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GEOLOGY

Probabilistic Mass Distribution of Hydrocarbons in the Dispersed-Scattered State

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It is known [1–5] that the size distribution of hydrocarbon (HC) pools within an arbitrary oil- and gas-bearing (hereafter, petroliferous) basin (PB) with initial geological resources Q is described by the truncated Pareto distribution (TPD). This distribution appears as a result of temporal development of processes of naphthide genesis. Thus, it is interesting to obtain this distribution theoretically by constructing a mathematical model of the processes of formation and decomposition of HC pools. One of the approaches that allows us to describe the process of HC pool formation in a PB at a macroscopic level is based on consideration of this process as structural organization of HC matter in a basin. In this work, we realize one version of such an approach.

It is known that hydrocarbon matter dispersed in sedimentary rocks consists of two parts: kerogen and bitumoids. Kerogen is part of the organic matter (OM), which is not dissolved in organic solvents. N.B. Vassoevich gave the name "microoil" to bitumoids dispersed (dispersed-scattered, according to I.M. Gubkin) in rocks. It is known that their distribution by concentration is described by a lognormal law.

Let us qualitatively consider the process of naphthide genesis. We assume the existence of an oil-productive layer A. At the initial time moment t_0, the concentration of kerogen (OM) at each point $M_i(x_i, y_i, z_i)$ of this layer is equal to c_i^0 and the concentration of bitumoids is b_i^0. In the multitude of points M_i, the values of c_i^0 and b_i^0 are distributed according to the lognormal law. At the same time, the distributions of both components of OM are limited from the right side: $c_i^0 < c_{\max}^0$, $b_i^0 < b_{\max}^0$. Submergence of column A and the consequent growth of temperature and pressure lead to destruction of kerogen. As a result, the values of c_i decrease but new portions of bitumoids are formed and $b_{\max}$ increases to certain limits before the beginning of the migration of bitumoids [6, 7].

Two processes take place immediately after the onset of migration of bitumoids from column A: formation of new bitumoids and their migration. The first process increases b_i^t (including its maximal value), while the second process decreases this parameter. The direction of the variation of b_i^t depends on the ratio of the rates of these processes [6, 7]. Let the mass of emigrated oil by moment t be equal to Q_{em}. The dissipative accumulation of bitumoids in traps and formation of oil begins simultaneously or slightly later. As a result, an insignificant part of Q_{em} is accumulated in traps Q_{oil}, while the major part Q_{diss} is dispersed [8]. Q_{oil} increases in the course of time. At any time moment, Q_{oil} is distributed over a multitude of oil pools N and the reserves in these pools have the same values of q_j^t so that $Q_{\text{oil}} = \sum q_j^t$. Actually, a structural organization of part of HC matter occurs. In reality, the process is even more complicated because as soon as oil is accumulated in traps and oil pools are formed, dissipation of oil from the pools begins. An oil pool is a live organism. An inverse process takes place for a certain period of time when the rate of bitumoid accumulation becomes smaller than the rate of dissipation. We shall distinguish between the progressive and regressive phases in the history of a PB: during the first phase, the rate of HC accumulation in traps dominates over the rate of dissipation. During the second phase, the relation between these rates is the opposite [8]. Nevertheless, at any time moment t, the set of values b_i^t is distributed according to the lognormal law, while the set of values of q_j^t is distributed according to the truncated Pareto law. We assume that at a certain time moment t_1, when all the microoil was in the dispersed-scattered state and the concentration of bitumoids in the rocks reached the

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maximal values $b_i^{t,\max}$, their distribution by mass can be described not by a lognormal law but by a uniform distribution $\omega_p(x) = \frac{1}{x_m - x_0}$ over the interval $[x_0, x_m]$. As we shall see from our further consideration, such an assumption appears applicable because the result obtained in this article is a lower bound estimate while this assumption can only decrease the estimate.

Hence, within the framework of simplifying assumptions accepted in this paper, the structural organization of hydrocarbon matter is in the transition from relatively homogeneous distribution of bitumoids by mass in oil producing parent rocks to extremely inhomogeneous distribution of part of the accumulations in oil pools. As was noticed earlier, the latter is described by amodal TPD. In this case, PB can be considered as a system developing in time from the condition without any structural organization to the state with definite and quite complicated structural organization.

In order to describe such a process, it is reasonable to use the concept of entropy as was done, probably, for the first time in [1, 2, 9] because it is known that the processes of structural organization in open systems are antientropy processes, i.e., processes occurring in the direction of decreasing entropy of the system. The differential entropy of the probability distribution specified by density $\omega(x)$ is defined as

$$S_p = -\int_{x_0}^{x_m} \omega(x) \ln \omega(x) dx,$$

where x_0 and x_m are the lower and upper boundaries of the distribution, respectively.

According to this expression, the entropy of uniform distribution is $S_p = \ln(x_m - x_0)$. Owing to the generation, migration, and accumulation of HC in the traps, the formation of the modern state of the basin is accompanied by accumulation of pools of greater and greater scales. Therefore, according to the probabilistic point of view, the structural organization is a transition from a uniform distribution to the superposition of the IUD and TPD with the right-hand boundary of this distribution and the number of large pools increasing in time. Hence, the right-hand TPD boundary is a parameter varying in time.

At time moment t_2, when the major part of HC pools has been formed already, their distribution is described by the TPD $\omega_P(x) = \frac{\alpha(x_0 x_m)^\alpha}{x_m^\alpha - x_0^\alpha}\frac{1}{x^{\alpha+1}}$. Unlike the TPD introduced in [3], the second term is missing in this expression and the notation $\alpha = \lambda - 1$ is introduced. Since the uniform distribution is a particular case of this distribution at $\alpha = -1$ ($\lambda = 0$), the latter expression describes the mass distribution of microoil in the dispersed-scattered state at time moment t_1 ($\lambda = 0$) and the size distribution of oil pools in the PB at time moment t_2 ($\lambda > 0$). The differential entropy of this distribution is

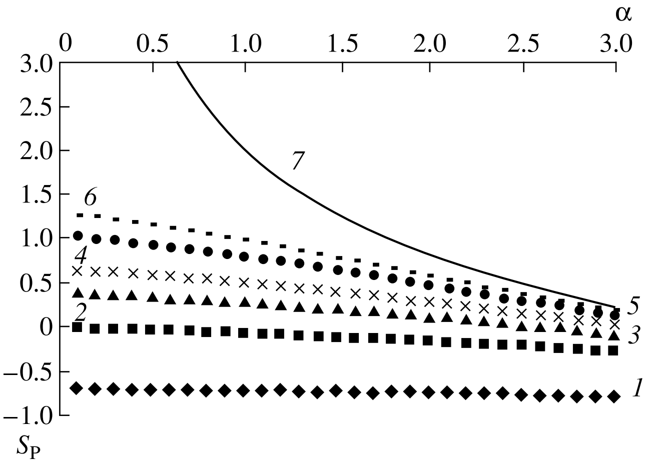

Fig. 1. Differential entropy of the TPD vs. parameter α for different values of the right-hand boundary of the distribution. (*1*) $x_m = 1.5$; (*2*) $x_m = 2.0$; (*3*) $x_m = 2.5$; (*4*) $x_m = 3.0$; (*5*) $x_m = 4.0$; (*6*) $x_m = 5.0$; (*7*) NPD.

$$S_P = \frac{\alpha+1}{\alpha} - \ln\alpha - \ln\frac{\alpha(x_0 x_m)^\alpha}{x_m^\alpha - x_0^\alpha} + \frac{(\alpha+1)(x_m^\alpha \ln x_0 - x_0^\alpha \ln x_m)}{x_m^\alpha - x_0^\alpha},$$

The entropy of the nontruncated Pareto distribution (NPD) S_{NP} is obtained from this expression if we set $x_m \to \infty$,

$$S_{NP} = \frac{\alpha+1}{\alpha} - \ln\alpha + \ln x_0.$$

Figure 1 shows the dependence of entropy for the Pareto distribution S_P on parameter α at $x_0 = 1$ and different values of the right-hand boundary of the distribution x_m. As was expected, the right-hand boundary of the distribution shows a positive correlation with its entropy, and the greatest entropy corresponds to the system described by the NPD. An increase in parameter α decreases the entropy. The influence of α on the entropy also shows positive correlation with the right boundary of the distribution x_m.

The formation of the modern state of the PB during the progressive phase of its development and an increase in the number of large pools, i.e., increase of the right-hand part of the TPD, should be accompanied by a decrease in the entropy of the basin as an oil and gas system. This can be achieved by increasing parameter α (Fig. 1). Thus, as the HC pools are formed and the right-hand boundary of the distribution increases, the initial uniform distribution (IUD) should be transformed into the TPD with increasing parameter α.

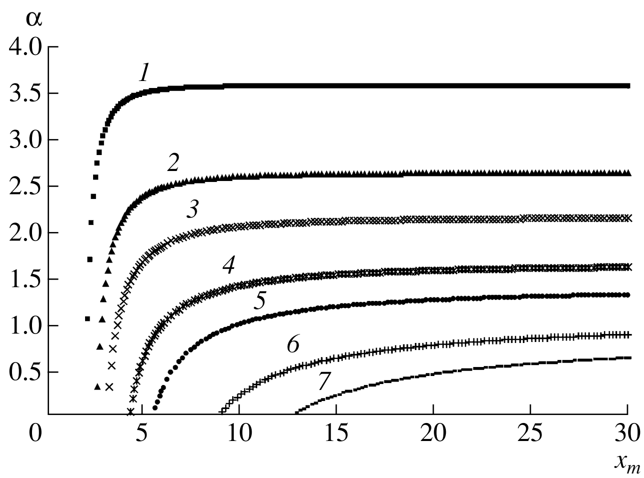

Fig. 2. Parameter $\alpha = \lambda - 1$ vs. the right-hand TPD boundary when its entropy remains constant. (*1*) $x_{mp} = 2.0$, $S_p = 0.00$; (*2*) $x_{mp} = 2.5$, $S_p = 0.41$; (*3*) $x_{mp} = 3.0$, $S_p = 0.69$; (*4*) $x_{mp} = 4.0$, $S_p = 1.10$; (*5*) $x_{mp} = 5.0$, $S_p = 1.39$; (*6*) $x_{mp} = 7.5$, $S_p = 1.87$; (*7*) $x_{mp} = 10.0$, $S_p = 2.20$.

At present, it is not possible to determine dependence $\alpha = f(x_m)$. However, it is possible to obtain its lower bound estimate assuming that the entropy of distributions in this process does not change and remains equal to the entropy of the IUD (because the entropy cannot be greater than the entropy of the uniform distribution during the formation of HC pools). As we shall see from the further considerations, this limitation leads to the lower bound estimate of the maximal value of HC micropools in the dispersed-scattered state.

Such an estimate can be obtained by solving equation $S_p(x_{mp}) = S_P(x_m, \alpha)$ with respect to α for all $x_m \geq x_{mp}$, where x_{mp} is the right-hand IUD boundary.

Figure 2 shows the dependences for such values of parameter α as functions of the upper TPD boundary. The entropy of distribution for these values remains constant and equal to the entropy of the IUD. Each curve corresponds to different values of the right-hand IUD boundary x_{mp}. Figure 2 also shows the value of its differential entropy. It is seen that when the upper IUD boundary only slightly exceeds the lower boundary, an increase in the size of oil pools (hence, the right-hand TPD boundary) leads to a significant compensating increase in parameter α. However, this decrease slows down very quickly because the further increase in the right-hand boundary of the distribution leads to a very small increase in its entropy, while parameter α practically does not change. The value of saturation of parameter α decreases with increasing value of the right-hand IUD boundary.

Figure 2 allows us to get an approximate estimate of the upper boundary x_{mp} for the IUD and the value of bitumoid accumulations in the dispersed-scattered state. The investigations carried out for a set of different (in terms of geological structure and history of development) PBs in the world [1, 3, 4] showed that parameter λ in the TPD, which currently describes the distribution of HC pools, ranges from 1.5 to 2.5 and tends to 2 (α varies from 0.5 to 1.5). As seen from Fig. 2, such α values correspond to the upper IUD boundary x_{mp} approximately from 4 to 10. Since the entropy in a real process does not remain constant but decreases, the obtained estimates for α are estimates of the lower bound. Correspondingly, the estimates of x_{mp} are also estimates of the lower bound (Fig. 2). When the x_{mp} values are smaller than 4, the value of parameter λ for the TPD would be greater than the values observed in real PBs. As for the value of $x_{mp} = 10$, it can be considered as the maximal value for x_{mp} only in the condition of constant entropy.

If the initial distribution differs from the uniform type, then its entropy would be smaller at equal boundaries, because it was shown in [1] that the uniform distribution is characterized by the maximal entropy. Hence, larger values of parameter λ would be needed to maintain a smaller value of entropy when the right-hand TPD boundary increases. Consequently, curves in Fig. 2 would rise and the α values (from 0.5 to 1.5) would correspond to greater values of the right-hand boundary of the initial distribution. Thus, the assumption of the IUD can only lead to a decrease in the estimate.

Thus, formation of HC pools in PB can be considered as an antientropy process of structural organization, which occurs in the following manner. We assume that at the initial moment t_1, oil is in a dispersed–scattered state with the corresponding distribution by mass and maximal entropy. In this case, the upper boundary of distribution x_{mp} exceeds the left-hand boundary x_0 by not less than four times. At this time moment, the PB is at a state close to equilibrium. As a result of some external forcing, which is manifested in a sharp variation of the governing parameters (for example, intense uplift of the West Siberian PB during the Neogene, regression of the sea in the Early Quaternary time, Late Quaternary temperature variation or glaciation), HCs are emitted into the free phase and they are accumulated in traps. Processes of migration and accumulation lead to an increase in the resources of individual pools, i.e., to an increase in the right-hand boundary of the distribution and its transformation into the TPD. In this case, a decrease in the entropy of the system is achieved by increasing parameter α. In the course of increase in resources of large pools, the right-hand boundary of the distribution increases and parameter α (or λ) also increases up to its asymptotic value by time moment t_2 when the processes of oil pool formation are generally completed. In this case, their size distribution corresponds to the TPD with the value of parameter $1.5 \leq \lambda \leq 2.5$.

The above-described process of transition from the initial distribution of microaccumulations of bitumoids to the size distribution of HC, which is accompanied by a decrease in entropy, reflects only the progressive stage of PB development (the stage of initial migration and formation of HC pools). The subsequent regression stage (destruction of pools) would be accompanied by growth of entropy, equalization of size distribution of HC pools, and a decrease in parameter λ. Alternating progressive and regressive stages would correspond to cyclicity in the behavior of entropy (and parameter λ) in time.

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