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Probabilistic Estimation of the Helium Resources in the Central and Southern Areas of the Lena–Tunguska Petroleum Province

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Abstract—We propose and test a method for probabilistic estimation of the scale and structure (distribution of helium concentrations in free gas, accumulations of different sizes, localization zones, and stratigraphic complexes) of helium and helium-containing gas resources. Summarizing the available geological information about the structure of the sedimentary cover and data on the revealed accumulations of helium-containing gases, we have first made probabilistic estimation of the scale and structure of their resources as well as helium resources in the central and southern areas of the Lena–Tunguska province. The forecast results will serve as a reliable basis for geological and economic estimation of helium resources, for long-term planning of gas field development in East Siberia and the Republic of Sakha, and for helium industrialization in these regions.

Keywords: Gas, helium, resources, reserves, probabilistic estimation, Lena–Tunguska province

INTRODUCTION

In 2017, global helium production amounted to about 160 mln m^3 (Helium, 2018). Helium production in Russia and its losses during the production of natural gas totaled >17 mln m^3, of which ~6 mln m^3 were extracted and utilized. The annual losses of commercial-grade helium (>0.05% helium concentration) in the country are estimated to be more than ~11 mln m^3 (Kontorovich et al., 2006).

The leading locations for helium reserves (88%) in the world are Qatar, Russia, the USA and Algeria. According to Piatnitskaya and Silant'ev (2013), Qatar was estimated to contain 10.0 bln m^3 of helium reserves; Russia – 9.2 bln m^3; the USA – 8.5 bln m^3; and Algeria – 8.4 bln m^3. Accelerating net depletion of the U.S. helium resources contained in natural gas is coinciding with the growth of helium resource base in Russia from the Lena–Tunguska petroleum province (Angara–Yenisei region and west of the Republic of Sakha (Yakutia), as well as in Algeria and Qatar. The natural gas in the gas fields of the United States contains usually the highest concentrations of helium, from 0.1 to 1.9%. In other countries, the average helium content of gas is much lower, 0.06–0.2%, whereas the natural gas in the fields of East Siberia and the Republic of Sakha, the largest undeveloped helium province in the world, contains much higher concentrations of helium, 0.19–0.67%. Current helium production in Russia is from the Orenburg gas-condensate field, which has a helium concentration in natural gas of 0.053–0.055%.

About half of current Russia's helium reserves are located in the fields of East Siberia, in the Irkutsk and Krasnoyarsk regions (Evenkia). The Russian Far East holds significant reserves of helium-containing gas in the fields of Yakutia, which account for over 30% of domestic helium.

Helium is used as an important component in nuclear and thermonuclear energy, as a coolant in superconducting devices, in medicine, breathing mixtures, etc. At present, Russia's domestic helium consumption is not very significant. However, decisions of Russia's leadership on military build-up and developing the Arctic Zone of Russia, including the shelves of the Arctic Ocean in the zone of perennial sea ice cover, laying the foundations for a transition to a low-carbon economy, etc. should lead in the short term to a sharp increase in the domestic demand for helium.

With the start of large-scale production of natural gas from the fields of East Siberia and the Republic of Sakha, Russia could become the first-largest helium supplier to major international markets, e.g., in Asia Pacific. To meet the projected helium demand in the Asia-Pacific region, Russia's future helium supply will increase to about 90 mln m^3 in 2030. In the long term, Russia's export to the European market is expected to replace supplies from the Orenburg helium extraction plant, which produces helium from low concentration natural gases from the depleting field (Kontorovich et al., 2006).

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Comparative analysis of development options for natural gas fields of East Siberia and the Republic of Sakha, alternatives to creating a new major-scale helium industry there, determination of the economic feasibility of various natural gas processing schemes will hardly be possible without an objective estimation of subsurface helium gas resources with taking into account a number of technologies for helium extraction, which determines the **relevance** of this study.

GOAL

The main goal of this study is to give a well-defined quantitative estimation of the resources and reserves of helium-containing natural gases in oil-gas, gas-oil and natural gas fields in the Riphean, Vendian and lower Cambrian reservoirs of the Lena–Tunguska province, which can be regarded as the basis for planning the development of the helium industry of Russia.

OBJECTS AND MATERIALS

Accumulations of free gas occurring as gas pools or gas caps, in the Proterozoic-Paleozoic sedimentary cover of the central and southern areas of the Lena–Tunguska petroleum province were chosen as the object of the study at the first stage. Such a choice was based on the following considerations. First, since these regions are relatively well explored, they allow the application of relatively reliable and validated methods for probabilistic quantitative estimation of helium-containing gas resources (see below). Second, it is obvious that gas fields adjacent to the Power of Siberia gas pipeline will be developed first. Third, resources of helium dissolved in oil accumulations (associated gas) are of much less interest due to their negligible volumes.

The data from the state balance sheet of hydrocarbon gas and helium reserves and data on the geological structure of the study areas summarized in previous reports (Archegov, 2015; Beilin et al., 2003; Kontorovich et al., 2005a,b, 2006 a,b; Piatnitskaya and Silant'ev, 2013; Yakutseni, 1968, 2008, 2009a, b) were used as the basis for this study.

In terms of oil and gas geological zoning, the study area covers the Baikit, Nepa–Botuoba, Angara–Lena, Sayan–Yenisei and Cis-Patom petroleum areas of the Lena–Tunguska petroleum province (Kontorovich et al., 2017). The results of our estimation can be used for the last two petroleum area only with a certain degree of conditionality, because they are relatively under-explored.

As of January 1, 2017, 78 fields were discovered in the study area; of this total, 68 fields have free gas accumulations (332 accumulations) (Fig. 1). Helium reserves contained in 32 fields (245 accumulations with helium-containing free gas) were put on the balance sheet. In 13 fields (115 accumulations with helium-containing gas), not all free gas accumulations are known to contain balance helium reserves.

In the study area, total initially-in-place reserves of free gas (categories A, B, C_1 and C_2 according to the 2001 provisional classification) as of January 1, 2017, were estimated at 8.31 trln m^3, including 0.50 trln m^3 contained in the Riphean petroleum play, 7.34 trln m^3 in the Vendian–lower Cambrian play and 0.47 trln m^3 in the Cambrian play. The balance reserves of helium in the amount of 20.51 bln m^3 are localized as follows: 0.76 bln m^3 in Riphean, 19.18 bln m^3 in Vendian–lower Cambrian 0.57 bln m^3 in Cambrian plays.

It is important to note that the balance gas reserves in the amount of 2.18 trln m^3 are not associated with helium reserves, although the presence of helium together with natural gas is not in doubt. This is based on the helium content of natural gases in the study area and the distribution trend of helium-containing gases in some accumulations. An analysis of the reasons why helium volumes remain not fully taken onto the books lies beyond the scope of this study. However, there is no doubt that they should be taken into account in the estimation of the initial resources.

The weighted average helium content of the natural gas is 0.158% in the Riphean play, 0.454% in the Vendian–lower Cambrian play, and 0.197% in the Cambrian play (Fig. 2). The average and modal helium contents of the free gas in the southern and central regions of the Lena–Tunguska province are slightly less than 0.3% and about 0.26%, respectively (Fig. 3). These data together with the size distribution of helium-containing gas accumulations were used as the basis for a probabilistic estimation of natural gas resources and helium contained in these potential gas resources.

METHODS

For the regions under consideration, the estimate of hydrocarbon resources, including free gas resources was usually made using the method of peer-review field analogues (Methodological Guide..., 2000). Unfortunately, using this approach makes it difficult to generate a probabilistic reserves estimate.

In the second half of the 20th century, the methodology and specific techniques for probabilistic quantification of hydrocarbon reserve estimates were actively developed both in Russia and abroad. The theoretical foundation and the unique database created in Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences (IPGG SB RAS) became the basis for improving methodological approaches to the evaluation of the size and structure of the initial and residual hydrocarbon resources. In this study, we use an approach based on the fundamental regularity of the size distribution of hydrocarbon accumulations (Shpil'man, 1982; Kontorovich et al., 2001). In the first decade of the 21st century, a team of researchers from IPGG SB RAS yielded meaningful results on this problem (Kontorovich and Livshits, 2002, 2007; Livshits, 2003, 2004a, b; Burshtein, 2004, 2006).

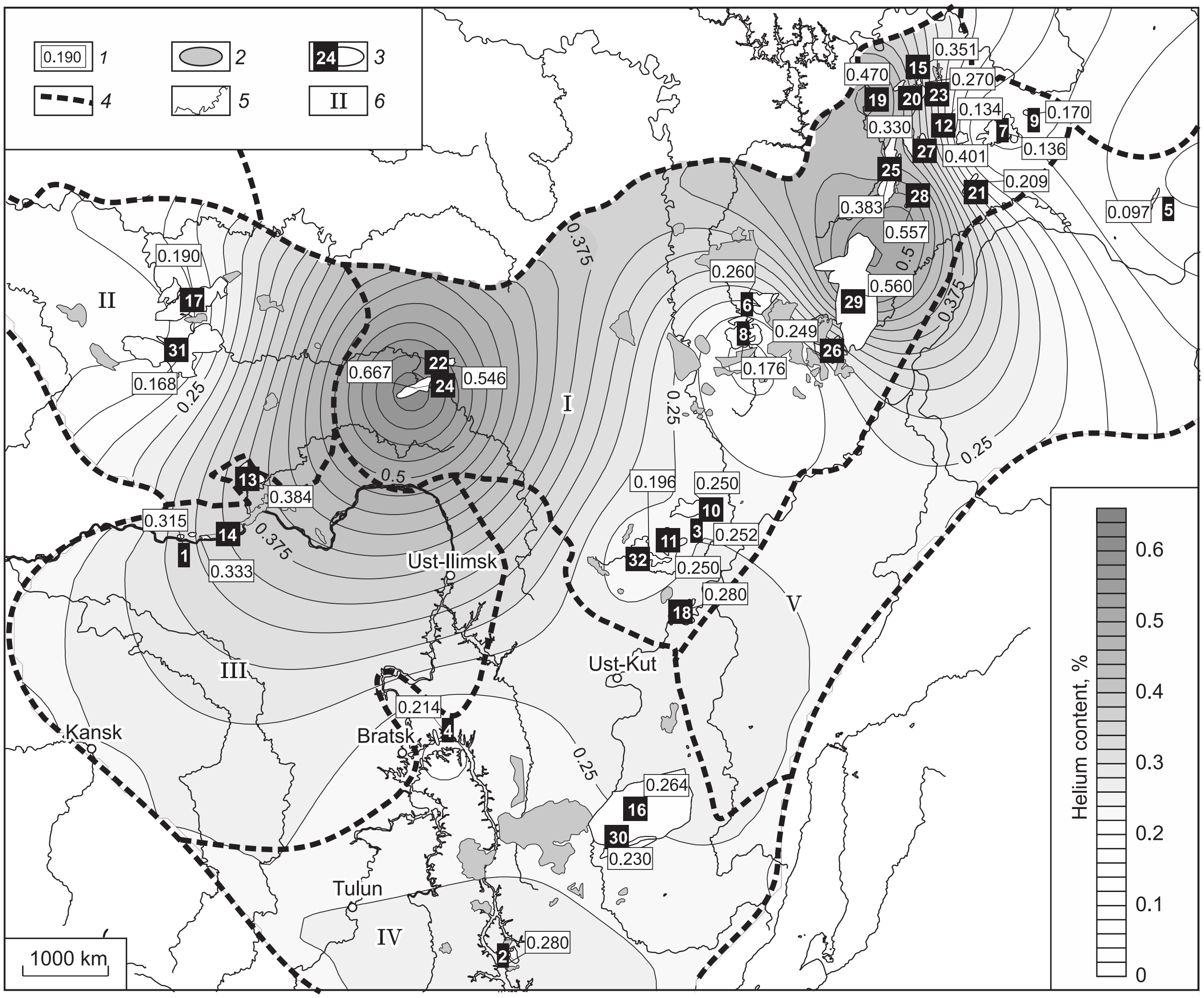

Fig. 1. Areal distribution of helium concentrations in free gas from the fields in the southern and central areas of the Lena–Tunguska petroleum province: 1, weighted average He concentration, %; 2, field; 3, field with He reserves; 4, boundaries of the petroleum area; 5, rivers; 6, populated localities; 7, petroleum area nos. Fields with He reserves: 1, Abakanskoe; 2, Atovskoe; 3, Ayanskoe; 4, Bratskoe; 5, Bysakhtakhskoe; 6, Vakunaiskoe; 7, Verkhnevilyuchanskoe; 8, Verkhnechonskoe; 9, Vilyuisko-Dzherbinskoe; 10, Dulisminskoe; 11, Zapadno-Ayanskoe; 12, Iktekhskoe; 13, Ilbokichskoe; 14, Imbinskoe; 15, Irelyakhskoe; 16, Kovyktinskoe; 17, Kuyumbinskoe; 18, Markovskoe; 19, Machchobinskoe; 20, Nelbinskoe; 21, Otradninskoe; 22, Paiginskoe; 23, Severo-Nelbinskoe; 24, Sobinskoe; 25, Srednebotuobinskoe; 26, Talakanskoe; 27, Tas-Yuryakhskoe; 28, Khotogo-Murbaiskoe; 29, Chayandinskoe; 30, Chikanskoe; 31, Yurubcheno-Tokhomskoe; 32. Yaraktinskoe.
Petroleum areas: I, Nepa-Botuoba; II, Baikit; III, Sayan-Yenisei; IV, Angara-Lena; V, Cis-Patom

The details of the proposed methodology will be described below. Now, we present the general sequence used in probabilistic estimation of helium-containing free gas and helium resources.

1. The first step is to perform a refinement of the estimation of helium volumes contained in free gas from known accumulations the helium amounts in which were not booked.

2. For known gas accumulations with unbooked helium reserves, the amount of helium contained in them is taken by analogy with other beds of the same field or nearby fields (Fig. 1) with booked helium reserves.

3. Helium reserves will generally be revised if the volumes of helium-containing gas in a particular accumulation show large differences on the helium and natural gas balance sheets.

4. The uncertainty in the gas volumes in specific accumulations is not taken into account, since the uncertainty in the estimated gas reserves is substantially greater.

5. The size distribution of free gas accumulations is analyzed to estimate the distribution parameters, assuming that a significant number of the largest accumulations have already been discovered.

6. The distribution of total initially-in-place resources of helium-containing gas and helium in undiscovered accumulations is calculated using the generated approximating distribution, the empirical distribution of helium volumes (Fig. 3) and Monte Carlo simulation.

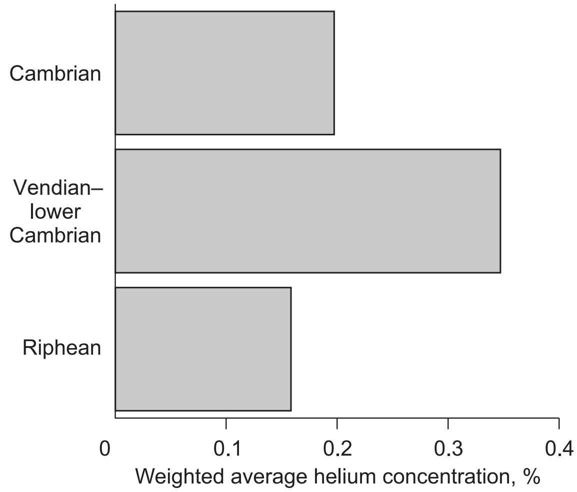

Fig. 2. Play-by-play distribution of helium concentrations in free gas from the fields in the southern and central areas of the Lena–Tunguska petroleum province.

Let us address in more detail the presented estimation procedure.

The natural cluster of hydrocarbon accumulations in large petroleum systems can, with certain reservations, be described by the truncated Pareto distribution (TPD) (Kontorovich et al., 1988; 2001; Kontorovich and Demin, 1977, 1979; Methodological guide..., 2000):

$$\varphi(\theta)=\frac{(\theta_{\max})^{\lambda}\cdot(1-\lambda)}{\lambda\cdot\theta_{\max}+\theta_0\cdot\left[1-\lambda-\left(\frac{\theta_{\max}}{\theta_0}\right)^{\lambda}\right]}\cdot\left[\frac{1}{\theta^{\lambda}}-\frac{1}{(\theta_{\max})^{\lambda}}\right],\quad(1)$$

where λ is the distribution parameter, θ is the reserves in the hydrocarbon accumulation, θ_0, θ_{max} are the minimum and maximum expected sizes of the hydrocarbon accumulation in the natural cluster. Most of the successful techniques for predicting the size distribution of hydrocarbon accumulations are based on the TPD, which is also used in the proposed method for evaluating the number and sizes of undiscovered accumulations. At least two sequential procedures are known for estimating the parameters of the TPD (Kontorovich and Demin, 1977, 1979; Livshits, 2003, 2004a, b).

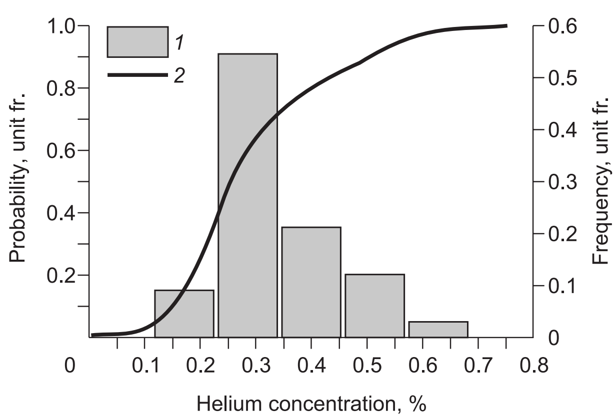

Fig. 3. Histogram and cumulative distribution of helium concentrations in free gas from the fields in the southern and central areas of the Lena–Tunguska petroleum province. 1, frequency, 2, cumulative distribution of helium concentrations

However, a far simpler and more vivid approach can be used for practical purposes. Although this approach is not statistically optimal, it can produce estimates strikingly similar to maximum likelihood estimates (Livshits, 2003, 2004a, b), and it can be typically carried out using standard mathematical software packages.

Introduce a non-normalized cumulative distribution function:

$$\Phi(\theta)=N\cdot\int_{\theta}^{\theta_{\max}}\varphi(x)dx,$$

where N is the total number of accumulations in the system.

The function $\Phi(\theta)$ is equal to the number of accumulations whose sizes are greater than θ.

All accumulations identified in a particular petroleum system will be numbered from the largest size, assuming that at least m accumulations were identified in the largest size class:

$$\theta_1\geq\theta_2\geq\ldots\geq\theta_m$$

In the context of the introduced function $\Phi(\theta)$, it is clear that if the natural cluster of accumulations is described by the TPD, then there are the parameters λ, θ_{max} и N for which the value of the non-normalized cumulative distribution function of the size of the i^{th} accumulation is in a way close to its number i:

$$\Phi(\theta_i)\approx i,\quad i=1\ldots m.$$

Then the problem of finding λ, θ_{max} и N can be reduced to minimizing the sum of the weighted squared deviations:

$$\sum_{i=1}^{m}\left(\Phi\left(\theta_i\right)-i\right)^2\cdot P_i\rightarrow\min,$$

where P_i is the weight function of a certain type. The case $P_i = 1$ corresponds to the ordinary least squares. If $P_i = (i)^{-1}$ or $P_i = \theta_i$, the data on the accumulations in the larger size class (with smaller numbers) would affect the results to a greater extent. This type of the weight function is used in this study.

According to a well-established empirical law (Shpil'man, 1982; Kontorovich et al., 1988), the law of the exploration filter, the accumulations in the largest size class would be found first. Therefore, for the relatively well-explored central and southern areas of the Lena–Tunguska province, it can be assumed that a certain number of the largest free gas accumulations have already been discovered.

It is clear that the parameters of the distribution of accumulations by consecutive size classes can be formally found

Table 1. The distribution of helium and helium-containing gas reserves in plays, central and southern parts of the Lena–Tunguska petroleum province

Petroleum plays	Helium-bearing gas initially-in-place, trillion m^3	Estimated helium initially-in-place, billion m^3
Total	**8.31**	**25.65**
incl. in known accumulations with unbooked helium volumes	**2.18**	**5.71**
incl. Cambrian play	0.47	1.04
incl. in known accumulations with unbooked helium volumes	0.17	0.45
incl. Vendian-Cambrian play	2.52	10.61
incl. in known accumulations with unbooked helium volumes	0.46	1.27
incl. Vendian play	4.82	13.21
incl. in known accumulations with unbooked helium volumes	1.52	3.94
incl. Riphean play	0.50	0.80
incl. in known accumulations with unbooked helium volumes	0.03	0.05

using any subset of the largest known accumulations m ($m > 3$). However, in practice, the robustness of such estimates is possible only for sufficiently large values of m. On the other hand, if the subset used in evaluation includes a size class of reserves that contain accumulations yet to be discovered, the individual parameter estimates will not be correct due to a change in the type of empirical non-normalized cumulative distribution of reserves. The attainment of a certain stability of the parameter estimates of the distribution can thus be taken as a criterion for choosing a sufficient value of m.

After calculating the parameters of the truncated Pareto distribution (1), we generated a series of samples of model accumulations using simulation methods. Generation in each case was performed until accumulations m with reserves greater than the reserves (θ_m) of the m-th accumulation from the natural cluster were obtained. Then for a number of generated accumulations with reserves less than θ_m, we generated the value of the helium content and calculated helium volumes based on the empirical distribution of helium contents (Fig. 3). The obtained series of volumes of helium-containing gas and helium in known accumulations were then used to derive empirical distributions of initially-in-place helium and helium-containing gas in undiscovered accumulations. It should be kept in mind that some accumulations in this size class have already been found, which causes the distributions obtained to be truncated on the left.

RESULTS

After refinement, in accordance with steps 1–3 of the estimation sequence (see above), the total initially-in-place reserves[1] of helium and helium-containing gas in the booked accumulations can be estimated at 25.65 bln m^3 and 8.31 trln m^3, respectively, including 5.71 bln m^3 and 2.18 trln m^3 contained in accumulations that were not normally booked in the state helium balance sheet (Table 1).

Our analysis revealed that the study area contains ~90 largest accumulations of free gas with reserves of at least 14 bln m^3. The obtained estimates of the parameters of the truncated Pareto distribution are: λ 1.98 and θ_{max} 15.85 trln m^3. The correspondence between the predicted and empirical non-normalized cumulative distribution functions of free gas accumulations by size classes for reserves less than 14 bln m^3 can be considered satisfactory (Fig. 4).

If we take the minimum expected size of gas accumulation θ_0 to be equal to 100 mln m^3 (15 smaller size accumulations were put on the balance sheet), then the average value of N is estimated to be 12,250 accumulations (as of January 1, 2017, a total of 336 accumulations were identified and put on the state balance sheet). If we take the minimum expected size of gas accumulation θ_0 to be equal to 1 bln m^3 (317 larger size accumulations were put on the balance sheet), then the average value of N is estimated to be 1320 accumulations.

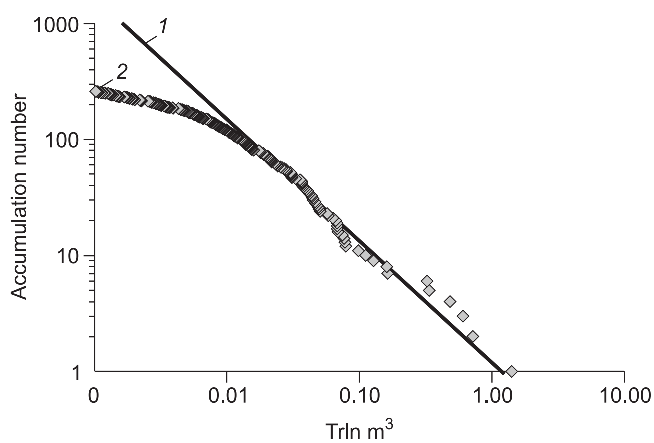

Fig. 4. Empirical and approximating non-normalized cumulative distributions by free gas reserve volumes in the central and southern areas of the Lena–Tunguska petroleum province. *1*, approximating curve, *2*, factual data.

[1] The term "reserves" is used in this study in a number of cases in a broad sense and often refers to the forecast volumes of hydrocarbon gases and helium that are not put on the state balance sheet.

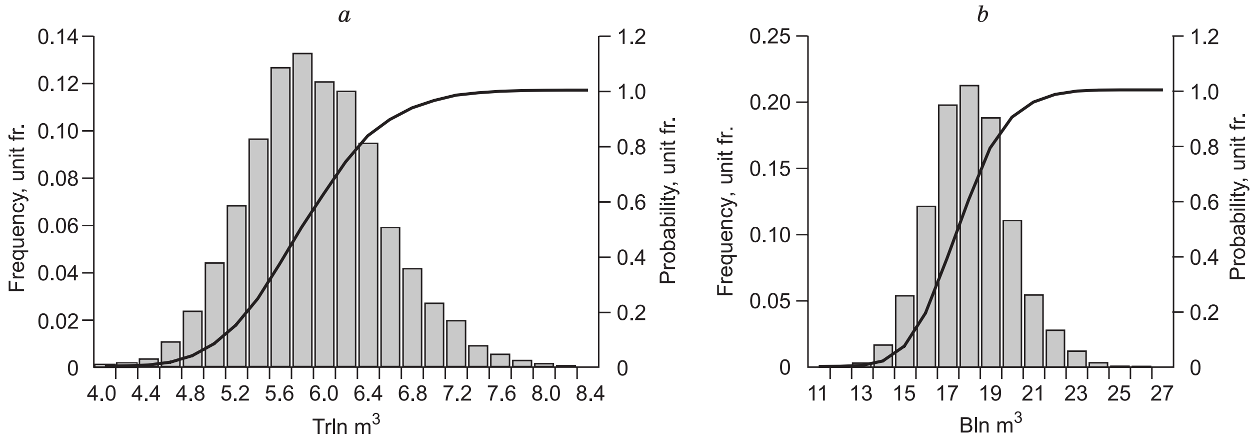

Fig. 5. Frequency and approximating cumulative distributions of total initially-in-place free gas resources in accumulations with reserves <14 billion m^3 (*a*), and helium resources in free gas accumulations with reserves <14 billion m^3 (*b*) in the central and southern areas of the Lena–Tunguska petroleum province.

Using the estimation sequence presented above, we performed a simulation (5,000 runs) and generated distributions of total initially-in-place resources of free gas and helium in accumulations in the size class of less than 14 bln m^3 (Fig. 5). For accumulations in this size class, the total free gas and helium reserves in discovered accumulations were estimated at 973 bln m^3 and 2.9 bln m^3 respectively. The probabilistic estimates of the total initial prospective resources of free gas and helium in undiscovered accumulations were estimated at the 0.9 confidence level as follows: a minimum of 4.1 trln m^3 and 12.3 bln m^3, and a maximum of 5.7 trln m^3 and 17.0 bln m^3, respectively (Table 2).

DISCUSSION

The total initially-in place resources of free gas and helium in the central and southern regions of the Lena–Tunguska province are estimated at 13.1 trln m^3 and 40.2 bln m^3, respectively (Table 3, Fig. 6). Helium resources in undiscovered accumulations and known accumulations with unbooked helium reserves are at least comparable to the already reported volumes of helium initially-in-place (Tables 2 and 3, Fig. 6). It should be noted that the existing estimates of the initial and prospective resources of free gas in these areas calculated using alternative methods are slightly larger than those of the present study. For example, the modal estimate of 16 trln m^3 has been recently obtained in IPGG SB RAS. The significant agreement between estimates obtained with different methods provides more confidence in the validity of the results. This, however, does not exclude reserve revisions based on the new data from a wider geological understanding of the petroleum play.

The method described above can be used to fairly consistently predict the probability distributions of both initial and prospective resources. However, there must be some reservations in the interpretation of the results, and methodology itself provides the primary source of justification and refinement.

The empirical data used in this study may represent various sets of accumulations characterized by different distributions, and the degree to which such accumulations have been identified, and corresponding, for example, to different stratigraphic complexes, regional reservoirs, etc. Significant deviations in reserve volume estimates for the reference sample associated with the insufficient degree of exploration maturity for the field can change the shape of the empirical distribution. In both cases, the shape of the empirical distribution can be significantly distorted.

Table 2. Probabilistic estimate of the prospective resources of helium and helium-containing gas

Estimate	Helium-bearing gas, trillion m^3	Helium, billion m^3
Median (P = 0.5)	4.8	14.6
Max (P = 0.10)	5.7	17.0
Min (P = 0.90)	4.1	12.3
Max (P = 0.05)	5.9	17.9
Min (P = 0.95)	3.9	11.7
Max (P = 0.025)	6.1	18.5
Min (P = 0.975)	3.7	11.2

Table 3. Initially-in-place resources and reserves of helium and helium-containing gas, central and southern parts of the Lena–Tunguska petroleum province

Resources and reserves	Helium-bearing gas, trillion m^3	Helium, billion m^3
Initially-in-place resources (median estimate)	13.1	40.2
Prospective resources (median estimate)	4.8	14.6
Initially-in-place reserves	8.3	25.7
incl. in known accumulations with unbooked helium volumes	2.2	5.7

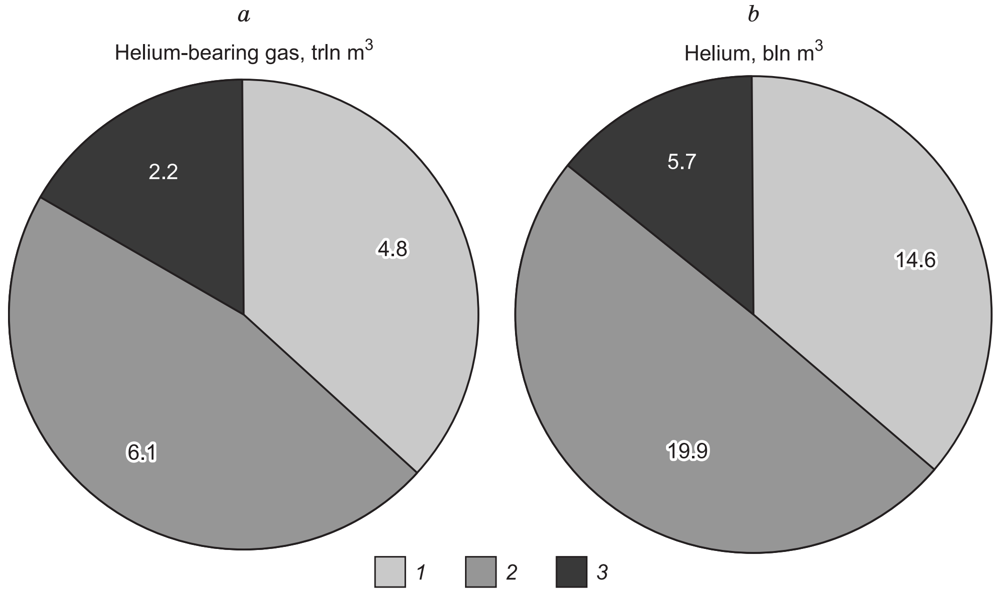

Fig. 6. Distributions of free gas initially-in-place resources (*a*) and helium initially-in-place resources (*b*) in the central and southern ares of the Lena–Tunguska petroleum province. 1, prospective resources (median estimate); 2, reserves of known accumulations with unbooked helium volumes; 3, reserves of known accumulations with unbooked helium volumes.

Empirical data can be well approximated by the truncated Pareto distribution. On the other hand, it is clear from theoretical considerations that the shape of a realistic distribution may be other than Prato, at least at some intervals of size classes. In a theoretical model for the size distribution of hydrocarbon accumulations (Burshtein, 2004, 2006), deviations from Pareto can be observed for relatively small accumulations in petroleum systems that undergo intensive processes of hydrocarbon accumulation. However, it is unlikely that this condition would exist in the sedimentary cover of the Lena–Tunguska province.

CONCLUSIONS

The results of this study were used to substantially refine the theoretical and methodological basis for a quantitative resource estimation of helium and helium-containing free gas in the relatively well-explored areas of the Lena–Tunguska petroleum province. The proposed methodological approaches and compilation of all available geological data were used to build a schematic map of the distribution of weighted average helium contents, to generate a distribution of helium contents in major petroleum plays, to revise the volumes of helium in known accumulations of free gas, and to perform a probabilistic quantitative estimation of the total initially-in-place and prospective resources of helium and helium-containing gas.

The results can be used in the geological and economic estimation of helium resources, in planning the development of a gas production complex of East Siberia and Yakutia (the Republic of Sakha). Further work will be focused on the updating and refinement of the estimates obtained.

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