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ANALYSIS OF REGULARITIES IN THE HYDRODYNAMICS OF DEEP STRATIFIED SYSTEMS

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One of the least studied and highly complicated problems of underground hydrosphere is that of hydrodynamics, hydrogeochemistry, and hydrogeothermal conditions of deep horizons of platforms. In this case deep horizons are the lower part of the section of the sedimentary cover (occurrence depth > 2-3 km), traditionally connected with the zone of extremely complicated water exchange. The formation of groundwater in the zone occurs beyond visible connection with the surface factors. The problem is of academic and practical significance because in the recent years the depth of prospecting, exploratory and operating wells for oil, gas, and mineral groundwater is obviously increasing. However, the efficiency of prospecting and the reliability of estimates of reserves are not great due to the absence of substantiated ideas of the regularities in the distribution of minerals in the deep horizons of platforms, in formation and preservation of which groundwater plays a great role.

In our previous works [1,3] we have shown theoretically that the main mass of the present deep runoff of artesian water forms in the marginal zones of structures, directly adjoining the regional feeding areas. The conclusion was based on regional regularities of distribution of filtration parameters of stratified platform systems, relationships between elements of water balance, and discharges of stratal water.

Earlier the same conclusions were made on the basis of inferences for specific regions: by A. V. Kudelskii (1964, 1972) for the foothills of the West Kopet Dag, by N. V. Rogovskaya and L. G. Sokolovskii for the Turan Plate, and by M. I. Zaidelson for the Cis-Ural region, etc.

We [1,3] were the first to show that this characteristic is **a general regularity of regional hydrodynamics of artesian basins of the platform type.** Formulated was the suggestion that beyond the marginal zones of structures (marginal discharge zones) in the basin, interior area proper for deep parts of the section of stratified basin systems, characteristic must be a structure of local deep-seated groundwater streams with abrupt changes of direction, speed, and discharge on relatively short distances, which excluded transit flows between regional supply and discharge areas.

The formation of a structure of groundwater flows will, under any conditions, be determined by: (a) the position of the main hydrodynamic boundaries of the flow (in the broadest sense of the notion) and the conditions there; (b) the nature of distribution of filtration parameters of water-bearing and low-permeable rocks.

In modern geology the main boundaries of the deep groundwater flows for stratified platform systems are usually regarded as outer geological and structural boundaries, on which hydrodynamic conditions can be established only in the most general terms [1]. The position and nature of interior (intrastructural) boundaries of deep groundwater flows are difficult to be appraised and in most cases are not taken into consideration in hydrodynamic constructions. At the same time data on the distribution of hydrodynamic potentials (below–potentials) of deep stratified systems, on mineralization and temperature of deep water, as well as materials of maintenance and testing of wells convincingly indicate the presence of interior hydrodynamic boundaries and their basic impact on the structure of deep groundwater flows.

The more representative in this sense are data on the heterogeneity of the potentials' field in natural conditions, which is most pronounced in regions of anomalously high potentials. It should be noted that the potential is an integral characteristic, jointly reflecting the properties of the medium, fluid, and the nature of inner and outer border conditions. Research of most relatively well studied oil- and gas-bearing regions shows that the spatial heterogeneity of potential distribution is manifest ubiquitously, increasing in the general case with the depth and intensification of tectonic activity.

Thus, in the central part of East Ciscaucasia (Prikumskii region), in the relatively calm tectonic conditions, the values of those potentials in the Lower Cretaceous deposits vary from $n \cdot 10^{-1}$ MPa to several MPa; in involved tectonic conditions with recent tectonic manifestations (Terek-Sunzha region), the potential drops in the same deposits are dozens of MPa over small distances [3]. In the Pripyat depression, in the intersalt complex (Zadonsk-Yeletsk horizon) the potential value change attains 4 MPa at a distance of 0.5 km (Sosnovskii area) and 8 MPa at 0.8 km (South Ostashkovich deposit). The pattern is similar for many other deposits of the Pripyat depression (subsalt and above-salt complexes).

In the deep aquifers the calculations of the given potential (gradient) may have significant errors due to abrupt changes in the density of the fluid (however, in the given examples the discrepancies in the values of the potentials are greater than possible reduction errors). In connection with this the more representative is the central part of West Siberia where groundwater of Mesozoic deposits has a low (to 25 g/l) mineralization and small density changes which minimizes the potential reduction error.

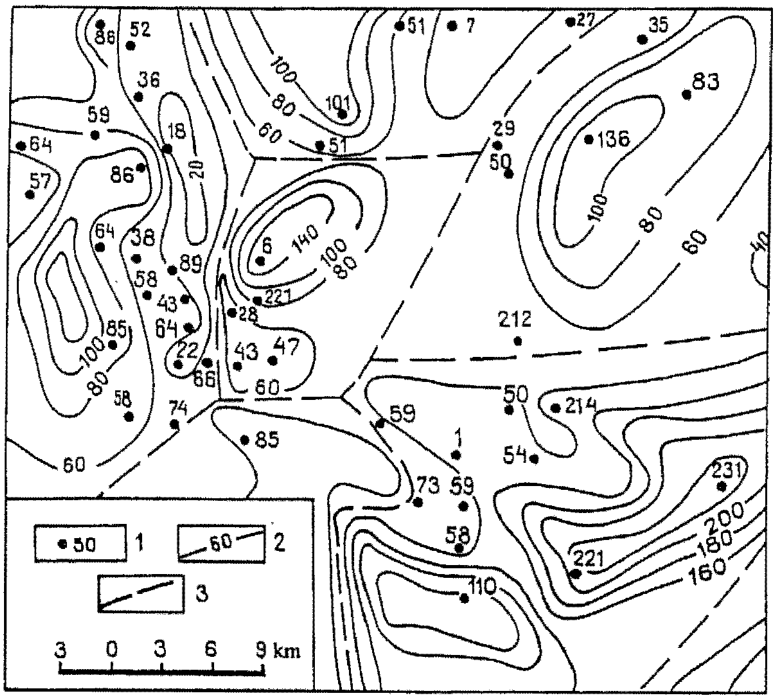

Fig. 1

Scheme of piezometric surface of the Lower Cretaceous water-bearing complex of the Surgut arch of West Siberia: *1*) well and its number; *2*) isolines of equal hydrodynamic potential; *3*) hydrodynamic boundaries.

Figure 1 is a scheme of the piezometric surface of groundwater of the Cretaceous water-bearing complex across several structures of the Surgut arch. Figure 2 is a scheme of Jurassic deposits of the Bukhara-Karshin region. Figure 1 shows that for relatively small distances the reduced potential changes from 0.3 to 2.3 MPa and more. The values of the gradient (in terms of water column meters) reach hundredths of a unity, which according to the existing notions cannot be characteristic of the hydrodynamic conditions of a zone with extremely complicated water exchange.

The same pattern of an involved distribution of potentials in deep aquifers with high values of lateral filtration gradient has been established by Yu. A. Yakovlev for the Perm Cis-Ural region, G. A. Aleksandrov and others for the Kura depression, V. N. Pashkovskii and E. T. Kudashev for Ust-Urt and the Bukhara-Karshin region, and G. G. Shelin for East Siberia, etc.

Sharp differences in the potential values observed on relatively small distances point to a non-relaxation of the potential, inevitable in a unitary stratified system (in the absence of interior relatively impermeable boundaries and inner supply sources). Moreover in the above examples without singling out inner hydrodynamic boundaries, dividing the stratified system into relatively isolated blocks, the actually existing distribution of potentials of deep groundwater cannot generally be presented as a single piezometric surface [1,3].

Data on hydrodynamic testing of deep wells and the experience of working of carbohydrate and mineral water deposits also convincingly point to the existence of inner impermeable or poorly permeable vertical boundaries within stratigraphically single stratified systems.

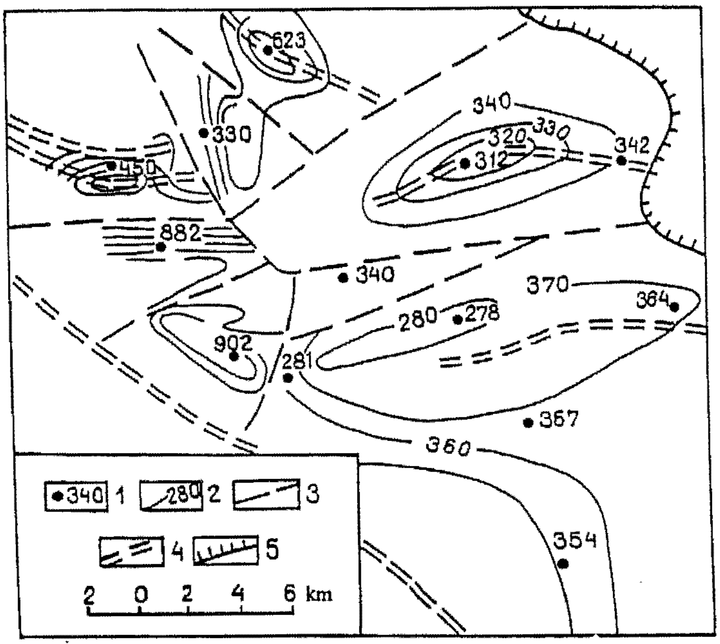

Fig. 2

Sheme of piezometric surface of the Jurassic sediments of the Bukhara-Karshin artesian basin: *1*) well and the reduced potential value; *2*) isolines of hydrodynamic potential; *3*) hydrodynamic boundaries; *4*) established faults; *5*) border of mountain-fold framing.

Thus, in the Uchkyr deposit (Bukhara-Karshin region), it has been established, under the depression of 13.2 MPa on the layer, that there was no hydrodynamic interaction between a series of wells [3]. There is no hydrodynamic interaction between the structures of Tashkuduk, Yangikuduk, Uchkyr, Gazli, Kurbanali, Atbakor, etc. in this region as well.

The working of many deposits in West Siberia points to a hydrodynamic isolation of separate structures or even their parts. The most salient example in this respect is the Salym oil field. When operating, the potential drops rapidly and on closing of wells it does not fully restore, which indicates the existence of borders in plan and in section, reliably isolating separate elements of the stratified system. The absence of hydrodynamic interaction between separate parts of the deposit is confirmed by sharp drops of the potential under natural conditions and under those of operating between closely located wells. Wells 54 and 55 located 6.5 km apart, after a year of operating of one of them and the beginning of testing of the other, had a gradient in the potential values up to 11.8 MPa. The potential drop between wells 64 and 92 (6 km apart) was 16.8 MPa. At the same time, with the most real values of piezoconductivity (10^5-10^6 m^2/day), the spread of a perturbation over 6 km should have been 160-16 days. Similar sharp potential differences were observed between wells 18 and 24, 72 and 24, etc. [3].

An analogous situation was observed in the Duvanny deposit (South-East Kobystan), where under the conditions of superhigh initial values of the potential (17.3 MPa higher than the provisional hydrodynamic one) the dynamics of their fall points to a hydrodynamically closed nature of the operating block.

Hydrodynamic testing of the Terek-Kumsk artesian basin wells showed the absence of interaction between seven pairs of wells on the Achikulak structure, between two pairs of wells on the Velichayev and Pravoberezhny structures, and between three pairs of wells on the East Bezvodnensk and Kolodez structures. Within the Terek-Sunzha region, the picture is still more contrasting in the deformed conditions [3].

Thus, the results of studies of the potential field in natural and deformed conditions show convincingly that the heterogeneity of this field is characteristic of deep-lying horizons, i.e., the presence of variously directed and occasionally high horizontal gradients, changing over short distances and growing in the areas of active neotectonics. Detailed study of hydrodynamics speaks in favour of widespread, in plan impermeable (or slightly permeable), boundaries of different genesis (see below), hindering the potential relaxation along and across the strike of host rocks and regional fluid migration. This conclusion is both quite important and new, and must be considered in regional constructions and search of mineral deposits.

Naturally, such acute manifestations of hydrodynamic boundaries in deep stratified systems can only be connected with **a filtration heterogeneity of the medium.** Nevertheless, issues connected with assessment of the spatial distribution of filtration and capacity properties remain the less explored and poorly described in scientific literature.

The data on distribution of capacity and filtration parameters in plan as a rule lack representativeness [1]. The nature of their distribution in the section of producing horizons of certain deposits and areas is much better studied. Data show that the general conclusion on the reduction of the capacity and filtration properties of sedimentary rocks with depth in connection with regional processes of consolidation [2], cementing, recrystallization, etc. are not confirmed in many cases. With a practically unified or little changing lithological composition of the rocks in the sections of individual structures often observed is an irregular alteration of relatively permeable, weakly permeable, and practically impermeable rocks. Such "bedding" of filtration properties is often observed in the very same rock lithological varieties, whereas their connection with depth is absent.

Thus, quartz monomineral and polymictic Jurassic and Cretaceous sandstones in the East Kuban depression have the following regularity. Their permeability drops and density grows from the central parts of the structures with a high permeability to the tops and foots.

In the central part of the Dnieper-Donetsk depression, in the fine- and medium-grain Early Carboniferous sandstones, against the background of a general deterioration of capacity properties (porosity 11-19%) at a depth of 4.1-4.5 km observed were 12 horizons with porosity up to 30-33%. A similar zone was encountered at a depth of 3.3-3.6 km. Zones of high permeability (1-2 orders of magnitude above the background) are connected with zones of high porosity. In the north-western part of the depression, according to testing data (N. E. Konetskii, 1977), in the interval of depths 3.4-4.2 km observed is a repeated alteration in the section of terrigenous rocks with significantly varied values of open porosity and permeability (see Table 1).

An approximately analogous distribution of the parameters in the vertical section within 2-4 km and deeper in rocks of varied composition and age was established in East Ciscaucasia, Black Sea coastal–Crimean province, Ciscarpathian trough, Vilyui syneclise, Ciscaspian and Fergana depressions, and other areas [3]. The values of effective porosity of rocks vary from 3-5 to 15-20% and higher, and those of permeability from $0.1\text{-}1\cdot10^{-15}$ to $25\text{-}28\cdot10^{-15}$ and to $25\text{-}28\cdot10^{-14}$ m^2 for rocks with fissure permeability (Ciscaspian depression). Facial heterogeneity is often a cause of such relatively high-permeable zones, as well as the secondary porosity connected with the development of tectonic fissuring, natural hydraulic break-up, leaching processes at the depth, and relative deconsolidation of rocks on penetration of fluids with anomalously high reservoir pressures [3]. It could be presumed that the presence of these pressures is one of the most important factors in formation (and preservation) of local zones of relatively increased permeability because a certain relationship between the reservoir properties and the values of anomalously high reservoir pressures has been established for many oil- and gas-bearing areas.

Along with this, under conditions of a practically common composition or proximate facial composition of rocks the presence of zones with extremely low values of open porosity and permeability (3-5%; $0.01\text{-}1\cdot10^{-4}$ μm^2) does not attract a special attention of researchers because of the generally accepted notion about a relatively low permeability of sedimentary rocks at a low depth. Thus, identification and study of relatively high-permeability zones is most attractive. At the same time, in terms of hydrodynamics of stratified systems, the analysis of the nature and conditions of the forming and position of poorly permeable elements in the section of sedimentary rocks is even more vital. Presumably, such zones are mainly the result of cementing of the filtering space of rocks due to new mineral formation processes.

These issues are characterized in detail in papers analyzing catagenesis of sedimentary rocks [8], where the formation of porous cement (authigenic carbonates, quartz and other minerals) is mainly seen as caused by interbed groundwater filtration. According to the V. N. Kholodov scheme (1982), in bedded sandy-clayey sequences at the carbonic acid-hydrogen sulfide stage of catagenesis (down to 2 km and deeper), the processes of new formation of minerals could be mainly linked with the dissolution of dispersed clayey carbonates and the subsequent crystallization of authigenic carbonates in permeable rocks or in zones weakened due to the outflow of CO_2, and at a depth of 3-4 km and deeper–due to the inflow of dehydrated water from clays. As a result, quartz and other authigenic minerals crystallize in intergrain and interfissural space [8].

Table 1

Alteration of Filtration and Capacity Properties (From Data by N. E. Konetskii, 1977)

Area studied	Well number	Depth interval, m	Open porosity, %	Permeability, $n\cdot 10^{-3}$ μm^2
Chizhevsk	10	3826-3875	3.3 14.3 2.1	0.01 5.8 0.0
		4150-4169	11.7 12.9 8.9	13.0 16.0 1.7
	20	3742-3783	13.6 19.2 7.0	- 537.7 3.5
Kharkov	1	3855-3871	12.0 19.8 9.1	37.0 327.0 1.6
Glinsk-Rozbyshev	126	3823-3875	7.2 14.4 5.5	2.0 87.5 0.1
	131	3800-3813	9.0 15.2 13.5	2.5 168.3 18.0

The analysis of these ideas combined with factual data (Table 1) allows us to make two basic conclusions:

–first, cementing of the porous space in sedimentary rocks as a result of processes of new formation of minerals under the conditions of a common lithological type of rocks can cause an abrupt (2-3 orders of magnitude or higher) reduction of filtration properties of water-bearing and poorly permeable rocks;

–second, because in the central submerged parts of platform-type basins the subvertical (uprising) interbed filtration, through poorly permeable clayey rocks as well, is the main form of groundwater movement, it may be presumed that due to authigenic mineral formation zones and areas with a relatively low permeability occur extremely wide.

Data on distribution of filtration and capacity parameters in plan show that it is basically characterized by the same scale of values [1]. Moreover, in most cases the distribution in plan is sufficiently well correlated with the structural form of varied magnitudes and with fault tectonics.

The character of distribution of filtration parameters in connection with sedimentogenic heterogeneity of the medium is sufficiently well studied. In this case, as a rule, relatively large-grain sediments with high values of permeability and capacity (for these conditions) form on areas of erosion and on arches of positive consedimentary structures [7], being facially replaced by more finely dispersed sediments toward structurally lowered zones. Presumably, even with relatively small differences between the proper sedimentogenic values of porosity and permeability, an increase in the clayey nature of sediments results in a sharp intensification of the influence of the consolidation processes at the stage of submerging of facially heterogenic rock masses because of substantially differing coefficients of consolidation in sandy and clayey rocks.

Due to this, already at the stage of accumulation and eventual compaction of facially heterogenic rocks there forms a "cellular" heterogeneity of filtration and capacity properties of the bed connected with the structural pattern of the sedimentation period. Relatively wide zones, related to the axial parts of negative structures of varied magnitude, are to be seen as impermeable boundaries proper.

A similar regularity of parameter distribution is characteristic of sedimentary rocks with fissural porosity [6]. According to E. M. Smekhov, the formation of intense synfold fissuring (hence, a greater fissural permeability) of lithified sedimentary rocks is characteristic of steep arches of positive (postsedimentary) structures, peaks that compound sloping arches of uplifts, steep limbs of asymmetric positive structures, etc.

These general conclusions are well confirmed by factual data of studies of parameter distribution on real structures. Thus, wide-scale research of fissural permeability of the Mesozoic Dagestan rocks [4] show that the highest values $(0.2\text{-}0.9)\cdot 10^{-12}$ m^2 are mainly characteristic of the central parts of structural uplifts (the Khadum uplift, Murgan anticline, etc.), but the values fall on the limbs of uplifts to $n\cdot 10^{-14}$ m^2. An analogous distribution has been established on a series of other structural uplifts. It should be noted that the fissural permeability of lithified sedimentary rocks, even more than fissuring proper, must be connected with arch parts of local uplifts (postsedimentary structures) where alongside the forming of synfold fissuring possible is a partial decompaction of rocks due to a fall of load of the over-lying sequences, as well as the development of regressive catagenesis [8]. Thus, even under the prevalence of fissural permeability of lithified sedimentary rocks, quite explainable is the formation of a block ("cellular") heterogeneity with shaping of relatively permeable blocks in positive structures, and of poorly permeable boundaries within negative structures of the second, third, and higher orders.

Basically important is also the possibility of formation of poorly permeable boundaries of stratified systems in connection **with the zones of tectonic faults.** Hydrogeological notions about relatively higher permeability in tectonic fault zones appeared mainly in studies of the upper part of the hydrogeological section, though the factual data [5] show that old "healed" zones of tectonic fault may also be seen as poorly permeable screens. In deep stratified systems, in the central parts of artesian basins of platforms, hydrogeodynamical (prevalence of uprising interbed filtration) and lithological-geochemical premises determine the possibility of a "rapid" healing of fissural permeability [8] and formation of poorly permeable boundaries. This was convincingly shown by A. A. Rozin for the conditions of West Siberia [5].

Figure 3 presents a fragment of a problem of numerical simulation of the field of potential for the Silurian-Lower Devonian oil-and gas-bearing complex in the northern part of the Pechora artesian basin. The position of the established hydrodynamic boundaries and their configuration allow us to assess their nature. No doubt, within this stratified system there is a poorly permeable boundary connected with a submeridional fault separating the Sorokin arch and the Khoreiver depression. The boundary has been established in drilling and geophysical works. Within the arch proper, poorly permeable boundaries of relatively isolated blocks of the stratified system are probably linked with transverse (sublatitudinal) low-displacement faults, which may not always be established through factual data. The dimensions of the blocks in this case change from several square kilometers to dozens and sometimes hundreds of square kilometers.

In the Khoreiver depression, the configuration of hydrodynamic boundaries (Fig. 3) suggests that their position is determined by the inner structural pattern of the depression (structures of the third and higher orders).

Proceeding from the general ideas, a generalized balance equation as to the isolated block of the stratified system can be presented as follows:

$$\frac{\partial}{\partial x}\left(\frac{k}{\mu} m \frac{p}{x}\right) + \frac{\partial}{\partial y}\left(\frac{k}{\mu} m \frac{p}{y}\right) +$$

$$+ \frac{k_0^{\text{o}}}{m_0^{\text{o}}}(P_{\text{o}} - P) + \frac{k_0^{\text{o}}}{m_0^{\text{u}}}(P_{\text{u}} - P) + \alpha\frac{\partial P_{\text{g}}}{\partial t} + \beta\frac{\partial P_{\text{gd}}}{\partial t} + \Sigma W = 0,$$

where $P = P_0 + g\int_{z_0}^{z} \rho(z)\,dz$ is the reduced potential (below–potential), P_0 is the measured potential in a well; ρ is the fluid density; g is the free fall acceleration; P_{o}, P_{u} are potentials in the over- and underlying complexes, respectively; k is the permeability of rocks according to the area of spread; m is the thickness of complexes; μ is the fluid viscosity; $k_0^{\text{o,u}}$ is the permeability of a separate over- and underlying bed, respectively; $m_0^{\text{o,u}}$ is the thickness of the over-and underlying beds, respectively; P_g is the geostatic pressure; P_{gd} is the geodynamic pressure; ΣW are the inner supply and discharge sources; α and β are coefficients depending on porosity, fissuring of rocks, compressibility of fluid and rocks, and density of fluid.

This equation is supplemented by limiting conditions of the I, II, and III kind depending on geological and hydrogeological conditions of the studied area.

The first two terms of the equation describe the groundwater discharge along bedding, the two following terms–the subvertical discharge of interlayer filtration, the fifth term describes the "inner supply" due to the pressing out of interstitial water (elision supply) or due to the dehydration of rock-forming minerals; the sixth term–the change of volume of capacity (geological) reserves of groundwater in the block as related to the change of the capacity characteristics of rocks (processes of new formation of minerals, deep-seated leaching, development of fissuring, and also due to compression or extension caused by dynamic processes).

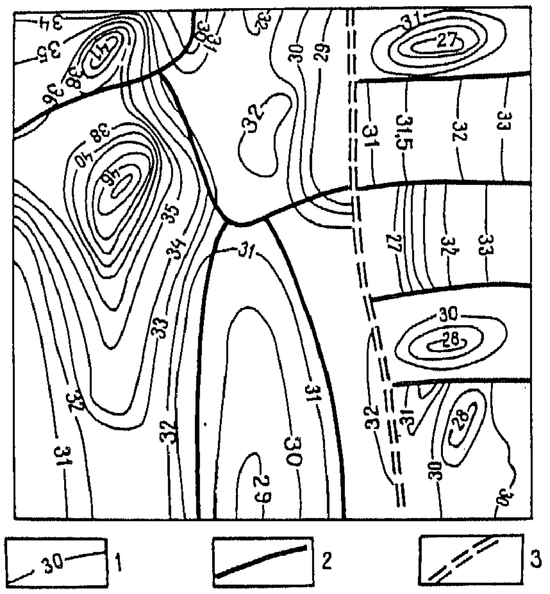

Fig. 3

Scheme of piezometric surface of the Silurian-Lower Devonian water-bearing complex of the Pechora artesian basin: *1*) isolines of hydrodynamic potential; *2*) hydrodynamically impermeable boundaries; *3*) established faults.

Balance-hydrodynamic calculations of deep stratified systems are effected based on assessment of bed and interbed filtration and to a lesser extent of elision supply values [1]. However, the results of balance-hydrodynamic assessments of actual stratified systems show that the formation of the block balance through the ratios of mainly bed and interbed discharges is characteristic only of relatively limited peripheral parts of stratified systems. In the central submerged parts of these systems the groundwater movement proper is manifest only as a **subvertical** (mostly ascending) **interlayer filtration**. Its discharge value is of the order $n \cdot (1\text{-}10)$ m^3/day km^2 [1]. Such insignificant values of discharges in the conditions of insufficient information on the spatial distribution of parameters of water-bearing and poorly permeable rocks determine not only a low reliability of any balance-hydrodynamic assessments but also a substantial uncertainty of qualitative ideas on the conditions of interactions as to isolated blocks, directions of movement, water balance structure, etc.

Analysis of distribution of potentials in deep stratified systems, results of solution of hydrodynamic problems, and the general appearance of the balance equation as related to an isolated block lead us to the following conclusions.

In the lower parts of platform-type artesian basins (and major intermontane basins) **within a concrete lithostratigraphic element of the section,** there forms, as a rule, a system of **hydrodynamically isolated blocks (laminar-block system).**

Characteristic of each relatively isolated block of the stratified system are specific **gradient values** of bed and interbed filtration, groundwater **movement directions, ratios of water balance elements**, and the related distribution of temperature and chemical composition of groundwater.

The genetic nature of poorly permeable boundaries separating relatively isolated blocks of the stratified system **may be substantially different** but practically in all cases the position of these boundaries is determined by the **inner structural pattern** of the basin (structural forms of the second, third, and higher orders, zones of faults).

In substantiating calculation schemes for deep systems it is necessary to proceed **from the presence of hydrodynamic boundaries** connected with the main structural elements of the basin's inner area, **proving their absence** by results of concrete assessments.

Fluid dynamic balance equation as related to an isolated block of a stratified system includes **elements substantially differing in nature**. In addition, due to poorly studied medium parameters and possible relations of values of the balance equation, the hydrodynamic calculations proper **do not** as a rule **ensure** even **a qualitative estimate of the structure of fluid dynamic balance** as related to the isolated block. Reliable estimates of the structure of such a balance are only possible on the basis of a **comprehensive analysis** of hydrodynamic, hydrogeochemical, and thermometric characteristics of the block.

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