Abnormally high formation pressures in jurassic-cretaceous reservoirs of Arctic regions of Western Siberia

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Abstract. Results of the study of the structure of hydrodynamic fields in Arctic part of the West Siberian sedimentary basin have designated the main region-specific hydrodynamic feature consisting in the phenomenon of abnormally high formation pressures widely spread at depths of 2.8-6.0 km within Jurassic-Cretaceous reservoirs. The two types of natural pressurized water systems which have developed in the region are: 1) elision (geostatic and geodynamic) system most common in the interior regions, and 2) infiltration aquifer system inherent in the external, near edge zones. As the depth increases, two hydrodynamic zones are distinctly distinguished (from top downwards): hydrostatic and enhanced evolving into AHFD (abnormally high formation pressure). Most of the Aptian-Albian-Cenomanian aquifers belong to the first type. Hydrodynamic field stresses tend to increase in the lower lying Neocomian complex where the already elevated formation pressures gradually build up, to the extent of AHFP in the lower horizons. The Jurassic aquifer complexes in the central parts of the Yamal-Kara depression exhibit either enhanced or abnormally high formation pressures, which decline to hydrostatic levels towards the basin periphery. The anomaly coefficients of formation pressure reach the value of 2.2. The established piezo-minima zones extending along major petroleum charge zones, extending along the major hydrocarbon generation zones (Bolshaya Kheta and Kara megasyneclises) associated with the largest areas of petroleum accumulation (Vankor-Suzun, Bovanenkovo, Urengoy, etc.).

1. Introduction

Given the complexity of hydrogeological conditions of Arctic part of the West Siberian sedimentary basin (WSSSB) it is critical to have reliable information on the hydrodynamic parameters of petroleum reservoirs. However, the quality of data obtained from exploration wells for most of the studied objects particularly those tested using drill-stem tester is very low. Analysis of the factual materials has shown that less than half of exploration wells that penetrated Mesozoic aquifers, provide reliable information on the hydrodynamic aspects. Notably, despite the thousands of deep exploration wells drilled in the studied region (Fig. 1), even the major hydrodynamic patterns have thus far been studied only in broad terms. The state of knowledge about the region’s hydrogeology varies greatly, depending on many factors. Thus, Neocomian complex has received the most extensive coverage due to its high prospects for oil and gas and because of the many actual discoveries of hydrocarbon deposits. Numerous hydrodynamic research with the focus on Western Siberia are represented by the...
works of B. L. Aleksandrov, G. D. Ginsburg, A. E. Gurevich, V. I. Dyunin, P. A. Kamenev, V. N. Kortenshtein, N. M. Kruglikov, B. F. Mavritskii, V. V. Nelyubin, O. V. Ravdonikas, A. D. Reznik, O. N. Yakovlev and many other researchers [1-13].

Figure 1. The fragment of tectonic zoning map for the top of Jurassic complex of the West-Siberian geosynclise (simplified after [14])

Boundaries of: 1-West Siberian sedimentary basin; 2-Jurassic sedimentary basin; 3-Internal region and External belt; 4-Yamal-Kara depression; Intermediate tectonic elements: 5 – mega-, meso-, monocline; 6 – mega-, meso-, saddle. Positive tectonic elements: 7- zero-order structures; 8 – I-order structures. Negative tectonic elements: 9- 0-order structures; 10-structures of order I.

Intermediate tectonic elements: I – mega-, meso-, monocline: I –North-Kara monocline, II – East-Pakhoy monocline, III –South-Taimyr megamonocline, IV –North-Messoyakha megamonocline, V – Dolgon mesomonocline, VI – East-Taz mesomonocline, VII – East-Pur megamonocline, VIII – Krasnosel’kup monocline; 2 – mega-, meso-, saddles: I – South-Kara megasaddle, II – North-Chaselka saddle; Positive tectonic elements: 3 – zero-order structures: A – Messoyakha inclined ridge, B – Khantey hemianticline; 4 – I-order structures: I – North-Gydan megaheadland, II –Pre-Paiakhoy megaheadland, III – Tundra megaheadland, IV – Bovanenkovo-Nurminsky inclined megaswell, V – Gydan megaheadland, VI – Ust’-Port megaheadland, VII – Yarudey megaheadland, VIII – Medvezhiye –Nuginsky inclined megaswell, IX – Chaselka inclined megaswell, X –Northern Arch, XI – Surgut Arch, XII –Var’yegan-Tagrin megaheadland; Negative tectonic elements: 5 – zero-order structures: A – Kara megasyncline, B – Agapa –Yenisei trench, C – Antipayuta-Tadebeyakha megasyncline, D – Bolshaya Kheta megasyncline, E – Nadym hemisyneclise, F –Middle-Pur inclined megatrench, G –Mansi syncline; 6 – I-order structures: I –South-Kara megadepression, II – Agapa megathrough, III –Middle-Gydan mega-gully, VI – Yaptiksale megadepression, V – Yenisei megadepression, VII – East-Antipayuta megadepression, VIII – North-Taz megadepression, IX – Nerutinsky megadepression, X – Taz structural megabay XI – Upper-Tanlova megadepression, XII – Middle-Pur inclined megatrough, XIII – Visim inclined megatrough, XIV – Pyakupur-Amputa inclined megatrough.
The many years of fundamental research into the processes of filtration, and experimental studies of hydrodynamic systems of petroleum basins around the world evidence that the even systematic observations are limited to providing data on water flow direction and rate only for groundwaters or shallow artesian waters, largely ignoring the problems faced in the development of hydrocarbon deposits. Therefore, the main approaches applicable to determining directions, velocities and discharge rates of subsurface waters in deep horizons of petroleum basins are basically calculus-based.

2. Materials and Methods
In most natural “pressurized” aquifer systems, the density of subsurface waters is subject to variation both within its areal extent and throughout the section, whereas the aquifers’ placement is non-horizontal. In this case, the differences in their water-table levels are largely controlled by variations in water density and the horizon occurrence depths, rather than by water motion alone. Ruling out the impact from these factors in order to focus on the dynamics effects alone, requires using calculated pressure heads (reduced, or corrected pressures) of subsurface waters, instead. It is only a differential of pressure head (i.e. reduced pressure) that can serve an indicator of the pressurized subsurface water flow. A reference (datum) plane is usually lined up with the bottom-hole of the deepest well. For the purpose of generalization and analysis of the hydrodynamic parameters of Jurassic-Cretaceous reservoirs, the following reference planes were accepted for major hydrogeological complexes: Aptian-Albian-Cenomanian – 2500 m, Neocomian – 4000 m, Upper Jurassic – 3800 m and Lower-Middle Jurassic – 5500 m. This study is largely based on the results of testing more than 4000 objects of 251 prospecting areas, as well as the interpretation of well-logs and drillcore analysis materials (more than 6200 samples). The best studied appear to be Cretaceous reservoirs. The structure of a hydrodynamic field of petroleum basins is known to evolve over a long time and is closely connected with the geological history through the processes of sedimentary rocks compaction and their post-sedimentation transformations from the ooze stage in early diagenesis and through the stage of metamorphism.

3. Results and Discussion
The revealed structural features and available information on the subsurface geology enabled identification of the Mesozoic-Cenozoic aquifer system in the cross section with characteristic pressurized (confined aquifers) and impermeable (aquicludes) complexes. The main hydrodynamic signature of this part of the WSSB is represented by a wide distribution of high formation pressures (AHFP) within the 2.8-6.0 km depth interval both in Jurassic aquifers and in the overlying horizons, up to Neocomian ones (Fig. 2). As the depth increases, two hydrodynamic zones become distinctly identifiable (from top downwards): 1) hydrostatic and 2) elevated pressures gradually developing into AHFP. Notably, most of the aquifers of the Aptian-Albian-Cenomanian aquifer complex belong to the first group. Given that the hydrodynamic field stress tends to increase in the lower lying Neocomian complex, the already elevated formation pressures gradually become AHFP in its lower horizons. Jurassic complexes in the central parts of the study area are dominated by elevated pressures and AHFPs, which anyway appear to be declining to the level of hydrostatic when approaching the basin periphery [15]. This pattern is distinctly observable on the example of the Yamal Peninsula, where in the direction from south to north from the Novoportovskoye oil and gas condensate field to the Malyginskoye field, the subsurface hydrogeological closure is tending to increase, which is explicitly manifested in the growth of Ka values from normal (0.95-1.00) to AHFP (1.60-1.92), respectively [13,16].

The Aptian-Albian-Cenomanian aquifer complex is characterized by formation pressures varying in the range between 3.5 and 28.4 Mpa and controlled by the occurrence depth of aquifers [17,18]. As is seen from Fig. 2, this complex is for the most part characterized by normal (hydrostatic) pressures. Notably, hydrodynamic stress analysis at a regional scale has shown that the study area falls almost entirely within the zone of normal pressures. In this context, quite extensive areas are confined to the elevated pressure zones in the areas of NW strike (the southern parts of the Kara megasyncline) and
in the central areas (the central regions of the Atipayuta-Tadebayakha megasyneclise and the southern slope of the North-Taz megadepression complicating the structural plan of the Bolshaya Kheta megasyneclise). The sporadically distributed low-pressure hydrodynamic anomalies are associated with the existence of HC accumulations within the sediments of the complex, in itself, being a major gas-producing area of Western Siberia. Arctic regions hold unique hydrocarbon reserves, which is illustrated below by gas fields classification according to their largeness, trln m³: Urengoysskoe – 9.5, Medvezhiye – 1.0, Yuzhno-Russkoe – 1.0, Yamsoveysskoe – 1.0, Komsomolskoe – 0.7, etc. [14,15].

The analysis of the low pressure anomalies propagation extents revealed a direct relationship between their existence and the presence of the unique and large gas deposits within the complex, which is, specifically, characteristic of the Cenomanian gas accumulations. As such, the anomalies were found within the Bovanenkovskoye, Messoyakhskoye, Tagulskoye, Utrenneye, Kharampurskoye, Yamsoveysskoye and other gas fields, where the Ka values vary in the range from 0.83 to 0.91.

Analysis of distribution of pressures reduced to the 2500 m plane within the Aptian-Albian-Cenomanian complex revealed extensive piezo-maxima zones acting as internal areas of groundwater recharge confined to the most plunging areas of the Middle Pur inclined megatrench, and the Bolshaya Kheta, Antipayuta-Tadebetakha and Kara megasyneclises. A general pressure differential of reduced pressures reaches 3.4 MPa. Whilst the piezo-minima zones delineate the contours of large zones of oil accumulation, for example, the Kharasaveyskoye field in the north, Vankor-Suzunskoye in the east, and Urengoiyskoye in the central part, etc. In the Neocomian aquifer complex cross section, formation pressures vary between 6.3 and 77.9 MPa. Aquifers confined to the lowermost parts of the complex exhibit the presence of AHFP zones, and elevated pressures are remarkably observed throughout the cross section (Fig. 2). Analysis of the Ka values distributions has shown the presence of three zones characterizing the formation pressure as: normal, elevated and abnormally high. Remarkably, likewise the overlying Aptian-Albian-Cenomanian hydrogeological complex, it is dominated by the normal pressure zone. Against this backdrop, two major regions of elevated reservoir pressures are distinguished, with one of them confined to the central regions and delimited by the areal extent of the Bolshaya Kheta megasyneclise, while the second is established in the north, partly comprising the structures of the Kara and Antipayuta-Tadebayakha megasyneclise, and encompassing the eastern part Agapa-Yenisei trench. Within these areas, we have identified seven hydrodynamic zones with IHFP.

In the north, these are the areas of the South Kara megadepression, Tadebeyakha megatrough, and Yenisei megadepression.

Within the Bolshaya Kheta megasyneclise, the developing AHFP areas are confined to the Neruta megadepression structures. Likewise within the Aptian-Albian-Cenomanian complex, a number of hydrodynamic anomalies with the lower background formation pressures (Ka values are in range from 0.86 to 0.91) were established, also confined to large fields (Salmanovskoye, Kharasaveyskoye, Vankorskoye, etc.). The total pressure differentials reduced to the 4,000 m plane reaches 28.0 MPa within Neocomian complex. Analysis of their distribution revealed extensive high-gradient piezo-maxima zones acting as internal areas of subsurface recharge and confined to the most plunging areas of the Bolshaya Kheta, Antipayuta-Tadebayakha, Kara megasyneclises and Agapa-Yenisei trench. The maximum lateral pressure decline gradients down to 0.8-1.2 MPa/km were established in the northeast of the study area in the transition region from the West Siberian artesian basin to the Khatanga basin, which is structurally confined to the Yenisei-Khatanga regional trough. What actually drives the values to be that large? A detailed consideration of the structural features of aquifers has thrown much light on the situation [9,11]. The identified localities on the North-Messoyakh megamonoclinal slope within the Nizhnyaya-Malaya Kheta structures cfault zones, have thus served as subsurface waters discharge areas. Westwardly, the top of Neocomian sediments has plunged deeper from 300 to 2000 m or more, while the reduced pressures have increased from 36 to 52 MPa. The revealed there extensive area with AHFP is delimited by the Paikhoy, Middle-Yarovalskoye, Turka and Tanama areas. The highest Ka values are observed in the wells: Turkovskaya 1 – 2.45; Turkovskaya 2 – 1.46; Paiyakhskaya 1 – 1.45, and Paiyakhskaya 2 – 1.49.
Figure 2. Change of porosity of sandstones/siltstones (a) and clays/argillites (b), reservoir pressures (c) and Ka (d) with depth within the Arctic regions of the West Siberian sedimentary basin [19].

a) Trends in the porosity of sandstones/siltstones with depth: 1 – global [20]; 2 – in the Central regions of Western Siberia (alevrolites) [21]; 3 – in the Central regions of Western Siberia (sandstones [21]; 4 – in the Arctic regions of Western Siberia.

b) Trends in porosity change of clay / argillites with depth: 1 – G. I. Alekseev et al. [21]; 2 – in the Arctic regions of Western Siberia. Curves of dehydration of argillaceous sediments: I – after Burst [22]; II – after Perry and Hower [23]. Sediment Dehydration stages: I – free-water elision, II – the initial stage. 50% elision of interlayer water at the depths of 2.0-2.7 km, III – the next stage of 25% elision of interlayer water at the depths of 2.7-3.5 km, IV – the rest 25% elision of interlayer water at a depth of 3.5 km.

c) Hydrogeological complexes: 1 – Aptian-Albian-Cenomanian, 2 – Neocom, 3 – upper Jurassic, 4 – lower-middle Jurassic, 5 – pre-Jurassic.

d) Zones of formation pressures in size Ka: 1 – lowered (0.8-0.95); 2 – normal (0.95-1.05); 3 – increased (1.05-1.15); 4 – anomalous-high (more than 1.15).

The AHFP zone is bordered on the zone of elevated pressures, which is expanding from the southwest and north-east, heading for the northwestern regions. The values of reduced pressures less than 35-36 MPa are associated with distribution of low pressures within the Ozernaya, Lower-Kheta, Malaya Kheta, Sukhaya Dudinka, Tochino, and Dolgan areas, which are interpreted to be influenced by the gas accumulations identified therein. These patterns also generally characterize the main piezominima proper to Arctic regions of Western Siberia, and account for their replicating the contours of major zones of petroleum accumulation. At this, the alignment of a number of oil and gas accumulation zones (e.g., the Urengoy area) with high pressure zones is remarkable, which may evidence the processes of vertical migration within them, from the deeper buried Jurassic complexes.

In terms of hydrodynamics, the upper Jurassic hydrogeological complex appears the most interesting, inasmuch as formation pressures vary considerably within its bounds, ranging from 9.9 to 67.7 MPa. The water dynamics specificity of the complex is represented by AHFP with anomaly
coefficient reaching the value of 1.87 (Fig. 2). The analysis of the hydrodynamic field stress revealed the dominance of two pressure zones in the study area described as: normal (eastern parts) and abnormally high (western and central parts), with the zone of elevated pressures ($K_a = 1.05-1.15$) in between, stretching from south to north. In eastern parts, the dominance of the normal pressures is sporadically interfered by hydrodynamic anomalies with elevated pressures confined to the structures of the Yustymalskoye, Tekto-Kharampurskoye and Ravninnoye fields [17,11]. The presence of such an extensive AHFP zone in the central and western parts of the Nadym-Taz interfluve (near the Oxfordian regional clayey reservoir boundary) can be explained by the elision water regime in this part of the region [17,18]. V.M. Matusovich and co-authors [24,25] have identified the following pressurized aquifer systems striking from west to east: elasion- lithostatic, elasion-geodynamic (controlled by the -Koltogor -Urengoy graben-rift) and infiltration.

Analysis of distribution of pressures reduced to the 3800 m plane within Upper Jurassic complex has revealed extensive piezo-maxima zones confined to the boundary of argillization of Oxfordian regional reservoir in the west of the Nadym-Taz interfluve and to the most plunged parts of the Middle-Pur inclined megatrough and the Bolshaya Kheta megasyncline. The total pressure differential across the complex reaches 34.0 MPa. The growth of reduced pressures at the boundary of the argillization of permeable sediments speaks of a reliable lithological screen and of possible lateral migration of fluids from west to east governed by the conditions of the elision lithostatic pressurized water system. The zones of the main piezo-minima also delineate the areas of large oil and gas accumulations (e.g. the Kharampur within the Middle-Pur inclined megatrench, etc.). The lowermost of the thoroughly studied, Lower-Middle Jurassic aquifer complex is characterized by formation pressures 6.6-101.9 MPa (Fig. 2). The dominant controls in the central and northern regions are represented by elevated pressures and AHFPs; and by the zone of normal pressures further to the east and west, expanding as far as the sedimentary basin boundaries. The AHFP zone is aligned with the main super-order tectonic elements: the Kara, Antipayta-Tadebeyakha and the Bolshaya Kheta megasynclises and the Arapa-Yenisei trench, where $K_a$ values often reaches 1.5 or more. For example, in the Lower-Middle Jurassic reservoirs of the Bovanenkovskoye field they reach 1.54-1.77, and 1.79 in the West-Tambeyskoye field; vary between 1.97 and 2.21in the Zapolyarnoye field; and between 1.65 and 1.98 in the Urengoiiskoye field [13].

Analysis of distribution of pressures reduced to the 5500 m plane within the Lower-Middle Jurassic aquifer complex has revealed extensive zones of piezo-maxima, delineating the areas of the developing AHFPs. The total pressure differential reaches 50 MPa, and the maximum pressure were identified within the Kara (>70 MPa) and the Bolshaya Kheta (> 80 MPa) megasynclises. This ultimately allows an inference that the pressurized water system of the Lower-Middle Jurassic aquifer complex has preserved the relics of the exfiltration hydrodynamic regime, since most zones of elevated pressures are confined to large negative tectonic elements. The major piezo-minima zones replicate the contours of large zones of oil and gas accumulation (e.g. Novy Pert area in the north, the Kharampur area in the central parts, etc.).
4. Conclusion
It follows from the above that the pressurized water systems of Cretaceous and Jurassic complexes in Arctic parts of the West Siberian sedimentary basin, including petroleum-producing reservoirs identifiable within the extensive area, are isolated from each other by reliable aquicludes (impermeable beds), which is confirmed by the results obtained. Their isolation is impaired only locally, at sites marked either by the presence of numerous faults and tectonic dislocations, or lithological windows. Even within one complex, hydrodynamic conditions change significantly, and isolated hydrodynamic blocks have been established within their bounds. The low hydrodynamic pressure anomalies within the complex of Aptian-Albian-Cenomanian and Neocomian aquifers are associated with the presence of unique and large reserves of gas and gas-condensate deposits in their cross section, especially in Cenomanian reservoirs. Manifestations of elevated and abnormally high pressures within them are interpreted as a sign of a high level of hydrogeological closure of the subsurface, which characterizes the elision type of pressurized water system. The currently observed manifestation thereof in the study region belong to two types of natural pressurized water systems (after A. A. Kartsev, V. M. Matusevich): elision waters (geostatic and geodynamic) in the interior regions, and infiltration waters in the exterior parts, in near edge zones.

Especially widespread areas of AHFP are found to be within the Jurassic aquifer systems, dominating in the western and central parts (Upper Jurassic reservoirs), and in the northern and central regions (Lower-Middle Jurassic reservoirs). The Neocomian, Upper Jurassic and Lower-Middle Jurassic aquifer complexes are marked by the presence of extensive areas of piezo-minima, extending along the main zones of oil and gas generation (the Bolshaya Kheta and Kara megasynclises), which are associated with the largest areas of petroleum accumulation (Bovanenkovo, Vankor-Suzun, Urengoy, and others).

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