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Using Size Distribution Analysis to Forecast Natural Gas Resources in Asia Pacific

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ABSTRACT

Increasing energy consumption in Asia Pacific will largely be met by fossil fuels. Natural gas production in the region presently ranks behind that of oil and coal. However, the abundance of gas could lead to a significant gas market share increase in the energy mix. The purpose of this paper is to estimate the total endowment of conventional gas in Asia Pacific. This is carried out with a Variable Shape Distribution (VSD) model that forecasts volumes in provinces that have not been previously evaluated. The endowment is then distributed across countries to show where volumes are most likely to be found. A breakdown between offshore versus onshore resources is also estimated. The results of the analysis show there is a significant gas endowment. The estimated distribution across countries and onshore/offshore areas provides insight into the relative economics of gas production, as well as a basis for potential investment decisions. With appropriate energy policies, it may be possible to tap the vast gas potential in Asia Pacific. Considering gas may be the most abundant, inexpensive, and clean fossil fuel, the outcome would be increased energy security and a low carbon economy.

Keywords: Natural gas; Availability; Size Distribution; Supply

1. Introduction

Energy services are a fundamental human need and are thus indispensable for human well-being. Significant challenges exist, ranging from energy security, to energy poverty, to environmental quality. In Asia Pacific, energy demand is expected to grow dramatically as the region experiences sustained

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economic growth [1]. A fossil fuel future, at least over the next 30 to 50 years, is the most realistic scenario. The mix of fossil fuel production over the long term remains uncertain. The issue is whether the role of natural gas in the energy mix will become more important and whether there will be enough gas in the region to satisfy growing demand.

Over the past decade there have been only a few assessments of global natural gas resources. In general, these estimates point to steadily growing resources. Although assessments are mostly in agreement regarding reserves, they tend to diverge for total resource endowments. The same holds true for the Asia Pacific region.

Some resource assessments also include gas from unconventional sources, such as coalbed methane, shale gas, tight gas sands and hydrate. The distinction between conventional and unconventional sources is becoming increasingly unclear. In fact, gas from unconventional sources gradually supplements conventional production, especially in the United States where unconventional gas accounts for nearly half of its domestic supply. This could become a reality in Asia Pacific as well, which is believed to hold vast unconventional gas potential. Future research will assess the availability of unconventional gas as well as the economic and policy implications for the region. In this paper, the focus is on conventional natural gas using a Variable Shape Distribution (VSD) model that estimates endowment volumes in previously unassessed provinces. The VSD is a statistical method known as size distribution analysis that has proved useful for many decades as a simple and effective complement to more complex and time-consuming geological methods. When various assessment methodologies converge in their results, a higher degree of confidence in those results is provided.

Notwithstanding the strong possibilities of a natural gas and perhaps an eventual hydrogen economy in Asia Pacific, there is concern among some energy analysts about a potential gas shortage in the coming years. This would probably force the region to resort to an even more intensive use of coal.

Furthermore, dramatic increases in energy prices would lead to devastating macroeconomic effects that would undermine economic and environmental conditions.

Eventually, there will be a maximum peak in natural gas production. The question is when will it occur, and will it happen because of depletion or because of substitution to other energy sources, perhaps unconventional or non-fossil. According to pessimistic sources, the peak for natural gas is estimated to occur only a couple of decades after that of oil. An important issue in the debate is whether society will experience a smooth or difficult transition.

The transition to sustainability depends on what energy sources are available and how much they cost. This includes not only production costs, but also externalities such as environmental and social costs. Over time, technological change will be important since it will presumably reduce all of these costs. Although the past is not always an indication of the future, experience suggests that viable energy alternatives, such as conventional and unconventional natural gas, could make the transition much smoother than expected.

Furthermore, recent work [2, 3] suggests that there is enough conventional and unconventional gas, available at economic production costs, for society to substitute alternative sources before depletion becomes a problem. However, to avoid an abrupt, depletion driven peak in natural gas production and the associated consequences, adequate investment in alternative sources must take place on a timely basis. Nevertheless, we must not ignore investment opportunities to enhance and extend our access to natural gas. The ability of technological advancement to offset the cost-increasing effects of depletion will be fundamental.

Given the sheer size of the potential natural gas demand in Asia Pacific, temporary shortages might still occur due to problems that include lack of infrastructure, lack of spare capacity, political instability, natural disasters, strikes, shortage of qualified workers, shortage of refining capacity, commodity manipulation by speculators, and the power of national gas companies.

2. Previously Evaluated Natural Gas Volumes in Asia Pacific

The United States Geological Survey World Petroleum Assessment 2000 [4] estimates conventional natural gas endowment volumes, which are equal to known (cumulative production plus remaining reserves) plus undiscovered volumes (see Figure 1), for 77 Asia Pacific provinces.[1] The study relies on various geological techniques combined with probability assessments to account for the uncertainty. They publicize the mean values, which are the volumes used in this paper.

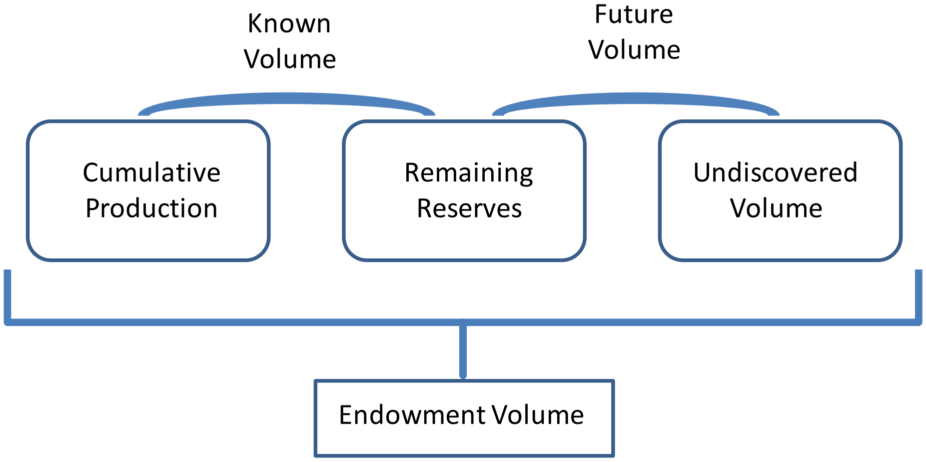

Fig. 1. The relationship between cumulative production, remaining reserves and undiscovered volumes.

In total, the USGS recognizes 290 provinces in the Asia Pacific region.[2] Thus, the volumes in 213 of those provinces are not presented in [4], probably because they were not expected to be exploited

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[1] *The USGS (2000) study [4] assesses 11 provinces in 'South Asia' and 66 provinces in their version of 'Asia Pacific'. In our study, the Asia Pacific region is equivalent to the combined USGS versions of both 'Asia Pacific' and 'South Asia'. Thus, our definition of Asia Pacific contains 77 provinces that were assessed by the USGS.*

[2] *USGS (2000) [4] recognizes totals of 29 provinces in 'South Asia' and 261 provinces in 'Asia Pacific'. Thus, there are 290 provinces in our definition of Asia Pacific.*

within the adopted 30-year time horizon. As stated by the USGS, “assessed areas were those judged to be significant on a world scale in terms of known petroleum volumes, geologic potential for new petroleum discoveries, and political or societal importance.” [3] Furthermore, many of the unassessed provinces are in remote areas where gas may exist but due to location and other factors are likely to be high-cost and so presumed by the USGS to be of little commercial interest over its 30-year timeframe.

Figure 2 is an Asia Pacific map that shows the region divided into geologic provinces. Those provinces assessed in [4] are highlighted with horizontal stripes. In this paper, we estimate the endowment volumes for the unassessed provinces using a previously defined size distribution model, called the Variable Shape Distribution (VSD) model [5]. Other models commonly used to forecast gas supply are life cycle models (e.g. Hubbert’s logistic curves), rate of effort models, geologic-volumetric models, subjective probability models, discovery process models and econometric models. With regard to size distribution analysis, Adelman et al. [6] state “the concept of deposit size distribution is an essential component of models of petroleum supply designed to reflect industry behavior in a logical way” (1983, p. 90).

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[3] *In this case, the term ‘petroleum’ includes natural gas. This is because the USGS defines conventional petroleum as the sum of natural gas, natural gas liquids, and oil with more than 15 degrees API.*

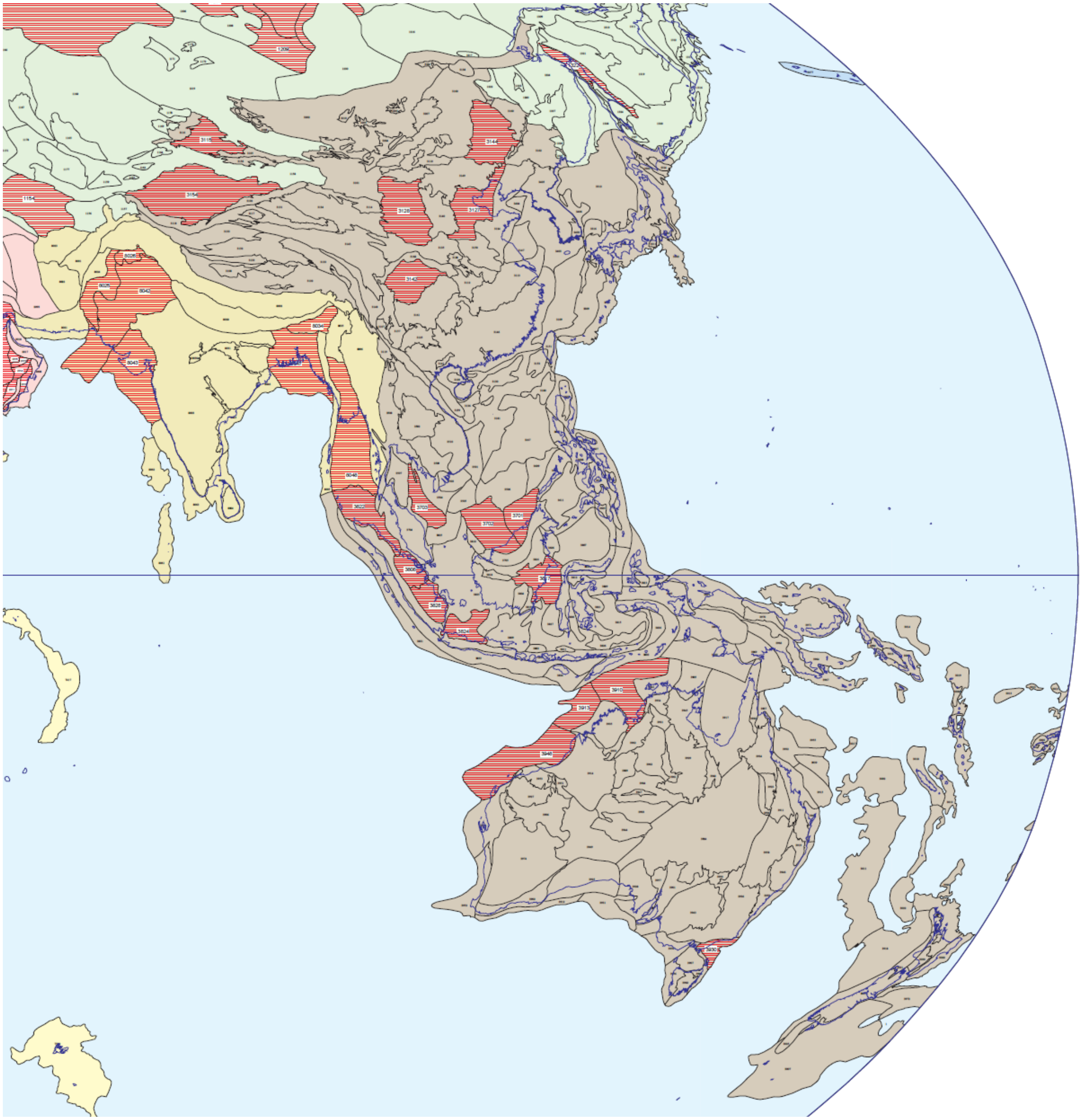

Fig. 2. Asia Pacific map divided into geologic provinces [4].

3. The Variable Shape Distribution (VSD) Model

Traditionally, all the methods used to forecast oil and natural gas volumes have been “based on an assumed form of the size-frequency distribution of the natural population of oil and gas accumulations” [7]. The lognormal and Pareto (fractal) distributions are common size distribution models used to estimate petroleum volumes of unassessed areas. These types of statistical distributions are believed to be representative of many natural and social occurrences (e.g. resource distribution in nature; income distribution across population).

Some researchers believe that the distribution of nature’s petroleum resources follow lognormal distributions [8]. However, other researchers claim that the lognormal distribution provides overly pessimistic results [9]. They observe that, with additional exploration, there is an on-going discovery process that can better be modeled with a Pareto distribution.

Over the past five decades, “scientists have engaged in honest debate about the form of the distribution. In the USGS, thinking has evolved from regarding the entire natural population as lognormal to recognizing that a fractal or power-law distribution better predicts the increasing numbers of small accumulations” [7]. More recently, it has generally been acknowledged that the Pareto distribution tends to overestimate petroleum resources, while the lognormal distribution tends to underestimate them.

The VSD is unique in that we start by observing the curvature (on a log-log plot) given by the size and number of provinces from [4]. We then develop the VSD model which allows the data to determine the specified relationship between the size and number of provinces. Next, the model is extended out of sample such that (1) the cumulative number of provinces is the sum of the number of assessed and unassessed provinces, (2) the largest and smallest provinces are constant and known.

3.1 Description of the VSD Methodology

The VSD method starts by ranking the assessed Asia Pacific provinces from [4] in decreasing order by endowment volume. When the data is plotted on log-log coordinates, the vertical axis shows the rank of a province according to its volume, while the horizontal axis shows the volume of the province. Assuming most of the larger provinces have already been assessed (e.g. Northwest Shelf, Kutei Basin, Greater Sarawak Basin, Malay Basin, Ganges-Brahmaputra Delta, Tarim Basin, and others), the VSD calculates volumes for provinces that have not been assessed in the past. Thus, the slope of the approximate straight line (i.e. the Pareto Distribution – see Figure 3) given by the assessed, larger provinces remains constant as we include unassessed provinces in the ranking.

As with all size distribution models, the original sample used to estimate the parameters contains most of the largest data in terms of endowment volumes. This allows us to estimate the slope and intercepts of the straight line given by the largest data. These parameters remain constant during the volumetric forecasting of the previously unassessed provinces. Many of these unassessed provinces are in areas where gas may exist but due to location and other factors are likely to be higher cost resources.

3.2 Parameter Estimation and Validation for Asia Pacific

The gas endowment volumes for the 77 Asia Pacific provinces assessed by [4], shown in the fourth column of Table 1, have been used to estimate the parameters of the VSD model using non-linear regression.

Table 1
Gas endowment volumes for 77 Asia Pacific provinces assessed by [4].

R^2 coefficient of determination =	**0.9900130**

a_p =	0.697	N_x =	77
r_m =	7.1429E-06	N_m =	1
		V_x =	1,540
V_s =	3707	V_m =	0.011
Ψ =	0.02532303	a_m =	0.367
severity =	1.1456242	$(r_m)^{am}$ =	0.013

Province Code	Province Name	Cumulative # of Provinces N_t	Gas Endowment (TCFG)	r_v	r_t	a_t	function	$\hat{V}_i$ (TCFG)
	TOTAL		**1099.632**					**1101.219**
3948	Northwest Shelf	1	120.956	0.98142	0.98143	0.00000	2.85484E-01	126.074
3817	Kutei Basin	2	110.230	0.35621	0.35622	0.67152	1.03030E-01	110.476
3702	Greater Sarawak Basin	3	101.411	0.19530	0.19531	0.67268	5.37363E-02	98.026
3703	Malay Basin	4	75.614	0.12676	0.12676	0.67119	3.32823E-02	85.583
8047	Ganges-Brahmaputra Delta	5	67.380	0.09023	0.09023	0.66911	2.27426E-02	74.099
3154	Tarim Basin	6	65.719	0.06808	0.06809	0.66683	1.65576E-02	64.041
3701	Baram Delta/Brunei-Sabah Basin	7	59.426	0.05347	0.05348	0.66449	1.25995E-02	55.463
3822	North Sumatra Basin	8	40.682	0.04325	0.04326	0.66211	9.90449E-03	48.228
3913	Browse Basin	9	38.053	0.03577	0.03577	0.65972	7.98220E-03	42.144
8043	Bombay	10	37.137	0.03010	0.03011	0.65733	6.56055E-03	37.020
3910	Bonaparte Gulf Basin	11	36.796	0.02569	0.02570	0.65495	5.47830E-03	32.688
8042	Indus	12	35.560	0.02219	0.02219	0.65257	4.63468E-03	29.006
8048	Irrawaddy	13	30.530	0.01935	0.01935	0.65019	3.96399E-03	25.858
3828	South Sumatra Basin	14	28.455	0.01701	0.01701	0.64781	3.42182E-03	23.151
8025	Sulaiman-Kirthar	15	28.376	0.01505	0.01506	0.64544	2.97725E-03	20.809
3127	Bohaiwan Basin	16	24.186	0.01341	0.01341	0.64306	2.60818E-03	18.771
3142	Sichuan Basin	17	22.837	0.01200	0.01201	0.64068	2.29847E-03	16.989
3824	Northwest Java Basin	18	15.508	0.01079	0.01080	0.63830	2.03610E-03	15.423
3930	Gippsland Basin	19	15.433	0.00975	0.00975	0.63591	1.81194E-03	14.039
3966	New Guinea Foreland Basin-Fold	20	11.000	0.00883	0.00884	0.63352	1.61900E-03	12.812
3805	Bintuni/Sulawati Province	21	9.500	0.00803	0.00803	0.63111	1.45181E-03	11.718
3507	Thai Basin	22	8.900	0.00732	0.00732	0.62870	1.30604E-03	10.740
3924	Eromanga Basin	23	8.500	0.00669	0.00669	0.62628	1.17825E-03	9.861
3159	Yingehai Basin	24	8.400	0.00612	0.00613	0.62384	1.06567E-03	9.070
3808	Central Sumatra Basin	25	7.944	0.00562	0.00563	0.62139	9.66024E-04	8.355
8034	Assam	26	7.712	0.00517	0.00517	0.61892	8.77470E-04	7.707
3809	East Java Basin	27	7.600	0.00476	0.00476	0.61644	7.98468E-04	7.118
3144	Songliao Basin	28	7.449	0.00439	0.00439	0.61393	7.27742E-04	6.582
3031	Taranaki Basin	29	7.200	0.00405	0.00406	0.61141	6.64220E-04	6.091
3505	Saigon Basin	30	6.000	0.00374	0.00375	0.60887	6.06998E-04	5.642
3825	Penyu/West Natuna Basin	31	5.700	0.00346	0.00347	0.60630	5.55309E-04	5.231
3128	Ordos Basin	32	5.630	0.00321	0.00321	0.60370	5.08500E-04	4.852
3605	Palawan Shelf	33	5.600	0.00297	0.00298	0.60108	4.66011E-04	4.503
3115	Junggar Basin	34	3.879	0.00275	0.00276	0.59844	4.27358E-04	4.181
3606	Pamusian Tarakan Basin	35	3.600	0.00255	0.00256	0.59576	3.92125E-04	3.884
8026	Kohat-Potwar	36	3.245	0.00237	0.00238	0.59305	3.59949E-04	3.608
3308	Niigata Basin	37	2.200	0.00220	0.00220	0.59030	3.30514E-04	3.353
3969	Papuan Basin-Shelf Platform	38	2.200	0.00204	0.00205	0.58752	3.03544E-04	3.116
3151	Taiwan Thrust and Fold Belt	39	2.000	0.00189	0.00190	0.58471	2.78797E-04	2.896
3304	Japan Volcanic Arc/Accreted Terr	40	1.600	0.00176	0.00176	0.58185	2.56057E-04	2.691
3181	South China Continental Shelf Slc	41	1.600	0.00163	0.00164	0.57895	2.35138E-04	2.500
3109	East China Sea Basin	42	1.400	0.00151	0.00152	0.57600	2.15870E-04	2.322
8045	Krishna-Godavari	43	1.400	0.00140	0.00141	0.57300	1.98106E-04	2.155
3958	Surat Basin	44	1.400	0.00130	0.00131	0.56996	1.81713E-04	2.000
3503	Mekong/Cuulong/Vung Tau Basin	45	1.300	0.00120	0.00121	0.56686	1.66573E-04	1.855
3306	Kanto Basin	46	1.300	0.00112	0.00112	0.56370	1.52580E-04	1.719
3903	Amadeus Basin	47	1.200	0.00103	0.00104	0.56048	1.39638E-04	1.592
3950	Otway Basin	48	1.200	0.00095	0.00096	0.55720	1.27663E-04	1.473
3131	Qaidam Basin	49	0.800	0.00088	0.00089	0.55384	1.16577E-04	1.361
3952	Perth Basin	50	0.700	0.00081	0.00082	0.55041	1.06310E-04	1.256
3502	Khorat Platform	51	0.700	0.00075	0.00075	0.54690	9.68009E-05	1.158
3806	Bone Basin	52	0.600	0.00069	0.00069	0.54331	8.79915E-05	1.066
3833	Sumatra/Java Magmatic Arc	53	0.500	0.00063	0.00064	0.53962	7.98304E-05	0.979
3153	Taixinan Basin	54	0.500	0.00058	0.00058	0.53584	7.22707E-05	0.898
3611	Sulu Sea Basin	55	0.400	0.00053	0.00053	0.53195	6.52696E-05	0.822
3832	Sumatra/Java Fore-Arc Basins	56	0.400	0.00048	0.00049	0.52794	5.87882E-05	0.750
3316	Tsushima Basin	57	0.400	0.00044	0.00044	0.52381	5.27911E-05	0.683
8044	Cauvery	58	0.400	0.00040	0.00040	0.51954	4.72458E-05	0.620
3130	Pearl River Mouth Basin	59	0.300	0.00036	0.00036	0.51512	4.21226E-05	0.561
3147	Subei Yellow Sea Basin	60	0.300	0.00032	0.00033	0.51054	3.73947E-05	0.506
3508	Thailand Mesozoic Basin Belt	61	0.300	0.00029	0.00030	0.50578	3.30371E-05	0.454
3907	Bass Basin	62	0.300	0.00026	0.00026	0.50082	2.90272E-05	0.406
3303	Ishikari Hidaka Basin	63	0.300	0.00023	0.00023	0.49564	2.53444E-05	0.360
8023	Central Afghanistan	64	0.271	0.00020	0.00021	0.49021	2.19698E-05	0.318
3804	Barito Basin	65	0.200	0.00017	0.00018	0.48450	1.88862E-05	0.279
3146	South China Fold Belt	66	0.200	0.00015	0.00016	0.47847	1.60778E-05	0.242
3305	Joban Basin	67	0.200	0.00013	0.00014	0.47207	1.35306E-05	0.208
3916	Carnarvon Basin	68	0.102	0.00011	0.00012	0.46524	1.12317E-05	0.177
3103	Beibuwan Basin	69	0.100	0.00009	0.00010	0.45791	9.16993E-06	0.148
3156	Turpan Basin	70	0.100	0.00007	0.00008	0.44999	7.33525E-06	0.122
3829	Sulawesi Accretionary Prism	71	0.100	0.00006	0.00006	0.44133	5.71923E-06	0.098
3160	Yinshan Da and Xiao Hingganling	72	0.100	0.00004	0.00005	0.43179	4.31507E-06	0.077
3609	Reed Bank Basin	73	0.100	0.00003	0.00004	0.42112	3.11789E-06	0.058
3810	East Natuna Basin	74	0.100	0.00002	0.00003	0.40903	2.12535E-06	0.041
3823	Northern Irian Jaya Waropen Basi	75	0.100	0.00001	0.00002	0.39516	1.33904E-06	0.028
3113	Jiangnan South Jiangsu Fold Belt	76	0.100	0.00000	0.00001	0.37954	7.68603E-07	0.017
8035	North Burma	77	0.011	0.00000	0.00001	0.36658	4.64894E-07	0.011

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Figure 3 shows this data on a log-log plot of the cumulative number (rank) of provinces versus the size of the provinces. These data points are plotted with the third and fourth columns from Table 1 and are represented by solid diamonds. Note that the data shows leftward curvature as the volumes become smaller.

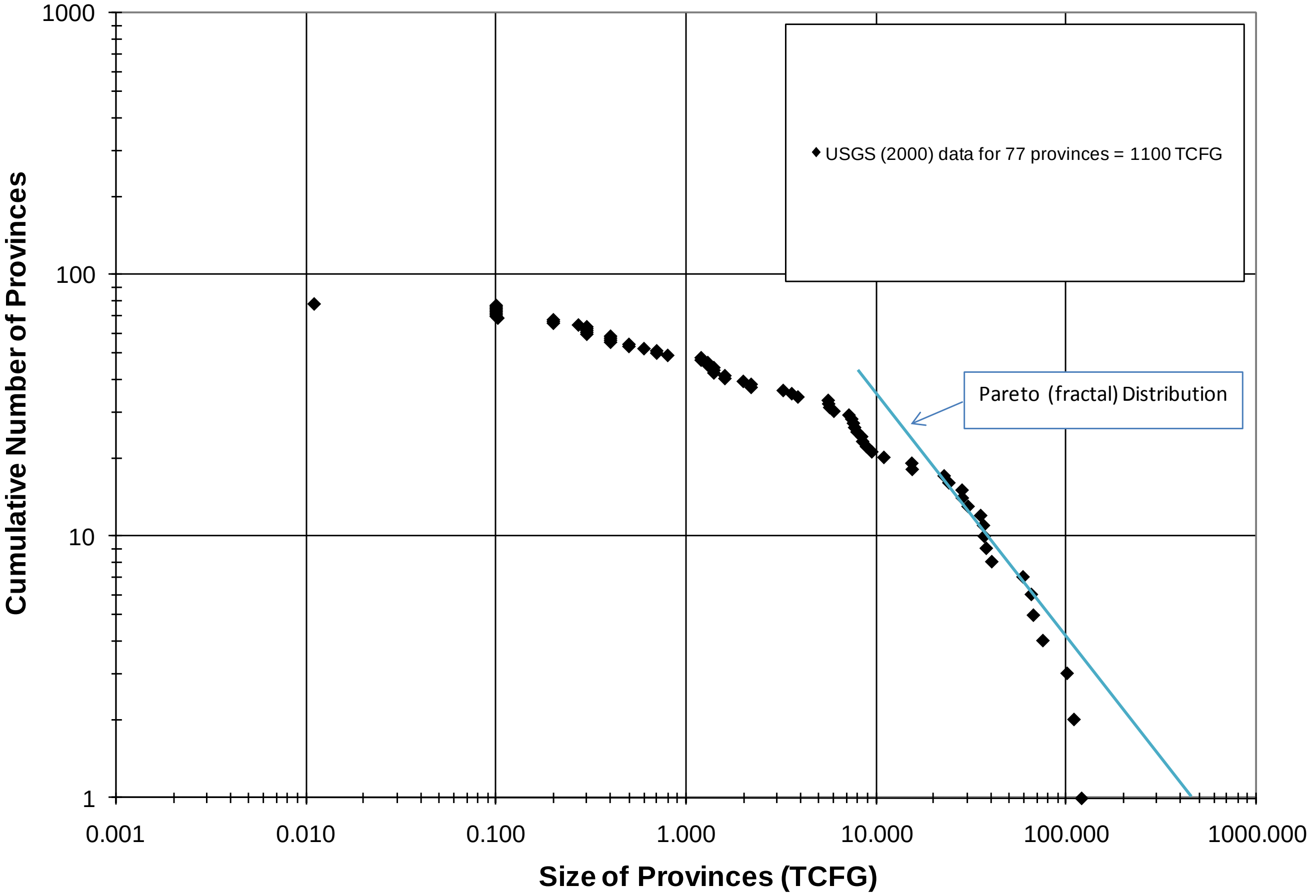

Fig. 3. USGS (2000) data shows endowment volumes for 77 Asia Pacific provinces.

The next step is to use the VSD model to provide the best possible fit of the USGS (2000) data in Figure 3. In Equation 1, we present the VSD model as a non-linear least squares (NLS) model. In particular, the problem is to minimize the sum of the squared differences between the observed and predicted sizes of the provinces:[4]

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

Subject to:

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

where:

a_p - slope of straight line approximated from USGS sample points with larger province volumes (same as slope of Pareto distribution).

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

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, near the largest volumes).

V_m - minimum USGS province volume (trillion cubic feet of gas, TCFG).

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

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[4] *Appendix A provides the mathematical development of Equations 1 and 2, and explains the nomenclature in detail. Schematics (Figures A.1 and A.2) illustrate some of the terms.*

V_i - observed volume of a province (TCFG).

$\hat{V}_i$ - estimated volume of a province (TCFG).

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

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).

As seen in Equation 1, there are five parameters being estimated in the VSD equation - V_x, a_p, V_s, ψ, and S – that cause the equation to best fit the volumes from [4] (i.e. to minimize the residual sum of squares). The parameters are estimated based on visual inspection of the curves, comparison of actual and estimated volumes, and inspection of the coefficient of determination (R^2). The VSD model is run on the 77 Asia Pacific provinces for which gas endowment data from [4] exists. Table 2 shows estimates of the five parameters that give the best fit.

Table 2
Parameters used for calculating assessed and unassessed natural gas in Asia Pacific. Parameters are defined under Equations 1 and 2.

Parameter	**Gas, Asia Pacific**
V_x - Maximum volume given by Pareto straight line at N_m equal to 1	1,540 TCFG
a_p - Pareto shape exponent	0.697
V_s - Volume of separation	3,707 TCFG
ψ - Separation ratio	0.025
S - Severity exponent	1.146

3.3 VSD Validation

Figure 4 is the same as Figure 3, but now shows a continuous solid line, which is the estimated curve generated by the VSD model, using the above parameters.

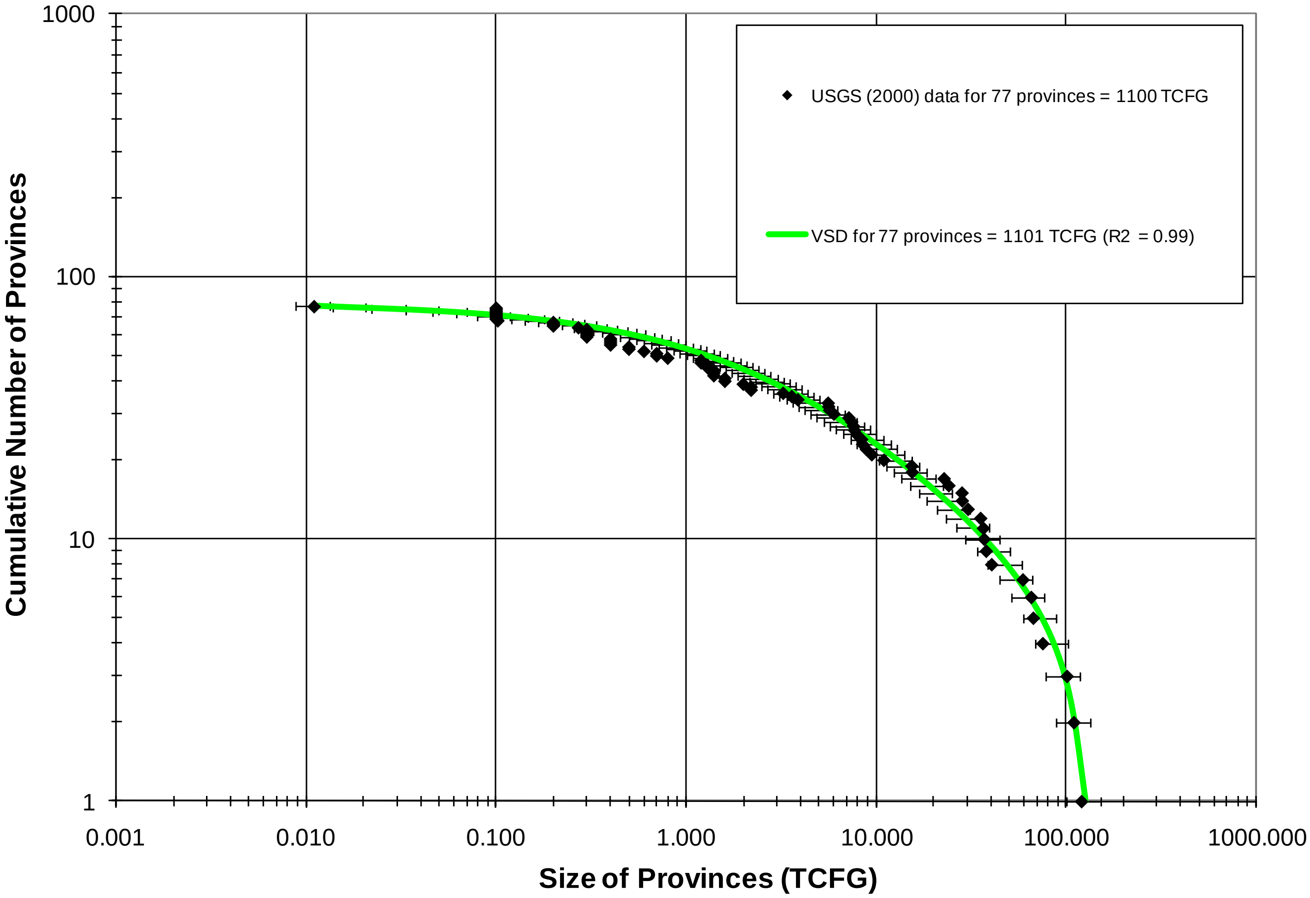

Fig. 4. VSD estimate for 77 Asia Pacific provinces. USGS (2000) data shows endowment volumes for 77 Asia Pacific provinces.

Visual inspection of the [4] data points and the estimated VSD curve shows a good fit, even for the largest provinces that do not lie on the Pareto straight line. In addition, the VSD calculated gas endowment volume of 1,101 TCFG, shown at the top of the last column ($\hat{V}_i$) in Table 1, compares well with the 1,100 TCFG published in [4]. This is supported mathematically by an R^2 coefficient of determination equal to 0.99. The good fit provides an initial validation of the VSD model. Estimated volumes ($\hat{V}_i$) generated by the VSD model for each province (presented in the last column of Table 1) compare favorably with the actual USGS estimates (shown in the fourth column of Table 1).

3.4 Accounting for Uncertainty

Probability distributions are used in [4] to address the uncertainty associated with estimating gas volumes. Fractiles (F95, F50, F5, and the mean) are shown graphically in their study for undiscovered gas. The value of F50, for instance, would imply that there is a 50% chance of the existence of at least the volume estimated. Inevitably, the uncertainties present in [4] extend to the VSD model.

The predictive power of the VSD model has been validated by a good fit of the size distribution of previously assessed Asia Pacific provinces. The fit is supported by a high coefficient of determination (R^2 of 0.99) and an estimated VSD volume that is very similar to the one published by the USGS. However, a comparison of the VSD curves with the USGS data points shows there are some differences at certain levels. The differences are accounted for in Figure 4 by plotting 20% horizontal error bars. As can be seen, in almost all cases the 20% error bars exceed the difference between the USGS and VSD calculated endowments.

3.5 Application of VSD to Unassessed Provinces

The VSD model may now be used to forecast gas endowment volumes in previously unassessed Asia Pacific provinces. The USGS has indicated that the region can be divided into 290 provinces, of which they have presented volumes for 77. Table 3 provides a list of the previously assessed and unassessed provinces in the region.

Table 3

Assessed and Previously Unassessed Provinces in the Asia Pacific region.

	Assessed Provinces
1	Northwest Shelf
2	Kutei Basin
3	Greater Sarawak Basin
4	Malay Basin
5	Ganges-Brahmaputra Delta
6	Tarim Basin
7	Baram Delta/Brunei-Sabah Basin
8	North Sumatra Basin
9	Browse Basin
10	Bombay
11	Bonaparte Gulf Basin
12	Indus
13	Irrawaddy
14	South Sumatra Basin
15	Sulaiman-Kirthar
16	Bohaiwan Basin
17	Sichuan Basin
18	Northwest Java Basin
19	Gippsland Basin
20	New Guinea Foreland Basin-Fold Belt
21	Bintuni/Sulawati Province
22	Thai Basin
23	Eromanga Basin
24	Yingehai Basin
25	Central Sumatra Basin
26	Assam
27	East Java Basin
28	Songliao Basin
29	Taranaki Basin
30	Saigon Basin
31	Penyu/West Natuna Basin
32	Ordos Basin
33	Palawan Shelf
34	Junggar Basin
35	Pamusian Tarakan Basin
36	Kohat-Potwar
37	Niigata Basin
38	Papuan Basin-Shelf Platform
39	Taiwan Thrust and Fold Belt
40	Japan Volcanic Arc/Accreted Terrane
41	South China Continental Shelf Slope
42	East China Sea Basin
43	Krishna-Godavari
44	Surat Basin
45	Mekong/Cuulong/Vung Tau Basin
46	Kanto Basin
47	Amadeus Basin
48	Otway Basin
49	Qaidam Basin
50	Perth Basin
51	Khorat Platform
52	Bone Basin
53	Sumatra/Java Magmatic Arc
54	Taixinan Basin
55	Sulu Sea Basin
56	Sumatra/Java Fore-Arc Basins
57	Tsushima Basin
58	Cauvery
59	Pearl River Mouth Basin
60	Subei Yellow Sea Basin
61	Thailand Mesozoic Basin Belt
62	Bass Basin
63	Ishikari Hidaka Basin
64	Central Afghanistan
65	Barito Basin
66	South China Fold Belt
67	Joban Basin
68	Carnarvon Basin
69	Beibuwan Basin
70	Turpan Basin
71	Sulawesi Accretionary Prism
72	Yinshan Da and Xiao Hingganling Uplift
73	Reed Bank Basin
74	East Natuna Basin
75	Northern Irian Jaya Waropen Basin
76	Jiangnan South Jiangsu Fold Belt
77	North Burma

	Unassessed Provinces
78	Himalayan
79	Jianghan Basin
80	Jiuquan Minle Wuwei Basin
81	Erlian Basin
82	Luxi Jiaoliao Uplift
83	Banda Arc
84	Akita Basin
85	Yunnan Guizhou Hubei Fold Belt
86	Temtsag Hailar Basin
87	North Banda Basin
88	Meratus High
89	Zhangguangcailing Uplift
90	Nanpanjiang Depression
91	Kunlunshan Fold Belt
92	Bowen Basin
93	Shanxi Plateau
94	Ryukyu Volcanic Arc
95	Java/Banda Sea
96	Canning Basin
97	Cagayan Basin
98	Ketuneau/Sintang Terrane
99	Great South Basin
100	Arafura Basin-Irian Jaya
101	Visayan
102	Malay Peninsula
103	Sydney Basin
104	Zambalez/Central Luzon Basin
105	Clarence-Moreton Basin
106	Maryborough Basin
107	New Zealand Orogenic Belt
108	Sagara Basin
109	Nanyang Basin
110	Qinling Dabieshan Fold Belt
111	Bali Basin
112	Gobi Basin
113	Sea Of Japan Backarc Basin
114	Taihangshan Yanshan Fold Belt
115	Altunshan Fold Belt
116	Qiongdongnan Basin
117	Korba Bay Basin
118	Qilianshan Fold Belt
119	Philippine Magmatic Arc
120	Cuoqing Lupola Basin
121	Georgina Basin
122	Lhasa Terrane
123	Bau Waters Basin
124	Bellona Plateau
125	Bligh Water Basin
126	Shorland Basin
127	Solomon Islands
128	Fiji Ridge
129	Hikurani Trough
130	Kermadec Ridge
131	Lord Howe Rise
132	Loyalty Island Ridge
133	Melanesia Border Plateau
134	East Ontong Java Rise
135	Russell Basin
136	Indispensable Reef
137	Mellish Reef
138	New Caledonia
139	New Hebrides Arc
140	New Zealand East Coast Basin
141	Norfolk Island Ridge
142	Northland Basin
143	Samoa Basin
144	Solander-Waiau Basin
145	Three Kings Rise
146	Tonga Ridge
147	Vanikoro Basin
148	Waikato Basin
149	Wanganui Basin
150	Wiso Basin
151	Alashan Yinshan Fold Belt
152	Bogdashan Fold Belt
153	Bose Basin
154	Chuxiong Basin
155	Karamay Thrust Belt
156	Kumukulig Basin
157	Lanping Simao Basin
158	Leidong Basin
159	Lhasa Basin
160	Longmenshan Dabashan Fold Belt
161	Qiangtang Tanggula Basin
162	Qiangtang Terrane
163	Qabdu Basin
164	Ushumun Basin
165	Sanshui Basin
166	Shiwan Dashan Basin
167	Songpan Ganzi Fold Belt
168	Sulongshan Fold Belt
169	Taikang Hefei Basin
170	Taiwan Melange Belt
171	Xichang Yunnan Fold Belt
172	Xisha Trough
173	Mohe Basin
174	Heilongjiang Basin
175	Yitong Graben
176	Bijianan Basin
177	South China Ocean Basin
178	Mongol-Okhotsk Folded Region
179	Choybalsan Basin
180	Nyalga Basin
181	Great Lake Basin
182	Great Lake Uplift
183	Ulan Bator Basin
184	Ulan Bator Basin
185	Honshu Ridge
186	Miyazaki Basin
187	Okinawa Trough
188	Sinzi Uplift
189	Tokachi Basin
190	Tottori Basin
191	Gensan Basin
192	Gyeongsang Basin
193	Huskan Platform
194	Korean Craton
195	Korean Continental Shelf
196	Central Vietnam Basin
197	Panjang/Cardomomes Basin
198	South China Sea Platform
199	Tonle Sap-Phnom Penh Basin
200	Truong Son Fold Belt
201	Tagaung Myitkyina Fold Belt
202	Bicol Shelf Basin
203	Cotabato Basin
204	Philippine Accretionary Prism
205	Sulu Arch
206	Rajang-Crocker Accretionary Prism
207	Celebes Sea
208	Flores Basin
209	Gorontalo Basin
210	Halmahera Basin
211	Halmahera Platform
212	Melawi Basin
213	Merauke Platform
214	South Banda Basin
215	South Makassar Basin
216	Sulawesi Magmatic Arc
217	Sumatra/Java Accretionary Prism
218	Sumba Province
219	Sunda Platform
220	Weber Basin
221	Adelaide and Kanmantoo Fold Belts
222	Albany-Fraser Province
223	Arunta Block
224	Australian Arafura Basin
225	Bangemall and Nabberu Basins
226	Bassian Rise
227	Birrindudu Basin and Tanami Block
228	Bremer Basin
229	Capricorn Basin
230	Carpentaria Basin
231	Challenger Plateau
232	Coen-Yambo Block
233	Daly River Basin
234	Darling Basin
235	Drummond Fold Belt and Anakie High
236	Eucla Basin
237	Galilee Basin
238	Gascoyne Block
239	Gawler Block
240	Great Australian Bight Basin
241	Halifax Basin
242	Halls Creek Province
243	Hodgkinson/Lachlan Fold Belt
244	Kimberley Basin
245	Lacklan Fold Belt
246	Laura Basin
247	Malakula/Aoba/Banks Basin
248	Marion Terrain
249	Money Shoal Basin
250	Mt. Isa Block
251	Murray Basin
252	Musgrave Block
253	McArthur Basin
254	New England Fold Belt
255	Ngalia Basin
256	Officer Basin
257	Paterson Province
258	Pilbara Block
259	Pine Creek Geosyncline
260	Queensland Plateau
261	Rocky Cape Block/Dundas Trough
262	Stuart Shelf
263	Tasmania Basin
264	Tennant Creek Block
265	Victoria River Basin
266	Cape Vogel Basin
267	New Guinea Mobile Belt
268	New Ireland Basin
269	Sepik-Ramu Basin
270	South Bismarck Volcanic Arc
271	Chatham Rise
272	Fiji Islands
273	Yilgarn Block
274	Indian Shield
275	Southeast Afghanistan
276	Sri Lanka
277	Makran
278	Baluchistan
279	Afghan
280	Himalayan Foreland
281	Chindwara
282	Satpura-Brahmani
283	Damodar
284	Pranhita-Godavari
285	Mahanadi
286	Maldives
287	Lakshadweep
288	Konkan
289	Tenasserim-Shan
290	Indo-Burman

The estimated VSD curve for all 290 provinces is shown in Figure 5. The gas endowment volume is calculated to be 1,437 TCFG. The same control parameters as before have been used to generate the curve and volumetric estimates. The only change is the number of provinces being evaluated, N_x, equal to 290. The estimate of 1,437 TCFG cannot be compared with any volumes estimated by the USGS or other organizations, since all 290 provinces have not been previously assessed. However, the validations discussed earlier provide some confidence that the estimate is reasonable. Although the VSD assumes most of the large provinces have already been discovered and presented by [4], it is possible that some of the unassessed provinces will also be among the largest.

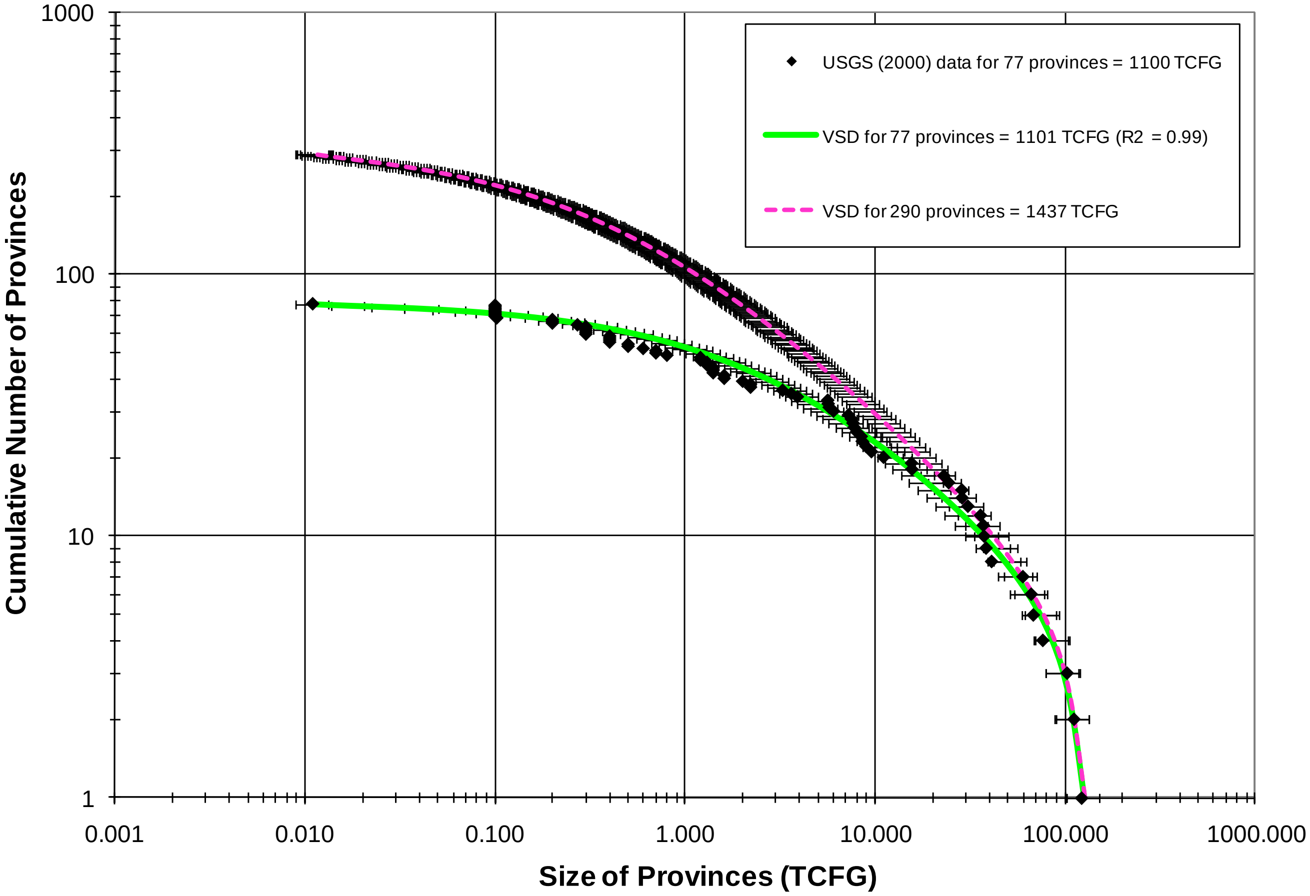

Fig. 5. VSD estimate for 290 Asia Pacific provinces (including previously unassessed provinces).

While the VSD model provides endowment volumes for all 290 provinces, it does not indicate which volumes correspond to which areas. To give an idea of where the natural gas may be located, we have allocated the volumes among Asia Pacific countries on the basis of a country's share of undiscovered volumes in USGS-assessed portions of the country. In other words, the distribution of the total gas endowment among Asia Pacific countries will be the same as the distribution of undiscovered volumes estimated by [4] in assessed portions of those countries. This approach assumes that countries with high amounts of undiscovered volumes in previously assessed provinces will have unassessed provinces with a generally proportional amount of gas. Using the chosen method, the largest gas endowment volumes are allocated to Australia, Indonesia, and China, which together account for over 60% of the total (see Table 4).

Table 4
Allocation by Country of Asia Pacific Gas Endowment Volumes.

Gas Endowment from VSD model for 290 Provinces (TCFG) =		**1,437**			
Country		**Gas Undiscovered Volumes (TCFG)** *(Source: USGS 2000)*	**% of Total**	**Gas Endmt from VSD Model (TCFG)**	**Gas Endmt plus Reserve Growth (TCFG)**
Australia		109.418	22.2	319.4	498.0
Bangladesh		33.581	6.8	98.0	152.8
Brunei		12.412	2.5	36.2	56.5
Cambodia		1.762	0.4	5.1	8.0
China		85.786	17.4	250.4	390.4
India		30.279	6.2	88.4	137.8
Indonesia		107.710	21.9	314.4	490.2
Malaysia		50.174	10.2	146.4	228.3
Myanmar		27.144	5.5	79.2	123.5
Pakistan		28.606	5.8	83.5	130.2
Thailand		4.674	0.9	13.6	21.3
Vietnam		0.777	0.2	2.3	3.5
	TOTAL	**492.323**	**100**	**1,437**	**2,240**

In addition to allocating results of the VSD model by country, we have also estimated the breakdown of gas endowment volumes by onshore versus offshore areas. The USGS [4] present their estimates of each country's undiscovered volumes in onshore and offshore categories. Columns 2 and 3 of Table 5 show this allocation of undiscovered volumes in Asia Pacific countries. The proportions are given as percentages in columns 4 and 5. We have distributed the gas endowment total from all 290 provinces based on the onshore/offshore proportions estimated by [4] for each country. The results, shown in columns 6 and 7, indicate that over 60% of the Asia Pacific natural gas endowment is located in offshore areas. In Australia, approximately 97% of the endowment is located offshore. By contrast, about 96% of the endowment in China is located onshore. Columns 8 and 9 include reserve growth, which is explained in the following sections.

Table 5
Onshore versus Offshore Allocation of Asia Pacific Gas Endowment Volumes.

1	2	3	4	5	6	7	8	9
Country	**Undiscovered Onshore Gas (TCFG)**	**Undiscovered Offshore Gas (TCFG)**	**Proportion Onshore (%)**	**Proportion Offshore (%)**	**Onshore Gas Endmt from VSD Model (TCFG)**	**Offshore Gas Endmt from VSD Model (TCFG)**	**Onshore Gas Endmt plus Reserve Growth (TCFG)**	**Offshore Gas Endmt plus Reserve Growth (TCFG)**
	(Source: USGS 2000)	*(Source: USGS 2000)*						
Australia	3.419	105.999	3.12	96.88	9.979	309.392	15.6	482.4
Bangladesh	15.445	18.136	45.99	54.01	45.081	52.936	70.3	82.5
Brunei	0.439	11.973	3.54	96.46	1.281	34.947	2.0	54.5
Cambodia	0	1.762	0.00	100.00	0.000	5.143	0.0	8.0
China	82.143	3.643	95.75	4.25	239.761	10.633	373.8	16.6
India	13.063	17.216	43.14	56.86	38.129	50.250	59.5	78.4
Indonesia	43.419	64.291	40.31	59.69	126.732	187.654	197.6	292.6
Malaysia	0.439	49.735	0.87	99.13	1.281	145.168	2.0	226.3
Myanmar	9.335	17.809	34.39	65.61	27.247	51.981	42.5	81.0
Pakistan	23.47	5.136	82.05	17.95	68.505	14.991	106.8	23.4
Thailand	0	4.674	0.00	100.00	0.000	13.643	0.0	21.3
Vietnam	0	0.777	0.00	100.00	0.000	2.268	0.0	3.5
TOTAL	**191.172**	**301.151**			**558**	**879**	**870**	**1,371**

4. Reserve Growth

Reserve growth (also known as field growth or appreciation), is a factor defined by the USGS as the increase in reserves of a previously discovered field through time. It can provide a very significant increase to gas reserves. Many commentators who are concerned about impending gas shortages do not give consideration to reserve growth. However, in spite of its complexity, it is essential to account for this factor when assessing the availability of gas.

As classified by the USGS, reserve growth applies to ‘known’ volumes (cumulative production plus remaining reserves). In this study, reserve growth also applies to endowment volumes. It is estimated by calculating a percentage for reserve growth, based on ‘known’ volumes from [4], and applying it to estimated gas endowment volumes of both assessed and unassessed Asia Pacific provinces.

We have calculated reserve growth percentages using values from Table 6. In the ‘world total’ section, for instance, we calculate the reserve growth percentage of known gas, which amounts to 55.92%. This comes from dividing reserve growth (3,660 TCFG) by the summation of cumulative production plus remaining reserves (1,752 TCFG + 4,793 TCFG).

Table 6

Calculation of Reserve Growth Percentages - based on data from [4].

	Natural Gas (TCFG)
World (excluding USA)	
Undiscovered conventional	4669
Reserve growth (conventional)	3305
Remaining reserves	4621
Cumulative production	898
Total	**13493**

	Gas (TCFG)
USA	
Undiscovered conventional	527
Reserve growth (conventional)	355
Remaining reserves	172
Cumulative production	854
Total	**1908**

	Gas (TCFG)
World Total	
Undiscovered conventional	5196
Reserve growth (conventional)	3660
Remaining reserves	4793
Cumulative production	1752
Total	**15401**
Known volumes	6545
Reserve growth based on known volumes (%) [a]	**55.92**

a. Calculated as [Reserve Growth / (Remaining Reserves + Cumulative Prod)] x 100

4.1 Discussion of Reserve Growth Application

The calculated percentages of world reserve growth are used in the estimation of endowment volumes plus reserve growth of both the previously assessed and unassessed Asia Pacific provinces. The basic assumptions in the application are that (1) the reserve growth percentages based on known volumes will be the same for endowment volumes, (2) the reserve growth percentage for the world is applicable to the Asia Pacific region, and (3) the ranking of endowment volumes plus reserve growth, by size, will be the same as the ranking of the endowment volumes without reserve growth.

The estimated VSD curve for gas endowment plus reserve growth (55.92%), for 290 Asia Pacific provinces, is presented in Figure 6. This figure is similar to Figure 5, with the only difference being the addition of the 'plus reserve growth' curve. It lies to the right of the original curve showing the VSD estimate of 290 provinces without reserve growth. It shows that at each province, each volume is now 55.92% greater than the original estimate. The calculated gas endowment volume for 290 provinces including reserve growth is 2,240 TCFG.

Figure 7 is a bar graph showing the Asia Pacific natural gas endowment estimated by [4], the VSD estimate for the previously unassessed provinces, and the calculated reserve growth for the region.

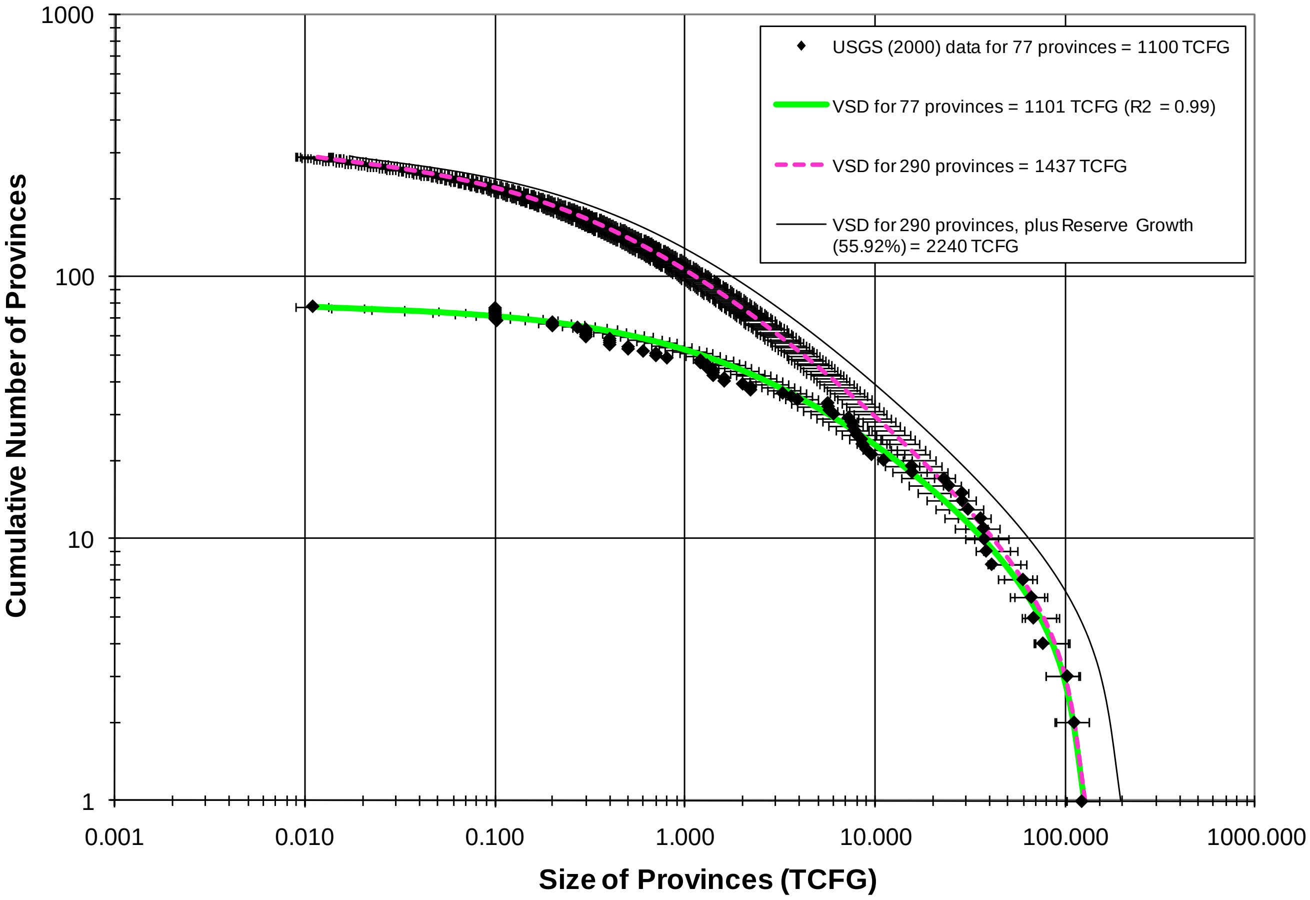

Fig. 6. VSD estimate for 290 Asia Pacific provinces (including unassessed provinces and reserve growth).

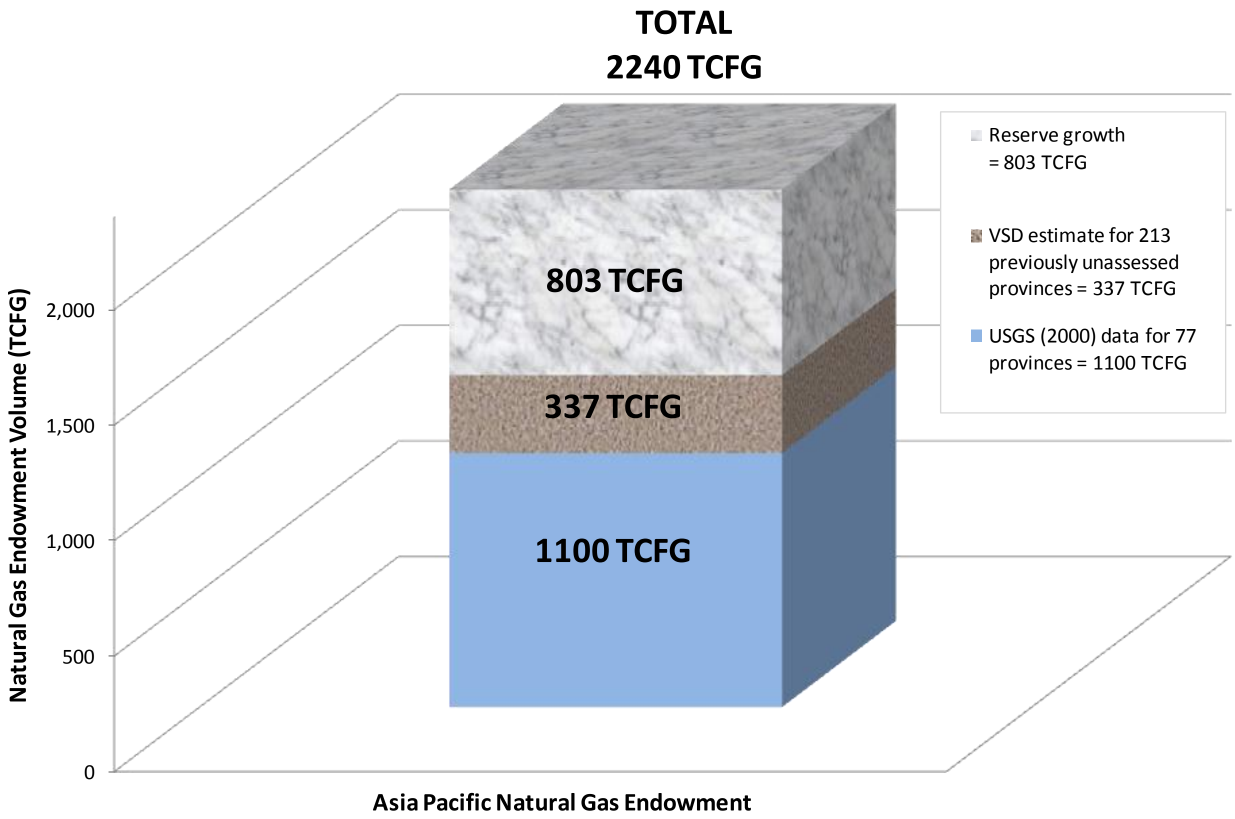

Fig. 7. Asia Pacific natural gas endowment divided into volumes from assessed provinces, unassessed provinces, and reserve growth.

5. Life Expectancies

The rows under column 4 in Table 7 indicate how many years future gas volumes in Asia Pacific would last assuming production grows in the future at 0%, 3%, 6%, or 10% per year.[5]

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[5] *'Future volumes' are equal to endowment volumes minus cumulative production. Thus, Asia Pacific cumulative production of 84 TCFG [4] is subtracted from the endowment volumes presented earlier, resulting in the following future volumes:*

From [4]: 1,100 TCFG – 84 TCFG = ***1,016 TCFG***
Including Unassessed Provinces: 1,437 TCFG – 84 TCFG = ***1,353 TCFG***
Including Unassessed Provinces and Future Reserve Growth: 2,240 TCFG – 84 TCFG = ***2,156 TCFG***

At current production rates, future volumes from previously assessed provinces assuming no reserve growth would last for 69 years. Adding in future volumes from unassessed provinces increases this figure to 91 years and considering reserve growth pushes it to 146 years.

Figure 8 shows the relationship between the life expectancy and the production growth rates of Asia Pacific future gas volumes in graphical form. The lower curve represents volumes from previously assessed provinces. The middle curve includes unassessed provinces, while the upper curve adds in reserve growth. As can be seen, the years of life expectancy decrease exponentially as production growth rates increase.

Table 7
Life Expectancies (Years).

1	2	3	4				5
Asia Pacific Conventional Gas	**Future Volumes (CFG)**	**2007-2009 [a] Average Annual Production (CFG)**	**Life Expectancy in Years, at Various [b] Growth Rates in Production**				**Average Annual [c] Growth in Production, 1979-2009 (%)**
			0%	**3%**	**6%**	**10%**	
From USGS (2000)	1.016E+15	1.48E+13	**69**	**37**	**27**	**21**	6.61
Including Unassessed Provinces	1.353E+15		**91**	**44**	**31**	**23**	
Including Unassessed Provinces and Reserve Growth	2.156E+15		**146**	**56**	**38**	**28**	

Notes:
a. Average annual production comes from [10]
b. Life expectancies estimated by this study
c. Average annual growth in production calculated from [10]

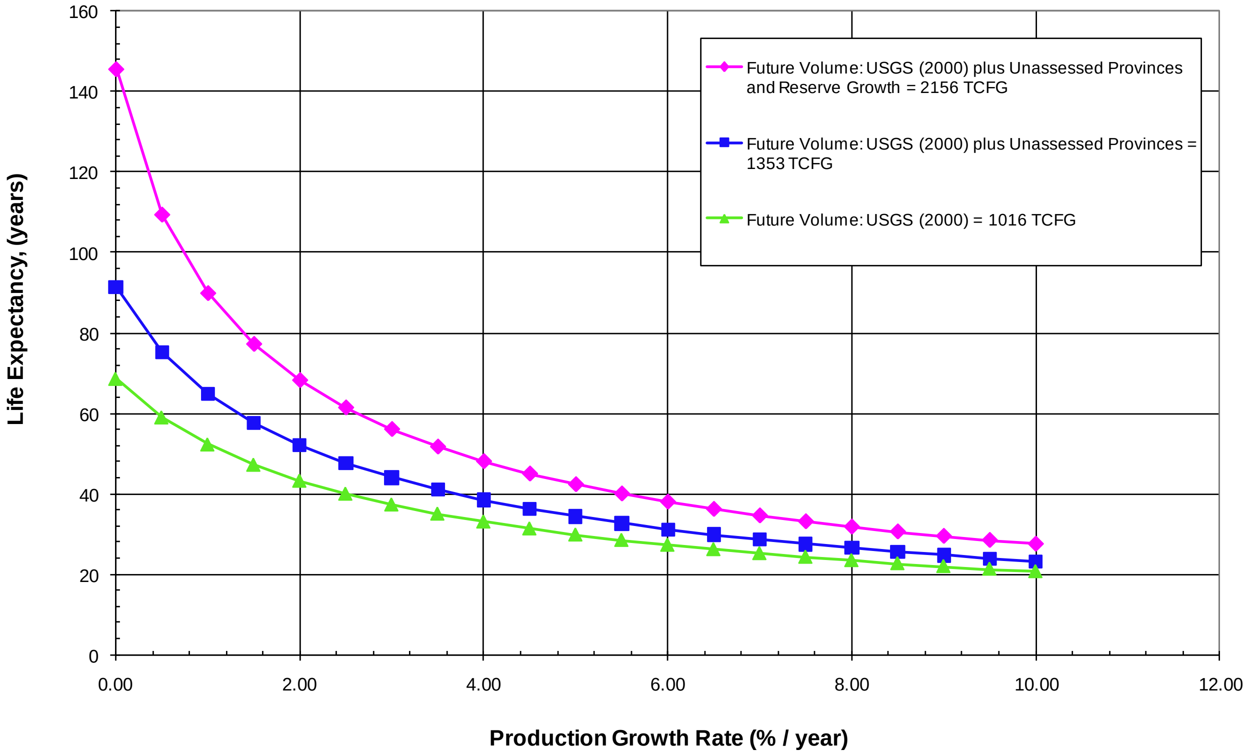

Fig. 8. Life Expectancies at Various Production Growth Rates

6. Conclusions and Implications

As energy use continues its upward trajectory in Asia Pacific, it will be important for policymakers to increase the market share of natural gas in the energy mix. Thus, it is also imperative to generate reliable estimates of the total conventional natural gas endowment. Size distribution analysis is useful in this regards as it provides a simple and effective complement to more complex and time-consuming geological methods.

This paper uses a Variable Shape Distribution (VSD) model to estimate the total gas endowment in previously assessed and unassessed Asia Pacific provinces. Historically, all methods used to determine the relation between the size and number of gas provinces were based on an assumed form of the size distribution (e.g. Pareto [fractal], or lognormal). The VSD model is unique in that it allows actual gas resource data to determine the relationship.

The VSD model is estimated and validated utilizing data from [4]. That study presents volumes for 77 Asia Pacific provinces out of a total of 290, so there are 213 provinces left unassessed. Given the validations of the VSD demonstrated in this paper, the model can be used to estimate reasonable endowment volumes of all 290 provinces.

Results of the VSD model indicate that there is a total of 1,437 TCFG in those 290 provinces. If reserve growth is accounted for, the gas endowment volume increases to 2,240 TCFG. It is estimated that Australia, Indonesia, and China together account for over 60% of this total endowment. In addition, over 60% of the Asia Pacific endowment is projected to be in offshore areas.

Thus, the quantity of available conventional gas in the Asia Pacific region is greater than often assumed, since there is a tendency to overlook unassessed provinces and reserve growth. An important implication is that natural gas is likely to last longer than some commentators claim. At current production rates, the volumes in previously assessed and unassessed provinces, including the effects of reserve growth, would last 146 years. If production grows at 3% per year, the life expectancy decreases to 56 years.

This abundance of natural gas in Asia Pacific should help satisfy energy demand as rapid economic growth continues. Furthermore, an increase of natural gas in the energy mix has the potential to lead towards a low carbon economy.

In spite of the benefits associated with a large conventional and unconventional gas endowment in Asia Pacific, there is some concern by major liquefied natural gas (LNG) exporters about a decrease in LNG demand. This would happen because rapidly developing countries like China and India, with their considerable domestic natural gas resources, would no longer demand large quantities of LNG.

However, given the sheer size of gas demand in these growing economies, the LNG market is unlikely to diminish in the foreseeable future. Furthermore, if gas can capture some of the huge market share currently occupied by coal, then China and India will require tremendous gas supply from domestic and foreign sources, conventional or unconventional.

To benefit from increased use of natural gas, public policy must facilitate the development of transparent and functional gas markets in Asia Pacific. Appropriate regulatory, legal, and fiscal conditions should exist in both producing and consuming countries in order to reduce the risk associated with investment, transportation, infrastructure, and carbon constraints.

APPENDIX A: MATHEMATICAL DEVELOPMENT OF THE VSD MODEL

A.1 Fractal and Pareto Distributions

A fractal distribution is provided by a power law of the form [11, 12]:

$$N(r) = Cr^{-D} \tag{A.1}$$

where:

D - constant fractal dimension.

C - constant of proportionality.

r - some quantity (e.g. natural gas volume in TCFG).

N(r) - number of objects with a quantity equal to or greater than *r*.

For conventional oil and gas volumes (*V*),

$$V = r^3 \tag{A.2}$$

and consequently, Equation A.1 becomes:

$$N(V) = CV^{-D/3} \tag{A.3}$$

where:

$N(V)$ - distribution function of V.

The density function, $n(V)$, is the derivative of the distribution function (Equation A.3), and is given by:

$$n(V) = \frac{dN(V)}{dV} \tag{A.4}$$

Conversely, the distribution function, $N(V)$, is the integral of the density function, and is given by:

$$N(V) = \int_{V\min}^{V\max} n(V)dV \tag{A.5}$$

where V_{min} and V_{max} are the minimum and maximum volumes, respectively.

The distribution function, Equation A.3, can be written as a Pareto power law, or Pareto distribution, as follows [12]:

$$N(V) = CV^{-a_p} \tag{A.6}$$

where a_p is a shape parameter (also known as shape exponent, Pareto exponent, Pareto constant, or fractal dimension). Note that based on the above development, the shape parameter (a_p) is equal to 3 times the fractal dimension (D).

Taking logarithms of both sides of Equation A.6 leads to:

$$\log N(V) = \log(C) - a_p \log V \tag{A.7}$$

Equation A.7 indicates that a log-log plot of $N(V)$ versus V should result in a straight line with a slope equal to $-a_p$ and an intercept, at $V = 1$, equal to C.

A.2 Variable Shape Distribution (VSD) Model

As mentioned earlier, development of the VSD starts by observing the curvature given by the data points from [4] on the log-log plot. We then create the VSD model which allows the data to determine the specified relationship between the size and number of provinces.

Following the work of Pareto and [11, 12], the VSD is given by:

$$N_t = \frac{1}{r_t^{a_t}} \tag{A.8}$$

where:

a_t - unknown, variable shape exponent.

N_t - cumulative number of provinces, bound by [4].

r_t - estimated normalized volume of a province.

Thus, the VSD equation is somewhat similar to Pareto's equation.[6] The significant difference is that the shape exponent in Pareto's equation is a constant, while the shape exponent in the VSD model can vary. When the shape exponent in the VSD model is constant, the VSD equation is a Pareto equation. By using normalized volumes, the constant of proportionality, C, is equal to 1. Since there are two unknowns in Equation A.8, a_t and r_t, an auxiliary equation has been developed for calculating the two unknowns. The equation has the form:

$$N_t = \frac{1}{r_t^{a_t}} = \frac{1}{r_v^{a_p} + r_m^{a_m}} \tag{A.9}$$

where:

---

[6] *Other extensions of the Pareto distribution include the Parabolic Fractal Distribution [13] and the Log-Pareto Distribution [14]. These extensions, like the Pareto and lognormal distributions, are based on assumed forms of the size distribution of oil and gas accumulations.*

a_m - slope of line between (1) point of maximum number of provinces (N_x) and minimum USGS province volume (V_m) and (2) point of minimum number of provinces ($N_m = 1$) and maximum volume (V_x) given by Pareto straight line at $N_m = 1$ (see Figure A.1).[7]

a_p - slope of straight line approximated from USGS data points; same as slope of Pareto distribution (see Figure A.1).

r_m - normalized, minimum USGS province volume ($r_m = V_m/V_x$, where V_m is the minimum USGS province volume, and V_x is the maximum volume given by the Pareto straight line at a number of provinces equal to 1).

r_v - estimated normalized volume of a province minus the normalized minimum USGS volume.

The right hand side of Equation A.9 has been empirically estimated and tested against the data published in [4], providing reasonable results. Since the number of provinces (N_t) and the normalized, minimum USGS province volume (r_m) are known from [4], and the slopes a_p and a_m can be determined from the graphed data, it is possible to re-arrange Equation A.9 to determine r_v, as follows:

$$r_v = \left(\frac{1}{N_t} - r_m{}^{a_m}\right)^{\frac{1}{a_p}} \qquad \text{(A.10)}$$

Equation A.10 gives the estimated normalized volume of a province minus the normalized minimum USGS volume (r_m). The minimum volume must be added to r_v to get the estimated, normalized volume of a province, as follows:

$$r_t = r_v + r_m \qquad \text{(A.11)}$$

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[7] *In equation form, this slope is given by* $a_m = \dfrac{\log N_x - \log N_m}{\log V_x - \log V_m}$

Then, to ‘de-normalize’ r_t, and get the estimated volume of a province, the following equation is used:

$$V_t = r_t V_x \tag{A.12}$$

where:

V_t - estimated volume of a province before right-tail adjustment.

V_x - maximum volume given by Pareto straight line at number of provinces = 1.

After calculating r_v and r_t using Equations A.10 and A.11, respectively, it is possible to re-arrange Equation A.9 to solve for the variable shape exponent (a_t), as follows:

$$a_t = \frac{\log[r_v^{a_p} + r_m^{a_m}]}{\log r_t} \tag{A.13}$$

where:

a_t - variable shape exponent; slope of line between point of any estimated volume and the maximum volume point given by the Pareto straight line at number of provinces equal to 1 (see Figure A.2).

A.3 Adjusting Right Tail (Largest Volumes) of VSD

Notice that in Figure A.2, the data point for the largest province, V_L, does not lie on the Pareto straight line. Often, more than one of the larger volumes will not lie on the line.[8]

To get a more accurate, estimated curve that fits over the largest volumes, an exponential function has been incorporated empirically into the VSD model. The function has the effect of smoothly bending the estimated curve in the direction of the actual USGS data. The exponential function is as follows:

$$f(V_t, V_s) = (1 - \exp(-V_t / V_s))^S \tag{A.14}$$

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[8] *This is a common occurrence in Pareto distributions. It has been interpreted by [12] to be the result of sub-populations, each of which have the same Pareto shape exponent (slope), but different largest volumes.*

where:

S - severity exponent that is determined by trial and error. It controls the extent to which the estimated VSD curve will separate from the Pareto straight line (on the right tail of the distribution, near the largest volumes).

V_s - parameter that corresponds approximately to the point at which the largest USGS provinces begin to deviate from the Pareto straight line, on the right tail of the distribution, near the largest volumes (see Figure A.2).

V_t - estimated volume of a province before right-tail adjustment.

Another parameter incorporated into the VSD model to get a more accurate fit of the largest USGS volumes is approximated by:

$$\psi = \frac{V_L}{V_X} \tag{A.15}$$

where:

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).

V_L - volume of the largest USGS province.

V_x - maximum volume given by Pareto straight line.

Three parameters (V_s, ψ, and S) only affect the right tail of the VSD curve, near the largest volumes. They are incorporated so that the VSD curve will fit over the largest volumes that do not lie on the Pareto straight line.

The exponential function (see Equation A.14) and the separation ratio (ψ) are used to improve the estimate of a province's volume as follows:

$$\hat{V}_i = \frac{V_t \cdot \psi}{\psi + (1-\psi) \cdot f(V_t, V_s)} \tag{A.16}$$

where:

$\hat{V}_i$ - estimated volume of a province.

Expanding the exponential function, $f(V_t, V_s)$, in Equation A.16 gives:

$$\hat{V}_i = \frac{V_t \cdot \psi}{\psi + (1-\psi)\cdot(1-\exp(-V_t/V_s))^S} \tag{A.17}$$

where, as shown earlier in Equation A.12:

$$V_t = r_t V_x = [(\frac{1}{N_t} - r_m{}^{a_m})^{\frac{1}{a_p}} + r_m]\cdot V_x \tag{A.18}$$

Further expansion of Equation A.18 results in:

$$V_t = \left[\left(\frac{1}{N_t} - \left(\frac{V_m}{V_x}\right)^{(\frac{\log N_x - \log N_m}{\log V_x - \log V_m})}\right)^{\frac{1}{a_p}} + \frac{V_m}{V_x}\right]\cdot V_x \tag{A.19}$$

When V_t, from Equation A.19, is substituted into Equation A.17, all the terms are expanded, giving:

$$\hat{V}_i = \frac{\left\{\left[\left(\frac{1}{N_t} - \left(\frac{V_m}{V_x}\right)^{(\frac{\log N_x - \log N_m}{\log V_x - \log V_m})}\right)^{\frac{1}{a_p}} + \frac{V_m}{V_x}\right]\cdot V_x\right\}\cdot(\psi)}{(\psi) + [1-(\psi)]\cdot\left[1-\exp\left(-\left\{\left[\left(\frac{1}{N_t} - \left(\frac{V_m}{V_x}\right)^{(\frac{\log N_x - \log N_m}{\log V_x - \log V_m})}\right)^{\frac{1}{a_p}} + \frac{V_m}{V_x}\right]\cdot V_x\right\}\cdot V_s{}^{-1}\right)\right]^S} \tag{A.20}$$

Equation A.20 is used to generate, via non-linear regression, the estimated VSD curve shown in Figure A.2. The validity of the equation can be confirmed by visual inspection of Figure A.2. Further confirmation is provided by the coefficients of determination (nearly always 0.98 or 0.99) and the volume estimates presented earlier that compare very well with the actual volumes published by the USGS (2000) study.

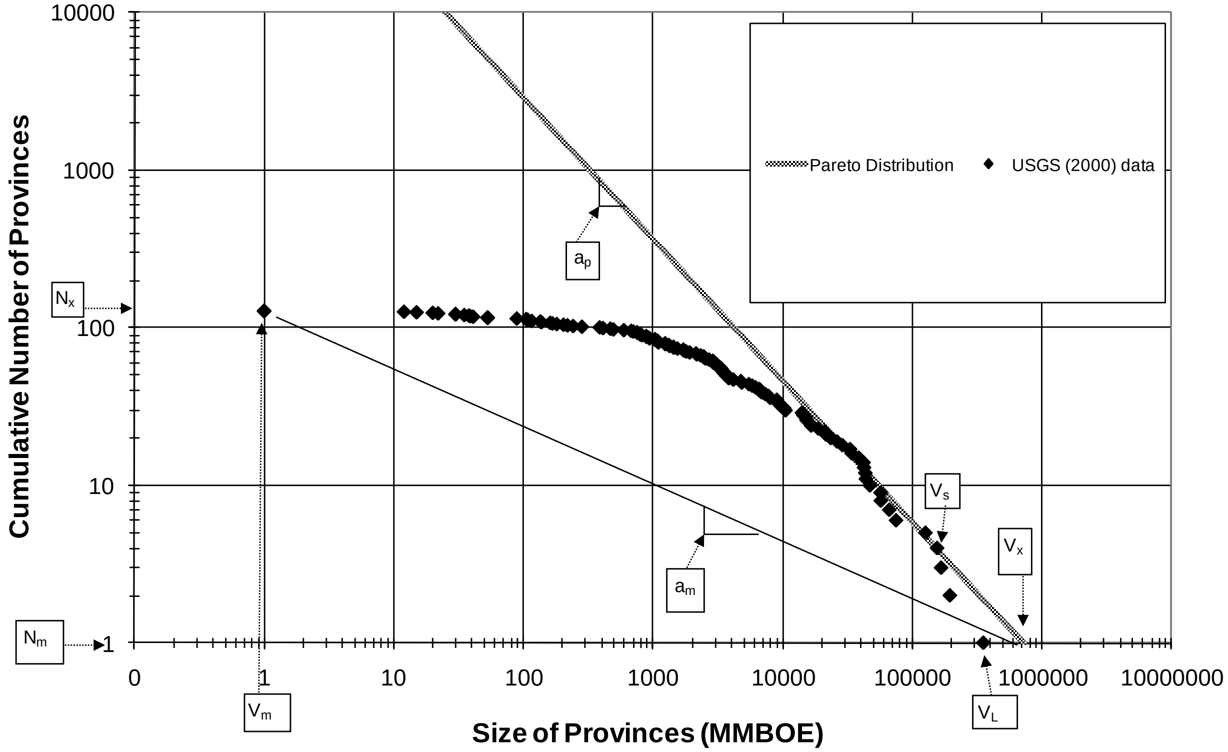

Fig. A.1. Schematic showing VSD model terminology.

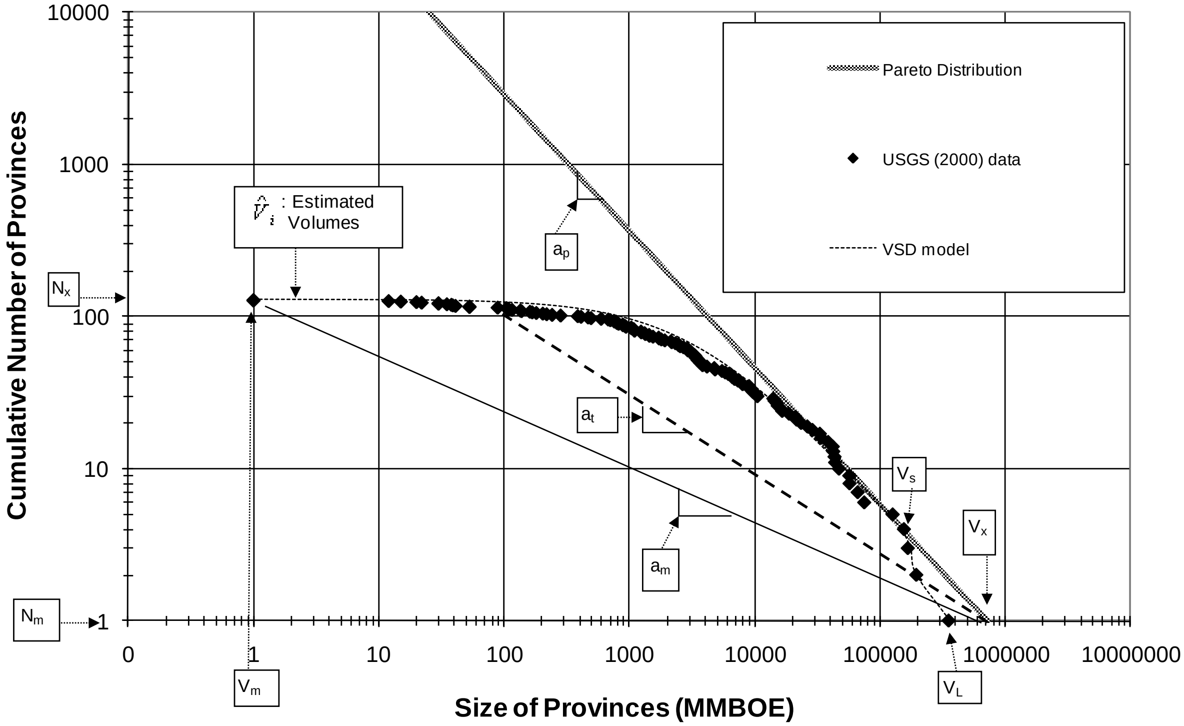

Fig. A.2. Schematic showing additional VSD model terminology.

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