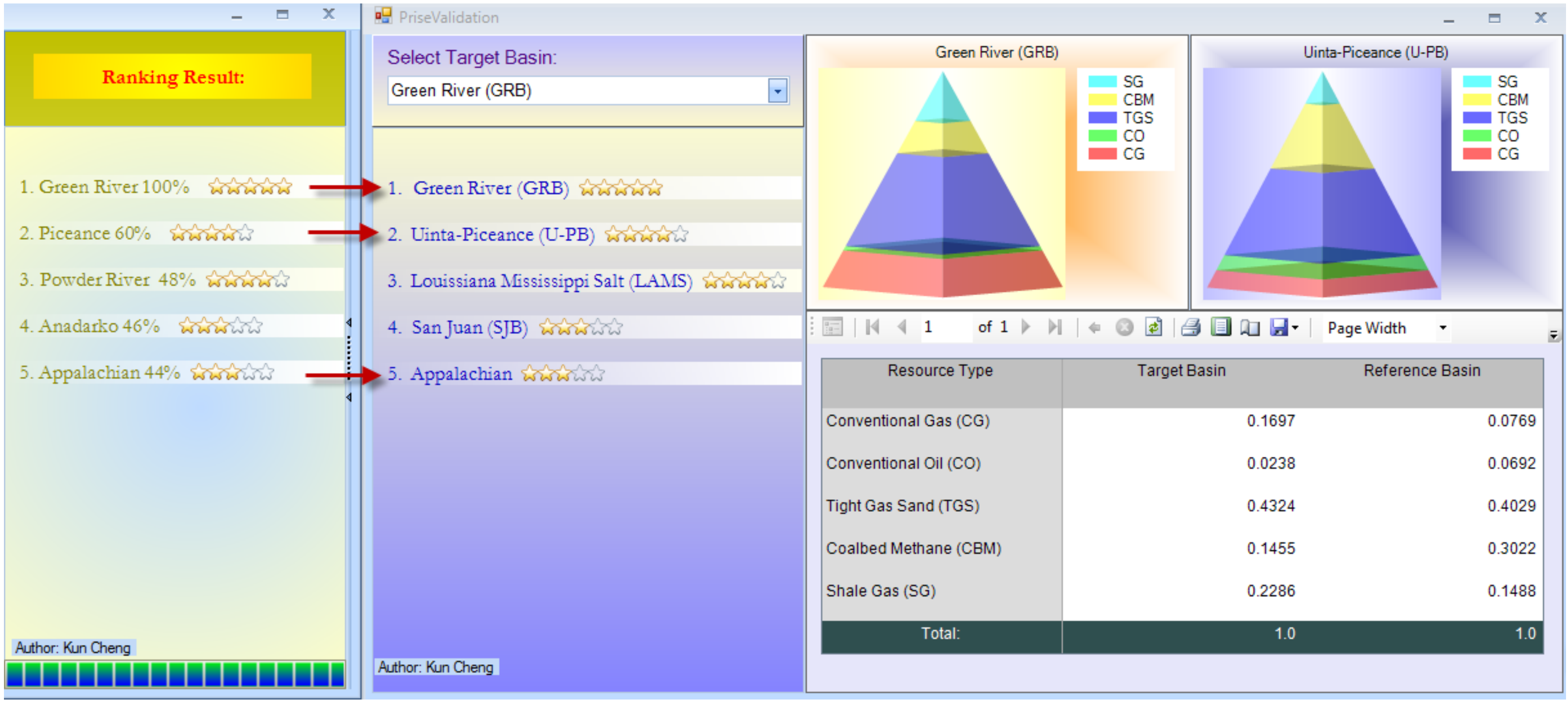
Select Target Basin: Williston (WILL)

1. Williston (WILL)
2. Michigan (MICH)
3. Paradox (PDX)
4. Illinois (IB)
5. Anadarko (ADKB)

Author: Kun Cheng

Resource Type	Target Basin	Reference Basin
Conventional Gas (CG)	0.06139386	0.1016898
Conventional Oil (CO)	0.2006799	0.1451855
Tight Gas Sand (TGS)	0	0
Coalbed Methane (CBM)	0.01259874	0.07979202
Shale Gas (SG)	0.7253275	0.6733326
Total:	1.0	1.0

Fig. 5.9—Comparison between improved BASIN and PRISE for Williston basin as target.



Ranking Result:

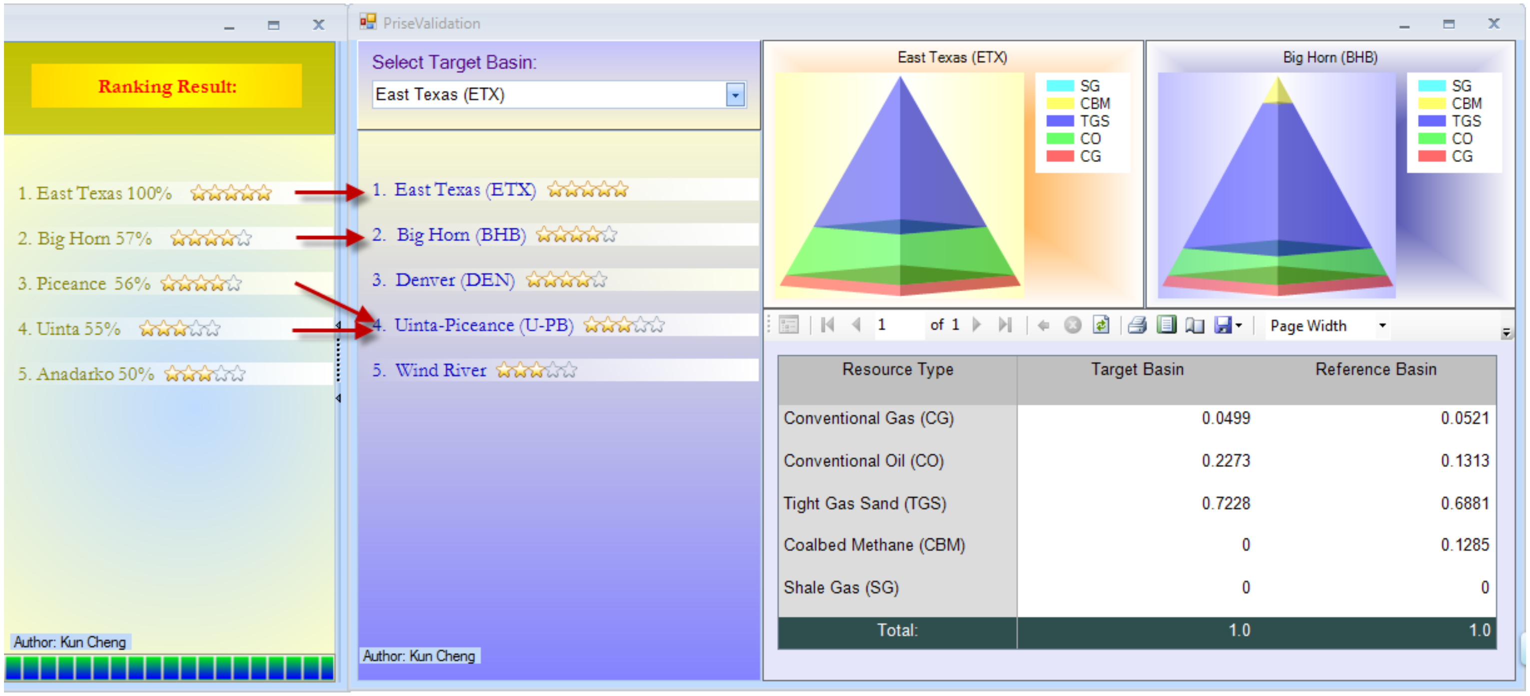
1. Green River 100%
2. Piceance 60%
3. Powder River 48%
4. Anadarko 46%
5. Appalachian 44%

Select Target Basin: Green River (GRB)

1. Green River (GRB)
2. Uinta-Piceance (U-PB)
3. Louissiana Mississippi Salt (LAMS)
4. San Juan (SJB)
5. Appalachian

Resource Type	Target Basin	Reference Basin
Conventional Gas (CG)	0.1697	0.0769
Conventional Oil (CO)	0.0238	0.0692
Tight Gas Sand (TGS)	0.4324	0.4029
Coalbed Methane (CBM)	0.1455	0.3022
Shale Gas (SG)	0.2286	0.1488
Total:	1.0	1.0

Fig. 5.10—Comparison between improved BASIN and PRISE for Green River basin as target.



Ranking Result:

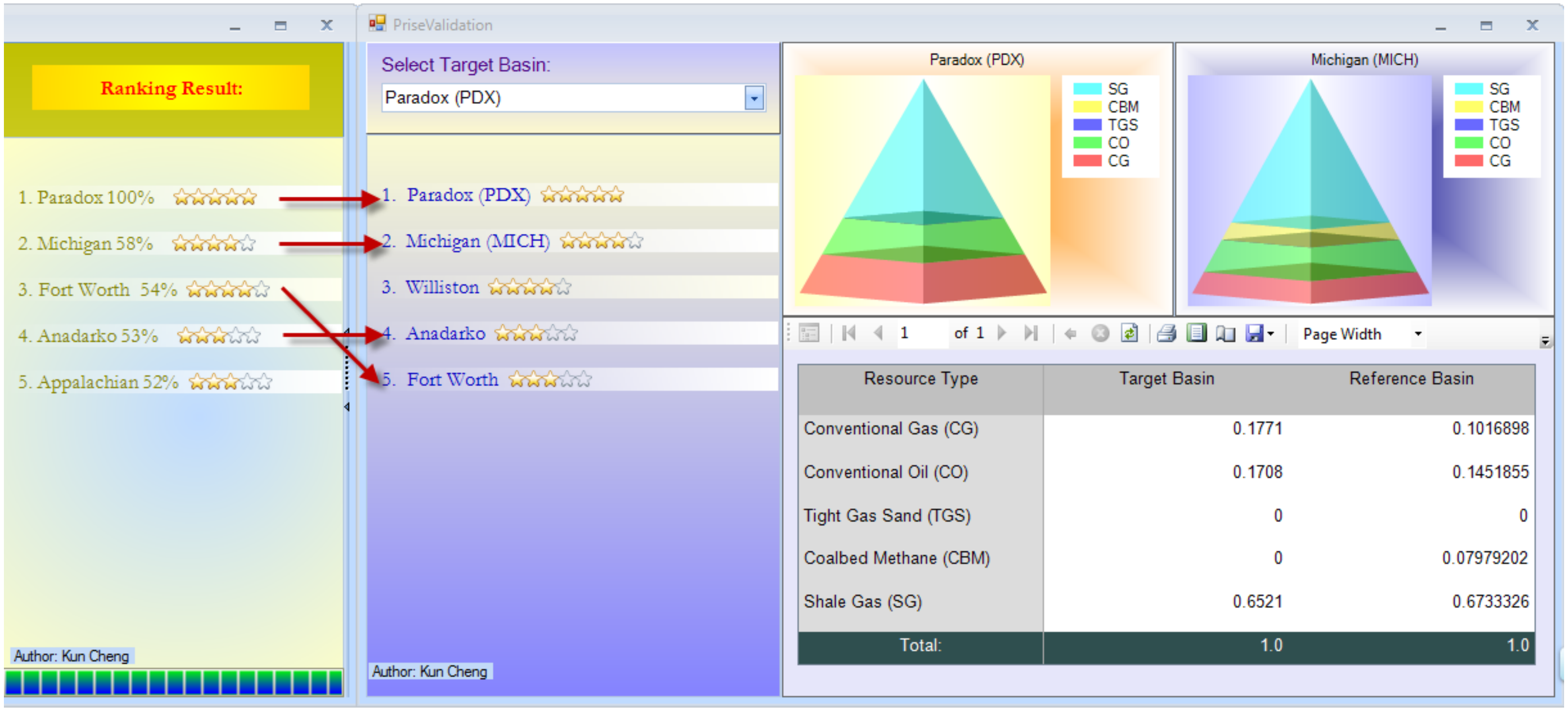
1. East Texas 100% ★★★★★
2. Big Horn 57% ★★★★☆
3. Piceance 56% ★★★★☆
4. Uinta 55% ★★★☆☆
5. Anadarko 50% ★★★☆☆

Select Target Basin: East Texas (ETX)

1. East Texas (ETX) ★★★★★
2. Big Horn (BHB) ★★★★☆
3. Denver (DEN) ★★★★☆
4. Uinta-Piceance (U-PB) ★★★☆☆
5. Wind River ★★★☆☆

Resource Type	Target Basin	Reference Basin
Conventional Gas (CG)	0.0499	0.0521
Conventional Oil (CO)	0.2273	0.1313
Tight Gas Sand (TGS)	0.7228	0.6881
Coalbed Methane (CBM)	0	0.1285
Shale Gas (SG)	0	0
Total:	1.0	1.0

Fig. 5.11—Comparison between improved BASIN and PRISE for East Texas basin as target.



Ranking Result:

1. Paradox 100%
2. Michigan 58%
3. Fort Worth 54%
4. Anadarko 53%
5. Appalachian 52%

Author: Kun Cheng

Select Target Basin: Paradox (PDX)

1. Paradox (PDX)
2. Michigan (MICH)
3. Williston
4. Anadarko
5. Fort Worth

Author: Kun Cheng

Resource Type	Target Basin	Reference Basin
Conventional Gas (CG)	0.1771	0.1016898
Conventional Oil (CO)	0.1708	0.1451855
Tight Gas Sand (TGS)	0	0
Coalbed Methane (CBM)	0	0.07979202
Shale Gas (SG)	0.6521	0.6733326
Total:	1.0	1.0

Fig. 5.12—Comparison between improved BASIN and PRISE for Paradox basin as target.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

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

1. The basin analogy process has been improved in four components: basin analog method, database, software, and validation method.

2. The improved analog method compares basins in terms of the distribution of each parameter at the basin level, which solves problems of incomplete analog data comparison units outside of the basin level, and limited comparison on quantitative parameters in the original basin analog method. It identifies analog basins more accurately and efficiently.

3. The updated BASIN database contains more geologic and petroleum systems information from reference basins and unifies the data used by BASIN, FAST, and PRISE. Two convenient and efficient approaches to populating the database are provided for different conditions: individual inputting from data management interface in BASIN and batch transfer from spreadsheets.

4. The improved BASIN software was developed in Microsoft Visual Studio.Net development software with VB.Net as the object–oriented programming language. The resulting component design improves data

management and supports data visualization that helps organize and display information about various data objects and their complicated relationships.

5. Validation not only includes checking the consistency of the improved BASIN software, but further provides important support for using improved BASIN and PRISE to quantitatively estimate the resource potential in frontier basins

6.2 Recommendations

In its present form, the improved BASIN software achieves essentially all the objectives and expectations mentioned in Chapter I. However, there are several directions where this system can be enhanced. I recommended that future work:

1. further characterize the geology and petroleum systems of the reference basins, not only using public literature, but also using industry data; and
2. use intelligent algorithms to objectively calculate the weighting factors.

GLOSSARY

%	Percentage
AAPG	American Association of Petroleum Geologists
BAS	Basin Analog System
BASIN	Basin Analog Systems Investigation
CBD	Component-Based Development
CBSE	Component-Based Software Engineering
CBM	coalbed methane
D&C	Drilling & Completion
FAST	Formation Analog Selection Tool
GRI	Gas Research Institute
GTI	Gas Technology Institute
PRISE	Petroleum Resource Investigation Summary and Evaluation
SEG	Society of Exploration Geophysicists
SG	shale gas
SPE	Society of Petroleum Engineers

TGS	tight gas sand
TRR	technically recoverable resources
UGR	unconventional gas resources
UGA	Unconventional Gas Advisor
USGS	United States Geological Survey
VAR	variable
VB	Visual Basic
VB .NET	Visual Basic .NET
WF	weighting factor
WYSIWYG	what you see is what you get

NOMENCLATURE

$[a, b]$	a class of the values of parameter k
$A(B_i, B_j)$	analog degree between B_i and B_j
B_0	a target basin
B_i	a reference or target basin (if $i \geq 0$)
B_i	a reference basin (if $i \geq 1$)
B_R	set of reference basin
$D(a \leq k \leq b \mid B_i)$	probability that the values of parameter k are in the class of $[a, b]$ for B_i
$D(a \leq k \leq b \mid s_i)$	probability that the values of parameter k are in the class of $[a, b]$ for s_i
$D(k \mid B_i)$	probability distribution of parameter k for basin B_i
$D(k \mid s_i)$	probability distribution of parameter k for petroleum system s_i
$D(k = x \mid B_i)$	probability that the value of parameter k is equal to x for B_i
$D(x_{min} \leq k \leq x_{max} \mid s_i)$	probability that the values of parameter k are in the range of $[x_{min}, x_{max}][x_{\mathrm{min}}, x_{\mathrm{max}}]$ for s_i
k	geologic or petroleum system parameter used for basin analog method
K	number of geologic or petroleum system parameters

m	number of petroleum systems in a target basin
n	number of petroleum systems in a reference basin
P_{ij}	sum of $P_{kij}\mathrm{P}_{kij}$
P_{kij}	a point calculated by Singh's basin analog method for s_i when s_j is compared to s_i on parameter k
p_{ki}	value of s_i for parameter k
p_{kj}	value of s_j for parameter k
$\mathrm{sim}(B_i, B_0)_k$	similarity between the reference basin B_i and the target basin B_0 on parameter k
$\mathrm{sim}(B_i, B_0)$	similarity between a reference basin B_i and a target basin B_0
s_i	petroleum system in a target basin
s_j	petroleum system in a reference basin
T_{ij}	sum of $T_{kij}\mathrm{T}_{kij}$
T_{kij}	a point calculated by Singh's basin analog method for s_j when s_j is compared to s_i on parameter k
WF_k	weighting factor of parameter k
x_{max}	the maximal value of a numeric variable x
x_{min}	the minimal value of a numeric variable x
x	a numeric variable

$[x_{min}, x_{max}]$	range of parameter k

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