DEVELOPMENT OF AN IMPROVED METHODOLOGY TO ASSESS POTENTIAL UNCONVENTIONAL GAS RESOURCES IN NORTH AMERICA

A Thesis

by

JESUS SALAZAR VANEGAS

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

MASTER OF SCIENCE

May 2007

Major Subject: Petroleum Engineering

DEVELOPMENT OF AN IMPROVED METHODOLOGY TO ASSESS POTENTIAL UNCONVENTIONAL GAS RESOURCES IN NORTH AMERICA

A Thesis

by

JESUS SALAZAR VANEGAS

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

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Duane A. McVay
Committee Members,	W. John Lee
	Eric Bickel
Head of Department,	Stephen A. Holditch

May 2007

Major Subject: Petroleum Engineering

ABSTRACT

Development of an Improved Methodology to Assess Potential Unconventional Gas Resources in North America. (May 2007)

Jesús Salazar Vanegas, B.S., Universidad Industrial de Santander (Colombia)

Chair of Advisory Committee: Dr. Duane A. McVay

Since the 1970s, various private and governmental agencies have conducted studies to assess potential unconventional gas resources, particularly those resources contained in tight sands, fractured shales, and coal beds. The US Geological Survey (USGS) has assessed the amount of unconventional gas resources in North America, and its estimates are used by other government agencies as the basis for their resource estimates. While the USGS employs a probabilistic methodology, it is apparent from the resulting narrow ranges that the methodology underestimates the uncertainty of these undiscovered, untested, potential resources, which in turn limits the reliability and usefulness of the assessments.

The objective of this research is to develop an improved methodology to assess potential unconventional gas resources that better accounts for the uncertainty in these resources. This study investigates the causes of the narrow ranges generated by the USGS analytic-probabilistic methodology used to prepare the 1995 national oil and gas assessment and the 2000 NOGA series, and presents an improved methodology to assess potential unconventional gas resources. The new model improves upon the USGS method by using a stochastic approach, which includes correlation between the input variables and Monte Carlo simulation, representing a more versatile and robust methodology than the USGS analytic-probabilistic methodology.

The improved methodology is applied to the assessment of potential unconventional gas resources in the Uinta-Piceance province of Utah and Colorado, and compared to results of the evaluation performed by the USGS in 2002. Comparison of the results validates the means and standard deviations produced by the USGS methodology, but shows that the probability distributions generated are rather different and, that the USGS distributions are not skewed to right, as expected for a natural resource. This study indicates that the unrealistic shape and width of the resulting USGS probability distributions are not caused by the analytic equations or lack of correlation between input parameters, but rather the use of narrow triangular probability distributions as input variables.

Adoption of the improved methodology, along with a careful examination and revision of input probability distributions, will allow a more realistic assessment of the uncertainty surrounding potential unconventional gas resources.

DEDICATION

To my awesome Colombian and Aggie families

ACKNOWLEDGMENTS

I want to express my gratitude to the State of Texas, Texas A&M University, and the Harold Vance Department of Petroleum Engineering for giving me the opportunity of achieving this goal.

Special recognition is extended to my advisor and committee chair Dr. Duane A. McVay and the other members of my committee: Dr. W. John Lee, and Dr. Eric Bickel.

I am also grateful to the Crisman Institute for Petroleum Research, its head Dr. Stephen A. Holditch, and the members of the unconventional resources research group:

Lead Investigators: Dr. W. John Lee, Dr. Duane A. McVay, and Dr. Walter B. Ayers Jr.

Graduate Research Assistants: Evi Yanty, Yamin Li, and Kalwant Singh

Finally, I want to thank everyone that contributed to the success of this project, especially to Mr. Paul Basinski from Conoco-Philips, Loring P. White from the United States Geological Survey, and the Sterling Evans library at TAMU.

NOMENCLATURE

AAPG	American Association of Petroleum Geologists
AU	Assessment Unit
Bcf	Billion Cubic Feet
CBM	Coalbed Methane
CLT	Central Limit Theorem
EIA	Energy Information Administration
EUR	Expected Ultimate Recovery
LHS	Latin Hypercube Sampling
MCS	Monte Carlo Simulation
NPC	National Petroleum Council
NOGA	National Oil and Gas Assessment
PGC	Potential Gas Committee
SD	Standard Deviation
SPE	Society of Petroleum Engineers
Tcf	Trillion Cubic Feet
TPS	Total Petroleum System
UCR	Unconventional Resources
US	United States
USGS	United States Geological Service

TABLE OF CONTENTS

Page

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

INTRODUCTION

Unconventional gas resources have become an important part of the North American energy balance. Currently about 28% of the North American undiscovered natural gas resources are predicted to exist in unconventional reservoirs, mainly tight gas sands, coalbed methane, and gas from shales.[1] Around the world, unconventional gas resources are expected to fill the gap between demand and supply by year 2025, especially in Asian countries like China and India.[2]

Several studies published over the past decade focus on potentially recoverable unconventional natural gas resources in North America.[3] Private and federal organizations directly involved in the analysis of natural gas industry trends, such as the United States Geological Survey (USGS), National Petroleum Council (NPC), Energy Administration Agency (EIA) and the Potential Gas Committee (PGC), have generated reports on remaining potential unconventional natural gas resources in the United States, including localization, settings, accessibility, and technology needed to exploit those resources.

Studies by these four United States-based agencies present very different values for total potential undiscovered North American unconventional gas resources, ranging from 169 to 358 Tcf. This spread of results shows the uncertainty that surrounds the assessment of this kind of resources. Current methodologies to assess potential unconventional natural gas resources in North America provide values based on analytic generalizations and simplified probability distributions for input variables which do not account well for the uncertainties surrounding unconventional petroleum accumulations. In a recent paper,

---

This thesis follows the style and format of the *SPE Journal.*

Haskett[4] observed that assessments of unconventional hydrocarbon resources using standard probabilistic methodology based on volumetric and production performance estimations have been problematic and, ultimately, those evaluations are anchored in rules of thumb or deterministic shortcuts.

In a recent work, Schmoker[5] presented the general USGS approach to assessing unconventional gas resources in continuous accumulations. The USGS considers unconventional gas resources, from a geologic point of view, to be those natural gas accumulations that exist pervasively in large spatial areas, that are more or less independent of the water column, and that do not owe their existence to the buoyancy of gas in water. Using this definition as a foundation, the USGS developed its methodology to assess these resources. This methodology is significantly different from the one typically used in conventional resource assessment, which depends on estimation of the size and number of undiscovered discrete fields. The USGS methodology to assess unconventional gas resources[6] relies on defining assessment units divided into petroleum-charged cells and predicting estimated ultimate recoveries (EUR). The use of an analytic probabilistic methodology determines the potential additions to reserves within the next 30 years.

The resource assessment results obtained by the USGS are used by other agencies, such as the NPC and EIA, as their base resource estimates. These two agencies include in their forecasts technology improvement factors that reflect primarily increases in EUR and cost reductions through time. They also perform economic analyses to determine if the resources are economically recoverable or not.

The USGS in its 1995 National Resource Assessment[7] presented its results, methodology and supporting data for the assessment of unconventional hydrocarbon resources in North America. Likewise, the 2003 NPC[8] and 2005 EIA[9] reports which use the USGS assessment as their resource base, presented their estimates of the total North

American unconventional gas resource. Recent USGS studies that started in the year 2000 are re-assessing potential unconventional gas resources for particular provinces in the United States. However, a national US resource assessment has not been performed since 1995.

The PGC methodology[10] is different from the three mentioned above and addresses only the assessment of coalbed methane as an unconventional gas resource. They use a volumetric calculation that relies on gas content values calculated from cores and the application of recovery factors determined by industry experts.

The USGS methodology is the most rigorous methodology applied to date for the assessment of potential unconventional gas resources in North America. However, an analysis of the probability distributions presented for the total US unconventional gas resources in the USGS 1995 national assessment indicate that there may be problems with the USGS methodology. Further study shows that more recent assessments performed by the USGS in 2002 also present the same concerns.

Table 1 presents the results for the USGS 1995 US national unconventional natural gas resource assessment. The resource estimate range from a P_{95} value of 262.3 Tcf to a P_5 value of 474.2 Tcf. The P_5/ P_{95} ratio is only 1.8 which is very small range considering that this is an assessment for the total US undiscovered, untested unconventional gas resources. **Table 2** shows the results for a most recent USGS study. The USGS unconventional gas resource assessment for the Uinta-Piceance of Utah and Colorado. The resource estimate ranges from a P_{95} value of 12,110 Bcf to a P_5 value of 33,875 Bcf. The P_5/ P_{95} ratio is only 2.8, which is also very small. In both cases it seems unreasonable to expect a 90% probability that the mean value for the actual unconventional gas resource falls within this narrow range.

TABLE 1—1995 US UNCONVENTIONAL GAS RESOURCE NATIONAL ASSESSMENT (Tcf)				
Source	P_{95}	P_{50}	P_5	P_5/P_{95}
Tight sands, shales, Chalks	219.40	308.10	416.6	1.9
CBM	42.90	49.90	57.6	1.3
US Total	262.30	358.0	474.20	1.8

In my view, there are three potential problems with the current USGS methodology to assess potential unconventional gas resources, which limit its reliability. First, it uses simplified probability distributions (mainly triangular) as input variables, which could introduce unconscious judgmental bias and produce narrow confidence intervals. Second, the USGS methodology does not include the effects of correlation between the input variables, and third, the USGS methodology assumes perfect positive correlation to aggregate the resulting probability distributions for the different assessment units to the total petroleum system and province levels.

According to Hudak[11], triangular distributions are closed probability distributions that are prone to including unconscious judgmental bias, especially when establishing the extreme values. This characteristic often leads to narrow confidence intervals for the variables under estimation. According to Hudak, triangular distributions should be used only when there are not enough data to create the proper probability distribution and when the assessor has very good knowledge of the minimum, most-likely and maximum values. The USGS uses four triangular distributions for area-related variables and a log-normal distribution for gas recovery per cell as inputs, as well as a set of analytic equations derived from probability theory to calculate the mean and standard deviation of unconventional gas resources in a particular area. This approach let the USGS create

TABLE 2—TOTAL UNDISCOVERED UNCONVENTIONAL GAS RESOURCES (Bcf)

TPS	AU	P_{95}	P_{50}	P_5	P_5/P_{95}
Mancos/Mowry	Piceance	649	1463	3297	5.1
	Uinta	1782	2965	4934	2.8
	Uinta-Piceance Trans.	1430	1743	2124	1.5
Ferron/Wasatch	Deep Coal & Sandstone	0.0	52	136	-
	Northern Coal Fairway	451	722	1156	2.6
	Central Coal Fairway	312	513	844	2.7
	Southern Coal Fairway	78	146	256	3.3
	Southern Coal Outcrop	0.0	10	31	-
Mesaverde	Uinta Continuous	4134	7019	11915	2.9
	Uinta Transitional	889	1432	2305	2.6
	Piceance Continuous	1902	2956	4594	2.4
	Piceance Transitional	162	285	500	3.1
	Uinta-Blackhawk – CBM	182	434	1034	5.7
	Mesaverde Group – CBM	139	323	750	5.4
Province Total		12110	20061	33876	2.8

a simple spreadsheet system to perform the assessments without the need for Monte Carlo simulation.

The objectives of this study are to determine the causes for the narrow distributions for potential unconventional gas resources generated by the USGS and to develop an improved methodology to account better for the great uncertainty surrounding these resources. The specific objectives of this research are:

1. Improve the existing USGS methodology to assess potential unconventional gas resources by better assessing the probability distributions for the input variables instead of using mainly triangular distributions.

2. Improve the existing USGS methodology to assess potential unconventional gas resources by using a stochastic approach, including variable correlation effects.

To achieve the research objectives I developed an improved methodology that uses a stochastic approach including Monte Carlo simulation with Latin hypercube sampling, and correlation of the input variables.

Realistic assessments of uncertainty are very important in the decision making process to explore for and develop these kind of resources, because they help to determine the upside and downside potential. Considering the fundamental role played today by unconventional gas resources in North America's gas supply, and its enormous potential for the future, the development of this improved methodology for assessment of potential unconventional gas resources is valuable to both industry and government for development of this resource for the public benefit.

In this thesis I first present the existing US unconventional gas resource definitions and propose a new definition, then I describe current US unconventional gas assessments and methodologies. Finally I describe in detail the USGS methodology and improved methodology. The improved methodology is applied to assess potential unconventional gas resources of the Uinta-Piceance province of Utah and Colorado. The results are compared to the assessment performed by the USGS in the same province in 2002.

STATE OF THE ART OF UNCONVENTIONAL HYDROCARBON RESOURCE ASSESSMENT IN THE UNITED STATES

UNCONVENTIONAL HYDROCARBON RESOURCES DEFINITIONS

The initial problem faced in this research project is that there is not a clear definition for unconventional hydrocarbon resources. There are almost as many definitions as organizations related to unconventional resources. Current definitions are in most cases imprecise, overlapping, and either limited or boundless. There is a need for a comprehensive, functional and concise definition for unconventional hydrocarbon resources. Many organizations and authors had proposed different definitions for unconventional hydrocarbon resources. The most popular are:

Nonconventional Gas (SPE[12])

Nonconventional gas is natural gas found in unusual underground situations such as very impermeable reservoirs, hydrates, and coal deposits.

Nonconventional Gas Resources (NPC[13])

Nonconventional gas resources are those large accumulations having regional spatial dimensions with diffuse boundaries that cannot be represented in terms of discrete, countable reservoirs delineated by down-dip hydrocarbon-water contacts. Nonconventional gas resources include CBM, fractured shale gas and basin-centered tight gas.

Unconventional Gas (EIA[9])

Unconventional gas refers to natural gas extracted from coal beds (coalbed methane), and from low permeability sandstone and shale formations (respectively, tight sands and gas shales)

For some authors unconventional hydrocarbon resources occur in so-called continuous-type accumulation, as presented in the two following definitions:

Continuous Accumulations (USGS[14])

Continuous accumulations are defined as petroleum accumulations that have large spatial dimensions and which lack well-defined down-dip petroleum/water contacts. Continuous accumulations are not localized by the buoyancy of oil or gas in water. Continuous petroleum accumulations include CBM, basin-centered gas, gas hydrates, oil and gas in fractured shales and chalk, tight gas, and shallow biogenic gas.

Continuous-type Deposit (SPE[12])

A continuous-type deposit is a petroleum accumulation that is pervasive throughout a large area and which is not significantly affected by hydrodynamic influences. Examples of such deposits include "basin-centered" gas and gas hydrate accumulations.

Unconventional (nonconventional or less conventional) Gas Resources (Federal Energy Regulatory Commission[15])

Unconventional gas resources is gas present in low-permeability (tight) reservoirs with matrix permeabilities generally less than 0.1 md. The gas may be present in sandstones, siltstones, carbonates, coalbeds, or shales.

Unconventional Reservoirs (Holditch[16])

An unconventional reservoir is one that cannot be produced at economic flow rates or that does not produce economic volumes of oil and gas without assistance from massive stimulation treatments or special recovery processes and technologies, such as steam injection. Typical unconventional reservoirs are tight gas sands, coalbed methane, heavy oil and gas shales.

Unconventional Gas Resources (Curtis[3])

Unconventional gas resources is natural gas present in reservoirs with matrix permeabilities generally less than 0.1 md. Such reservoirs include coalbeds, shales, and tight sandstones, siltstones and carbonates.

Unconventional Resources (Haskett [4])

According to Haskett, resources recoverable from reservoirs of difficult nature have come to be called "unconventional resources." These include fractured reservoirs, tight gas, gas/oil shale, oil sands and CBM.

There are many definitions but most of them are overlapping, imprecise and do not describe fully the nature of unconventional resources.

A NEW DEFINITION FOR UNCONVENTIONAL RESOURCES

An extensive literature review showed that there is a need for a comprehensive, functional and concise definition for unconventional resources.

It is important to determine what to define. Do we want to define unconventional reservoirs or unconventional resources? To define unconventional reservoirs it is important to describe characteristics of the geological setting and the reservoir framework. To define unconventional resources it is necessary to include not only the reservoir characteristics, but also the extent to which the hydrocarbons are recoverable and the technology needed to exploit them.

What makes a hydrocarbon accumulation unconventional is a combination of one or more of the first three characteristics with the fourth characteristic:

1. Special reservoir framework: low matrix permeability and/or presence of natural fractures.
2. Special reservoir charge: adsorbed gas in self-sourced reservoirs or presence of methane clathrates.
3. Fluid characteristics: high viscosity at reservoir conditions.
4. Technology and economics: The resources are economically exploitable only by applying advanced technologies, massive stimulation treatments and/or special recovery processes.

Based on the previous rationale, my proposed definition of unconventional hydrocarbon resources is:

> Unconventional hydrocarbon resources are those oil and gas accumulations that, owing to their special reservoir rock properties (i.e., 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 with advanced technologies, massive stimulation treatments, and/or special recovery processes.

By this definition, unconventional resources include tight gas sands, oil and gas shales, coalbed methane, heavy oil and gas hydrates.

EXISTING ASSESSMENTS FOR UNCONVENTIONAL GAS RESOURCES

The most important US assessments in the last ten years were performed by four agencies: USGS, NPC, EIA, and PGC. **Fig. 1** shows the results of these assessments.

Fig. 1 shows a wide spread between the values of potential unconventional gas resources. There are also significant changes in the assessments by the same organization from one year to another. The most recent studies present a range between 169 and 358 Tcf.

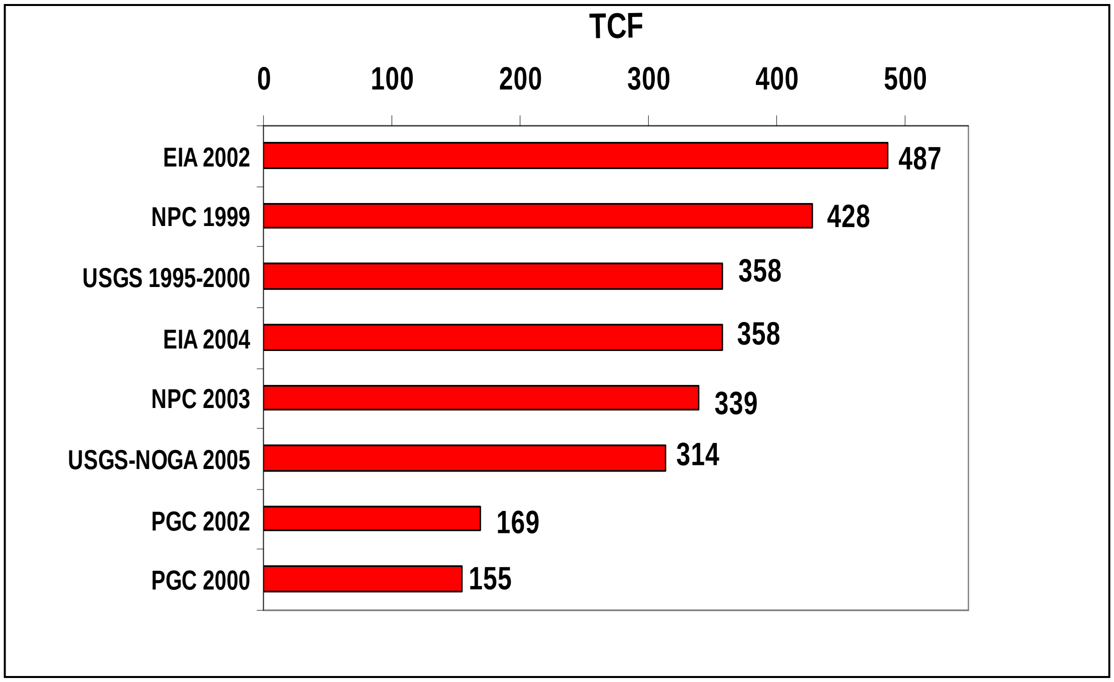

Fig. 1—Total US future potentially recoverable unconventional gas resources, under existing and foreseeable technology (Data from Curtis[4]).

Different definitions, methodologies, and the large uncertainty surrounding this kind of resource cause the wide spread in the values assessed by the four agencies. For example, the PGC considers CBM the only unconventional gas resource and does not include gas shales and tight gas sands in their assessment. The NPC and EIA take the resources assessed by the USGS as their resource base.

United States Geological Survey (USGS)

The USGS had performed conventional oil and gas resource assessments short after the turn of the 20^{th} century. Systematic national conventional oil and gas resource assessments have been conducted regularly since 1975. Early efforts to assess unconventional oil and gas resources started in the late 1970's and early 1980's. Those assessments were based on geologic and engineering calculations of in-place volumes.[17] In-place volumes were estimated using the volumetric equation, which requires area, thickness, porosity, fluid saturation, and recovery factors. Assessments were conducted for specific basins or plays, such as the Devonian gas shales in the Appalachian Basin. Other studies covered tight gas sands in specific basins in the western US region. However, it was not until 1991 that the USGS started a systematic assessment of technically recoverable resources from continuous-type accumulations. These resources were not evaluated systematically in previous assessments not only due to the fact that, historically, these resources contributed little to the national energy supply, but also because of lack of data and difficulties in developing adequate methodologies..

The USGS 1995 National Assessment

In 1995 the USGS presented their national assessment of United States oil and gas resources, results, methodology, and supporting data.[7] The 1995 national assessment was the result of a 3-year study of the oil and gas resources of onshore areas and state waters of the United States. The technically recoverable unconventional gas resources were estimated to be 308 Tcf for continuous-type accumulations (sandstones, shales and chalks) and 50 Tcf for coalbeds.

The USGS National Oil and Gas Assessment Project (NOGA)

In year 2000 the USGS started the NOGA project, which intends to re-assess conventional and unconventional oil and gas resources in priority areas of the United States. Priority provinces such as the Uinta-Piceance, Powder River, Southwestern Wyoming, Appalachian, and San Juan have been evaluated because of their potential for significant natural gas resources. A total of 25 provinces which are thought to contain 90% - 95% of US oil and gas resources will be re-assessed. As of November 2005, 13 provinces have been evaluated, 5 of them with a published final report. In the NOGA series, the USGS uses an assessment methodology somewhat different from the one used in the 1995 national assessment. As a result of the NOGA project, the reviewed total US potentially recoverable unconventional gas resource is 314 TCF, including CBM.[18]

The National Petroleum Council (NPC)

The NPC is a federal advisory committee to the Secretary of Energy, based in Washington D.C., which purpose is to advise, inform and make recommendations to the Secretary of Energy in any matter relating to oil and natural gas or to the oil and natural gas industries.

The NPC's most recently generated reports were in 1992, 1999 and 2003. In the 2003 NPC report they took the USGS 1995 national oil and gas assessment as the resource base and revised 20% of the basins that are thought to contain 80% of the US oil and gas resources. The other 80% of the basins were reviewed only superficially.

The NPC does not assess resources using a prescribed methodology. In their regional meetings they review the USGS estimates and vote to decide if the numbers should be kept the same, increased or decreased. The 2003 NPC study reported 339 Tcf for total US potentially recoverable unconventional gas resources.[19] This value is 19 Tcf lower than the one reported by the USGS in 1995.

The Energy Information Administration (EIA)

The EIA is a statistical agency of the U.S. Department of Energy. They provide policy-independent data, forecasts, and analyses to promote sound policy making, efficient markets, and public understanding of energy and its interaction with the economy and the environment.

The EIA generates an annual energy outlook report.[9] The EIA does not perform its own assessment of oil and gas resources; it uses the 1995 USGS national assessment as their base resource estimate to generate production and economic forecasts to define supply curves for the US for the next 25 years.

The Potential Gas Committee (PGC)

The PGC consists of volunteer members from all segments of the oil and gas industry, government agencies and academic institutions who are concerned with natural gas resources. The Committee functions independently but with the guidance and assistance of the Potential Gas Agency at Colorado School of Mines. The PGC has prepared and published biennial estimates of the potential supply of natural gas since 1964.

The objective of the PGC is to provide estimates, based upon expert knowledge, of the potential supply of natural gas, which together with estimates of proved reserves of natural gas, make possible an appraisal of the nation's long-range gas supply.

The PGC estimates two kinds of natural gas resources: "traditional" resources and unconventional resources (coalbed methane). They do not include what they call "frontier" resources: gas hydrates, gas from geo-pressured, geo-thermal accumulations, deep earth gas, and gas contained in very low-permeability formations and not recoverable with existing or foreseeable technology. The PGC 2002 report[10] presents an estimate of 169 TCF as the total potentially recoverable unconventional gas resource (CBM only).

EXISTING METHODOLOGIES TO ASSESS UNCONVENTIONAL GAS RESOURCES

Of the four different US-based agencies revised in this study, only two (USGS and PGC) have unique methodologies to assess potential unconventional gas resources. The other

two agencies (NPC and EIA) do not independently assess resources; they take the 1995 USGS national assessment as the base to create supply forecasts.
The PGC methodology is a volumetric assessment of CBM resources, which is the only unconventional gas resource they consider. The PGC methodology is not reviewed in this study.

The USGS methodology is generally considered to be the most rigorous and comprehensive to assess unconventional hydrocarbon resources. The methodology is described in detail in the following section.

Description of the USGS Methodology

The USGS methodology to assess potential unconventional gas resources is based on their definition for continuous accumulations as a specific geological setting, as depicted in **Fig. 2**.

The USGS assessments of resources in continuous accumulations are performed by geoscientists. According to the USGS, an accumulation is one or more reservoirs that share a particular trap, charge, and set of reservoir characteristics, generally known as a total petroleum system (TPS). Continuous accumulations are areally extensive reservoirs not necessarily related to conventional structural or stratigraphic traps. Following the USGS definition, continuous-type gas is pervasively present throughout the continuous accumulation, so that gas can be found in almost every location drilled in the AU. However, it can be produced economically only in “sweet spots,” which are areas within an AU where production characteristics are more favorable.

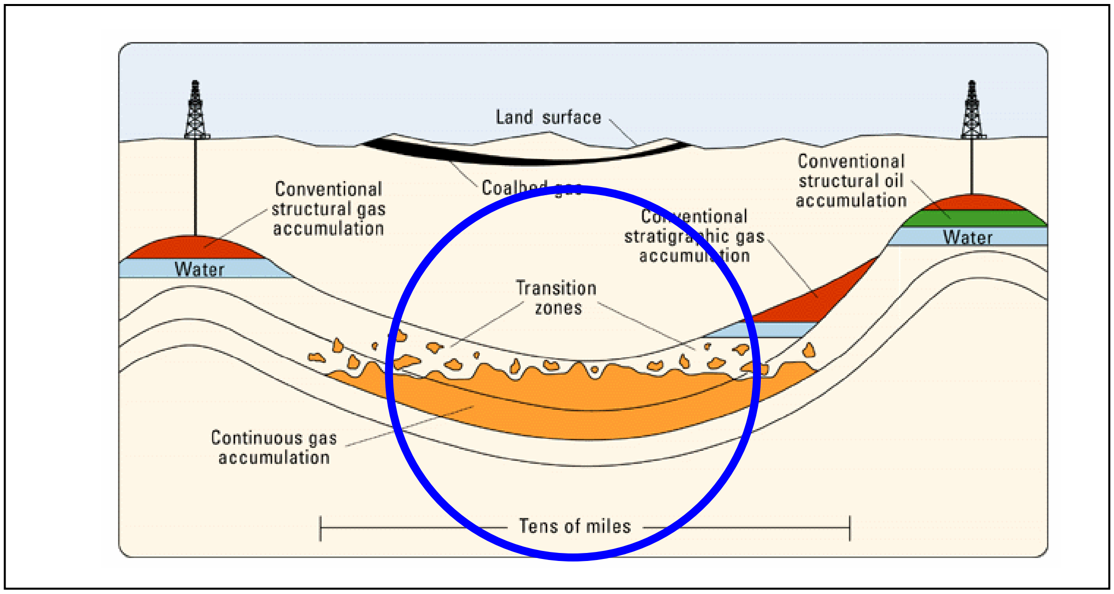

Fig. 2—Geological setting for continuous accumulation according to the USGS definition (From USGS[20]).

The USGS developed a hierarchical scheme that consists of regions, geologic provinces, total petroleum systems (TPS) and assessment units (AU). The regions serve as organizational units. A geological province is a spatial entity with common geologic attributes that encompasses a natural entity such as a sedimentary basin or a thrust belt. A total petroleum system (TPS) is a mappable entity encompassing genetically related oil and/or gas that have been generated by a pod of mature source rock, together with the fundamental processes of generation, migration, entrapment and preservation of petroleum. An AU is a mappable part of a TPS in which discovered and undiscovered oil and gas accumulations constitute a single relatively homogeneous unit in terms of geology, exploration considerations and associated risk.

Periodically, the USGS performs assessment meetings where they discuss and approve the evaluation performed by the assessors. The general approach followed by the USGS to assess undiscovered petroleum resources is presented in **Fig. 3**.

The FORSPAN Model

The FORSPAN geologic assessment model was designed by the USGS for the assessment of continuous accumulations of oil and natural gas.[21] Continuous accumulations include tight gas reservoirs, coalbed gas, oil and gas in shale, oil and gas in chalk, and shallow biogenic gas. FORSPAN is an acronym for "forecast span."

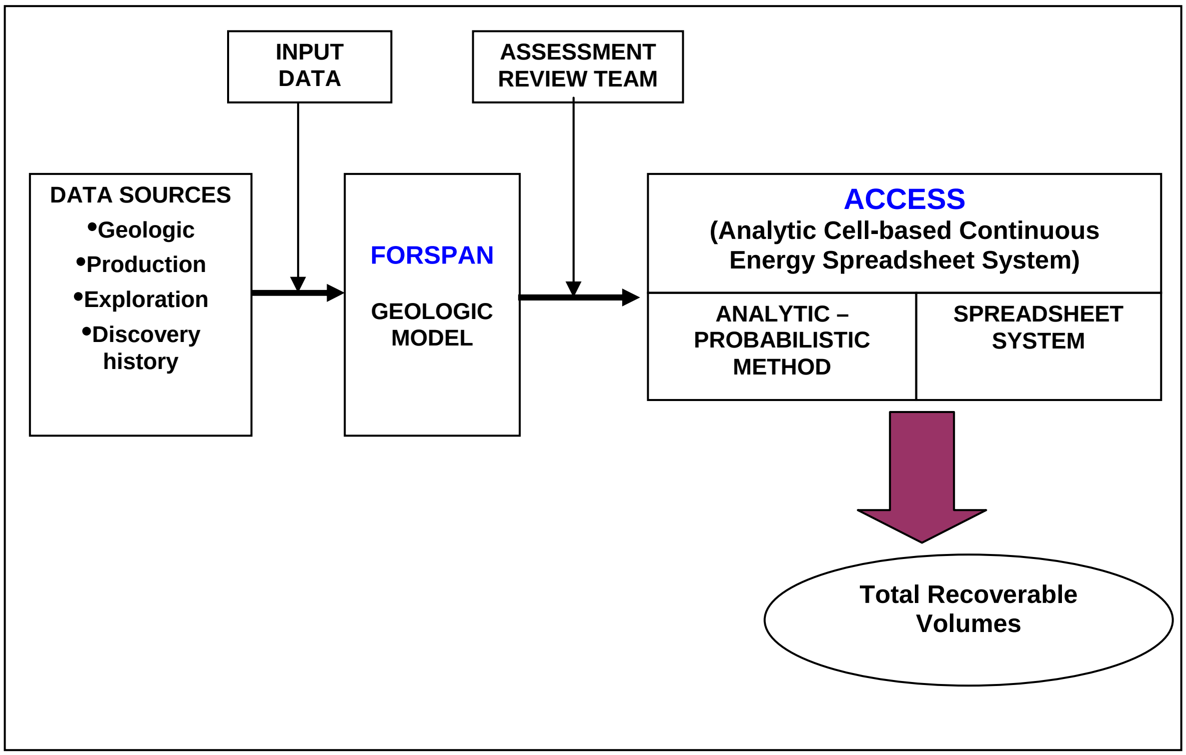

Fig. 3—Schematic of the USGS general methodology to assess continuous-type resources.

The USGS methodology does not calculate in-place volumes of oil or gas. According to the USGS, volumetric assessments are not suitable for continuous accumulations because geologic characteristics and rock properties, such as area, thickness, porosity and hydrocarbon saturation have huge associated uncertainties and are particularly difficult to model in continuous accumulations. Instead, using the FORSPAN model, the USGS treats the continuous accumulation as a collection of cells containing oil and/or gas. Cells are areas capable of producing oil or gas and could each potentially be drained by one well.

FORSPAN is a reservoir-performance-based assessment model in which production data are used to forecast potential additions to reserves. This model is particularly well suited to continuous accumulations that are already partially developed. In the absence of sufficient drilling and production data, the assessor must use information from analog continuous accumulations. The FORSPAN model is based on the concept of the AU. The AU concept and the division of the AU into cells are presented in **Fig. 4**. Proper identification and delineation of continuous assessment units is essential to the FORSPAN assessment model.

The 1995 USGS national resource assessment took the TPS as the basic unit. The USGS 2000 NOGA series takes the AU as the fundamental unit. A TPS may equate to a single AU. In some cases a TPS may be subdivided into two or more AUs in the event each AU is sufficiently homogeneous to be identified as so.

The FORSPAN Procedure

The FORSPAN model requires geological and engineering input data. Essential geographic, geologic, discovery history, production and engineering data are required for the proper use of FORSPAN. The USGS uses data from IHS Energy Group, the PI/Dwight's US well data and PI/Dwight's US production data. Additional field and reservoir data come from Richard Nehring's NRG associates database. The USGS has adopted a 30-year forecast span for its assessments of continuous resources.

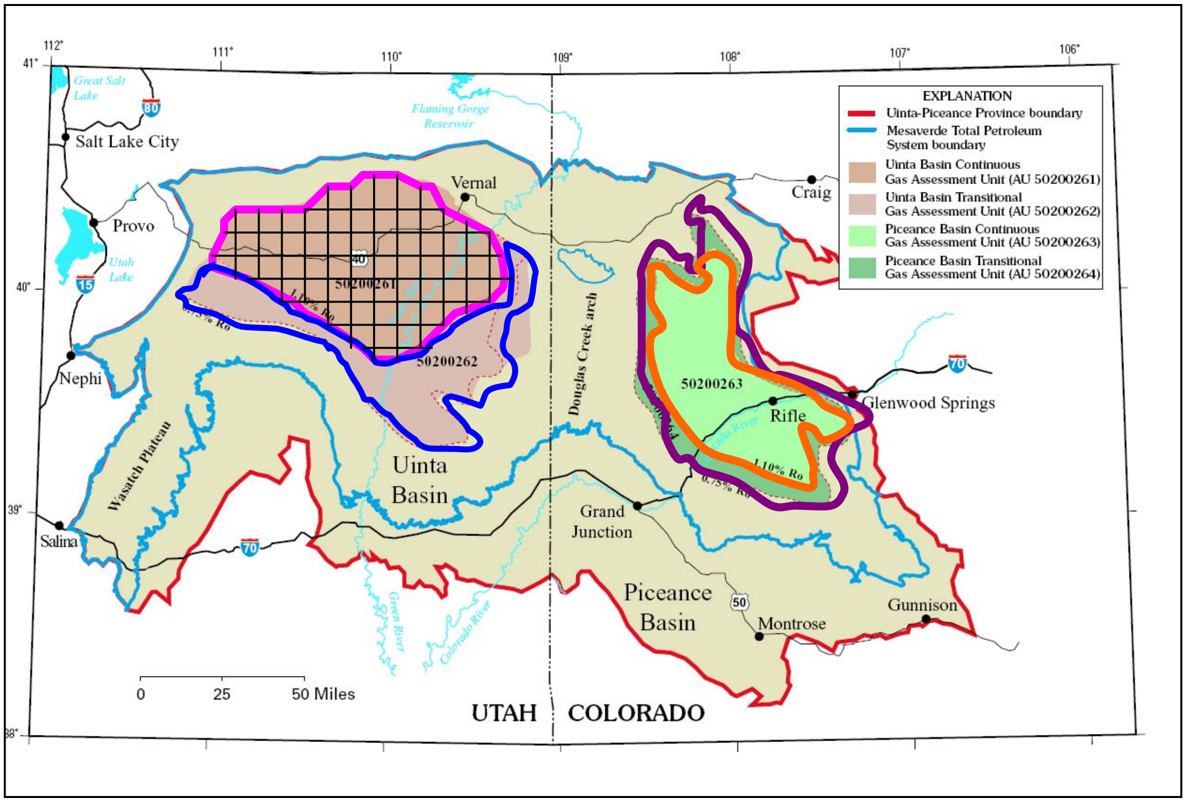

Fig. 4—Map of the Uinta-Piceance province showing four different assessment units for continuous accumulations (After USGS[14]).

To define the geologic model using FORSPAN the assessor has to perform spatial analysis using a geographic information system (GIS) and volumetric analysis using petroleum engineering models to define the following variables:

Total AU area (U)

To define the AU area the assessor has to define boundaries based on mapped geologic characteristics such as outcrops, depth, or degree of thermal maturation. These boundaries may be fixed or may possess varying amounts of uncertainty. The range in the AU area should reflect the uncertainty in the geologic extent of the AU. Boundaries of TPS and AU should be properly drawn and digitized. For the Uinta-Piceance province, the AU boundaries are upward vertical projections to the surface of vitrinite reflectance (Ro) contours as presented in **Fig. 5**. The AU area is represented by a triangular distribution with a minimum, mode, and maximum value, from which the mean value is calculated.

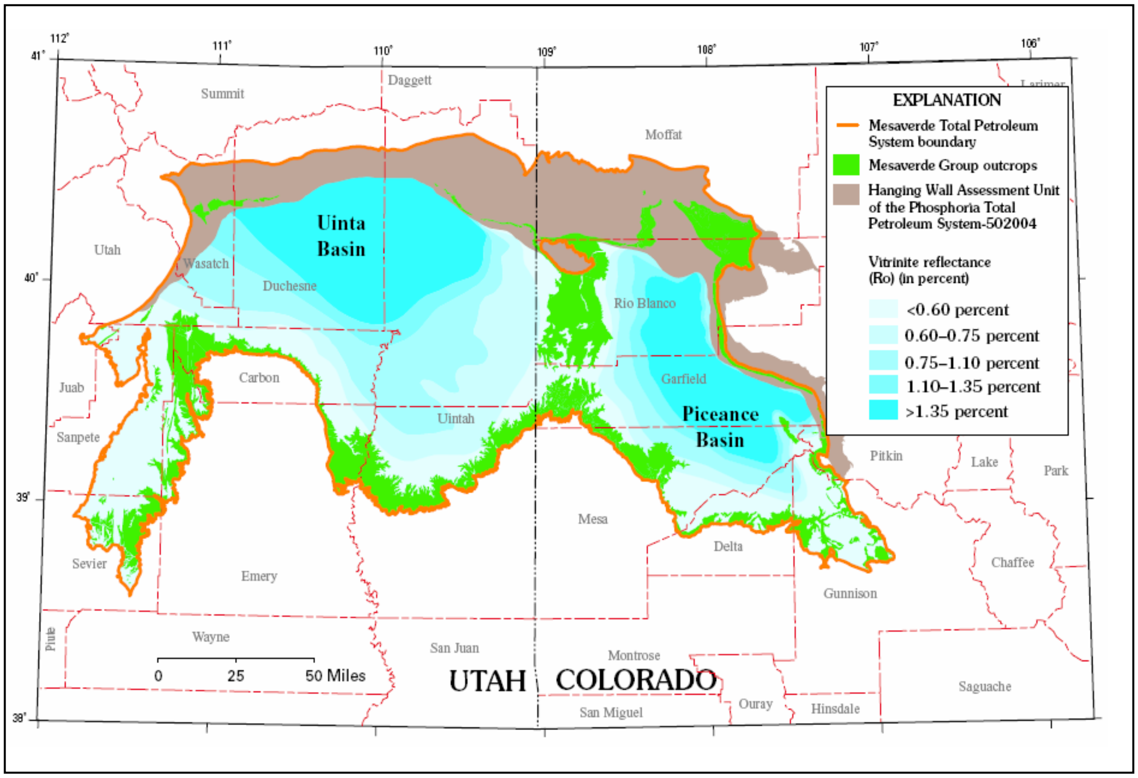

Fig. 5—Assessment unit boundaries defined by variations in thermal maturity based on vitrinite reflectance, Ro (From USGS[21]).

Area per cell of untested cells having potential for additions to reserves (V)

To determine this variable, the assessor has to perform a number of prior calculations. Once the boundaries of the AU are determined, it is necessary to create a list of those wells that exist within the AU boundaries. This list is then used to select all the wells that could have tested the reservoir intervals of cells within the AU. Now the assessor can determine the total number of tested cells in the AU. Thus the analysis recognizes two types of cells: tested cells and untested cells. Tested cells include those evaluated by drilling where hydrocarbons are produced, production is demonstrated by formation tests, evidence of hydrocarbon presence is observed on cores or well logs, or hydrocarbon shows present in mud logs. Untested cells have not been evaluated by drilling. It means there are no wells inside them. **Fig. 6** shows the concept of tested and untested cells in the AU.

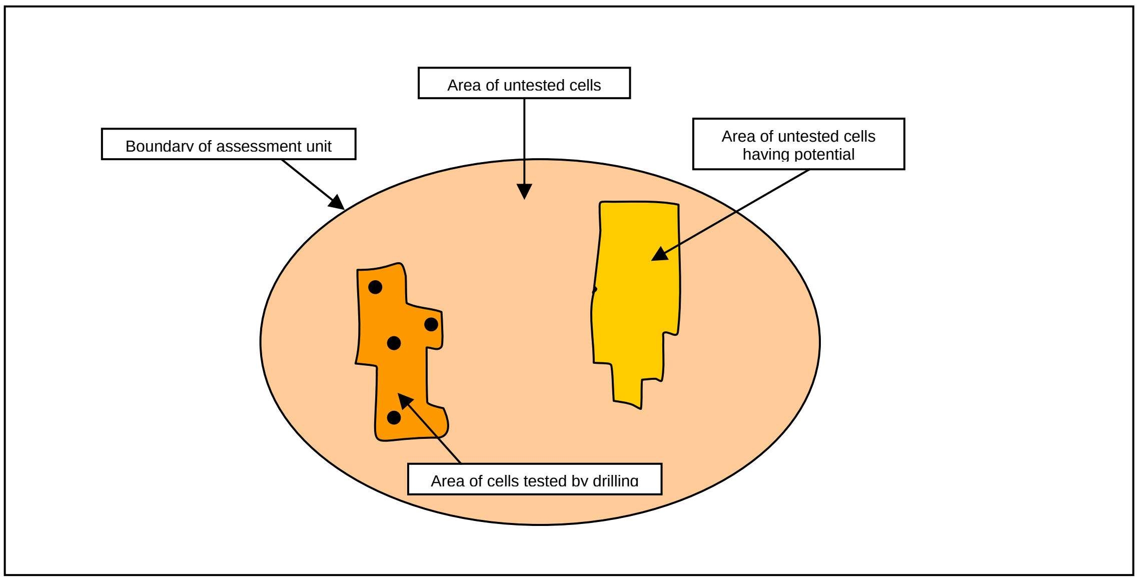

Fig. 6—Description of the three different types of petroleum-charged cells used in the USGS methodology.

The area per cell of productive (tested) cells is determined from the drainage areas of productive wells calculated from EUR estimations. The area per cell of untested cells is the area that could potentially be drained by one well (**Fig. 7**). As this area is not uniform, it is represented by a triangular probability distribution.

Percentage of total AU area that is untested (R)

The mean value of this variable is easily calculated if we know the total AU area and the percentage of total AU area that has been tested. The minimum and maximum values are calculated in the following way. The minimum value of untested area is expected if the minimum total AU area and the maximum area per cell occur. The maximum value of untested area is expected if the maximum total AU area and the minimum area per cell occur. A triangular distribution represents the percentage of total AU area that is untested.

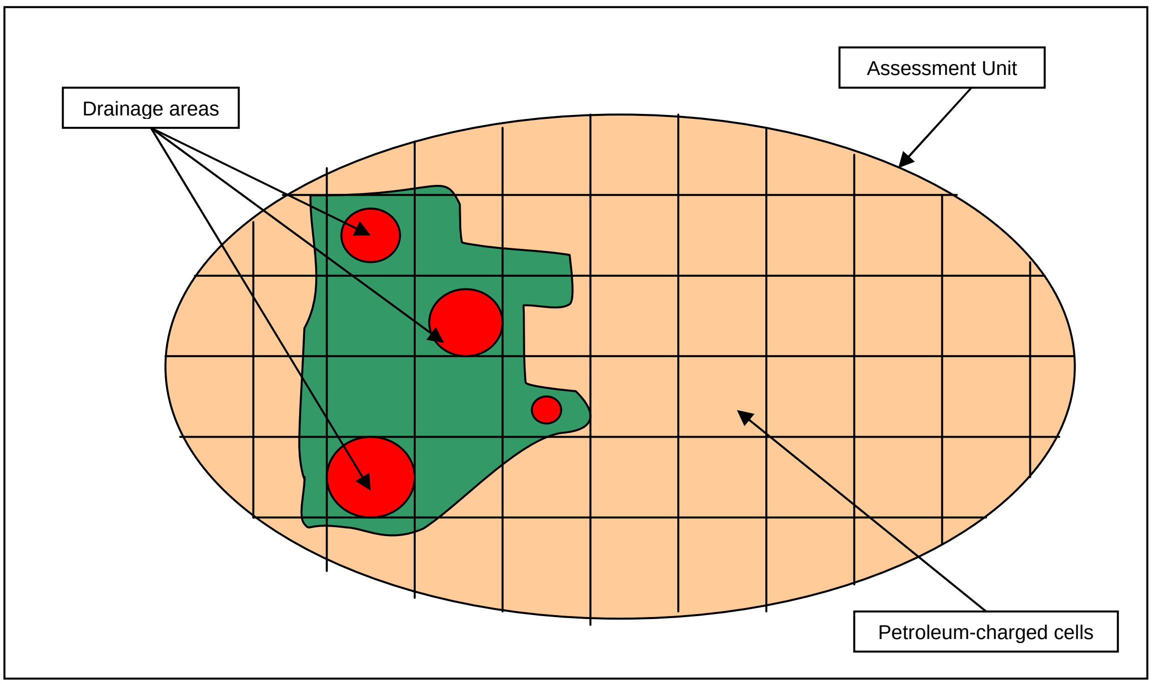

Fig. 7—Drainage areas of producing wells in a continuous accumulation.

Percentage of untested AU area that has potential for additions to reserves(S)

This variable reflects the size (area) of known and unknown sweet spots. According to the USGS, there are different ways to estimate the percentage of untested AU area that has potential for additions to reserves. These include, visual inspection of maps combined with geologic knowledge of the area, and educated guess. A triangular distribution is used to describe this input variable.

Total recovery per cell (X)

Historical production data from wells in the study area or analogs and decline curve analysis are used to calculate the expected total recovery per cell of cells yet to be drilled using. **Fig. 8** shows the distributions of EURs of wells within the AU. A shifted truncated lognormal distribution is used to represent this variable.

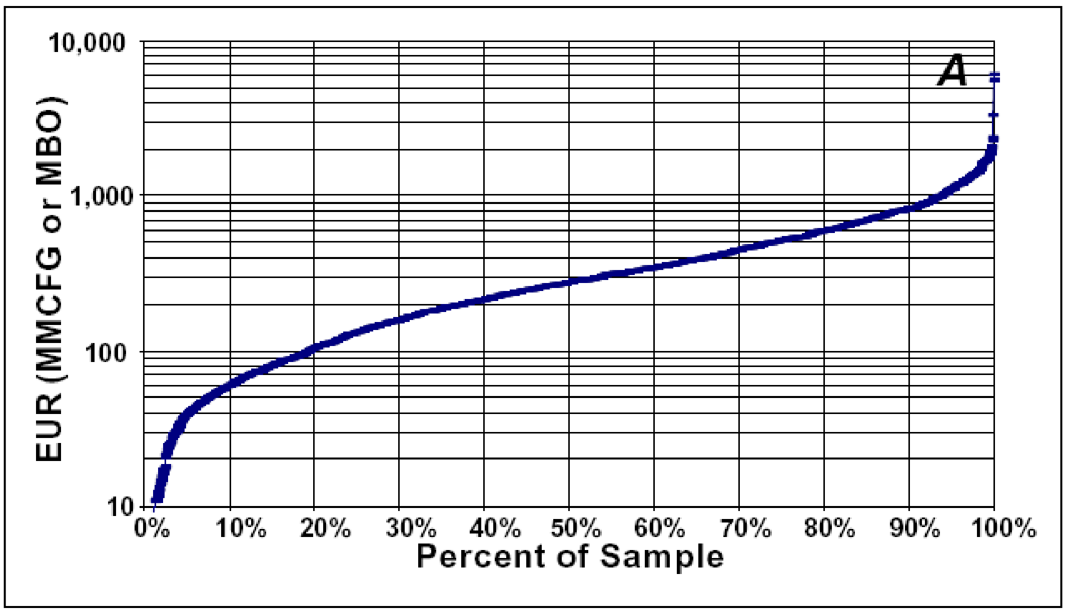

Fig. 8—EURs of oil or gas are used to determine the distribution of total recovery per cell in cells yet to be drilled (From USGS[21]).

The USGS Analytic-Probabilistic Methodology

The USGS Analytic Cell-based Continuous Energy Spreadsheet System (ACCESS) method was developed to calculate continuous-type petroleum resources for the geologic assessment model called FORSPAN. The ACCESS method is based upon mathematical equations derived from probability theory in the form of a computer spreadsheet.[22] The ACCESS model combines the random variables of the geologic assessment model,

1. AU area (U)
2. Percentage of total AU area that is untested (R)
3. Percentage of untested AU area having potential for additions to reserves (S)
4. Area per cell of untested cells (V)
5. Total recovery per cell (X),

to determine new random variables of interest such as oil in oil AU or gas in gas AU. The USGS developed a probabilistic method to compute the estimates of unconventional hydrocarbon resources in terms of the following parameters: mean, standard deviation, and fractiles F_{95}, F_{50} and F_5 for a resulting probability distribution.

The three main characteristics of the ACCESS methodology are that it:

1. Relates the input and output variables with mathematical equations
2. Computes the mean, standard deviation, minimums and maximums directly and exactly, and
3. Computes the estimates instantaneously (no need for iterative processes).

The USGS procedure to calculate the total oil or gas in an AU is:

Step 1: Determine the potential untested percentage of assessment-unit area. The following random variables are defined:

R: Percentage of total AU area that is untested

S: Percentage of untested AU area that has potential for additions to reserves

T: Potential untested percentage of assessment-unit area

$$T = R * S \qquad (1)$$

The mean (μ_T) and standard deviation (σ_T) of T are:

$$\mu_T = \mu_R * \mu_S \text{ ....} \quad (2)$$

$$\sigma_T = \sqrt{\mu_R^2 \sigma_S^2 + \mu_S^2 \sigma_R^2 + \sigma_R^2 \sigma_S^2} \text{ …………………} \quad (3)$$

Step 2: Calculate the potential untested area of assessment unit. The following additional random variables are defined:

U: Total AU area

W: Potential untested area of assessment unit

W = T * U

The mean (μ_w) and standard deviation (σ_w) of W are:

$$\mu_W = \mu_T * \mu_U \text{ ....} \quad (4)$$

$$\sigma_W = \sqrt{\mu_T^2 \sigma_U^2 + \mu_U^2 \sigma_T^2 + \sigma_U^2 \sigma_T^2} \text{ ………..................} \quad (5)$$

Step 3: Determine the number of potential untested cells. The following additional random variables are defined:

V: Area per cell of untested cells having potential for additions to reserves

N: Number of potential untested cells

$$W = \sum_{i=1}^{N} V_i \text{ …………………………………………..……} \quad (6)$$

The mean (μ_N) and standard deviation (σ_N) of N are:

$$\mu_N = \mu_W / \mu_V \quad \text{..} \quad (7)$$

$$\sigma_N = \sqrt{(\sigma_W^2 - \mu_N \sigma_V{}^2) / \mu_V{}^2} \quad \text{........................} \quad (8)$$

Step 4: Determine the amount of gas in the AU. This is calculated as a summation of total recovery per cell over all the potential untested cells:

$$Y = \sum_{i=1}^{N} X_i \quad \text{..} \quad (9)$$

N: Number of potential untested cells

X: Total recovery per cell (BCF)

Y: Gas Resources in the AU (BCF)

The mean and, standard deviation of Y can be derived from probability theory:

Mean Value:

$$\mu_Y = \mu_N * \mu_X \quad \text{..} \quad (10)$$

Standard Deviation:

$$\sigma_Y = \sqrt{\mu_N \sigma_x{}^2 + \mu_x{}^2 \sigma_N{}^2} \quad \text{.................................} \quad (11)$$

To derive the standard deviation in Eqs. 6 and 9 which are summations, the USGS applied the central limit theorem (CLT) which establishes that the sum of a large number of independent random variables has a distribution that is approximately normal.[23]

According to the Central Limit Theorem, the variance and standard deviation of the new probability distribution (H) resulting from the summation of *n* trials sampled from a given probability distribution are calculated as:

$$Var_{(H)} = \frac{\sigma^2}{n} \quad \text{..} \quad (12)$$

$$\sigma_{(H)} = \frac{\sigma}{\sqrt{n}} \quad ,\text{.......................................} \quad (13)$$

where σ is the standard deviation of the original probability distribution being sampled.[24]

According to the presented above, Eqs. 8 and 11 represent the standard deviation of an approximately normal distribution resulting from the summation of *N* number of cells in the AU.

Because unconventional gas resources are expected to be log-normally distributed in nature, the mean and standard deviations for the resources calculated using the analytic-probabilistic equations are used by the USGS to create a log-normal distribution. The F_{95}, F_{50} and F_5 fractiles are then read from this distribution and tabulated. **Fig. 9** shows a comparison between the log-normal distribution presented by the USGS for the total unconventional gas resources in the Uinta AU in the Mancos Mowry TPS and a normal distribution with the same mean and standard deviation. Although the USGS distribution is log-normal, it is not highly skewed and is similar to a normal distribution.

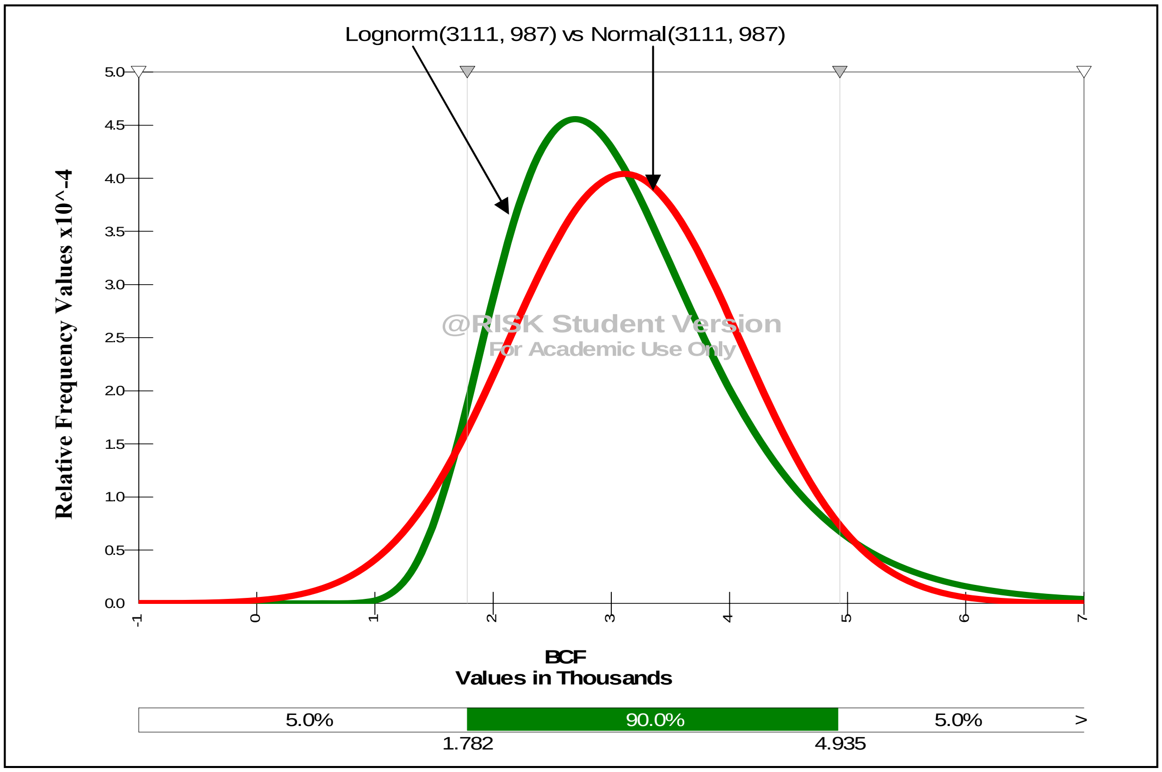

Fig. 9—Comparison of the USGS log-normal distribution for total unconventional gas resources in the Uinta AU of the Mancos Mowry TPS and a normal distribution with the same mean and standard deviation.

POTENTIAL PROBLEMS WITH THE USGS METHODOLOGY

The first indication that there may be problems with the USGS methodology is in the final distributions for potential unconventional gas resources presented. **Table 1** presents the results for the USGS 1995 US national unconventional natural gas resource assessment. The resource estimate ranges from a P_{95} value of 262.3 Tcf to a P_5 value of 474.2 Tcf. The P_5/P_{95} ratio is only 1.8, which is very small range considering that this is an assessment of total US undiscovered, untested unconventional gas resources.

Table 2 shows the results for a most recent USGS study performed in 2002, the USGS unconventional gas resource assessment for the Uinta-Piceance province of Utah and

Colorado. **Fig. 10** shows the distribution for potential unconventional gas resource in the entire province. An examination of this probability distribution shows a small standard deviation and narrow confidence interval. The resource estimate ranges from a P_{95} value of 12,110 Bcf to a P_5 value of 33,876 Bcf. The P_5/P_{95} ratio is only 2.8, which is also very small. Similar narrow ranges are observed for resource estimates for individual AUs. P_5/P_{95} ratios range from 1.5 to 5.7 with a median P_5/P_{95} ratio of 2.85. In both cases mentioned above it seems unreasonable to expect a 90% probability that the actual unconventional gas resources fall within these narrow ranges, given that these are assessments of *undiscovered*, *untested* unconventional gas resources. Thus I sought to determine the reason for these narrow ranges.

Based on a detailed review of the current USGS methodology, I identified three potential problems with the methodology to assess potential unconventional gas resources, which limit its reliability:

1. Use of mainly triangular distributions for the input variables, which are prone to include unconscious judgmental bias and generate narrow ranges.
2. Assumption of independence between the input variables.
3. Assumption of perfect positive correlation between output probability distributions for the aggregation of individual AUs to the TPS and province level.

Use of Mainly Triangular Distributions

Triangular distributions are bounded probability distributions that require the estimation of minimum, most-likely, and maximum values. A triangular distribution is typically used as a subjective representation of a population for which there are only limited data.[25] It is based on estimates of the minimum and maximum values and an inspired guess of the modal value. This kind of distribution is commonly used in the absence of data or when data are insufficient to construct a more appropriate distribution. In any

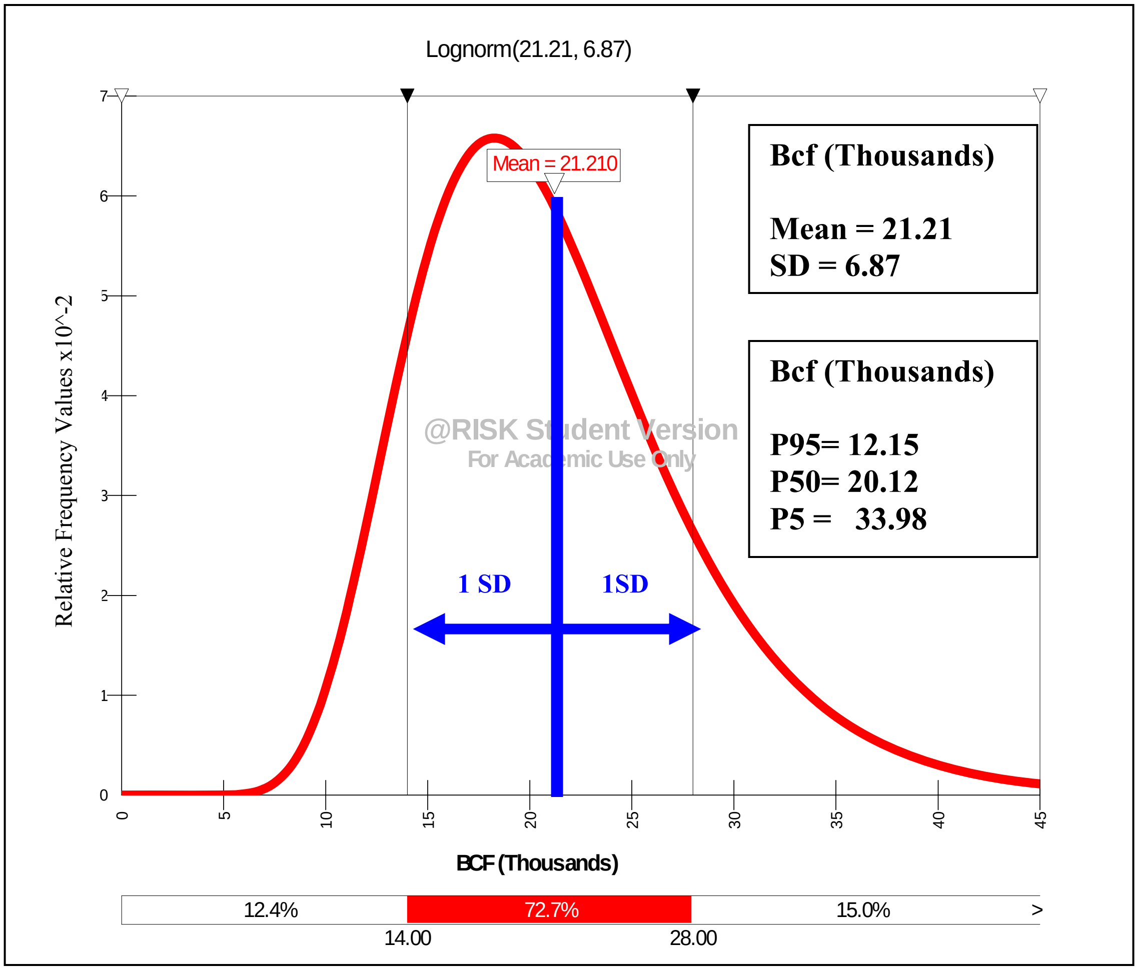

Fig. 10—Probability distribution for the total potential unconventional gas resources in the Uinta-Piceance province showing small standard deviation and a narrow confidence interval.

case, the assessor has to have a very good knowledge of the extreme values. The triangular distribution can be used as an improvement over the uniform distribution for modeling situations where central values are more likely to occur than the upper or lower bounds. It is useful as a ballpark model when minimum, maximum, and most-likely values are known, typically on the basis of subjective judgment, but not much is known about the shape of the distribution.

Triangular distributions are prone to include unconscious judgmental bias, which narrows the range of their extreme values.[11] Subjective estimates provided by experts are subject to potential biases, especially when dealing with extreme values such as the minimum F_0 and maximum F_{100}, of a triangular distribution. The more common types of human biases that tend to narrow the range between endpoints are over reliance on certain information and neglect of other information; recalling events that occur more frequently (experts tend to neglect extreme outcomes because these low-probability events rarely occur); adjustment or anchoring, which consists of selecting the most-likely value and then adjusting from that point to determine the distribution endpoints; and overconfidence in their predictive abilities.

Correlation Between Input Variables

The USGS methodology assumes independence between the input variables. Two variables are said to be independent when there is no correlation between them; i.e., the correlation coefficient between them is zero. Correctly establishing the degree of correlation between variables and including it in the calculation process is critical to avoid nonsensical results. For example, in the oil industry it is very well known that, for a heavy oil reservoir under steam injection, well spacing and total recovery are negatively correlated. This means that if well spacing increases, total recovery decreases, and vice versa. If correlation is not included between these two variables during the sampling process, we can pick a high well spacing value corresponding to a high total recovery value, which is not a realistic combination.

Concern about lack of correlation between input variables arises in the USGS methodology because it includes input distributions for area per cell and recovery per cell. Because the area per cell is related to drainage area, we would expect there to be a positive correlation between the distributions for area per cell and recovery per cell. Cursory examination of other input distributions indicates that there may be correlation between other parameters, possibly introduced by the use of common assessors for multiple assessment units. **Fig. 11** shows the existence of correlation between input variables for the Mesaverde TPS from USGS data. **Fig. 12** presents correlation coefficients found using data from six AUs in the Mesaverde TPS. Despite the fact that some of the correlation coefficients seem unrealistic (possibly because they are based on few data points), all of them are different than zero as assumed by the USGS.

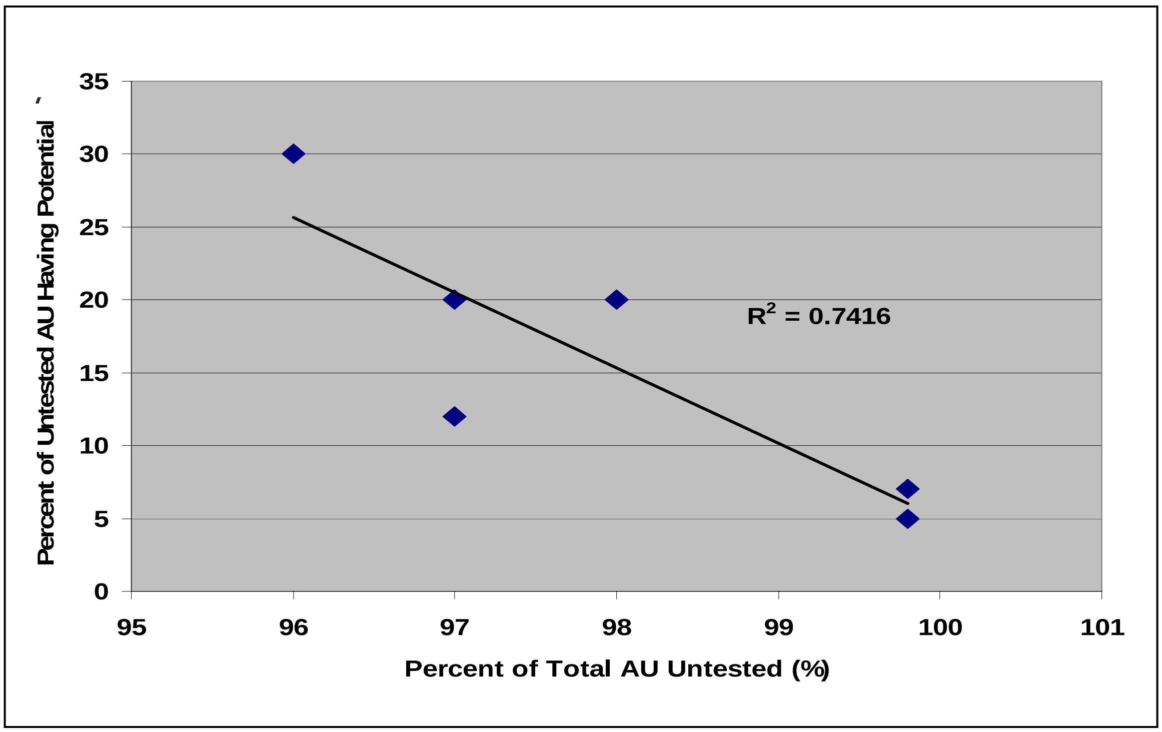

Fig. 11— Bivariate correlation for the Mesaverde TPS showing correlation between variables for the different AUs.

Concerns with the Assumption of Perfect Positive Correlation in the Aggregation from the AU Level to the TPS and Province Level

The USGS methodology assumes perfect positive correlation for the aggregation of resources from the AU level to the TPS and province levels. Perfect correlation implies that, during the aggregation, picking a high value in one distribution implies picking a high value in the other, and vice versa. The assumption of perfect positive correlation allows the USGS to add not only the mean values but also all the percentiles, which simplified greatly the calculations. The USGS claims that common geologic factors within a province will produce positive correlation between AU gas resources.[26] However, perfect positive correlation between AUs is highly unlikely. Making this assumption results in a greater range for the aggregated result than if there were not

	Total AU Area (U)	Area per Cell of Untested Cells (V)	Percentage of total AU Area that is Untested (R)	Percentage of Untested U Having Potential (S)	Total Recovery per Cell (X)
Total AU Area (U)	**1**				
Area per Cell of Untested Cells (V)	**0.459**	**1**			
Percentage of total AU Area that is Untested (R)	**0.3181**	**0.6821**	**1**		
Percentage of Untested AU Having Potential (S)	**-0.1641**	**-0.3618**	**-0.7416**	**1**	
Total Recovery per Cell (X)	**-0.272**	**-0.4702**	**-0.6324**	**0.6946**	**1**

Fig. 12—Correlation coefficient matrix for the Mesaverde TPS.

perfect positive correlation. This means that the ranges for potential unconventional gas resources in the 1995 USGS national unconventional gas assessment as well as in the entire Uinta-Piceance province are actually narrower than presented in Tables 1 and 2, which sheds even more doubt on the validity of the uncertainty quantification in these resource estimates.

The narrow ranges produced by the USGS methodology and the identification of these potential problems with the methodology led me to develop an improved methodology to better account for the great uncertainty surrounding these resource assessments.

DEVELOPMENT OF AN IMPROVED METHODOLOGY

The assessment of unconventional hydrocarbon resources embraces a great amount of uncertainty, especially when dealing with undiscovered and untested potential unconventional gas resources. A realistic assessment of the uncertainty surrounding potential unconventional gas resources is crucial in making development decisions for these kinds of resources. A more realistic quantification of uncertainty helps to determine the upside and downside potentials of the resources.

BETTER ASSESSMENT OF THE INPUT VARIABLES

The USGS uses triangular distributions to describe four area-related input variables,

1. AU area (U),
2. Percentage of total AU area that is untested (R),
3. Percentage of untested AU area having potential for additions to reserves (S), and
4. Area per cell of untested cells (V).

Total recovery per cell (X) is represented by a shifted, truncated log-normal distribution.

There are two different situations to define a probability distribution for an input variable: when data are available, and when scarce data or no data available.

When Data Are Available

If there are enough data to create a probability distribution, there is no justification to use only triangular distributions, unless the distributions are actually triangular. In the presence of data, the assessor can use a commercial probabilistic analysis program to try to find the best fit of the data to an adequate probability distribution. An unbiased estimator should consider the beta distribution,[27] which offers a lot of modeling possibilities because of the variety of shapes the beta density function can assume by changing its shape parameters α and β (**Fig. 13**). The beta distribution can generate triangular, normal, log-normal, weibull, among many other distributions.

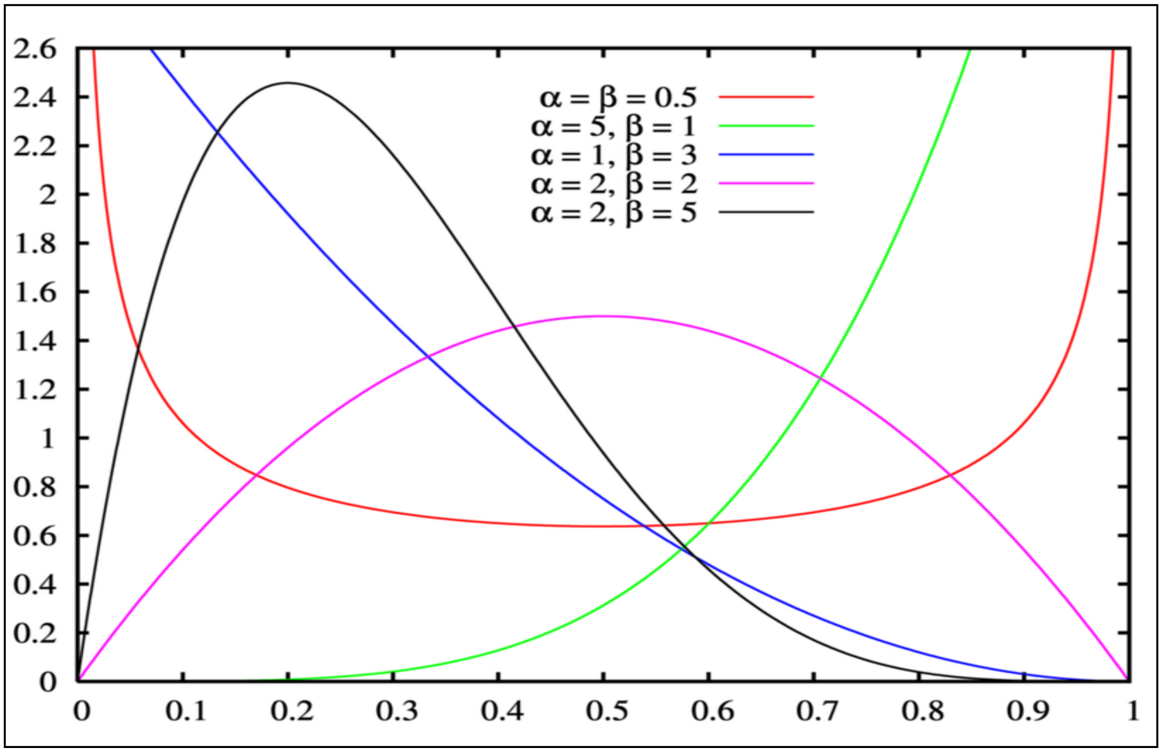

Fig. 13—Probability density functions for a beta distribution showing different shapes according to the values assigned to α and β (Graph from: www.Wikipedia.com).

Scarce Data or No Data Available

For this particular case, triangular distributions can be suitable if we prevent the inclusion of unconscious judgmental bias. Instead of assigning the most-likely and the extreme values F_0 and F_{100}, the assessor assigns other percentiles, such as the F_{20} and F_{80} or F_{10} and $F_{90.}$ This procedure avoids in part the heuristics and biases for judgment under uncertainty.

Adjustment and anchoring is one of the most common biases. It consists on starting from an initial value that is anchored, and then adjusting to get the extreme values. Adjustments are typically insufficient and estimates are biased to the initial value.

There is a procedure presented by Hudak[11] to extend triangular probability distributions and calculate the extreme values F_0 and F_{100} departing from any percentiles calculated by the assessor. The Hudak's procedure can be easily implemented using a spreadsheet. **Fig. 14** shows the procedure based on similar triangles to extend triangular probability distributions.

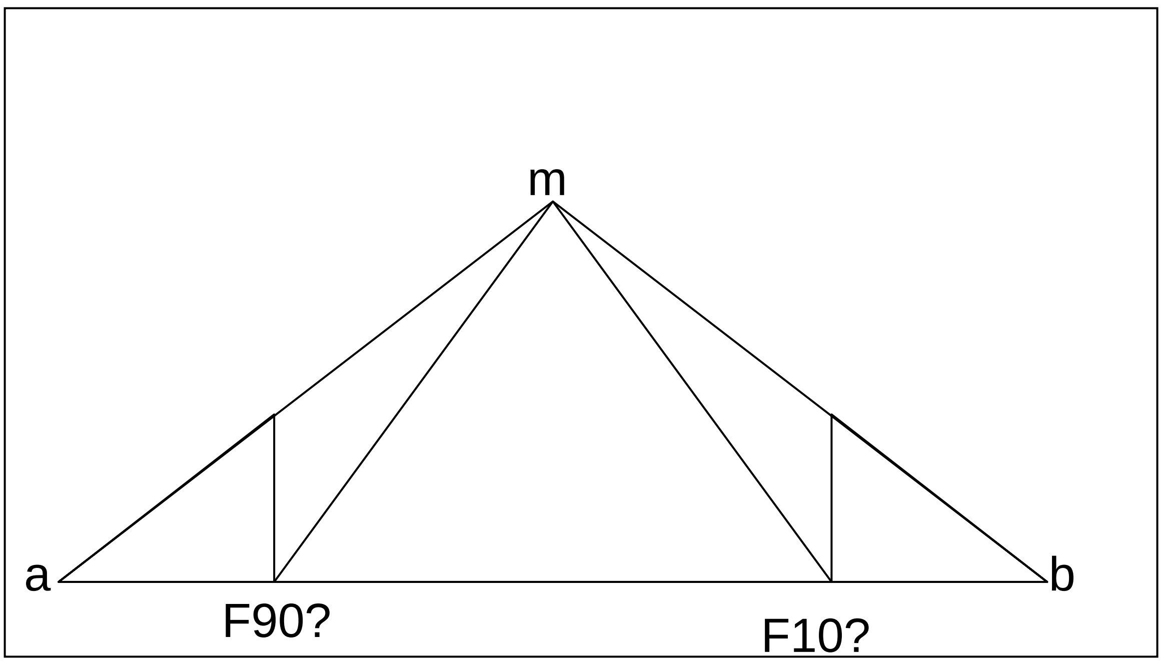

Fig. 14—Schematic showing the creation of narrow triangular probability distributions caused by unconscious judgmental bias and the procedure to correct this problem.

From the original probability distribution provided by the assessor, m, F_{90} and F_{10} or any other pair of percentiles is known. The problem consists of finding the values of *a* and *b*, which are the actual extreme values F_0 and F_{100} of the extended probability distribution.

$$d_1 b^4 + d_2 b^3 + d_3 b^2 + d_4 b + d_5 = 0 \quad \text{...}(15)$$

$$a = \frac{b - (b - F_{10})^2}{(1 - F_{10})(b - m)} \quad \text{...}(16)$$

Eqs. 15 and 16 are implemented and solved in a spreadsheet to find the values *a* and *b*. Description of the "*d*" coefficients in Eq. 15 is available in Hudak's paper.[11]

THE STOCHASTIC APPROACH

My improved methodology to assess potential unconventional gas resources encompasses a stochastic approach that includes:

1. Monte Carlo simulation (MCS) with Latin hypercube sampling (LHS), and
2. Correlation of the input probability distributions.

My model includes the five original USGS probability distributions as input variables, to quantify only the impact of the difference in methodology. To rigorously sample V and X and represent the summations presented in Eqs. 7 and 10, I included individual spreadsheet cells for all the possible number of potential untested cells in an AU, as many as 10,000 cells in some cases. For each Monte Carlo iteration the model samples the input probability distributions and calculates the potential untested area of the AU (W). Then the model samples values of area per cell (V) and total recovery per cell (X) for a maximum number of potential untested cells determined in the spreadsheet. A running sum of areas per cell equal to the potential untested area (W) determines the number of cells (N) for that iteration. Finally, the recoveries per cell for the N cells are summed to get the total recovery in the AU (Y) for that iteration. Inclusion of a correlation matrix allows me to investigate the effects of correlation between input distributions.

To implement this methodology I used the commercial risk analysis package @Risk™ from Palisade DecisionTools. I developed a spreadsheet model for both the USGS analytic methodology and my improved methodology, so I could compare results.

APPLICATION OF THE IMPROVED METHODOLOGY AND ANALYSIS OF RESULTS

The USGS methodology and my Monte Carlo model were both applied to estimate potential unconventional gas resources in several AUs in the Uinta-Piceance province. For consistency, I am going to present first a complete analysis for the Piceance transitional AU of the Mesaverde TPS, and then an analysis of the total Uinta-Piceance province. I used the original USGS probability distributions for the five input variables in both cases, to quantify only the impact of the differences in methodology. In this first comparison, I assumed no correlation between input variables.

Analysis of the Piceance Transitional AU

Fig. 15 shows the histogram and best-fit distribution for total gas resources in the Piceance transitional AU resulting from the Monte Carlo approach, using 5,000 iterations. The distribution is near normal in shape, although slightly skewed to the left. The distributions of number of potential untested cells resulting from the two methods are compared in **Fig. 16.** A comparison of the distributions for total AU gas resources from the two methods is presented in **Fig. 17**. For each quantity, the means and standard deviations of the distributions from the two methods are very close (e.g., mean and standard of 302 Bcf and 107 Bcf for USGS versus 288 Bcf and 102 Bcf for the stochastic model in Fig. 17). This validates the USGS methodology, at least partially. However, the distribution shapes resulting from the two methods are noticeably different.

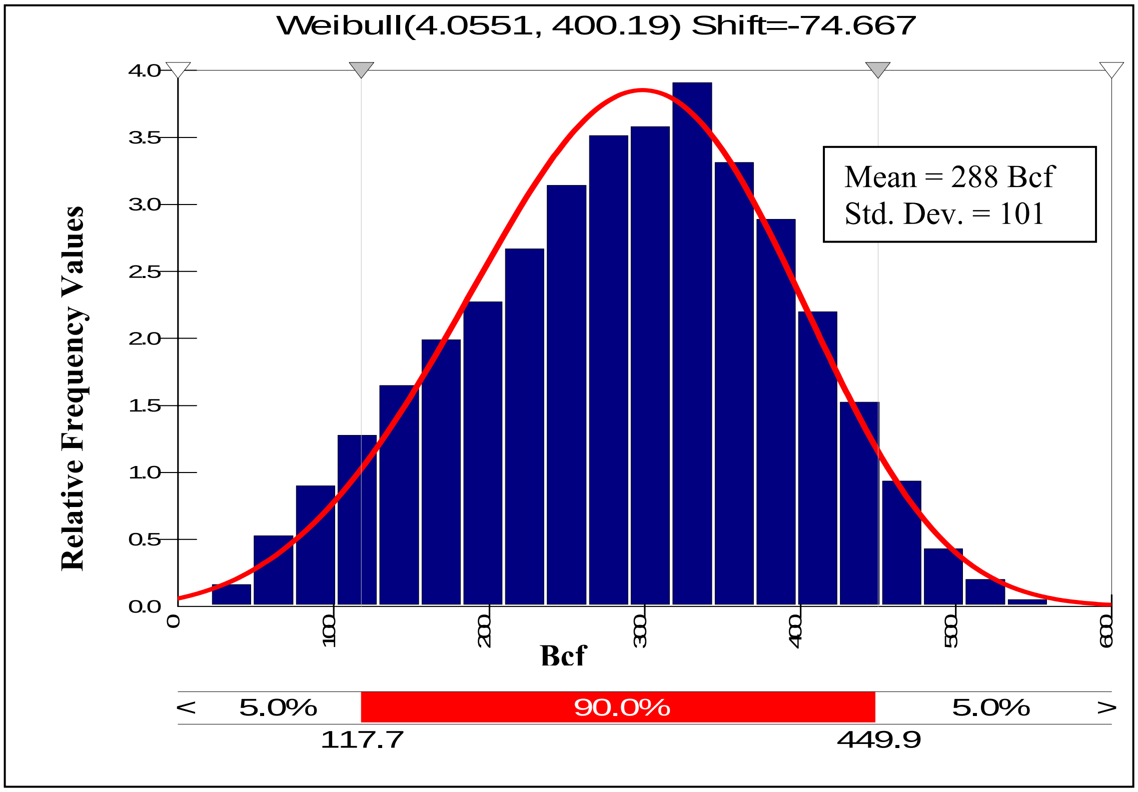

Fig. 15—Histogram and best-fit distribution for the total gas recovery in the Piceance transitional AU. The distribution is near normal in shape, and slightly skewed to the left.

It is important to recall that the USGS methodology produces only a mean and standard deviation value from the analytic equations, and then generates a log-normal distribution with the calculated mean and standard deviation. A log-normal distribution is assumed because the resources are expected to be log-normally distributed. Figs. 16 and 17**,** and **Table 3** show that the actual distributions calculated using the USGS equations. and data, instead of being log-normal in shape, are actually skewed in the opposite direction, albeit slightly.

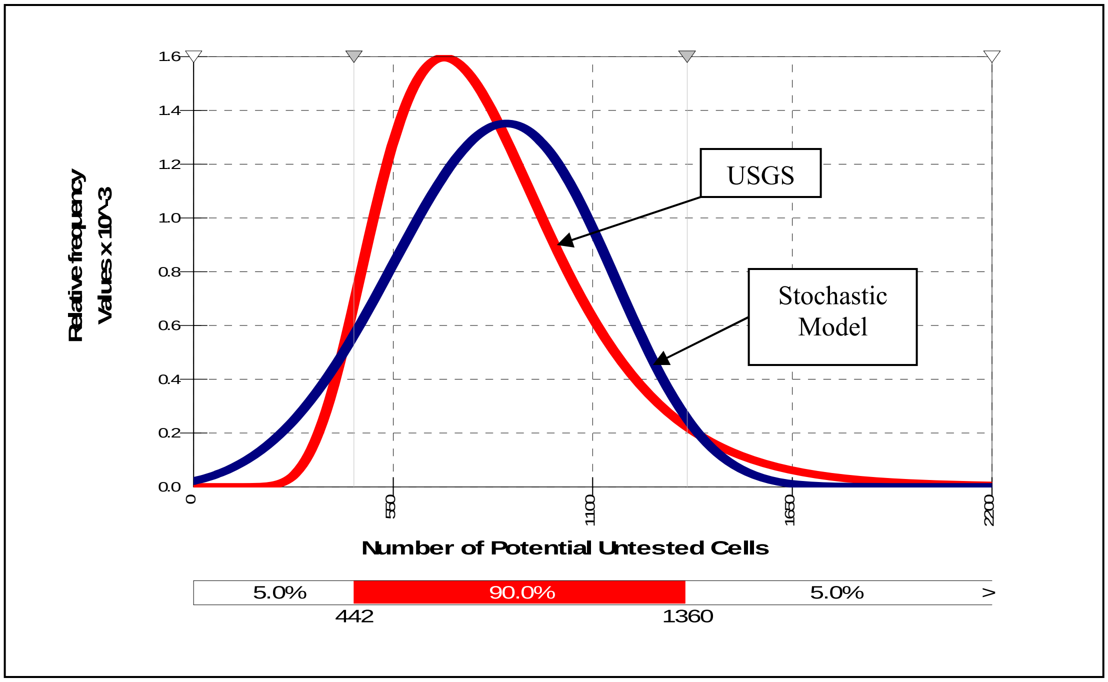

Fig. 16—PDF comparison for the number of potential untested cells in the Piceance transitional AU. The USGS and stochastic model distributions have virtually the same means and standard deviations, but different shapes.

Table 3 shows a comparison of statistical parameters for the distributions generated for the total gas recovery in the AU (*Y*) by the USGS methodology and the stochastic method. Skewness and kurtosis values are rather different, especially the skewness of the probability distributions generated by the stochastic model (MCS), which are opposite in sign.

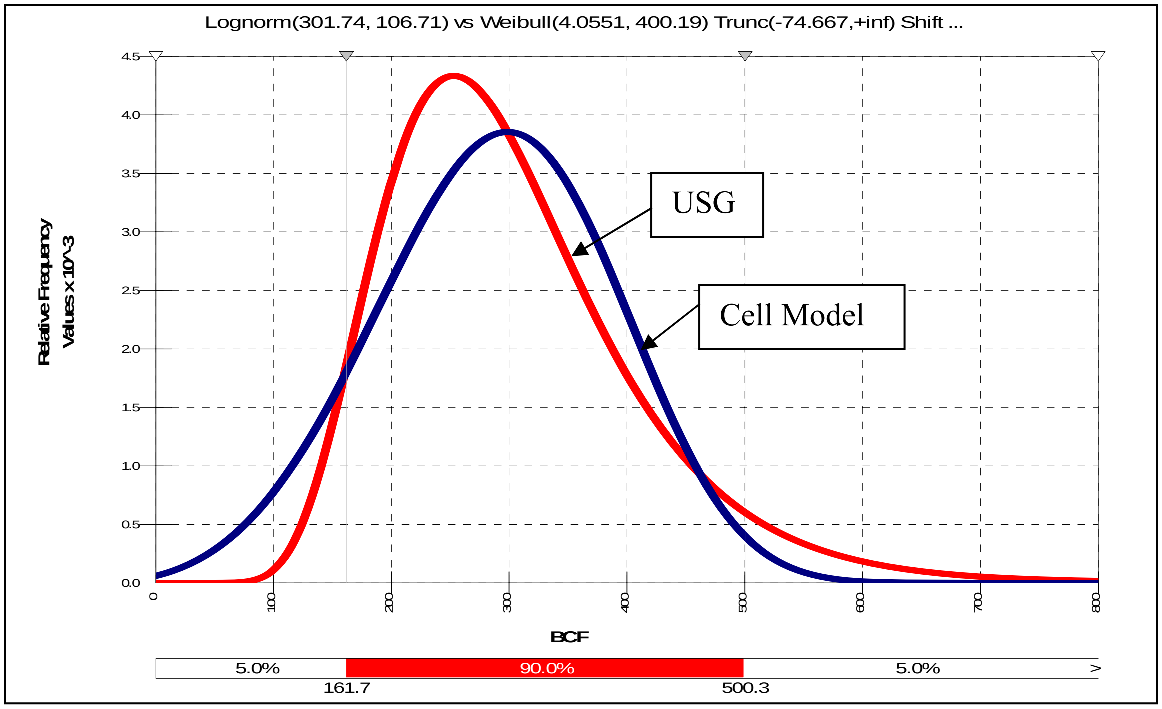

Fig. 17—PDF comparison for the total AU gas resources in the Piceance transitional AU. The USGS and stochastic model distributions have virtually the same means and standard deviations, but different shapes.

TABLE 3— STATISTICAL PARAMETERS OF RESULTING PROBABILITY DISTRIBUIONS

Variable	Mean (Bcf)	Std. Dev (Bcf)	Skewness	Kurtosis
N (USGS)	822	289	1.099	5.22
N (MCS)	828	292	-0.184	2.43
Y (USGS)	302	107	1.105	5.25
Y (MCS)	288	102	-0.168	2.45

Analysis of the Total Uinta-Piceance Province

The stochastic model is applied to each of the fourteen AUs of the Uinta-Piceance province. I use the original USGS input probability distributions to account only for the different methodologies. **Table 4** shows a comparison of statistical parameters of the resulting probability distributions for the USGS and stochastic models.

TABLE 4— STATISTICAL PARAMETERS

Assessment Unit	Model	Best Fit	Mean (Bcf)	Std. Dev (Bcf)	P95 (Bcf)	P50 (Bcf)	P5 (Bcf)	Skewness	Kurtosis
Mancos Moury / TPS									
Piceance Basin Continuous Gas	Stochastic	Triangular	1414	752	432	1286	2828	0.562	2.4
	USGS	Log-normal	1653	867	649	1463	3297	1.718	8.7
Uinta Basin Continuous Gas	Stochastic	Triangular	2664	855	1550	2520	4270	0.559	2.4
	USGS	Log-normal	3111	987	1782	2965	4934	0.984	4.8
Uinta-Piceance Trans. & Migrated Gas	Stochastic	Weibull	1645	197	1316	1647	1968	-0.007	2.7
	USGS	Log-normal	1755	212	1430	1743	2124	0.364	3.2
Mesa Verde TPS									
Uinta Basin Continuous Gas	Stochastic	Beta General	7391	2458	3238	7456	11317	-0.113	2.3
	USGS	Log-normal	7391	2441	4134	7018	11915	1.027	4.9
Uinta Basin Transitional AU	Stochastic	Beta General	1493	430	892	1436	2289	0.582	2.8
	USGS	Log-normal	1493	441	889	1432	2305	0.912	4.5
Piceance Basin Continuous Gas	Stochastic	Beta General	3030	817	1735	3002	4417	0.138	2.3
	USGS	Log-normal	3064	836	1902	2956	4594	0.840	4.3
Piceance Basin Transitional Gas	Stochastic	Beta General	288	102	117	289	452	-0.077	2.5
	USGS	Log-normal	302	107	162	284	500	1.107	5.3
Uinta Basin Blackhawk Coalbed Gas	Stochastic	Triangular	516	297	125	467	1073	0.545	2.4
	USGS	Log-normal	499	283	182	434	1034	1.884	9.9
Mesa Verde Group Coalbed Gas	Stochastic	Triangular	325	177	95	295	657	0.560	2.4
	USGS	Log-normal	368	202	139	323	750	1.812	9.4
Ferron/ Wasatch Plateau TPS									
Deep 6000 ft plus Coal & Ss Gas	Stochastic	Beta General	59	34	12	54	123	0.564	2.6
	USGS	Log-normal	66	40	0	52	136	2.040	11.2
Northern Coal Fairway/Drunkards	Stochastic	Triangular	641	192	290	666	921	-0.399	2.4
	USGS	Log-normal	752	220	451	722	1156	0.903	4.5
Central Coal Fairway/Buzzards	Stochastic	Beta General	480	147	218	492	699	-0.414	2.8
	USGS	Log-normal	537	166	312	513	844	0.957	4.7
Southern Coal Fairway	Stochastic	Triangular	154	55	54	162	234	-0.406	2.4
	USGS	Log-normal	156	54	78	146	256	1.080	5.1
Southern Coal Outcrop	Stochastic	Beta General	13	6	4	12	24	0.736	3.2
	USGS	Log-normal	18	9	0	10	31	1.630	8.0

Results from Table 4 show that the stochastic model does not produce log-normal distributions as claimed by the USGS. Instead, the stochastic model produces triangular, beta general and weibull distributions with means and standard deviations close to the

USGS values, but with rather different shape parameters (skewness and kurtosis). In several cases, the resulting probability distributions from the stochastic model have negative skewness, opposite to what is expected for log-normal distributions. The resulting probability distributions from the stochastic model are input in a spreadsheet and summed probabilistically using 10,000 iterations to get the aggregated unconventional gas resource distribution at the province level. The USGS aggregates unconventional gas resources from individual AUs to the province level by adding directly the mean and F_5, F_{50}, and F_{95} percentile values (perfect positive correlation). A log-normal probability distribution is then created using the aggregated percentiles. **Fig. 18** shows the best-fitted distribution for the stochastic model aggregation at the province level. A comparison of the distributions for the USGS and stochastic models at the province level is presented in **Fig. 19**.

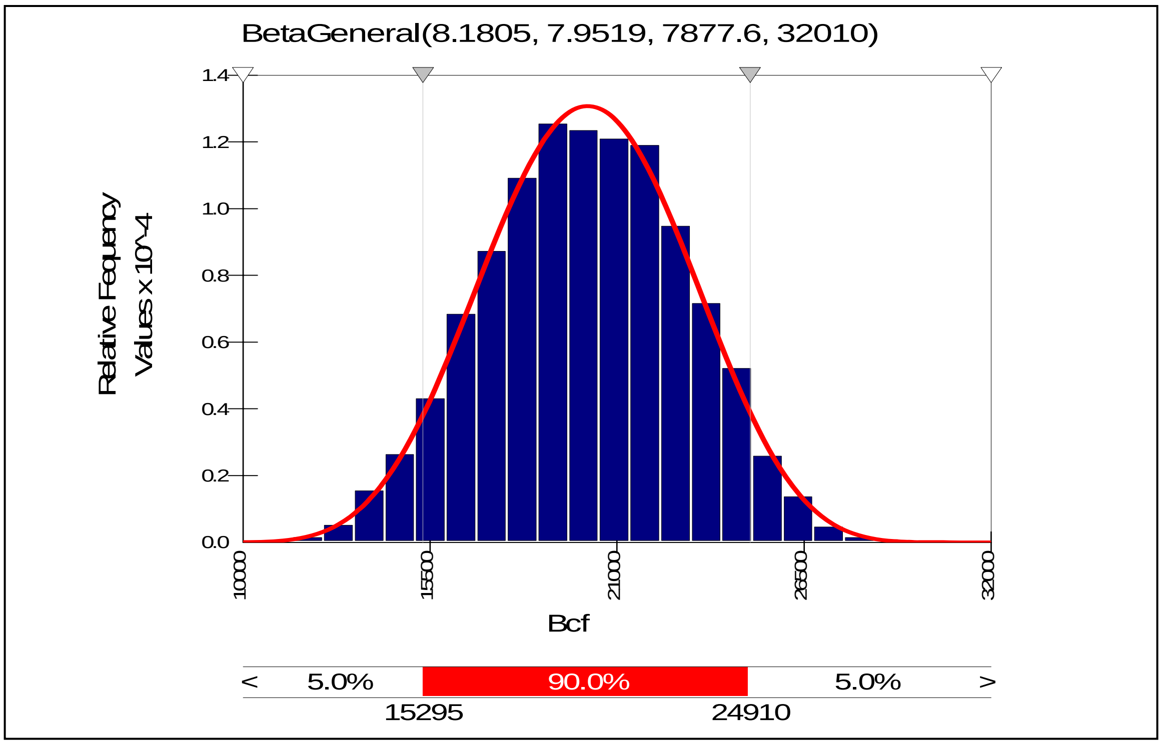

Fig. 18—Probability distribution for the aggregation of individual AUs to the province level for the cell model, showing a resulting non log-normal shape.

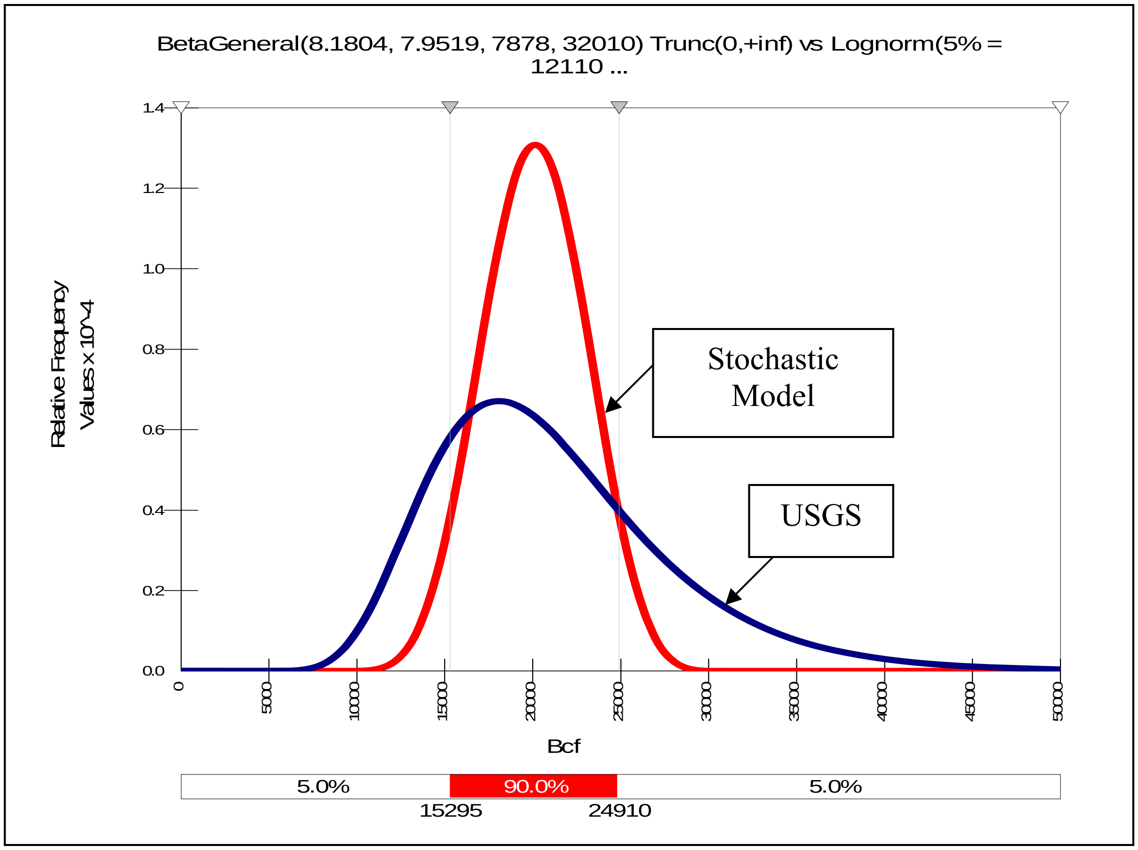

Fig. 19—PDF comparison of the aggregated total Uinta-Piceance province unconventional gas resources for the stochastic and the USGS models, showing a resulting non log-normal shape and a narrower range for the stochastic model.

TABLE 5— TOTAL PROVINCE AGGREGATION COMPARISON

Model	Mean (Bcf)	Std. Dev (Bcf)	P_{95} (Bcf)	P_5 (Bcf)	P_5/P_{95}
USGS	21147	6849	12110	33876	2.8
Stochastic	20115	2915	15295	24910	1.6
Stochastic Correlated.	20153	2881	15377	24837	1.6

Perfect positive correlation between AUs, as the USGS has assumed, is highly unlikely. Results from the stochastic model probabilistic aggregation show a significantly narrower P_{95}-P_5 range, as expected, which sheds even more doubt on the validity of the uncertainty quantification in the USGS resource estimates.

Effect of Including Correlation Between Input Variables

In an effort to explain why the USGS model produces narrow and non-log-normal distributions, I investigated the effect of correlation between input variables, which is not accounted for in the USGS methodology. I do not know exactly what correlation exists between input variables. However, I would expect a strong positive correlation to exist between area per cell (*N*), which is related to drainage area, and recovery per cell (*X*).

Thus, for the next test I assumed perfect positive correlation between area per cell of untested cells (*V*) and total recovery per cell (*X*), as depicted in the correlation matrix in **Fig. 20**. A comparison of distributions of total gas resources in the AU (*Y*) for the Piceance transitional AU, resulting from the Monte Carlo approach run both with and without correlation is presented in **Fig. 21**. The impact is small. Strong positive

	Total AU Area (U)	Area per Cell of Untested Cells (V)	Percentage of total AU Area that is Untested (R)	Percentage of Untested U Having Potential (S)	Total Recovery per Cell (X)
Total AU Area (U)	**1**				
Area per Cell of Untested Cells (V)	**0**	**1**			
Percentage of total AU Area that is Untested (R)	**0**	**0**	**1**		
Percentage of Untested AU Having Potential (S)	**0**	**0**	**0**	**1**	
Total Recovery per Cell (X)	**0**	**1**	**0**	**0**	**1**

Fig. 20—Correlation coefficient matrix showing strong positive correlation between area per cell (V) and recovery per cell (X).

correlation, at least between these two variables, does not have a significant effect on either the shape or standard deviation of the resulting distribution. The same test was performed for the total Uinta-Piceance province, assuming perfect positive correlation between area per cell of untested cells (V) and total recovery per cell (X) for the fourteen AUs. The aggregation of the resulting probability distributions to the province level also indicates that correlation between these two parameters does not have much effect, as presented in Table 5.

Effect of Increasing the Standard Deviation of the Original USGS Triangular Distributions

I next investigated the effect of the input probability distributions on the calculated distribution of total gas resources in the AU. I increased the standard deviations of the original USGS triangular distributions by a factor of 3 (except for area per cell, V, which

I increased by a factor of 1.8), by extending the minimum and maximum values by the same amount, and reran the Monte Carlo simulation. The resulting distribution for total gas resources in the Piceance transitional AU (**Fig. 22**) has a much larger standard deviation (219 Bcf) than the original (101 Bcf), as expected.

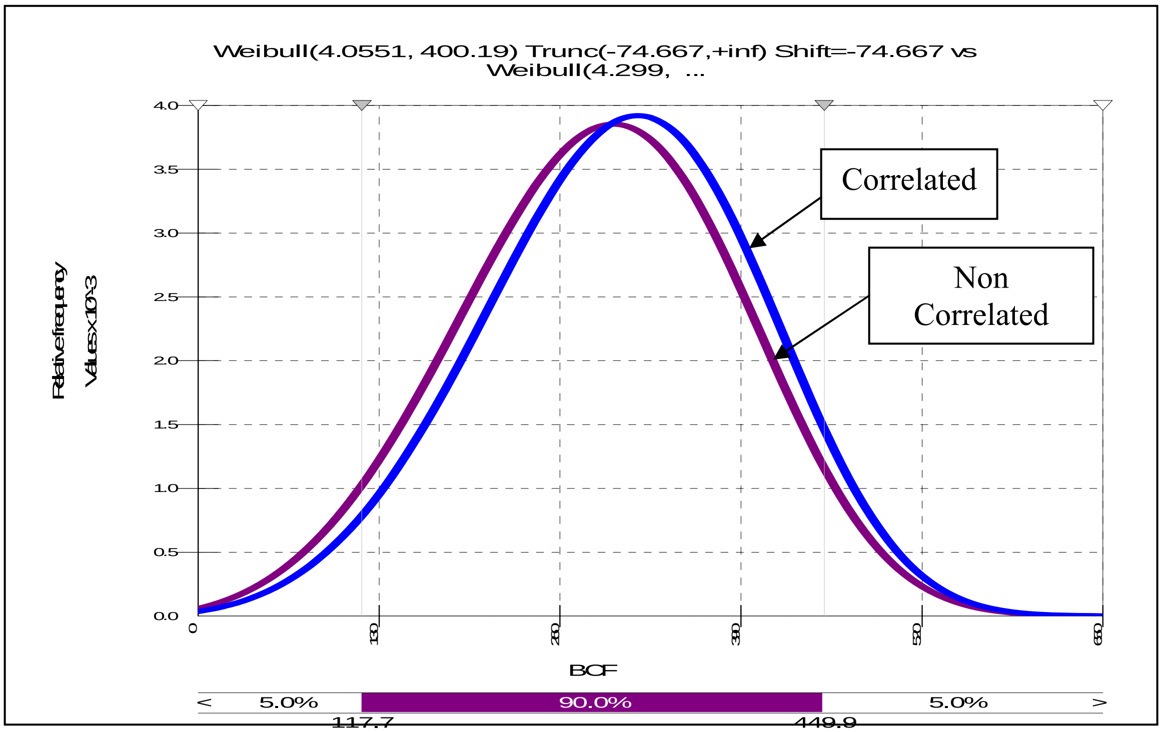

Fig. 21—PDF comparison for total AU gas resources in the Piceance transitional AU, showing the effect of assuming perfect positive correlation between the area per cell of untested cells (V) and the recovery per cell (X).

Correspondingly, the P_{95}-P_5 range increases from 118-450 Bcf to 90-794 Bcf. However, changing the input distributions also had a significant effect on the shape of the resulting distribution. Instead of being slightly skewed to the left, with the original input distributions, the resulting distribution using wider input distributions is now highly skewed to the right. It is near log-normal in character, as is expected for the distribution of unconventional gas resources.

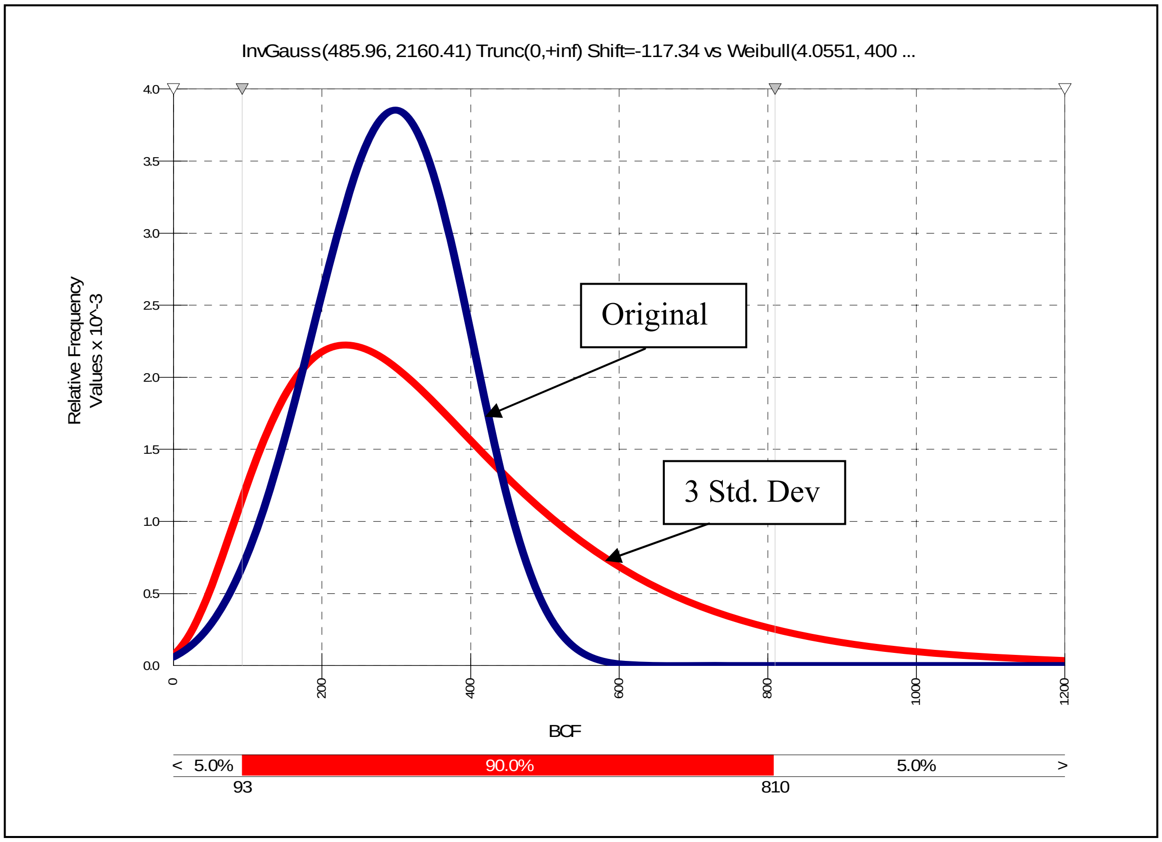

Fig. 22—PDF comparison for the total AU gas resources in the Piceance transitional AU with the original triangular input distributions versus input distributions with standard deviations increased by a factor of 3.

In summary, the unrealistically narrow distributions for potential unconventional gas resources produced by the USGS do not appear to be related to the methodology itself (i.e., use of analytic equations instead of a stochastic approach and lack of correlation between input variables), but rather appear to be caused by the narrow triangular input distributions that are used in the assessment. Use of wider input distributions produces both (1) wider distributions for potential unconventional gas resources, more in line with the uncertainty that we would expect for undiscovered, untested resources, and (2) significantly right-skewed distributions, in line with what we would expect for the distribution of a natural resource.

Effect of Changing the Shape of the Original USGS Input Probability Distributions

Up to this point I have investigated only the effect of width of the input distributions. I also investigated the shape of the input distributions, in particular, non-bounded distributions. For the Piceance transitional AU, I changed the shape of the original USGS triangular probability distributions to log-normal distributions with the same USGS mean and standard deviation values, but leaving all the log-normal distributions unbounded to the right (**Fig. 23**). The stochastic model generates a log-normal probability distribution (**Fig. 24)**. However, the mean and standard deviation are very close to the values obtained with the original triangular distributions (mean and standard deviation of 288 Bcf and 101 Bcf for triangular distributions versus 292 Bcf and 104 Bcf for log-normal distributions) as depicted in **Fig. 25**.

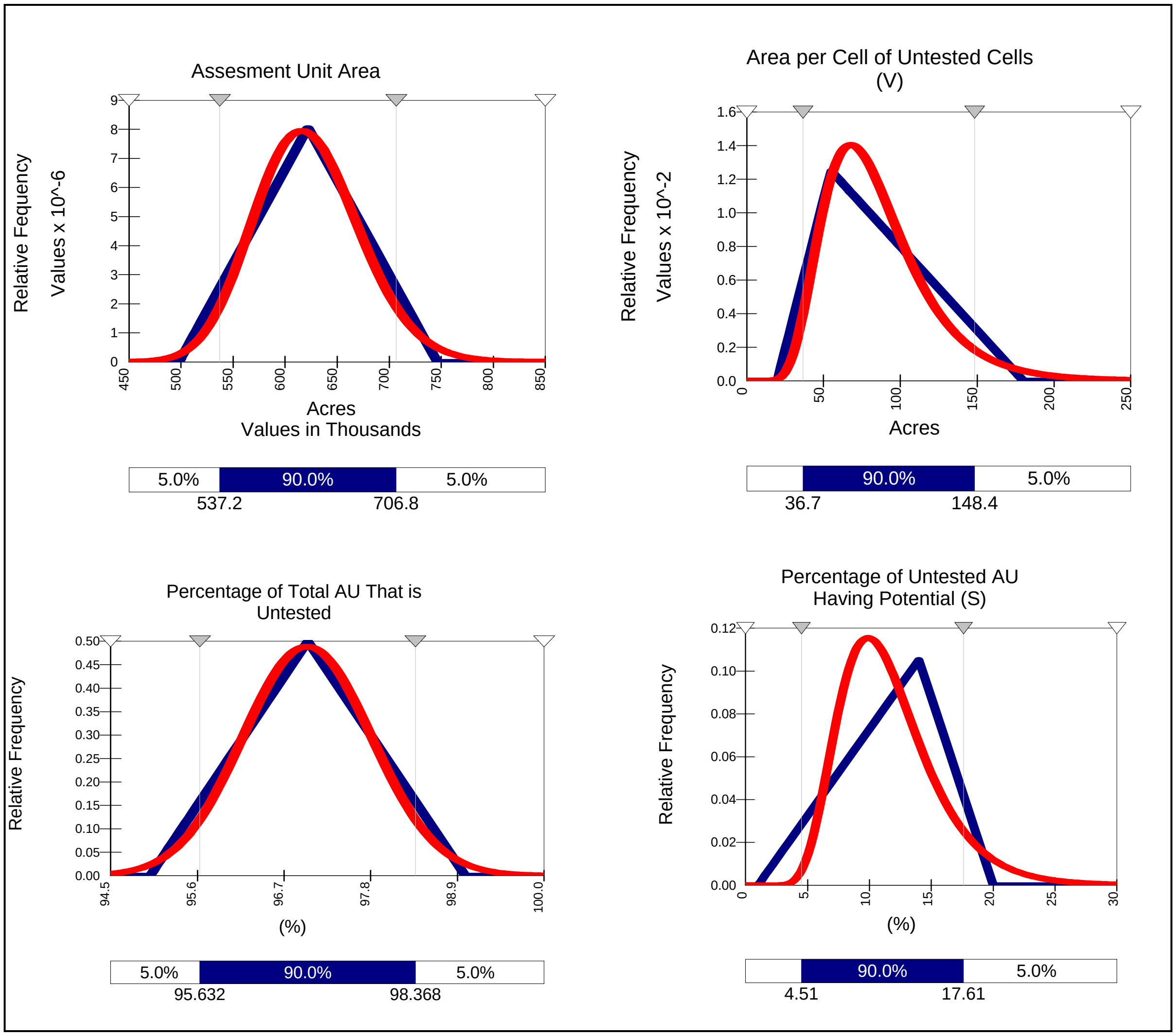

Fig. 23—PDF comparison for the Piceance transitional gas AU when the original USGS triangular input distributions are changed to log-normal distributions with the same mean and standard deviation.

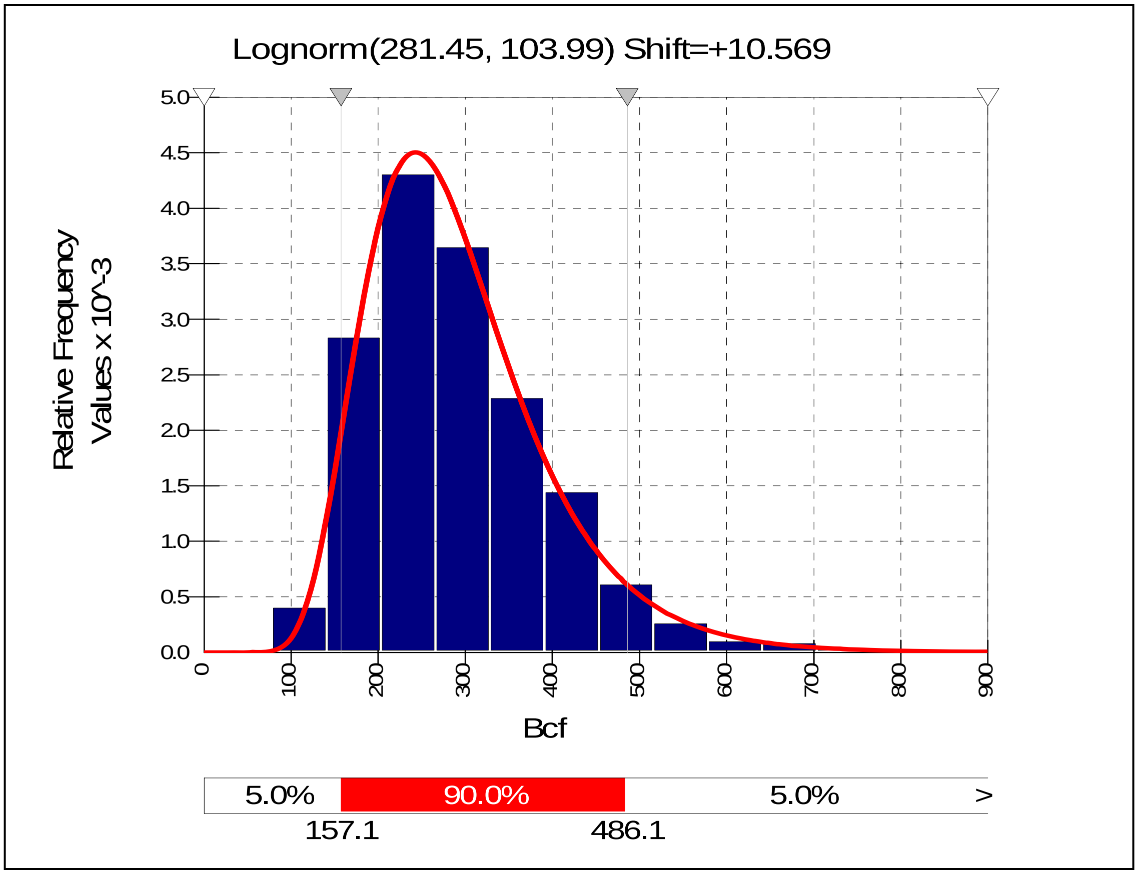

Fig. 24—Histogram and best fit probability distribution for the case where the USGS original input probabilities are changed from triangular to log-normal with the same mean and standard deviation, in the Piceance transitional AU.

Effect of Changing the Shape and the Standard Deviation of the Original USGS Input Probability Distributions

In this case I investigate the effect of changing the original USGS triangular probability distributions to log-normal distributions with standard deviations increased by a factor of 3. Variables involving percentages are limited to a maximum value of 100.

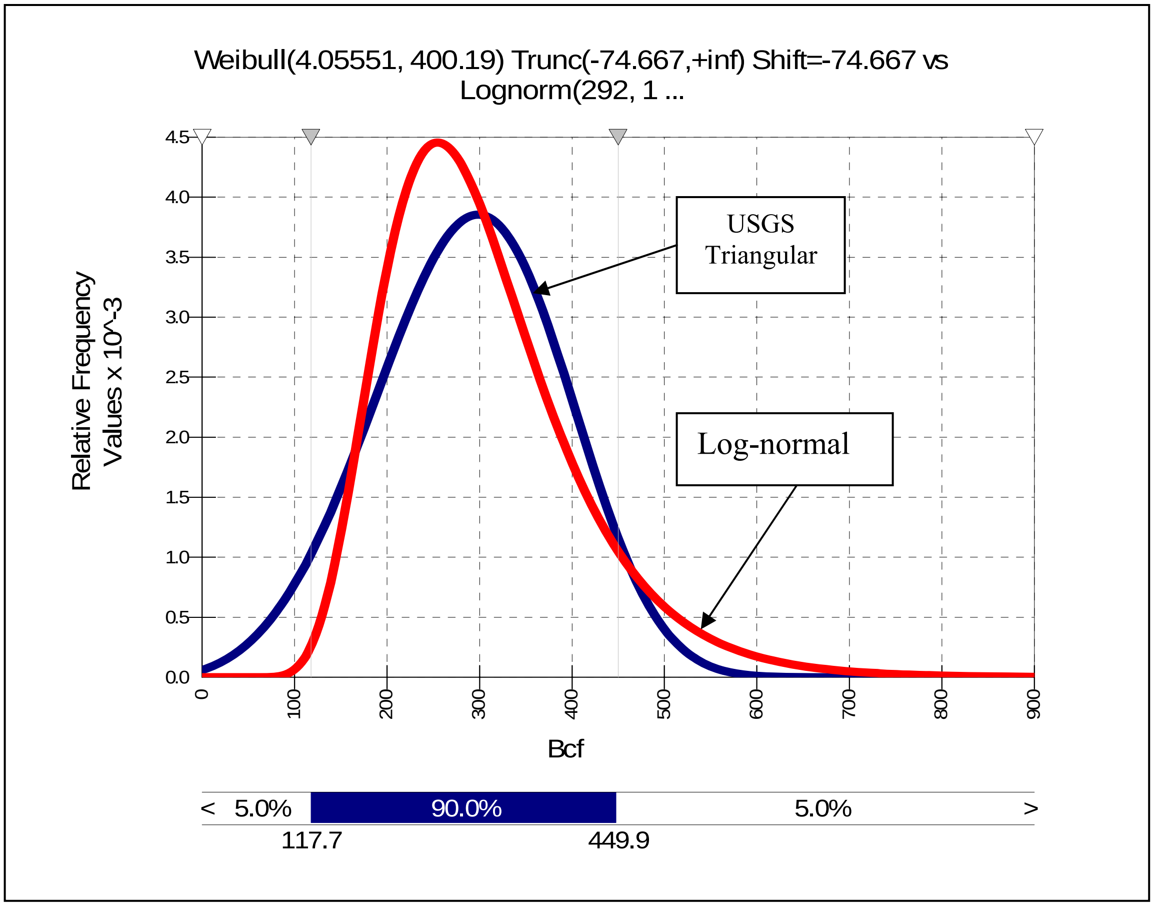

Fig. 25—PDF comparison of the distributions generated with the original USGS triangular distributions and log-normal distributions with the same mean and standard deviation values, for the Piceance transitional AU.

Fig. 26 shows that the modified input distributions result in a log-normal distribution highly skewed to the right. In this case, the standard deviation and P_5/P_{95} range are increased. Mean and standard deviation are 288 Bcf and 101 Bcf for triangular distributions versus 278 Bcf and 277 Bcf for log-normal distributions with increased standard deviations, as depicted in **Fig. 27**. The P_{95}-P_5 range increased from 118-450 Bcf to 45-775 Bcf.

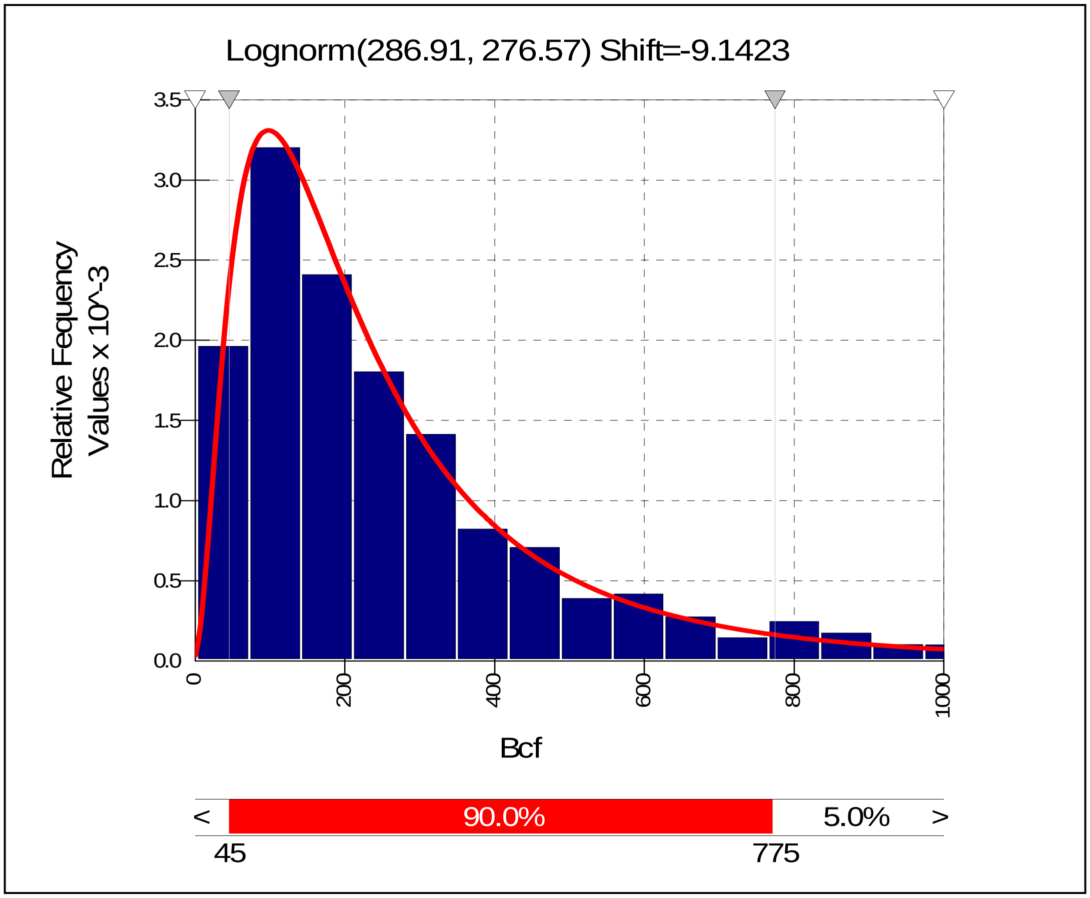

Fig. 26—Histogram and best fit probability distribution for the case where the USGS original input probabilities are changed from triangular to log-normal and the standard deviation increased by a factor of 3, for the Piceance transitional AU.

Effect of Including Variable Correlation with Unbounded Probability Distributions

For the case where the original triangular probability distributions are changed to log-normal with standard deviations increased by factor of 3, I investigated the significance of strong positive correlation (index =1) between the area per cell (*V*) and the recovery per cell (*X*). **Fig. 28** shows that, again, correlation between these two parameters seems to have a small effect on the shape of the resulting probability distribution.

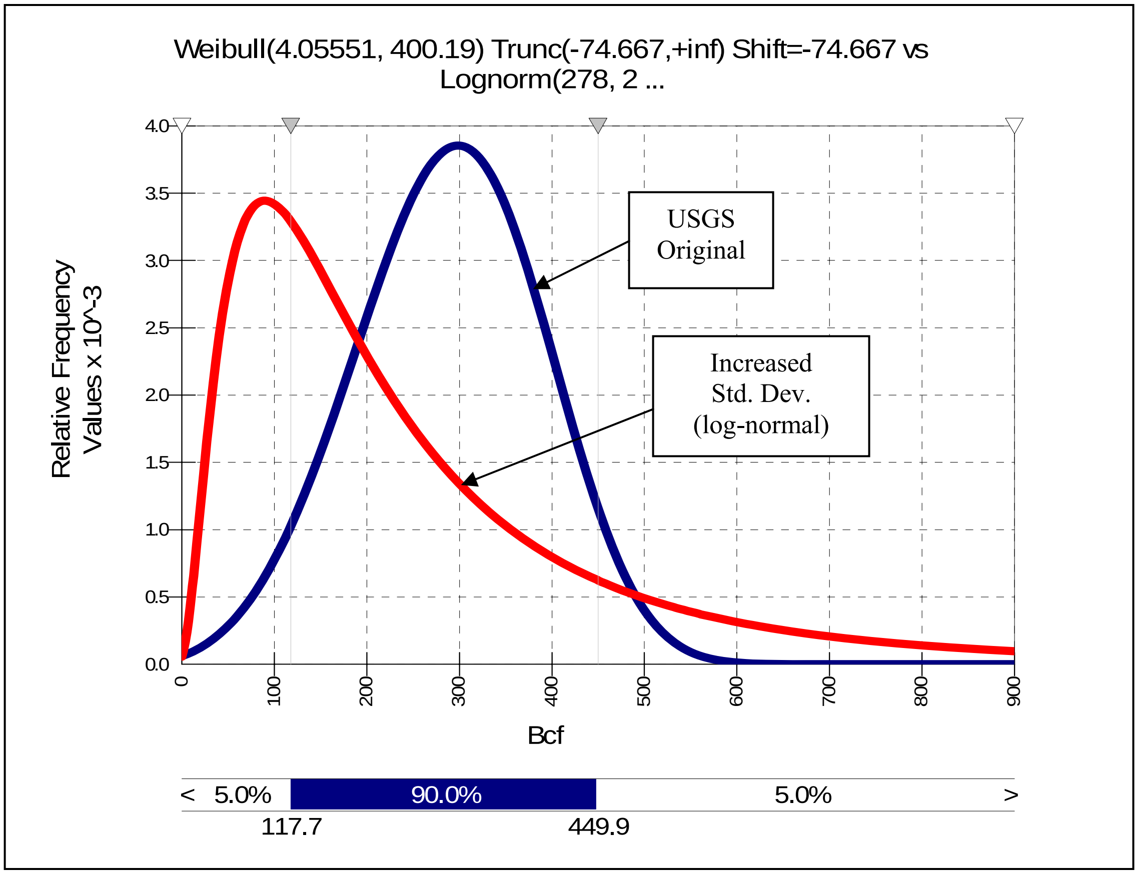

Fig. 27—PDF comparison of the distributions generated with the original USGS triangular input distributions and log-normal distributions with standard deviation increased by a factor of 3, for the Piceance Transitional AU.

This thesis presents an improved probabilistic methodology to assess potential unconventional gas resources. A more realistic assessment of the uncertainty is essential in the decision making process because it helps in the estimation of the upside and downside potential.

Adoption of a stochastic methodology by organizations such as the USGS, along with a careful examination and revision of input distributions, will allow a more realistic assessment of the uncertainty surrounding potential unconventional gas resources. More realistic assessments should be valuable to both industry and government in the effort to develop unconventional gas resources for the public benefit.

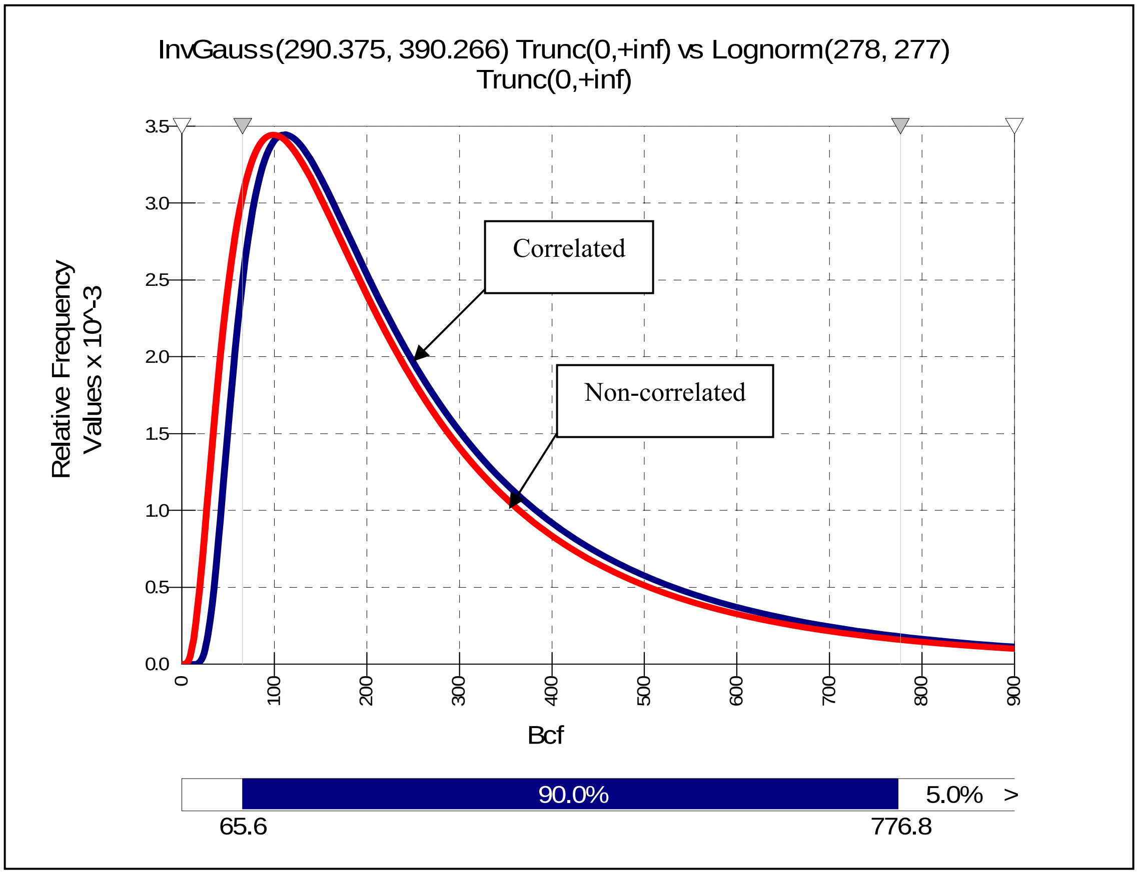

Fig. 28—PDF comparison for total AU gas resources in the Piceance transitional AU, showing the effect of assuming perfect positive correlation between the area per cell of untested cells (V) and the recovery per cell (X) for unbounded input probability distributions.

FUTURE WORK

Although correlation between input variables did not have a significant impact in the tests I ran, correlation should be investigated further since it is possible that correlations could exist and could have more significant impacts in other situations, e.g., between other input distributions. The Monte Carlo approach I have proposed is more versatile and robust than the analytic approach and will allow these effects to be readily investigated.

I have introduced the problem related to the use of mainly triangular distributions in the USGS methodology, presented a procedure to try to avoid the inclusion of unconscious judgmental bias in triangular distributions, and quantified the impact of hypothetically changing the input probability distributions. However, lack of access to the USGS data base and particular considerations of the experts that performed the USGS assessment of unconventional gas resources in the Uinta Piceance province do not allow me to calculate new input probability distributions based on actual data. Future work should incorporate the effect of considering different probability distributions as input variables, if data are available.

CONCLUSIONS

1. Results of the assessment of unconventional gas resources performed by the USGS in the 1995 US national assessment and in the Uinta-Piceance province in 2002 show probability distributions that are unrealistically narrow for undiscovered and untested resources.

2. The stochastic model validates the means and standard deviations produced by the USGS methodology, but shows that the probability distributions generated are rather different and that the USGS distributions are not right skewed, as expected for a natural resource.

3. Lack of correlation between input variables in the USGS methodology does not appear to be the cause for the incorrect shape and narrowness of the resulting distributions for total gas resources. Instead, the cause appears to be narrow triangular input parameter distributions. Use of wider input distributions produces distributions for total gas resources that are both wider and log-normal in character, more in line with the large uncertainty associated with these resources.

4. The stochastic methodology presented here is more versatile and robust than the USGS analytic methodology for assessing potential unconventional gas resources. Adoption of the methodology along with a careful examination and revision of input probability distributions should provide a more realistic assessment of the uncertainty associated with these resources.

REFERENCES

1. "Balancing Natural Gas Policy," National Petroleum Council, Library of the Congress, Washington, DC (2003) **2**, 134.

2. Terasaki, D. and Fujita, K.: "The Role of Unconventional Natural Gases in the Next 30 Years in Asia," paper SPE 93779 presented at the 2005 Asia Pacific Oil and Gas Conference, Jakarta, 5-7 April.

3. Curtis, J.B. and Montgomery, S.L.: "Recoverable Natural Gas Resource of the United States: Summary of Recent Estimates," *AAPG Bull*. (October 2002) 1671.

4. Haskett, W.J. and Brown, P.J.: "Evaluation of Unconventional Resource Plays," SPE paper 96879 presented at the 2005 Annual Technical Conference and Exhibition, Dallas, 9-12 October.

5. Schmoker, J.W.: "Resource Assessment Perspectives for Unconventional Gas Systems," *AAPG Bull*. (November 2002) 1993.

6. "Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta-Piceance Province, Utah and Colorado," US Geological Survey Digital Data Series 69-B, Denver (2002) Chap. 17, 1-7.

7. "1995 National Assessment of United States Oil and Gas Resources – Results, Methodology and Supporting Data," US Geological Survey Digital Data Series DDS-30, Release 2, Reston, Virginia (1996).

8. "Balancing Natural Gas Policy," National Petroleum Council, Library of the Congress, Washington, DC (2003) **4,** 2.

9. "Annual Energy Outlook 2005," Energy Information Administration, www.eia.doe.gov/oiaf/aeo, February 2005.

10. "Potential Supply of Natural Gas in the United States," Potential Gas Committee, Potential Gas Agency, Colorado School of Mines, Golden, Colorado (April 2003).

11. Hudak, D.G.: "Adjusting Triangular Distributions for Judgmental Bias," Risk Analysis J. (1994) **14**, No. 6, 1025.

12. "SPE Glossary," Society of Petroleum Engineers, www.spe.org. (retrieved, August 2006)

13. "Balancing Natural Gas Policy," National Petroleum Council, Library of the Congress, Washington, DC (2003) **4**, 20.

14. "FORSPAN Model User Guide," US Geological Survey Open-File Report 03-354, Reston, Virginia (2003).

15. "Order Extending Authorization to Export Liquified Natural Gas from Alaska," DOE/FE Opinion and Order No. 1473, http://www.ferc.gov/industries/gas/indus-act/angtp/doe1473.pdf, April 1999.

16. Holditch, S.A.: "The Increasing Role of Unconventional Reservoirs in the Future of the Oil and Gas Business," *JPT* (November 2003) 34.

17. "National Oil and Gas Assessment," US Geological Survey, http://energy.cr.usgs.gov/oilgas/noga/, November 2005.

18. "2005 Assessments Updates," US Geological Survey, http://energy.cr.usgs.gov/oilgas/noga/ (retrieved, September 2006)

19. "Balancing Natural Gas Policy," National Petroleum Council, Library of the Congress, Washington, DC (2003) **4**, 134.

20. Schenk, C. J.: "Geologic Definition and Resource Assessment of Continuous (Unconventional) Gas Resources in the United States," US Geological Survey, http://pubs.usgs.gov. (retrieved, July 2006)

21. "Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta-Piceance Province, Utah and Colorado," US Geological Survey Digital Data Series 69-B, Denver (2002) Chap. 7, 23.

22. "Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta-Piceance Province, Utah and Colorado," US Geological Survey Digital Data Series 69-B, Denver (2002) Chap. 22, 1-7.

23. Crovelli, R.A.: "Probability and Statistics for Petroleum Resource Assessment," USGS Open File Report 93-582, Denver (1993) 93.

24. Sheldon, M.R.: *Introduction to Probability and Statistics for Engineers and Scientists*, Elsevier Academic Press, London (2004) 204.

25. "Triangular Distributions," http://brighton-webs.co.uk/distributions/triangular.asp (retrieved, June 2006)

26. "U.S. Geological Survey World Petroleum Assessment 2000– Description and Results," US Geological Survey Digital Data Series DDS-60, Version 1.1, Reston, Virginia (2000).

27. Law, A.M., and Kelton, W.D.: *Simulation Modeling and Analysis*, McGraw Hill, New York, (1991).

VITA

Name:	Jesús Salazar Vanegas
Address:	3116 TAMU Room 311 Richardson Building Texas A&M University College Station, TX 77843
Email Address:	jesus.salazar@tamu.edu
Education:	Texas A&M University – College Station, Texas Master of Science in petroleum engineering, May 2007
	Universidad Industrial de Santander – Bucaramanga, Colombia Bachelor of Science in petroleum engineering, 1992
Experience:	More than 10 years working in the oil and gas industry in Colombia (South America)