Underground waters of salt-dome basins: a case study of the Caspian depression and its northern surroundings (Volga-Ural Anteclise and Pre-ural foredeep)

N G Myazina

Federal State Budgetary Educational Institution of Higher Education «Orenburg State University», Orenburg, Russia

E-mail: miazinanatalia@rambler.ru

Abstract. The area under study is located in the place where the Caspian Depression joins the Pre-Ural Foredeep and the Volga-Ural Anteclise and where the salt-dome and salt-gypsum tectonics is manifested. The development of salt-gypsum tectonics is a specific feature of the Pre-Ural Foredeep from the viewpoint of tectonics. The modern relief of the Caspian Depression was developed in the Quaternary Period. Its development was accompanied by repeated transgressions of the sea. There are many springs with potable water that are suitable for drinking in the northern part of the Caspian Depression and in the southern part of the Volga-Ural Anteclise and the Pre-Ural Foredeep. There are springs with mineral water and springs that can be used for balneotherapy. Springs with potable water of good quality with mineralization 0.3-0.7 g/dm are revealed in the zone of active water exchange. Sulphate-sulphate-chloride groups of mineral waters without “specific” components and properties with mineralization 1.7-2.7 g/dm are revealed in the zone of slow water exchange 1.7-2.7 g/dm. The class of sulphate-chloride waters is widely represented in the territory under study, there are mineral waters drained by springs with mineralization 1.9-4.9 g/dm. The springs are close analogues of Krainka, Kazanian, Kashin, Khilovo and Chartak types of mineral potable waters. Springs with chloride sodium waters of leaching zones that can be used for balneotherapy with mineralization from 14.5 to 192.3 g/dm are linked to salt dome structures. Elton salt-dome structure of the western Caspian Depression is rich in hydromineral resources - mineral springs, rivers, brine of the lake Elton with bromine and sulphurous waters.

1. Introduction

Our planet features not so many geological objects - bodies of sedimentary-hemogenic genesis, where unique salt dome tectonics is manifested. The Caspian Depression that smoothly passes into the Volga-Ural Anteclise with the Pre-Ural Foredeep of the Russian Platform is one of these regions [1, 2, 3]. In the Pre-Ural Foredeep, drilling of deep wells gives a general idea of the structure of the Kungurian sequence, the deposits of which undergo abrupt changes in the composition and powers. This is related both to the conditions of sedimentation in different parts of the basin and the intensive plastic relocations of salts and manifestations of gypsum tectonics. These processes result in the occurrence of “salt shelters” or “salt overhangs” and, respectively, repeated opening of the wells of Kungurian deposits under the covering of red sequences of the Upper Perm.
Total power of the Kungurian sequence in the western (and the most embedded) part of the Nikolsk-Krasnousolsk structural-geological zone of the Pre-Ural Foredeep is 2,000 m in the arcs of salt domes and reduces up to hundreds and, sometimes, dozens meters in inter-dome troughs.

As for tectonics, the development of salt anticlines with the manifested "salt-gypsum tectonics", which may conditionally be related to intermediate-type folding, is the specific feature of the Pre-Ural Foredeep. The development of various morphological and genetic types of folding within the specified zones enables to divide them into smaller structural units.

Anticlinal salt structures of the central zone of the trough are in most cases of diapir type complicated with disjunctive faults. Synclinal structures in the Mesozoic and Cenozoic layers, which are known in the geological literature as "disjunctive troughs" or "subsidence troughs", are often linked to the arcs of the Kungurian uplifts.

Disjunctive faults as well as plicative dislocations are widely spread within the area under consideration. They are the most frequent in the Pre-Ural Foredeep and most of them are related to salt tectonics.

In the Pre-Ural Foredeep, the past-salt Kungurian complex of rocks is intensively broken by fractured zones. All the bars and stocks are limited from all the sides by fractures. The amplitude of salt displacements throughout these zones, according to the data of seismic papers, varies from the hundreds of meters in the north-western cut-off part of the Pre-Ural Foredeep to 5,000 meters in the south at the right bank of the Ilek river. Sometimes, bars can be clearly seen; however, the fractured zones in these cases are not interrupted.

Together with zones, which surround bars and stock, there are fractures that break inter-stock structures into blocks. They are traced for dozens of kilometers; there is no clearly expressed system in the directions of these zones. They are various-directional, but close to meridian direction. It is impossible to see all these fractured zones through the Upper-Eocene-Middle-Quaternary structural strata. They are specified using geophysical data. In the platform part of the area under study, fractured zones are much rarer and are also related to salt tectonics. Finishing the consideration of structural forms of the western structural-geological zone, we should note that its general structural plan is developed under the influence of the Kungurian sulphate-halogen sequence. Salt and gypsum tectonics is clearly manifested here.

Within the strips of elevated bedding of the Kungurian roof revealed by electrical survey, in some points, outcrops of gypsum are mapped out. They are linked to the salt structure crests and are usually located in the edge parts of disjunctive troughs.

2. Materials and Methods
To study spring waters, the following methods have been used:

1) Analysis of fund and literary sources, chemical analyses.
2) To define the ionic composition of underground waters, the shortened chemical analysis has been conducted. The purpose of the analysis was to study water-bearing strata and to obtain the quality characteristics of the spring waters.
3) Systematization of natural waters by chemical compositions is based on Alekin-Posokhov classification. According to this classification, three types of waters have been identified (IIb – gypsum, IIIb–calcium chloride, IIIa-magnesium chloride). Waters are named according to the prevailing anions and cations. Ions that constitute 20% and more are considered prevailing if the sum of anions and cations is 100% separately [2, 3].
4) To describe the ion composition of natural waters, Kurlov formula has been used. This is a pseudofraction, where the numerator shows the percentage of anions in descending order, and the denominator shows the percentage of cations.

3. Results of Discussion
Pre-Ural Foredeep lies in the south-eastern Volga-Kama Artesian Basin. In the south, it borders with the Caspian Megabasin (within the Emba Artesian Basin), in the west - with Syrt Artesian Basin.
Here, water-bearing strata and sedimentary sheath complexes of the upper post-salt complex prevail from the alluvial Quaternary sediments to the Upper Permian sediments; they occur in the regional aquiclude of the Kungurian salts.

Relatively water-resistant Kungurian strata (P₁ k) locally come out to the day in the salt-dome structures and are vertically embedded in the stocks as deep as 1,000 m and more, in the salt anticlines of the Pre-Ural Foredeep, where the power is 350 m, and in gypsum fields. Water-bearing rocks are represented by gypsum, with interlayers of sandstone and anhydrite. The upper part of the complex consists of strongly weathered and fissured rocks; at the depth of 4.6-34.4 m, ground non-pressure water-bearing strata and pressure water-bearing strata occur, where the pressure height is 18.0 m. Salt deposits of the halogen sequence are almost free of water, except for water-bearing sandstones, with small discharges of water-intake springs 0.28-0.91 l/s. Brackish waters occur. Mineralization changes from 3 to 7 g/dm³. In underground waters of the complex, the analogues of Staraya Russa and Usolsk mineral waters occur that can be used for balneotherapy.

Water-bearing Asselian-Kungurian complex (P₁ a–k) is linked to the active fissility zone of the rocks of this age. Water-bearing reservoir rocks are represented by limestone, sandstone and mudstone. As for hydrodynamics, non-pressure waters in the upper part of the section become pressure waters as the depth increases. The power of the sediment complex is 850 m. Low-discharge and average-discharge springs and wells with 0.06-6.0 l/s discharge are sampled. Mineralization of waters increases as the depth increases and does not exceed 0.25-0.96g/dm³ in the upper part of the complex. Chemical composition of waters is mixed sulphate-hydrogene carbonate varying in kations sodium-calcium-magnesium, the spring water is limitedly used by local people for household purposes.

In the zone of active water exchange, where potable underground waters prevail and where the conditions in the strata are pressure-non-pressure, there are mineral waters of all classes near the daylight surface: hydrogenate carbonate, sulphate, sulphate-chloride (chloride-sulphate), chloride with mineralization from 0.5 to 192 g/dm³. All the explored pools of potable underground waters are linked to this part of the section.

The zone of slow water exchange is less studied. In this part, water-bearing strata are mostly stagnant, and hydrochemical situation does not allow using underground waters for water supply; however, they can be used for balneology.

There are many springs with potable water that are suitable for drinking in the northern Caspian Depression and in the southern Volga-Ural Anteclise and Pre-Ural Foredeep. Springs with mineral water that can be used for balneology are frequent. They are represented in table 1.

Potable waters are revealed in the spring located in the upper reaches of a gully located to the east of the village Shapovalovo, Akbulak district, Orenburg Region in the Caspian Depression. Waters with high drinking quality are revealed, the composition is sulphate-hydrogene carbonate sodium-calcium, with mineralization 0.4 g/ dm³, moderately hard with the total hardness of 3.39 mg-equiv./l, geochemical type IIa according to O. Alekin. Waters are drained from the water-bearing strata. They are linked to the zone of active water exchange within the water cycle.

The tests were performed in the laboratory of Volgograd hydrogeological expedition (for surveying and thematic works with my direct participation), and in the laboratory of Orenburg. The results of the chemical analyses of spring waters from the report provided by V. Petrischev, I. Yakovlev, D. Grudinin and titled "Assessment, passportization and development of measures to protect and rationally use spring waters of the Orenburg Oblast", 2009 were used.

Potable waters of optimal good quality with mineralization 400 mg/l, very soft, with total hardness of 1.4 mg-equiv./l, geochemical type I according to O. Alekin that comply with the WHO requirements are revealed in the Tatar deposits (P₂ t) in the Durneyevskiy spring at the southern edge.

Sulphate waters are formed locally in small areas, where water-bearing strata are represented by gypsified Upper Permian strata and Kungurian gypsum. Sulphate ions enrich the water-bearing strata of Artinskian and Kazanian sediments due to the desalinization of minerals and rocks. In the class of sulphate waters, the analogues of Krainka, Kazanian, Kashin type mineral potable waters of
balneological groups without "specific" components and properties are found in springs. Kazanian, Artinskian water-bearing strata with mineralization 1.7-2.7 g/dm$^3$ are drained by springs with sulphate-calcium and magnesium-calcium waters.

**Table 1. Hydrogeochemical characteristics of water bodies (springs, rivers, in areas with salt-dome tectons).**

(a)
| No | Name of water sources | pH unit weight | Br, B mg/dm$^3$ | I mg/dm$^3$ | $\text{H}_2\text{S}$ mg/dm$^3$ | Chemical composition formula | Water index by O. Alekin | GOST P 54316-2011 |
|----|-----------------------|---------------|----------------|-------------|----------------|----------------------------|------------------------|------------------------|
| 1  | Akbulak District, spring No. 29 in the upper reaches of the balka (gully) to the east of the village Shapovalovo, Caspian Depression | 7.2 1.0 | 0.8 | - | HCO$_3$, SO$_4$, Cl$_{15}$ | NaCa SC IIa Fresh potable water | |
| 2  | Spring Durneyevskiy (235) Sol-Ilets District, southern edge of the village Durneyevka P$_2$t | 7.2 1.0 | | | HCO$_3$, SO$_4$, Cl$_{19}$ | MgCa Na C I Fresh potable water | |
| 3  | Akbulak District, spring No. 55, village Shkunovka in the upper reaches of the balka (gully), the Ural Foredeep | 1.0 3.0 | - | - | Cl$_{48}$ HCO$_3$, SO$_4$, Cl$_{24}$ | Na SCCI Iib no analogue | |
| 4  | Sol-Ilets District, spring No. 5, Caspian Depression | 7.3 1.0 | 1.4 | - | Cl$_{49}$ SO$_4$, HCO$_3$, Cl$_{15}$ | MgCaNa SO$_4$, Cl Iib Khilovo type Na Cl IIIa Usolsk type | |
| 5  | Spring Tuzlukkol spring (14) 8 km to the south of the village Burlykskiy, elevation 182.8 m Pre-Ural Foredeep | 6.6 1.07 | - | - | Cl$_{195}$ SO$_4$ | Na Cl IIIa Usolsk type | |
| 6  | Spring Khomentovskiy (13) near the brook Tuzlukkol, elevation 179.5 m, Pre-Ural Foredeep | 6.2 1.2 | - | - | Cl$_{196}$ SO$_4$ | CaNa SO$_4$, Cl Iib no analog | |
| 7  | Spring the Second Tuzlukkol, (15) 8 km to the south-west of the village Burlykskiy, elevation 181.8 m, Pre-Ural Foredeep | 7.0 1.0 | - | - | Cl$_{175}$ SO$_4$, Cl$_{25}$ | CaNa SO$_4$, Cl Iib no analog | |
| 8  | Spring Bolshaya Smorogda, Elton salt-dome structure | 7.5 | - | - | Cl$_{160}$ SO$_4$, HCO$_3$ | S Cl Na Chartak type | |
| No | Name of water sources                        | pH unit weight | Br, B mg/dm$^3$ | I mg/dm$^3$ | H$_2$S mg/dm$^3$ | Chemical composition formula | Class of sulphate-chloride waters |
|----|---------------------------------------------|----------------|-----------------|--------------|-----------------|-------------------------------|----------------------------------|
| 9  | River Solyanka, Elton salt-dome structure   | 7.0            | 33.3            | 0.38         | 22.1            | Cl$^7$HCO$_3$ $\text{SO}_4$ $^1$ (Na+K)$^7$Mg$^{15}$Ca$^{10}$ | Na Cl IIIb Hydrogen sulfide, bromine Staraya Russia |
| 10 | Spring Soloniyi, Sol-Iletsk District, salt- dome structure of the mountain Boyevaya, Volga-Ural Anteclise at the contact with the Caspian Depression | 7.0 | 1.0 | - | - | CI$^9$SO$_4$ $^8$ (Na+K)$^{100}$ | (Na+K)100 |
| 11 | Spring 164, Tyulgan district, Pre-Ural Fored deep | 7.1            | 0.3             | -            | -               | SO$^9$HCO$_3$ $^9$Cl$^1$ Ca$^9$Mg$^{5}$(Na+K)$^4$ | S Na Krainka type |
| 12 | Spring Alekseyevsky (204), Buguruslan District, Volga-Ural Anteclise | 7.4            | 1.0             | -            | -               | SO$^8$9HCO$_3$ $^{10}$Cl$^1$ Ca$^6$8(Na+K)$^{17}$Mg$^{15}$ | S Ca Kashin type |
| 13 | Spring Kalikinskiy (212), Aleksandrovka District, 4.9 km to the north-east from the village Kalikino | 7.4            | 1.0             | -            | -               | SO$^9$0HCO$_3$ $^{8}$Cl$^{12}$ Ca$^7$1Mg$^{22}$(Na+K)$^7$ | S MgCa Kazanian type |

Class of sulphate-chloride waters is widely represented in the study area, there are mineral waters drained by springs with mineralization 1.9-4.9 g/dm$^3$. They are analogues of the Khilovo and Chartak group types without "specific" components and properties.

In the class of chloride waters, springs are revealed in the Kungurian water-bearing sulphate-halogen rocks with mineralization from 14.5 to 192.3 g /dm$^3$. In the section of underground hydrosphere of the region, most of underground waters are represented by the chloride class. They are the analogue of the Usolsk balneological type.

The Elton salt dome structure is rich in hydromineral resources - mineral springs, rivers, brine of the Lake Elton and sulphide muds [1, 4, 5, 11].

The area of the Elton salt-dome structure is rich in sources that can be used for balneology. Surface water of the river Solyanka that runs into the lake Elton is salty, sodium chloride, calcium chloride type (IIIb) with mineralization 22.2 g/dm$^3$. It contains bromine - 33 mg/l, hydrogen sulphide - 22.1 mg/l. The river is fed by the inflow of calcium chloride brine in fractured zones all round the broken Elton salt dome. In the warm season, surface waters of the river Solyanka may be used as balneological multicomponent bromine and hydrogen sulfide sources.

Past-salt layer of salt-dome territories is rich in various waters and classes with different mineralization.
In the northern Caspian Depression and in the southern Volga-Ural Antecline and Pre-Ural Foredeep of the ancient East European Platform, springs are drained by water-bearing strata, and many springs are suitable for drinking. However, there are also many springs with mineral water and springs that can be used for balneology.

Springs with fresh water are revealed in the active water exchange zone. They are used by local people.

Slow water exchange zone is formed by mineral waters of sulphate, sulphate chloride, chloride classes. Springs with sodium chloride waters of leaching zones and weak brines are linked to salt-dome structures.

4. Conclusions
The research conducted for the first time has enabled to make the following conclusions:

1) The chemical composition of natural sources in the springs of the Quaternary, Mesozoic, Upper Paleozoic and Kungurian age has been studied. The ion-salt structure varies, and the mineralization level lies in the wide range from fresh 0.4 to strong brines 192 g/dm³. In Mesozoic–Upper Paleozoic brines, when sediments are close to the daylight surface, sources are revealed on domes with leaching zone waters and brines of I, IIb, IIIa, IIlb geochemical and genetic types.

2) Fresh waters, mineral waters and chloride brines are systematized and typified based on the classification of O. Alekin, E. Posokhov and V. Sulin. Fresh waters for household and drinking purposes of good quality are revealed. The analogues of Kazanian and Kashin types of sulphate waters as well as Khilovo and Chartak types of sulphate-chloride waters are found. Weak and strong brines are revealed in natural sources. Two chemical types of sodium chloride brines are classified: leaching Cl-Na and weak Cl-Mg IIIa type according to E. Posokhov, V. Sulin.

3) Waters are typified for using as sources for balneology. The analogs of Usolsk and Staraya Russa types of mineral waters are revealed in the class of sodium chloride mineral waters. Weak brines with mineralization 79.2 g/dm³ and 192 g/dm³ can be used for curative balneotherapeutic baths (hydrogen chloride, bromine etc.)

4) Springs with low and moderate discharge (from 0.06 to 0.1 less often 5.0 l/s) are sampled. However, the water of many springs cannot be used commercially for drinking purposes. Fresh water from good quality springs can be used by local people for drinking.

Structured fresh water from springs can be very useful for society by improving the quality of life and increasing the period of human life.

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