Indexation and Normalization Modeling of Natural Gas Endowment

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Abstract

A novel modeling method is presented for indexing and normalizing natural gas endowments of petroleum provinces. The approach is demonstrated with data from Canada, the United States, and Latin American and Caribbean (LAC) countries. A variable shape distribution model (VSD) is used to fit the conventional natural gas endowment published by the United States Geological Survey (USGS) for 29 provinces in LAC countries and 85 provinces in Canada and the United States. This data is indexed and normalized to generate curves showing number of provinces versus normalized endowments. Results are compared with normalized endowments from provinces in other regions around the world, including Europe, Asia Pacific, the Middle East, North Africa, and the former Soviet Union (FSU). The comparison gives the method predictive power for estimating the natural gas endowment, particularly in LAC provinces, that at present have little exploration activity. Of particular importance is the fact that all the curves of the various regions display a generally concave pattern throughout. The exception is the LAC curve, which displays the shape of an inverted “S” and has a distinct convex pattern at the largest gas endowment volumes. This comparison suggests there is potentially a large volume of natural gas in the region that has not been considered in previous studies.

Keywords: Natural gas; Indexation; Normalization; Modeling; Size distribution; VSD model; Canada; United States; LAC countries

1. Introduction

There is a significant endowment of hydrocarbons in North, Central and South America, which given enough research and development, may help satisfy the energy needs of these regions for several decades to come (Aguilera and Aguilera, 2010). The data used in Aguilera and Aguilera (2010) was published originally by the USGS (1995, 2000), the Minerals Management Service (MMS, 1996) and Klett et al. (1997).

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The present study concentrates on indexation and normalization modeling of the conventional natural gas endowment in Canada, the United States, and LAC. It then compares these results to normalized curves from other regions around the world in order to gain insights about regions with underestimated endowments. The paper does not include unconventional sources of gas such as tight gas, shale gas or coal bed methane. It uses the definitions of the USGS (2000) study (see **Table 1**). Each of the USGS definitions that deal with volumes can be applied to petroleum or to oil, natural gas and natural gas liquids (NGL) separately. Conventional petroleum is the sum of oil with more than 15 degrees API, gas and NGL.

Figure 1 is a diagram explaining the relation between some of the definitions that are most relevant to this paper. Both known volumes and future volumes are used to develop the variable shape distribution (VSD) graphs for Canada and the United States, LAC, Europe, Asia Pacific, Middle East and North Africa, and the FSU. Note that North America, as defined by the USGS, includes Canada, the United States and Mexico. The LAC countries presented in our study include Mexico, while there is a separate evaluation for the United States and Canada.

The shape variation is one of the unique and important points of the methodology used in this paper. Similar approaches have been used in the past, but all of those methods incorporate constant shapes. Based on our observation of global USGS data, the constant shape technique is not as reasonable as the variable shape method proposed in this paper. In section 5 (VSD Validation), we explain the VSD methodology, highlight its advantages and demonstrate that the VSD - in addition to handling variable shapes - also encompasses the assumption of constant shapes considered in previous methods. In efforts to align the USGS (2000) definitions with those developed by the SPE/WPC/AAPG/SPEE/SEG (2011) in the Petroleum Resources Management System (PRMS), we have compared terminology as shown in **Fig. 2**. The comparison applies to classes associated with the chance of commerciality.

There is always uncertainty in petroleum province size estimation because of data shortages in the oil and gas industry. As such, there are uncertainty levels inherent in the USGS reports. Generally, the larger the reservoir, the larger the amount of available data, thus reducing the uncertainty associated with the largest province (which is critical for the indexations proposed in this paper). The USGS publicizes the mean values, which are the volumes used in this paper as a starting point. These uncertainties extend necessarily to the VSD model. However, once the mean values of the USGS are accepted as reasonable, the results of the VSD work well. This statement is supported by (1) coefficients of determination (R^2) that are generally greater than 0.98 and (2)

VSD-estimated endowments that are very similar to those published by the USGS. The core of the USGS procedure is the use of high quality geologic evaluations, specialized techniques like reservoir-simulation modeling, discovery-process modeling, and application of geologic and production analogs. Probability distributions are also used in the USGS study to account for the uncertainty associated with estimating undiscovered volumes.

2. Study Area

Figure 3 shows a map that includes Canada, the United States, and LAC - the primary study areas in this paper. The secondary study areas, included for comparison purposes, are Europe, Asia Pacific, the Middle East, North Africa, and the FSU. The USGS province codes, names and gas endowments of petroleum provinces in the United States and Canada are presented in columns 1, 2 and 4 of **Table 2**, respectively. The same information for LAC petroleum provinces is presented in **Table 3**. There are a total of 85 petroleum provinces assessed by the USGS for Canada and the United states (in addition to seven provinces showing zero gas endowment and one province, Salina Basin, with less than 100 billion cubic feet of gas [BCFG]). For LAC countries, there are 30 petroleum provinces assessed by the USGS (but no data is available for province 5310, Sierra Madre de Chiapas-Peten Foldbelt). As a result, our study includes only 85 petroleum provinces for Canada and the United States and 29 petroleum provinces in LAC countries. The tables include the mean conventional gas endowment (column 4) for each province as reported by the USGS, the normalized gas endowment (column 5), the calculated endowment (column 6) and the calculated normalized endowment (column 7). The mean conventional gas endowment includes undiscovered volumes estimated by the USGS. It does not include reserve growth or unconventional sources of gas.

The actual and calculated data are also presented in **Fig. 4** for Canada and the United States, and **Fig. 5** for LAC countries, as log-log cross plots of the cumulative number of provinces in the abscissa versus the normalized gas endowment in the ordinate. The black diamonds represent natural gas endowments published by the USGS. The solid blue continuous line corresponds to the endowments calculated with the VSD model. The “variable” part of the VSD name is meant to distinguish it from the crossplots utilized in fractal analysis, which is based on a “constant” shape (i.e. a straight line on log-log coordinates). The straight lines are not observed on the crossplots of hydrocarbon endowments presented in this paper or those prepared previously by Aguilera (2006) and Aguilera et al. (2009). The comparison of the USGS data and VSD modeling results is good, as corroborated by visual

inspection and a coefficient of determination (R^2) equal to 0.99. However, a comparison of the VSD curves with the USGS (1995, 2000), MMS (1996) and Klett et al. (1997) endowments show that there are some differences at certain levels. The differences are accounted for in **Figs. 4 and 5** by plotting 20% horizontal error bars. Note that in nearly all cases, the 20% error bars exceed the difference between the USGS and VSD calculated endowments.

Table 2 and **Fig. 4** show that the USGS endowment for Canada and the United States in 85 petroleum provinces is 1687 trillion cubic feet of gas (TCFG). This compares well with 1684 TCFG estimated by the VSD model. **Table 3** and **Fig. 5** show that the USGS endowment for LAC in 29 petroleum provinces is 857 TCFG. This too compares well with 855 TCFG estimated by the VSD model. **Figure 4** also includes a VSD curve (magenta squares) which predicts the endowment for all 172 petroleum provinces recognized by the USGS to exist in Canada and the United States. The estimated endowment is equal to 1,921 TCFG. The predictive power of the VSD is good as shown in section 5 and in previous studies by Aguilera (2006) and Aguilera et al. (2009). **Figure 5** accounts for 128 petroleum provinces recognized by the USGS to exist in LAC countries. In this case, the VSD estimated endowment is 1487 TCFG. The methods used to generate, index and normalize these data are discussed next.

3. Variable Shape Distribution model (VSD)

The methodology used to develop the VSD curves shown in **Figs. 4 and 5** has been published previously in the literature (Aguilera, 2006; Aguilera et al., 2009) and therefore is not repeated here. However, for completeness and to facilitate the flow of the paper, the VSD modeling equation is shown below:

$$\min_{\{V_x, a_p, V_s, \psi, S\}} \sum_{i=1}^n (V_i - \hat{V}_i)^2 \quad (1)$$

Subject to:

$$\hat{V}_i = \frac{\left\{ \left[\left(\frac{1}{N_t} - \left(\frac{V_m}{V_x} \right)^{\left(\frac{\log N_x - \log N_m}{\log V_x - \log V_m} \right)^{a_p}} + \frac{V_m}{V_x} \right) \cdot V_x \right] \times (\psi) \right\}}{(\psi) + [1 - (\psi)] \cdot \left[1 - \exp \left\{ - \left[\left(\frac{1}{N_t} - \left(\frac{V_m}{V_x} \right)^{\left(\frac{\log N_x - \log N_m}{\log V_x - \log V_m} \right)^{a_p}} + \frac{V_m}{V_x} \right) \cdot V_x \right] \div V_s \right\} \right]^S} \quad (2)$$

where a_p = absolute value of slope of straight line approximated from USGS sample points (same as absolute value of slope of Pareto distribution), N_m = minimum number of USGS provinces, N_t = cumulative number of provinces, N_x = maximum number of provinces, S = severity exponent that controls the steepness of the slope of the estimated VSD curve where it separates from the Pareto straight line (on the right tail of the distribution, typically near the largest volumes), V_m = minimum USGS province volume, V_s = separation parameter that controls the point at which the VSD curve begins to deviate from the Pareto straight line (generally on the right tail of the distribution, near the largest volumes), $\hat{V}_i$ = estimated volume of a province, and V_x = maximum volume given by the Pareto straight line (at $N_m = 1$). The actual maximum volume could be larger, equal to, or smaller than V_x , ψ = separation ratio that controls the amount of separation between the Pareto straight line and the estimated VSD curve (on the right tail of the distribution, near the largest volumes).

Table 4 shows five parameters that are estimated in the VSD equation: V_x , a_p , V_s , ψ , and S . These parameters are used to obtain the best possible fit of the USGS endowments for Canada and the United States (**Fig. 4**), LAC countries (**Figs. 5, 7 and 8**), and other normalized regions considered in this paper (**Figs. 6(A) to 6(G)**). Fundamentally, the question that must be asked is: does any of this make sense geologically? We think it does and this is supported in publications by researchers of the USGS (Drew, 1990, 1997; Drew et al., 1979, 1988; Crovelli and Barton, 1993; Barton and Scholz, 1995). They discovered that as exploration advanced in a given area, there was a continuous on-going discovery process that could best be modeled at the time with a power law distribution. Drew (1997) published a significant book with data from different areas (e.g. the Frio Strandplain play in Texas) explaining the importance of geology in the discovery process. His data showed that, as the number of discoveries increased, the mode of the reserves volumes was not constant; it was decreasing continuously. This led him to conclude that nature's parent population of petroleum resources followed a log-geometric distribution. The relation between log-geometric and Pareto distributions have been further discussed by Charpentier et al. (2007). Drew and his colleagues work was innovative, though an actual straight line (i.e. constant shape) on log-log coordinates was never reached. Essentially, they had to truncate their data based

on economic considerations to obtain a straight line. This was one of the motivations for the development of our VSD model, where the line does not have to be truncated at any point and the volumes are constrained only by the number of USGS-defined provinces. The USGS Frio Strandplain data are used in section 5 to demonstrate the predictive power of the VSD.

4. Indexation and Normalization Modeling

In this study, the selected index is the natural gas volume of the province with the maximum endowment for each region (marked by asterisks in **Tables 2** and **3**). For example, the index for the USGS data shown in column 2 of **Table 4** for LAC is equal to 221.679 TCFG. The index for the VSD-calculated LAC data is 222.040 TCFG, as shown in column 3. The indexes for the other regions are also presented in **Table 4**. Normalization is carried out dividing the endowment of each petroleum province by the index (or maximum endowment) shown in **Tables 2 and 3**. Using the maximum endowment for this purpose is reasonable as our experience generally shows that the largest amounts of data are available for the largest reservoirs.

For comparison, **Figs. 6(A) to 6(G)** shows log-log crossplots of normalized endowments (or sizes of provinces) versus cumulative number of provinces for (A) LAC countries, (B) Canada and the United States, (C) Europe, (D) Asia Pacific, (E) FSU, (F) Middle East and North Africa, and (G) the world. These graphs were developed following the same procedure described above. Visual inspection of the modeling shows that fits, vis-a-vis the USGS endowments, are always good with coefficients of determination (R^2) greater than 0.98. **Figure 6(A)** shows that in the case of LAC countries, the curve resembles an inverted ‘S’ and has a convex shape at large normalized province sizes (or endowments). However, the USGS and VSD curves for other regions (curves in **Figs. 6(B) to 6(G)**) generally have concave shapes throughout, with the possible exception of the FSU. Are the shape differences simply a coincidence or the result of significantly different geologic features? These are possibilities but they are unlikely. A plausible explanation is that the convex shape is the result of lack of research and exploration for natural gas in LAC countries. Our experience from working in all the LAC countries is that exploration and drilling density per unit area of sedimentary basins is very small, although to our knowledge this has not been published explicitly in the literature.

If the LAC curves had concave shapes like other regions around the world, the conclusion might be reached that LAC gas endowments could be larger, as shown by the VSD comparisons of concave and convex curves in **Fig. 7**. The data used to generate

the concave curve in **Fig. 7** is presented in the second LAC line of **Table 4**. The VSD model indicates that the concave curve assumption would add approximately 222 TCFG to the LAC endowment of 855 TCFG (from the convex shape) resulting in a grand total of 1,077 TCFG for the 29 provinces evaluated by the USGS in the region. Note that the concave line starts at the same maximum endowment (province 1) as the convex line in **Fig. 7**. The next data points (USGS provinces 2 to 12 in **Table 3**, represented by black diamonds in the convex line of **Fig. 7**) are replaced by VSD values calculated with control parameters shown in the second LAC line of **Table 4**. The idea of the concave curve is that it has to fit the maximum endowment as well as the smaller endowments in provinces 13 to 29.

The same approach is used to generate **Fig. 8**, where the control parameters are identical except for the number of provinces that in this case are 128. The modeling shows that if the previously unassessed provinces in LAC countries are also taken into account, the concave assumption - presumably emanating from additional research and exploration - will increase the LAC endowment from 1,487 to 1,816 TCFG, a significant increase of 329 TCFG. The natural gas endowment in 172 provinces recognized by the USGS to exist in Canada and the United States is also large (1,921 TCFG, as shown in **Fig. 4**). Combining this with the LAC countries gives a total endowment of conventional natural gas for the Western Hemisphere equal to 3,777 TCFG that should lapse for several decades.

5. VSD Validation

The validation of the VSD model is demonstrated in this section with data published by the USGS (Drew, 1990, 1997; Crovelli and Barton, 1993; Barton and Scholz, 1995). All these authors assumed a constant shape (a Pareto-type straight line on log-log coordinates) in the evaluation of the Frio Strandplain play in Texas. The Frio Strandplain geology and depositional system have been summarized by Drew (1990, 1997). The original distribution of production data are presented in **Fig. 9** for 3 different periods - through 1960, 1970 and 1985. Drew indicated that the parent population of oil and gas fields was log-geometric. His equivalent log-log crossplot for the distribution to 1985 is shown in **Fig. 10** (Crovelli and Barton, 1993). The graph truncates 7 data points corresponding to the smaller field sizes because of economic and exploration considerations. Crovelli and Barton (1993) stated that “a correlation coefficient of -0.97 indicates a good fit where -1.0 is a perfect negative fit. We propose that this is an appropriate though approximate fit to the data and that extrapolation of the line to smaller field sizes may be a valid basis for prediction of the ultimate undiscovered petroleum in field-size classes less than or equal to eleven.” Although we agree that their fit is good for the

truncated data set, we show it can be improved with the VSD model (even without truncating the data). **Figure 11** contains data we digitized from a publication by Barton and Scholz (1995). This log-log plot is equivalent to the graph in **Fig. 9**. The data from Barton and Scholz are not truncated as in the case of **Fig. 10**. The following demonstrates a step by step application of the VSD:

- 1) **Figure 12** shows the exact same USGS data represented by the lower curve in **Fig. 11**, but now we have added a continuous solid line that is calculated with the VSD model using the following control parameters: $\alpha_p = 0.61$, $N_m = 1$, $N_t = 1$ to 315.01, $N_x = 315.01$, $S = 2.3$, $V_m = 0.032$, $V_s = 3000$, $V_x = 50,000$, $\psi = 0.2$. Visual inspection shows a very good fit that is supported by a coefficient of determination (R^2) equal to 0.98.
- 2) Given the information in step 1, what would be the predicted theoretical distribution for 500 fields discovered in the Frio Strandplain play? The answer is provided by the VSD model in **Fig. 13** using the exact same control parameters shown in step 1. The only difference is the number of fields that are now $N_x = 500.01$. **Figure 14** brings in the actual data for the 500 fields as it occurred in 1970 (shown in **Fig. 11**). The predicted distribution is excellent with an R^2 equal to 0.98.
- 3) Finally, what would be the predicted theoretical distribution for 700 fields discovered in the Frio Strandplain play? The answer is provided by the VSD model in **Fig. 15** using the exact same control parameters shown in step 1. Again, the only difference is the number of fields that are now $N_x = 700.01$. **Figure 16** brings in the actual data for the 700 fields as it occurred in 1985 (shown in **Fig. 11**). The predicted distribution is excellent once more with an R^2 equal to 0.98. The data in **Fig. 16** are not truncated as in the case of **Fig. 10**, which eliminates 7 data points with the smallest field sizes. Even though we do not truncate a single data point in **Fig. 16**, the fits with the VSD curves are very good. This gives the methodology presented in this paper an imperfect yet remarkable predictive power.

The same types of fits have been obtained with the VSD model for several cases throughout the world. The method is not a panacea but is certainly a significant improvement for predicting the endowment of hydrocarbons in places where the geoscience and engineering data are limited. As discussed, the method is robust as it allows matching actual data when the shape of the curve on log-log coordinates is concave, convex, or straight. For the latter, $\psi = 1.0$, N_x is very large (for example, $N_x = 1E+50$), and V_m is very small (for example, $V_m = 1E-50$). This is because Pareto's straight line can theoretically reach infinitesimally small sizes and an infinite number of fields. For this situation, the V_s and S values do not have any significance but they could remain as in this

example ($V_s = 3,000$ and $S = 2.3$). The values of a_p and V_x would also remain the same ($a_p = 0.61$ and $V_x = 50,000$). The parameters would generate the outer dashed straight line shown in **Fig. 17**. If we want to generate a straight line cutting more data points, as in the case of **Fig. 10**, we could maintain the same parameters but make V_x equal to 25,000. This generates the dash-dot straight line in **Fig. 17**. Although this shows that the VSD model encompasses fractal or Pareto distributions, note that none of the straight lines in **Fig. 17** are as accurate as the curves generated by the VSD.

6. Summary and Conclusions

Indexation and normalization of the natural gas endowment has been demonstrated with the use of a variable shape distribution (VSD) model and data published by the USGS for Canada, the United States, and LAC. The VSD model encompasses fractal or Pareto distributions as well as the deviations from straight lines on log-log coordinates. The normalized modeling results for Canada, the United States, and LAC have been compared with other regions including Europe, Asia Pacific, the Middle East and North Africa, and the FSU using log-log crossplots of cumulative number of provinces versus the normalized sizes of provinces. The comparison shows that the LAC curve has a clearly unique convex shape at the larger normalized endowments, while the complete curve has the shape of an inverted “S”. This is different than the other regions considered (with the possible exception of the FSU) that generally show distinctive concave shapes throughout the lengths of the curves.

The unique shape of the LAC curve suggests that the LAC natural gas endowment is probably much larger than estimated in previous studies. The endowment for 29 provinces evaluated by the USGS is 857 TCFG (855 TCFG using the VSD model), while the endowment for 128 provinces recognized by the USGS to exist in LAC countries is estimated at 1,487 TCFG by the VSD model. If the VSD curve is assumed to be concave throughout (as opposed to convex at the largest provinces), the endowment is estimated at 1,077 TCFG for 29 provinces and 1,816 TCFG for 128 provinces. Extended research, exploration and development should help move the LAC curve towards a more concave shape.

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Appendix A: Nomenclature

a_p – absolute value of slope of straight line approximated from USGS data points with larger province volumes (same as slope of Pareto distribution).

D – fractal dimension in Fig. 10

N_m - minimum number of USGS provinces (= 1).

N_t - cumulative number of provinces.

N_x - maximum number of provinces.

r^2 – coefficient of determination in Fig. 10

S - severity exponent that controls the steepness of the slope of the estimated VSD curve where it separates from the Pareto straight line (on the right hand side of the distribution, near the largest volumes).

V_i – volumetric size (endowment) of a petroleum province

V_m - minimum USGS province volume

V_s - approximate volume at which the USGS data begins to deviate from the Pareto straight line (on the right hand side of the distribution, near the largest volumes).

V_{if} – final, estimated volume of a province

V_x - maximum volume given by the Pareto straight line (at $N_m = 1$).

α - slope of Pareto straight line in Fig. 10

ψ - separation ratio that controls the amount of separation between the Pareto straight line and the estimated VSD curve (on the right hand side of the distribution, near the largest volumes).

Appendix B: Acronyms

BCFG = billion cubic feet of gas

FSU = former Soviet Union

GEM = global energy market

LAC = Latin America and the Caribbean

MMS = Minerals Management Service

TCFG = trillion cubic feet of gas

USGS = United States Geological Survey

VSD = variable shape distribution model

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Table 1 Terms and definitions used throughout this study. USGS (2000) definitions are highlighted by asterisks.

Cumulative Production*	The reported cumulative volume that has been produced.
Endowment Volume*	The sum of the known volume (cumulative production plus remaining reserves) and undiscovered volume.
Future Volume*	The sum of the remaining reserves and undiscovered volume. Cumulative production does not contribute to the future volume, neither does reserve growth.
Known Volume*	The sum of cumulative production and remaining reserves.
Petroleum Province*	An area having characteristic dimensions of perhaps hundreds to thousands of kilometers encompassing a natural geologic entity (for example, sedimentary basin, thrust belt, delta) or some combination of contiguous geologic entities.
Remaining Reserves*	The volume in discovered fields that has not yet been produced. Remaining reserves are equal to known volumes minus cumulative production.
Reserve Growth*	The increases in ‘known’ volumes that commonly occur as fields are developed and produced. It is synonymous with field growth and appreciation.
Undiscovered Volume*	The volumes postulated by the USGS, from geologic information and theory, to exist outside of known volumes.
Future reserve growth	This accounts for growth in ‘future’ volumes (Aguilera, 2006).
Index	The volume of conventional natural gas in the province with the largest gas endowment in a given region.
Normalized Endowment	The endowment volume of natural gas in each petroleum province divided by the index in a given region.

Table 2 Conventional gas endowment for Canada and the United States (Source: USGS, 1995, 2000; MMS, 1996; Klett et al., 1997); calculated endowment using the VSD model, indexes and normalized endowments. Index corresponds to the volume in the petroleum province with the maximum endowment and is highlighted with asterisks.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
		Cumulative	USGS	USGS-based	VSD Model	VSD-based
		# of CAN&US	Gas	Normalized	Calculated	Normalized
		Provinces	Endowment	Gas	Endowment	Gas
Province Code	Province Name	N _i	(BCFG)	Endowment	(BCFG)	Endowment
	TOTAL FOR ALL PROVINCES		1,687,228		1,684,214	
5047	Western Gulf	1	319690*	1.0000	323882*	1.0000
5097	Gulf of Mexico - Cenozoic Province	2	234,200	0.7326	198,173	0.6119
5044	Permian Basin	3	110,470	0.3456	145,648	0.4497
5058	Anadarko Basin	4	107,300	0.3356	115,308	0.3560
5001	Northern Alaska	5	96,500	0.3019	95,061	0.2935
5243	Alberta Basin	6	90,565	0.2833	80,396	0.2482
5200	East Greenland Rift Basins	7	80,709	0.2525	69,200	0.2137
5049	Louisiana - Mississippi Salt Basins	8	72,290	0.2261	60,334	0.1863
5078	Chukchi	9	51,800	0.1620	53,125	0.1640
5043	Palo Duro Basin	10	48,400	0.1514	47,142	0.1456
5081	Beaufort Shelf	11	43,500	0.1361	42,097	0.1300
5022	San Juan Basin	12	39,180	0.1226	37,790	0.1167
5048	East Texas Basin	13	34,800	0.1089	34,072	0.1052
5099	Atlantic - Mesozoic Province	14	27,500	0.0860	30,835	0.0952
5031	Williston Basin	15	22,290	0.0697	27,997	0.0864
5245	Rocky Mountain Deformed Belt	16	18,295	0.0572	25,491	0.0787
5062	Arkoma Basin	17	18,080	0.0566	23,266	0.0718
5037	S.W. Wyoming	18	17,880	0.0559	21,283	0.0657
5244	Williston Basin	19	17,756	0.0555	19,505	0.0602
5215	Labrador-Newfoundland Shelf	20	15,523	0.0486	17,907	0.0553
5010	San Joaquin Basin	21	15,070	0.0471	16,465	0.0508
5036	Wyoming Thrust Belt	22	14,680	0.0459	15,160	0.0468
5045	Bend Arch - Fort Worth Basin	23	13,850	0.0433	13,976	0.0432
5009	Sacramento Basin	24	12,520	0.0392	12,897	0.0398
5063	Michigan Basin	25	9,880	0.0309	11,914	0.0368
5098	Gulf of Mexico - Mesozoic Province	26	9,700	0.0303	11,015	0.0340
5003	Southern Alaska	27	9,640	0.0302	10,192	0.0315
5020	Uinta - Piceance Basin	28	9,240	0.0289	9,437	0.0291
5094	Los Angeles Basin	29	8,610	0.0269	8,742	0.0270
5013	Ventura Basin	30	7,700	0.0241	8,103	0.0250
5091	Pacific Northwest	31	7,000	0.0219	7,514	0.0232
5084	North Aleutian Basin	32	6,800	0.0213	6,970	0.0215
5083	Navarin Basin	33	6,200	0.0194	6,468	0.0200
5092	Central California	34	5,200	0.0163	6,002	0.0185
5089	Gulf of Alaska	35	4,900	0.0153	5,572	0.0172
5065	Black Warrior Basin	36	4,740	0.0148	5,172	0.0160
5093	Santa Barbara - Ventura	37	4,600	0.0144	4,802	0.0148
5039	Denver Basin	38	4,250	0.0133	4,457	0.0138
5033	Powder River Basin	39	4,200	0.0131	4,137	0.0128
5082	Hope Basin	40	4,100	0.0128	3,840	0.0119
5035	Wind River Basin	41	4,040	0.0126	3,563	0.0110
5061	Southern Oklahoma	42	3,720	0.0116	3,304	0.0102
5055	Nemaha Uplift	43	3,270	0.0102	3,064	0.0095
5028	Central Montana	44	3,140	0.0098	2,840	0.0088
5085	St. George Basin	45	3,000	0.0094	2,631	0.0081

Table 2 (Continued) Conventional gas endowment for Canada and the United States (Source: USGS, 1995, 2000; MMS, 1996; Klett et al., 1997); calculated endowment using the VSD model, indexes and normalized endowments. Index corresponds to the volume in the petroleum province with the maximum endowment and is highlighted with asterisks.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
		Cumulative # of CAN&US Provinces	USGS Gas Endowment (BCFG)	USGS-based Normalized Gas Endowment	VSD Model Calculated Endowment (BCFG)	VSD-based Normalized Gas Endowment
Province Code	Province Name	N_i				
5021	Paradox Basin	46	2,920	0.0091	2,436	0.0075
5067	Appalachian Basin	47	2,920	0.0091	2,254	0.0070
5096	Outer Borderland	48	2,800	0.0088	2,084	0.0064
5002	Central Alaska	49	2,760	0.0086	1,925	0.0059
5086	Norton Basin	50	2,700	0.0084	1,777	0.0055
5090	Shumagin - Kodiak Shelf	51	2,700	0.0084	1,639	0.0051
5059	Sedgwick Basin	52	2,520	0.0079	1,509	0.0047
5034	Big Horn Basin	53	2,420	0.0076	1,389	0.0043
5095	Inner Borderland	54	2,100	0.0066	1,276	0.0039
5027	Montana Thrust Belt	55	1,930	0.0060	1,171	0.0036
5012	Santa Maria Basin	56	1,620	0.0051	1,073	0.0033
5088	Cook Inlet	57	1,600	0.0050	981	0.0030
5060	Cherokee Platform	58	1,580	0.0049	896	0.0028
5007	Northern Coastal	59	1,190	0.0037	816	0.0025
5066	Cincinnati Arch	60	1,020	0.0032	742	0.0023
5053	Cambridge Arch - Central Kansas	61	1,010	0.0032	673	0.0021
5004	Western Oregon - Wash.	62	790	0.0025	609	0.0019
5040	Las Animas Arch	63	630	0.0020	549	0.0017
5029	Southwest Montana	64	600	0.0019	494	0.0015
5064	Illinois Basin	65	490	0.0015	442	0.0014
5018	Western Great Basin	66	430	0.0013	395	0.0012
5051	Superior	67	420	0.0013	351	0.0011
5005	Eastern Oregon - Wash.	68	390	0.0012	310	0.0010
5069	Piedmont	69	390	0.0012	273	0.0008
5023	Albuquerque - Santa Fe Rift	70	360	0.0011	239	0.0007
5019	Eastern Great Basin	71	330	0.0010	208	0.0006
5332	Salton Trough	72	300	0.0009	179	0.0006
5094	Los Angeles Basin OCS	73	300	0.0009	153	0.0005
5011	Central Coastal	74	250	0.0008	130	0.0004
5025	S. Ariz - S.W. New Mexico	75	200	0.0006	109	0.0003
5087	St. Matthew - Hall Basin	76	200	0.0006	90	0.0003
5024	Northern Arizona	77	170	0.0005	73	0.0002
5046	Marathon Thrust Belt	78	140	0.0004	59	0.0002
5056	Forest City Basin	79	70	0.0002	46	0.0001
5008	Sonoma - Livermore Basin	80	60	0.0002	35	0.0001
5041	Raton Basin - Sierra Grande Uplift	81	40	0.0001	27	0.0001
5050	Florida Peninsula	82	40	0.0001	20	0.0001
5068	Blue Ridge Thrust Belt	83	30	0.0001	15	0.0000
5038	Park Basins	84	20	0.0001	11	0.0000
5017	Idaho - Snake River Downwarp	85	10	0.0000	10	0.0000
5006	Klamath - Sierra Nevada	86	0			
5015	San Diego - Ocean Side	87	0			
5026	South - Central New Mexico	88	0			
5032	Sioux Arch	89	0			
5042	Pederal Uplift	90	0			
5052	Iowa Shelf	91	0			
5057	Ozark Uplift	92	0			
5054	Salina Basin	93	<100			

Table 3 USGS (2000) conventional gas endowment for LAC countries; calculated endowment using the VSD model, indexes and normalized endowments. Index corresponds to the volume in the petroleum province with the maximum endowment and is highlighted with asterisks.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
		Cumulative	USGS	USGS-based	VSD Model	VSD-based
		# of LAC	Gas	Normalized	Calculated	Normalized
		Provinces	Endowment	Gas	Endowment	Gas
Province Code	Province Name	N_i	(BCFG)	Endowment	(BCFG)	Endowment
	TOTAL FOR ALL PROVINCES		857,099		854,959	
6098	East Venezuela Basin	1	221679*	1.0000	222,040*	1.0000
6036	Santos Basin	2	81,672	0.3684	81,502	0.3671
5305	Villahermosa Uplift	3	56,915	0.2567	59,066	0.2660
6045	Santa Cruz-Tarija Basin	4	48,092	0.2169	50,709	0.2284
6099	Maracaibo Basin	5	44,277	0.1997	46,031	0.2073
6103	Tobago Trough	6	42,703	0.1926	42,700	0.1923
6021	Guyana Basin	7	42,058	0.1897	39,937	0.1799
6059	Magallenes Basin	8	38,848	0.1752	37,419	0.1685
6034	Espirito Santo Basin	9	34,509	0.1557	34,992	0.1576
6055	Neuquen Basin	10	33,119	0.1494	32,577	0.1467
6022	Foz de Amazonas Basin	11	29,840	0.1346	30,137	0.1357
6035	Campos Basin	12	25,935	0.1170	27,661	0.1246
6037	Pelotas Basin	13	22,806	0.1029	25,151	0.1133
5304	Saline-Comalcalco Basin	14	18,669	0.0842	22,626	0.1019
6060	North Malvinas Basin	15	16,581	0.0748	20,110	0.0906
6096	Llanos Basin	16	15,651	0.0706	17,636	0.0794
6107	Lesser Antilles Deformed Belt	17	11,979	0.0540	15,238	0.0686
6063	Malvinas Basin	18	11,402	0.0514	12,953	0.0583
6029	Sergipe-Alagoas Basin	19	9,741	0.0439	10,813	0.0487
5301	Tampico-Misantla Basin	20	8,712	0.0393	8,849	0.0399
6090	Middle Magdalena	21	8,294	0.0374	7,082	0.0319
6081	Talara Basin	22	7,687	0.0347	5,530	0.0249
6058	San Jorge Basin	23	7,339	0.0331	4,200	0.0189
5302	Veracruz Basin	24	6,437	0.0290	3,095	0.0139
5307	Campeche-Sigsbe Salt Basin	25	5,565	0.0251	2,210	0.0100
6041	Putamayo-Orient-Maranon Basin	26	3,212	0.0145	1,536	0.0069
5308	Yucatan Platform	27	1,496	0.0067	1,062	0.0048
6083	Progreso Basin	28	1,193	0.0054	776	0.0035
6117	Greater Antilles Deformed Belt	29	688	0.0031	672	0.0030
5310	Sierra Madre de Chiapas-Peten Foldbelt		NA			

Table 4 Parameters, variables, and indexes used in VSD analysis and normalizing of regions A through F.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)		
		Index	Index	ap	Vx	Ψ	Vs	S	Vm	Nx	Nx	Endowment		
		USGS	VSD							Assessed	Assessed +	Assessed	Assessed	Assessed +
		(TCFG)	(TCFG)								Unassessed	USGS	VSD	Unassessed
												(TCFG)	(TCFG)	VSD (TCFG)
	Region													
A	LAC	221.679	222.040	0.547	22,691	0.01030	4,763	0.94	0.688	29	128	857	855	1,548
	LAC (concave assumption)	221.679	222.040	0.550	30,365	0.00138	363,972	0.67	0.672	29	128	857	1,077	1,816
B	Canada and USA	319.690	323.880	0.555	11,400	0.00067	4,151,548	0.64	0.010	85	172	1,687	1,684	1,921
C	Former Soviet Union	1912.983	2001.561	0.970	880	3.28000	94	1643	0.100	30	141	3,687	3,688	5,009
D	Asia Pacific	120.956	120.921	0.654	1,316	0.02300	3,669	1.23	0.100	66	261	888	887	1,142
E	Europe	197.584	198.289	0.796	840	0.26000	83	48	0.152	13	62	796	796	1,403
F	Middle East and North Africa	611.451	596.700	0.420	38,800	0.00150	338,515	1.05	0.005	33	88	3,279	3,276	3,948

Fig. 1 The relationship between cumulative production, remaining reserves and undiscovered volumes, terminology from USGS, 2000 (Source: Aguilera, 2006).

Fig. 2 Comparison between terminology from USGS (2000) and PRMS (2011).

Fig. 3 USGS World Petroleum Assessment regions with geologic provinces (USGS, 2000). In the USGS report, Mexico's endowment is included in the North America region. In this paper, Mexico is included within the LAC assessment. The LAC results are then compared with normalized endowment from other regions around the world.

Fig. 4 Conventional natural gas endowment for Canada and the United States. The black diamonds represent endowments published by the USGS (1995, 2000); MMS, 1996; Klett et al. (1997). The solid blue continuous line corresponds to the endowments calculated with the VSD model. The magenta squares show VSD predictions of the endowment for all 172 petroleum provinces recognized by the USGS to exist in Canada and the United States. Horizontal error bars (plus and minus 20%).

Fig. 5 Conventional natural gas endowment for LAC. The black diamonds represent endowments published by the USGS (2000). The solid blue continuous line corresponds to the endowments calculated with the VSD model. The magenta squares show VSD predictions of the endowment for all 128 petroleum provinces recognized by the USGS to exist in LAC countries. Horizontal error bars (plus and minus 20%).

Fig. 6(A) Normalized conventional gas endowment (size of provinces) vs. cumulative number of provinces for LAC countries.

The shape of the curve is convex at large values of the normalized endowments. The shapes of the curves in Figs. 6(B) to 6(G) are generally concave. Horizontal error bars (plus and minus 20%).

Fig. 6(B) Normalized conventional gas endowment (size of provinces) vs. cumulative number of provinces for the United States and Canada. Horizontal error bars (plus and minus 20%).

Fig. 6(C) Normalized conventional gas endowment (size of provinces) vs. cumulative number of provinces for the Former Soviet Union. Horizontal error bars (plus and minus 20%).

Fig. 6(D) Normalized conventional gas endowment (size of provinces) vs. cumulative number of provinces for Asia Pacific. Horizontal error bars (plus and minus 20%).

Fig. 6(E) Normalized conventional gas endowment (size of provinces) vs. cumulative number of provinces for Europe. Horizontal error bars (plus and minus 20%).

Fig. 6(F) Normalized conventional gas endowment (size of provinces) vs. cumulative number of provinces for Middle East and North Africa. Horizontal error bars (plus and minus 20%).

Fig. 6(G) Normalized conventional gas endowment (size of provinces) vs. cumulative number of provinces for the entire world, The shapes of the curves in Figs. 6(B) to 6(G) are generally concave. The shape of the curve in Fig. 6(A) for LAC countries is convex at large values of the normalized endowments. Horizontal error bars (plus and minus 20%).

Fig. 7 Conventional natural gas endowment for LAC. The triangles show the additional gas endowment assuming a concave VSD curve for 29 provinces. The assumption of a concave shape like in other petroleum provinces of the world increases the endowment from 855 to 1,077 TCFG. Horizontal error bars (plus and minus 20%).

Fig. 8 Conventional natural gas endowment LAC. The circles show the additional gas endowment assuming a concave VSD curve for 128 provinces. The concave assumption increases the endowment from 1,487 to 1,816 TCFG. Horizontal error bars (plus and minus 20%).

Fig. 9 Observed field size distribution for the Frio Strandplain play, onshore Texas. The distribution has three segments representing the cumulative number of fields discovered through the specified year (Source: Drew, 1990, 1997; Crovelli and Barton, 1993; Barton and Scholz, 1995).

Fig. 10 Cumulative frequency plot of petroleum field sizes for the Frio Strandplain play, onshore Texas. Data points for only the largest 9 fields are shown. The remaining fields have been truncated due to economic considerations (Source: Crovelli and Barton, 1993).

**OBSERVED FIELD DISTRIBUTION, OIL AND GAS, FRIO STRANDPLAIN EXPLORATION PLAY,
TEXAS (Source of data: Barton and scholz, 1995)**

Fig. 11 Log-log plot by time segments of cumulative frequency of oil and gas fields vs. field size (Source: Barton and Scholz, 1995).

Fig. 12 Log-log plot by time segments of cumulative frequency of oil and gas fields vs. field size to 1960 and best fit obtained with the VSD model. The hydrocarbon endowment is not truncated and is shown even for small fields that were not economic at that point in time. The VSD fits the USGS data with a coefficient of determination (R^2) equal to 0.98 (Source of actual data: Barton and Scholz, 1995).

**OBSERVED FIELD DISTRIBUTION, OIL AND GAS, FRIIO STRAIN EXPLORATION PLAY, TEXAS
Actual and Calculated to 1960, and Predicted to 1970 with VSD Model**

Fig. 13 Log-log plot by time segments of cumulative frequency of oil and gas fields vs. field size and best fit obtained with the VSD model to 1960 (Source of actual data: Barton and Scholz, 1995). Also shown is the predicted distribution of the VSD to 1970.

Fig. 14 Log-log plot by time segments of cumulative frequency of oil and gas fields vs. field size and best fits obtained with the VSD model for 1960 and 1970. The VSD fits the USGS data with coefficients of determination (R^2) equal to 0.98 (Source of actual data: Barton and Scholz, 1995).

OBSERVED FIELD DISTRIBUTION, OIL AND GAS, FRIIO STRAIN EXPLORATION PLAY, TEXAS
Actual and Calculated to 1960 and 1970 and predicted to 1985 with VSD Model

Fig. 15 Log-log plot by time segments of cumulative frequency of oil and gas fields vs. field size and best fit obtained with the VSD model to 1960 and 1970 (Source of actual data: Barton and Scholz, 1995). Also shown is the predicted distribution of the VSD to 1985.

Fig. 16 Log-log plot by time segments of cumulative frequency of oil and gas fields vs. field size and best fits obtained with the VSD model for 1960, 1970 and 1985. The VSD fits the USGS data with coefficients of determination (R^2) equal to 0.98 (Source of actual data: Barton and Scholz, 1995).

Fig. 17 Log-log plot by time segments of cumulative frequency of oil and gas fields vs. field size and best fits obtained with the VSD model for 1960, 1970 and 1985. The VSD fits the USGS data with coefficients of determination (R^2) equal to 0.98 (Source of actual data: Barton and Scholz, 1995). Graph also includes Pareto straight lines for 2 different cases, neither of which are as accurate as the curves generated with the VSD model.