Paleohydrogeochemistry of the Upper Jurassic Deposits of the Arctic Regions of the West Siberian Megabasin

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Abstract: The paper considers the paleohydrogeochemistry of the Upper Jurassic sediments of the Arctic regions of Western Siberia. On the territory under investigation during the late Jurassic marine sedimentation was predominant; the sea depths reached 400 m in the Volga time. Under these conditions, syngenetic sodium thalassogenic chloride waters were buried, in some places with a high content of magnesium, the salinity of which reached 35–40 g/dm3. A comparative analysis of the buried syngenetic waters of the Oxford basin and data on the modern hydrogeochemistry of groundwater of the Upper Jurassic aquiferous complex revealed very significant differences. The analysis of distribution value the total mineralization allowed to establish areas of positive and negative anomalies. In the first case, most of the anomalies are associated with the processes of vertical discharge of groundwater of the Lower Middle Jurassic and Paleozoic aquifers in the zones of tectonic disturbances. Negative anomalies regularly trace the clay boundary of the Oxford regional reservoir, expanding significantly in the north-east direction. Their nature is associated with the development of processes of elision water exchange and thermal dehydration of clay minerals.

1. Introduction
As a separate science, paleohydrogeology emerged early in the 20th century and studies the past stages in the development of sedimentary basins, aiming to clarify the role played by ancient groundwaters in the formation and preservation of mineral deposits, which was extensively discussed in the pioneer works of P.N. Chirvinskiy. Later, this research line was largely contributed by many prominent scientists, among them L.A. Abukova, E.A. Baskov, E.A. Bars, S.B. Vagin, A.A. Kartsev, K.I. Makov, A.M. Nikanorov, E.V. Pinniker, A.N. Semikhatov, Ya. A. Semikhatov, Ya.A. Khodzhakuliev, S.A. Shagoyants, G.P. Yakobson and others. [1-3]. Modern advanced-level scientific research requires aggregation of the latest data from many areas of the Earth Sciences, such as hydrogeology, lithology, stratigraphy, tectonics, etc. whose results and findings are helpful in solving many problems of modern hydrogeochemistry of oil and gas accumulations, including the composition of groundwaters, their origin, type of vertical hydrogeochemical zonality, the processes of petroleum generation and accumulation, and other aspects.

Paleohydrogeological studies of petroleum basins focus primarily on periodization of their hydrogeological history, consisting in determination of hydrogeological cycles and stages. According to A. A. Kartsev, S. B. Vagin and E. A. Baskov, a hydrogeological cycle begins with transgression and
includes depositional processes with concomitant burial of sedimentary waters, spanning the period of subsequent elevation and regression, and culminates in a new submergence and transgression. The first part of hydrogelogical cycle is a sedimentary (elision) stage during which the formation of sedimentary waters and the elision water exchange take place. Its second part accounts for infiltration stage characterized by impoundment of waters of infiltration over the sedimentary basin progressively expulsing and replacing sedimentary waters [1, 3].

Discrimination of elision cycles was largely based on the study of paleogeographic maps and lithofacies schemes, which provided the data on the predominantly marine regime of sedimentation. Infiltration cycles were determined from the data on the continental sedimentation regime existing in most of the study area, on the presence of hiatuses in sedimentation, inconformities, scours and basal layers of the overlying deposits [3]. Due to the inconsistencies between the boundaries of some cycles and those of large stratigraphic units (erathems, systems, divisions), their names were derived from their assignment to the generally accepted stages of the stratigraphic scale.

The restoration technique for the salt composition of waters from the ancient Mesozoic marine and lacustrine-alluvial basins is based on paleogeographic reconstructions and comparative-lithological analysis using natural-historical approach, which, in itself, is reduced to the fact that the formation of the ion-salt composition of waters in the continental and marine environments had common controls and are the product of identical processes occurring both in the past geological epochs and at the present time. The paleohydrological reconstructions were based on the method for restoration of salt composition of waters of ancient Mesozoic marine and lacustrine-alluvial basins; by studies of paleogeographic maps of the Jurassic periods compiled by the IPGG SB RAS researchers [4], hydrogeological databank available at the IPGG SB RAS Laboratory for Hydrogeology of sedimentary basins of Siberia for the Arctic regions of Western Siberia, resulted from testing more than 3000 objects of 211 target areas, including the results of full chemical analysis of 3205 groundwater samples (Fig. 1).

![Figure 1. Location map of the study area in Arctic regions of Western Siberia.](image)

Groundwaters of Upper Jurassic sediments are characterized by varied chemical composition with dominance of Na with Cl, Cl-HCO3 and HCO3-Cl water types whose TDS values vary in a wide range— from 5 to 63.3 g/dm3 [5-11]. With increasing salinity, the chemical type of water changes from sodium bicarbonate chloride to sodium chloride. The diversity of waters with respect to chemical composition tends to decrease, as their salinity increases. The seven types allocated in water salinities ranging from 2
to 5 g/dm³ are distributed among the following groups: 10-15 g/dm³ – five, at 20-25 g/dm³ – two, with TDS value more than 25 g/dm³ – only one (sodium chloride) type. The background salinity of the upper Jurassic aquifer complex in the studied region averages 19.9 g/dm³. The area comprising the Severny (Northern) and Nizhnevartovsk arches, East Pur megamonocline and South Nadym megamonocline is characterized distribution of groundwaters with salinities exceeding 25 g/dm³. The highest values of the zonal hydrogeochemical background are accounted for the Severny arch structures where TDS of the background formation waters reaches 33.5 g/dm³.

The periodization of hydrogeological history revealed three hydrological cycles in the Jurassic and Cretaceous: Induan-Sinemurian, Pliensbachian-Cenomanian, Turonian-Serravallian. However, in this study the Pliensbachian-Gotérov stage of the Pliensbach-Cenomanian cycle is considered, since the groundwaters of the Upper Jurassic sediments were selected as the object of study.

In the earliest Pliensbachian-Cenomanian hydrogeological cycle, the sea moved inland from the north-west and north-east. The marine basin was shallow (25 m) with desalinated water, while the Gydan and Yamal Peninsulas were represented by the shoal zone, where significant fluctuations of water salinity from 2 to 15 g/dm³ resulted from the unstable marine regime and river discharge [2, 4]. The largest transgression of the sea basin over the time spanning the Early and Middle Jurassic is assigned to the Toarcian. The marine sedimentation zone has significantly extended within the study area, causing the basin deepening to a depth of 100 meters in the central part, with water salinity probably reaching 15-20 g/dm³. The second half of the Toarcian – the beginning of Aalenian is characterized by short-term, but extensive regression of the boreal seas, which led to the shallowing and desalination of the West Siberian marine basin. The area of marine sedimentation (25-100 m) in the north-west has declined due to the expansion of the shallow (< 25 m) water zone. In the second half of Aalen, the climate gradually turned to cool and humid, causing vegetation to perish, along with the wide distribution of carbonaceous strata and the appearance of Arctic genera of ammonites and belemnites in the basin [4]. The beginning of Bajocian was marked by short-term sea-level rises leaving no significant impact on the position of the paleogeographic regions. Despite the fact that in the Bathonian, the subsidence of the Arctic regions of Western Siberia continued, the position of zones of marine sedimentation practically remained unchanged, however the periods of sea ingressation extended. In the north of the region, the extent of shoaling has increased due to the flooding of the low plain of accumulation rimming the basin boards. Callovian age is characterized by a continuation of the extensive marine transgression which resulted in further deepening of the marine basin occupying almost the entire area of the West Siberian geosyncline, except its southern margins. At the turn of the Callovian and Oxfordian, the transgression was succeeded by regression which reached its maximum in the middle of Oxfordian. Given that the basin was shoaling, thick sand layers began to accumulate in its central and southern parts, forming the known today Oxfordian regional reservoir. The northern areas were still dominated by the marine environments, providing for the formation of predominantly clayey sediments of the Golchikha Formation, rich in organic matter and containing abundant remains of diverse marine fauna. Since almost the entire study area was represented by a zone with depths between 25 and 200 m, salinity levels of the waters that experienced burial were, accordingly, close to 30 g/dm³. Given that the Jurassic transgression was the lengthiest event, the extent of the marine sedimentation have widened, and the depth in most of the area reached 200 m in the Late Oxfordian-Kimmeridgian time [6]. In the Volgian time (Tethonian-Early Berriasian) the dipping of the basin proceeded intensely, with the transgression reaching its maximum in the middle of the century. Climate in the Volgian was close to semiarid, causing thereby the dominance of chemical weathering conditions in the onshore areas and the accumulation of mainly clay and organogenic rocks on the continental shelf. In view of relief peneplanation, biogenic sedimentation was dominating, with clay sediments rich in organic matter, calcium, and silicon forming ubiquitously in the area (Bazhenov, Golchikha, Yanov Stan, Danilovka, Tutleima Formations) [4]. Thus, by the end of the Volgian time, a deep basin with signs of hydrogen sulfide exposure had formed in Arctic region of Western Siberia. Almost the entire study area was flooded by the sea with depths of 200-400 m, where water salinity reached 35 g/dm³. In addition, two deep depressions were distinguished within the borders
of the Kara and the Bolshaya Kheta megasynclises, where depths exceeded 400 meters, assumingly reaching 600 m where water salinity, hypothetically, could be 35 g/dm$^3$. The zone was surrounded by a narrow strip of shallower part of the basin (100-200 m), where marine sedimentation was complexed with the burial of saline thalassogenic waters featured by salinity 20-30 g/dm$^3$ and predominance of Cl$^-$ and Na$^+$ ions in the composition, and enhanced Mg$^{2+}$ ion concentrations. Delineation of the coastal zones has practically not changed: the coastal plain was almost entirely flooded by the sea and marked only by small narrow strip along the eastern board of the basin, while the alluvial plain existed only in the coastal part adjacent to the Taimyr upland. The basin coasts became flatter and peneplenized, representing by themselves elevated denudation land area. In addition, a series of peninsulas was discriminated along the eastern board. The burial of fresh atmogenic, slightly saline Ca HCO$_3$ waters with salinity not exceeding 1-2 g/dm$^3$ was taking place within the continental sedimentation zones.

The modern chemistry of groundwater sediments of the Upper Jurassic of the Arctic regions of Western Siberia is the product of a long geological evolution of the water-rock-gas-organic matter system. Let consider in more detail the change in the hydrogeochemistry of the syngenetic waters of the Oxford regional reservoir from the moment of burial to the present.

The formation of the modern appearance of the hydrogeochemical field of the Oxford regional reservoir of the northern and arctic regions of the West Siberian sedimentary basin was influenced by the processes: 1) compaction of sediments under the influence of geostatic load accompanied by wringing of physically-related waters; 2) thermo-dehydration of clay minerals of the main fluid blocks when entering them in the range of reservoir temperatures of 100°C or more and as a result of the appearance of lithogenic (chemically-bound, regenerated) waters of low mineralization in the hydrogeological section; 3) interfacial overflows from the Paleozoic basement deposits in the areas with no Triassic deposits; 4) transformations of organic matter of the main oil source formations and oil and gas formation; and 5) interactions in the water-rock system.

A comparative analysis of the buried syngenetic waters of the Oxford basin and data on modern hydrogeochemistry of groundwater revealed very significant differences (Fig. 2). Identified areas of positive and negative anomalies, primarily in terms of the total mineralization. Positive anomalies are characterized by an increase in the total mineralization of initially buried waters by 10 g/dm$^3$ or more, and negative anomalies by its decrease by 15 g/dm$^3$ and above. In the first case, the majority of anomalies are confined to the structures of the South Nadym (Izvestinskoe, Komsomolskoye, Vyngapurovskoye and other fields) and the Pre-Yenisei megamo-monocline (the Chernichnoe and Termokarstovoye fields). Negative anomalies naturally trace the clay boundary of the Oxford regional reservoir in the central regions of the Nadym-Tazovsky interfluve, expanding significantly to the north-east direction and capturing almost the entire territory of the adjacent areas of the Yenisei-Khatanga regional trough, and also cover the central regions of the Krasnoselkupsikaya and western Predisenyiyskaya megamonoclines.

The nature of the positive anomalies is associated with widely manifested processes of vertical unloading of groundwater of the Lower-Middle Jurassic and Paleozoic aquifer complexes in the zones of tectonic disturbances [5-11]. In particular, when comparing the waters of the Oxford and Bat reservoirs in the Gubkinsky field in the east of the South Nadym megamonocline, their significant similarity in terms of the total mineralization of water, but also in the content of microcomponents Br, I, B and naphthenic acids. The question of the possibility of vertical fluid flows in the West Siberian sedimentary basin was previously discussed and discussed in the works of A.E. Kontorovich, A.A. Rosin, N.M. Kruglikov, V.V. Nelyubin, O.N. Yakovlev and others [10]. The study of the distribution of chlorine-normalized concentrations of the main cations (sodium, calcium, magnesium and potassium) revealed a regular change of chemical types of groundwater from the most saline sodium chloride to bicarbonate-sodium chloride. In the same direction, there is a decrease in the degree of metamorphization of groundwater and their relationship to seawater.

Extensive areas of desalination of the reservoir under study (negative anomalies) are associated with a wide manifestation of the processes of thermal dehydration of clay minerals. As shown in [12-13], dehydration (squeezing of interlayer water) of clay minerals begins from depths of about 2 km, which
takes place in several stages. D.B. calculated the depths and temperatures of clay dehydration for more
than 2,000 US fields and found that the depth of dehydration varies between 1280 and 4850 m, while
temperatures vary between 83 and 111°C [14]. Such a wide interval of depths is primarily associated with
different heat flux values at the studied fields.

Considering the results of geothermal studies of the sedimentary cover of Western Siberia, obtained by
G.D. Ginsburg, A.D. Duchkov, Yu.G. Zimin, A.E. Kontorovich, V.A. Koshlyak, N.M. Kruglikov, A.R.
Kurchikov, B.F. Mavritsky, I.I. Nesterov, B.P. Stavitsky, E.E. Fotiadi, G.A. Cheremensky and others, and
the geothermal field models resulting from them, it can be assumed that within the studied region the
elision geostatic (lithostatic) system is from a depth of about 2–2.5 km, where abnormally high reservoir
pressure (AHP) begins to occur, acquires the features of thermal dehydration. Analysis of the strength of
the hydrodynamic field within the Oxford reservoir revealed the presence of pressures: from normal in the
east to elevated turning into abnormally high in the western and central regions of the Yamal-Kara
depression. Against the background of normal reservoir pressures, hydrodynamic anomalies with elevated
pressures have been established in the eastern region of the studied region within the Utyrmaly, Tekto-
Kharampursky and Ravniny fields, indicating vertical flow from deeper horizons. The presence of an extensive AHP zone in the central and western part of the Nadym-Taz interfluve (near the border of the ubiquitous Oxford regional reservoir according to [15]) is associated with the elision type of regime in this area. According to our research, here the elision geostatic (lithostatic) water pressure system acquires the features of thermal dehydration, since the reservoir temperatures exceed 100°C [5, 8 - 10].

The results of paleohydrogeochemical reconstructions shows that the composition of groundwater of the Upper Jurassic deposits of West Siberia was formed in basin with mainly sedimentary waters. A comparison was made of the composition of sedimentary waters with sea waters, which, as our studies showed, for the most part were the source of the first [16]. It is noted that the greatest degree of concentration is observed in the traditional range of microcomponents, such as iodine, boron, ammonium, which have a biogenic nature. In the macrocomponent composition the degree of concentration is different. In groundwater there is no accumulation of magnesium and sulfate ion. In our case, the sulfate ion is reduced to hydrogen sulfide, as noted above. A slight accumulation of magnesium in the solution occurs due to its binding in the secondary mineral compounds (authigenic aluminosilicates). A high degree of bicarbonate ion concentration was also detected. In the microcomponent composition, a high degree of concentration is characterized by ammonium (99-110 mg/dm$^3$) and iodine (89-387 mg/dm$^3$), medium - boron (3-10 mg/dm$^3$) and silica (6-17 mg/dm$^3$) and low - bromine (1-1.3 mg/dm$^3$) [9-10].

The chemical composition is primarily determined by the genetic type of groundwater, the duration and direction of the transformation processes of the host rocks [17]. The interaction in the water-rock system is diverse: on the one hand, water interacts with the terrigenous component of water-bearing rocks, and on the other, with clay. With primary aluminosilicates, water is nonequilibrium everywhere, which leads to their constant dissolution. As a result, the formation of secondary (authigenic) cement (clay or carbonate), which binds a part of chemical elements from a solution, takes place. The clay component of rocks with the development of the sedimentation basin is transformed in the direction of hydromucisation, chloritization, kaolinization, and gives part of the elements to the solution.

The third main source of enrichment with elements of groundwater is dispersed organic matter. As a result of its metamorphism, biogenic elements enter into water (iodine, boron, ammonium, phosphorus, etc.) and release into water-soluble, and then under favorable conditions, and free phase, significant volumes of methane, its homologues, nitrogen and carbon dioxide. [7-10, 18-20].

Summarizing, it should be noted that the prevailing factors in the formation of groundwater composition are genetic type of groundwater, interaction processes in the system “water-rock-gas-organic matter”, its equilibrium-nonequilibrium state.

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