Overpressure phenomena in the Precaspian Basin

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ABSTRACT: Overpressured zones in the Precaspian Basin occur at depths below 4000 m. The most extensive zone is in the subsalt reservoirs throughout the basin. In spite of the extended literature database on overpressure phenomena, the Precaspian Basin and its Palaeozoic rock sequence is of a special interest because of its long geological history. The delineation of overpressure generation in the completely compacted sediments is very important in order to exclude disequilibrium compaction as the most significant overpressure mechanism for the Tertiary basins. Seal effectiveness and pressure compartment longevity have mainly resulted from other processes: origin of secondary minerals, hydrocarbon saturation and bitumen incorporation in mudrocks. Solid bitumen precipitation in clays forms a more perfect seal than the capillary pressure. The Astrakhan gas field is the best example, where the compositional evolution of formation fluids has changed the clay permeability.

KEYWORDS: *overpressured reservoir, seal (geology), Precaspian Basin, Astrakhan Field*

INTRODUCTION

The existence of abnormal pressures is caused on the one hand by mechanisms for generating overpressure, and on the other by the effectiveness of the seal. Recent critical appraisals of the possible causes of overpressure were carried out by Martinsen (1997) and Osborne & Swarbrick (1997). The factors summarized in these reviews are of varying degrees of importance and depend on authors' experience of the different geological situations. All the experts generally agree that disequilibrium compaction and hydrocarbon generation are the principal causes of overpressure.

Overpressure phenomena have mainly been studied in Tertiary basins where overpressure generation is very active. Burial histories play a crucial role in determining the natural rock properties and the distribution of the overpressure zones. Osborne & Swarbrick (1997) noted that ovepressuring is more common in Tertiary sequences than in Palaeozoic successions, suggesting that the amount of overpressure might have diminished through time. Overpressure zones in the Neogene and Palaeogene sediments of the Tertiary basins can be located at depths of 1000–1500 m. In contrast, the depth of these zones in the Mesozoic and Palaeozoic strata are between 3500 and 4000 m. Analysis of only one type of basin is insufficient to demonstrate a full range of the processes that generate and preserve overpressure.

The ancient Precaspian Basin, with its hydrocarbon-bearing Palaeozoic rock sequence, is of special interest in assessing the role of the time factor in compaction. The generation of abnormal pressure occurs as a result of reduced pore-fluid volume. The period of geological time was sufficient for dissipation of the abnormal pressures. The existence of abnormal pressure and undercompacted zones under such conditions is possible in the presence of active neotectonic movements and reliable seals. Evaluation of the presence and nature of pressure transition zones in such geological situations is important. In ancient basins the thickness of a transition zone may be some metres (perfect seal), whereas in young basins a thickness of several hundred metres is not uncommon and the sealing mechanism is disequilibrium compaction.

OUTLINE OF ABNORMAL PRESSURE DISTRIBUTION

The Precaspian Basin contains a sedimentary column up to 20 km thick, comprising Palaeozoic subsalt formations, Permian salt and Mesozoic and Cenozoic suprasalt terrigeneous formations. The basin extends over more than 600 000 km^2 and can be subdivided into two zones: an outer zone with a normal rock sequence and an inner zone with salt diapirs (Fig.1). The overpressured zones of the basin are located mainly in the Palaeozoic subsalt formations, in the permeable zones of salt deposits and in the deepest Mesozoic rocks in the interdiapiric depressions. They have not been discovered in Mesozoic and Cenozoic rocks at depths less than 3500 m, in spite of the active salt diapirism.

The seals for the Palaeozoic reservoirs are salt and shales. Lower Permian evaporites consist of layers of halite interbedded with anhydrite, sylvinite and magnesium salts. The permeability of the salt rocks is low as expected, but some zones of the salt section contain free fluids, mainly brine lenses and inclusions, with overpressure gradients ranging from 1.3 to 1.7. The average volume of inclusions related to sample volume is 1–2%, but some samples show higher contents (to 10–20%) of fluids confined in the rocks. If the origin of brine lenses and inclusions is generally primary (during sedimentation), the oil and gas inclusions are generated by fluid intrusion from subsalt overpressured reservoirs. Dilation and fracturing of salt rocks during halokinesis creates the possibility of fluid intrusions via connected systems of micro-cracks. After confining, the pressure in these inclusions may be even higher than in the subsalt reservoirs and may be close to lithostatic.

Shale layers control the development and distribution of overpressure in two principal stratigraphic units of the subsalt formations: terrigeneous Devonian strata and Upper Devonian,

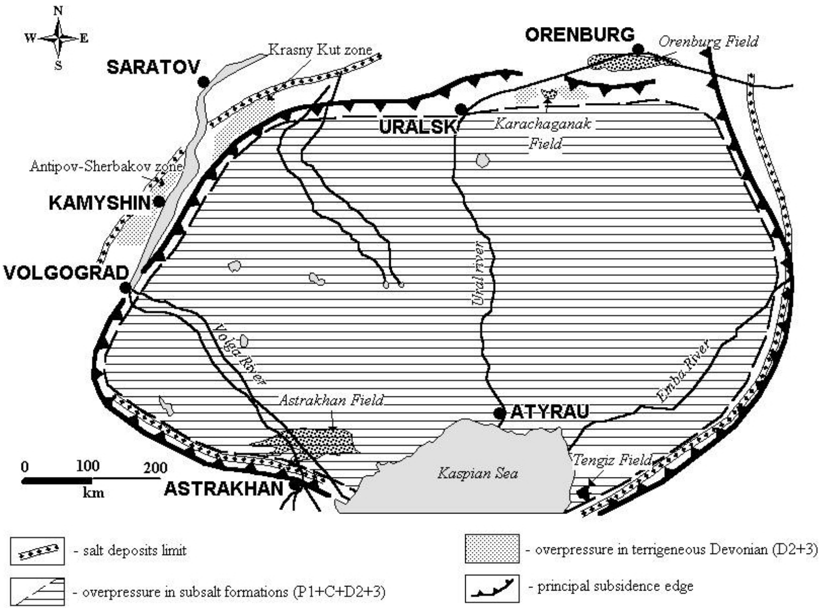

Fig. 1. Distribution of overpressured zones in the subsalt formations of the Precaspian Basin. Overpressured zones in the terrigeneous Devonian (D_{2+3}) are more extensive than in the overlying carbonate reservoirs (P_1+C+D_3).

Carboniferous and Lower Permian mainly carbonate formations. Overpressured zones in the first stratigraphic unit are located in the inner part of the basin and expand to the outer parts in the west and north of the basin (Fig.1).

Overpressured zones in the second unit are located mainly in the inner part of the basin. The Antipov–Scherbakov zone on the western flank of the Precaspian Basin is well studied and contains overpressured compartments in terrigeneous Devonian sediments and in the Sargavian transition horizon. The shale/carbonate section of the Sargavian unit is situated at a depth of about 4000 m. There are many small permeable zones in this unit with oil saturation. The high pressure zones are located along two lines with a zone of normal pressure between them (Fig. 2). Tectonics and vertical fluid transfer are the main factors causing overpressure in this unit. This has been proven by the correlation of the hydrodynamic anomalies with the principal fault zones and by the linear configuration of the abnormal pressure zones.

Sharp pressure transition zones are often present in mudrocks of the Precaspian Basin. In the Sargavian horizon the thickness of the transition zone is some metres: the top of this zone is marked by indurated and carbonate-rich shales with low drilling penetration rates. A sharp pressure transition zone is also present on the Tengiz–Karaton zone in the southeast of the Precaspian Basin (Fig. 3). Salt sediments are absent completely in some areas of this uplift (Karaton area, for example). Here the transition zone is represented by bituminous Permian shales with high levels of radioactivity. The same bituminous clay formation is present as a seal on the Astrakhan Arch, where formation pressure in the main carbonate reservoir is 62–63 MPa at a depth of 4000 m.

SEALS AND SEALING MECHANISMS

The primary requirement for the existence of abnormal formation pressure is a seal. Deming (1994) showed that the minimum permeability needed for a geological unit to act as a pressure seal for more than 1 million years is 10^{-6} to 10^{-8} mD. This range is lower than most measured values of shale permeability. Additional mechanisms are needed to form a perfect seal under natural conditions, especially in ancient rocks.

Our database shows that clay mineralogy does not cause significantly decreasing permeability in such narrow intervals (some dozen metres) and it is proposed that some additional processes occur in clays to create a perfect seal: secondary mineralization; hydrocarbon generation; and bitumen incorporation.

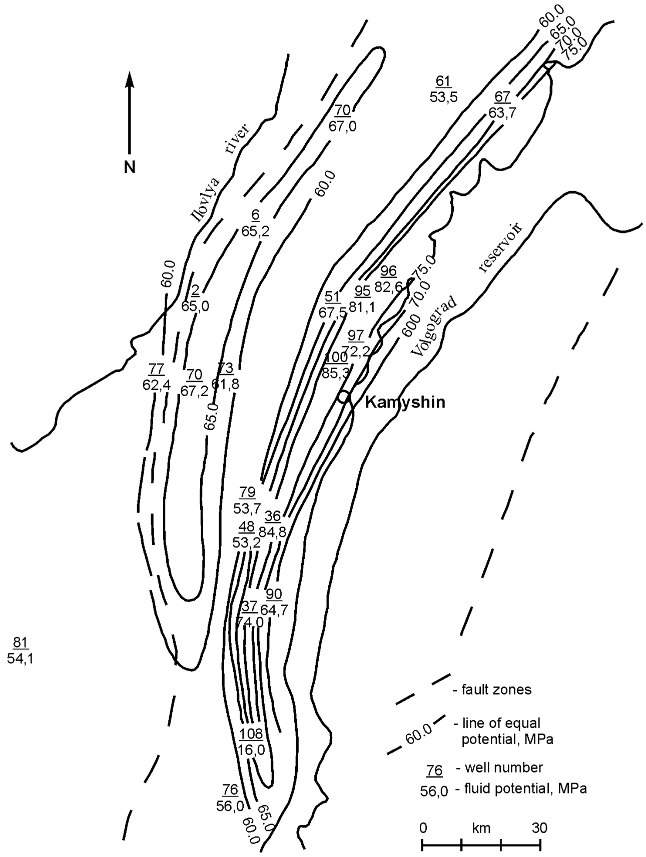

Fig. 2. Hydrodynamic map of the Sargaevian horizon (D_3). Two overpressured anomalies are correlated with fault zones orientated along the Volga valley.

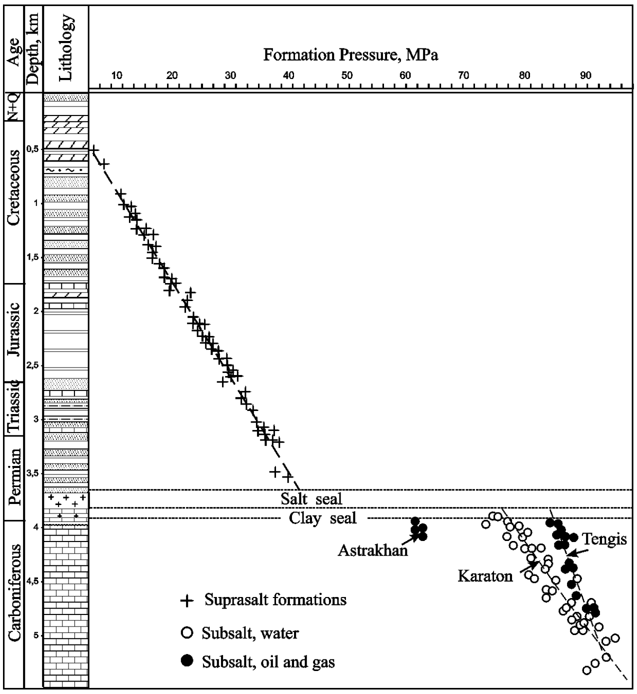

Fig. 3. Formation pressure vs depths and lithology-stratigraphic column in the southern part of the Precaspian Basin. Permian salt and shale are the principal seals to maintain the overpressure in Palaeozoic rocks.

Cores taken from seals overlying overpressured compartments in the Devonian sediments are calcite- and silica-cemented. These transition zones are characterized by a slow down in drilling penetration rate. This phenomenon is typical for transition zones in many basins (Martinsen 1997). Some sedimentological studies show the extensive dissolution of feldspars, with the reaction products being removed from the sandstones. Wilkinson *et al.* (1997) showed that this process could occur at great depth in locations sited close to regional overpressure leak-off points. Secondary porosity generation and the export of solute must be accompanied by silica precipitation in the transition zones.

Some studies carried out in the last few years have concluded that the principal cause of sealing is hydrocarbon generation and the difference in permeability for different fluids. Commonly, the expulsion process begins after oil saturation reaches 20–30% of the shale porosity. This saturation is sufficient for hydrocarbon migration. In a normal pressure zone there is hydrodynamic transmission through the clay; in an abnormal pressure zone there is no hydraulic transmission and the hydrocarbon movement is dominant. In the overpressure zone there is hydrocarbon transmissivity through only the small zone of the hydrocarbon pool, thus in a reservoir the area of water saturation is much greater than the area of hydrocarbon saturation. Under such conditions the pressure discharge depends on the area of the hydrocarbon pool, the thickness of the tranzition zone and the hydrocarbon reserves.

Two or three-phase saturation in the shale decreases its permeability and creates capillary pressure to improve the sealing capacity of mudrocks. However, in undercompacted clays the hydrocarbon generation and expulsion processes widen the interlayer space and improve permeability. Such seals cannot be perfect permanently, implying periodical vertical flow of pore fluid across the leaky seal.

Examination of the Sargavian (Devonian) and Lower Permian seals overlying the overpressured zones in the Precaspian Basin shows they have common features: a high solid bitumen content and a high level of radioactivity (Fig. 4). Such seals are postulated for many accumulations of sour gases (Anissimov & Potapov 1983). In-reservoir tar-mat processes have been discussed in the literature and oil deasphalting during oil and gas mixing is one of the probable mechanisms of asphaltene precipitation ((Wilhelms & Larter 1995). This mechanism may be realized in oil-saturated shales overlying productive reservoirs where reservoir filling by gas is the second stage of hydrocarbon accumulation. Gas migration through the shales (diffusional or gravitational) creates asphaltene aggregates either in pores and interlayer space or in fissures, forming a perfect seal.

DEWATERING AND HYDROCARBON GENERATION IN THE DEVONIAN SHALES

Clay dewatering is considered as mechanical compaction when porosity decreases from 40% to 2–3% down to a depth of

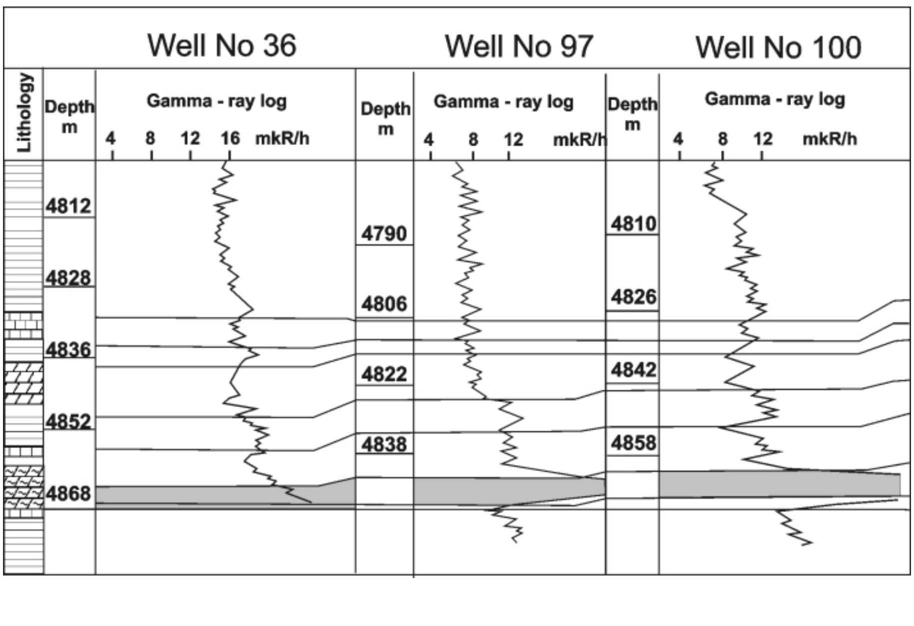

Fig. 4. Transition zone characteristics of the Sargaevian horizon. High content of solid bitumen and high level of radioactivity (dark colour) are the important features of the perfect seals.

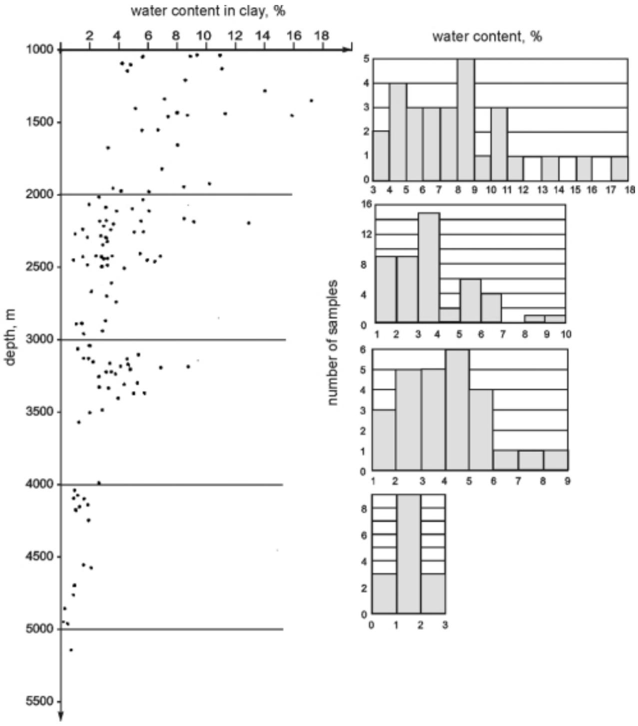

Fig. 5. Water content of the Devonian clays vs depth (Morozov 1981). The clay dehydration corresponds to formation water demineralization at depths >3000 m.

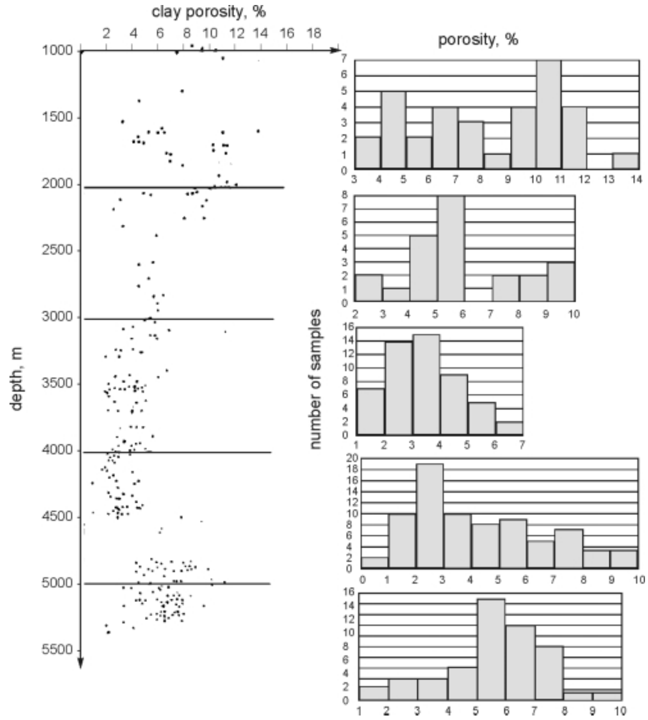

Fig. 6. Porosity of the Devonian clays vs depth (Morozov 1981). Increasing porosity at depths of 4500–5500 m corresponds to the position of overpressured reservoirs.

3000 m (normal trend for Palaeozoic shales of the Precaspian Basin). At the next burial stage, water and hydrocarbon generation from organic matter and mobilization of interlayer water increase the clay porosity. The alteration of smectite to illite is considered as the principal process of clay dewatering and it is concurrent with the hydrocarbon generation. Surdam et al. (1997) postulated that the depth of the principal stage of smectite–illite transformation in the Laramide Basins of Wyoming is at 2440–2845 m. This is the same depth at which significant increases in the displacement pressure and sealing capacity occur in the shale.

For shales of the Volgograd region the shale dehydration stage begins at a depth of 3000 m (Fig. 5). Released dehydration waters have low salinity compared to the reservoir waters and the process of water demineralization begins at depths greater than 3000 m (Anissimov 1995). High concentration of HCO_3, iodine and benzene is characteristic for low salinity formation waters relative to 'normal' salinity waters.

The principal undercompacted zones are situated at depths of more than 4000 m. Clay porosity distribution during burial in the Volgograd region is shown in Figure 6. The average porosity increases up to 6% in the interval 4500–5500 m, in comparison with values of 2–4% in the interval 3000–4500 m. These undercompacted zones correspond to the overpressured reservoirs and to the onset of the oil window. It proves that hydrocarbon impregnation is the most probable mechanism for the increase in fluid volume. This process can be caused either by hydrocarbon generation or by the fluids penetrating the seal of an underlying high-pressure zone.

The existence of a correlation between the quality of seals and hydrocarbon saturation is postulated by numerous authors. The different phenomena in the Devonian strata (the top of decreasing salinity at the depth of 3000 m and the top of the overpressured zone at the depth of 4000 m) suggest that hydrocarbon generation is the most important factor to change shale into reliable seal in the relatively narrow interval. Many samples with low salinity waters have been taken from the normal pressure zones of the terrigeneous Devonian strata at depths from 3500 m to 4000 m (Fig. 7).

CASE STUDY: THE ASTRAKHAN GAS FIELD

The Astrakhan Field is a good example where the hydrocarbon distribution in the subsalt reservoirs can show how the permeability of a seal has been changed during the history of the hydrocarbon accumulation. The data show that the two-phase saturation and capillary pressure are not sufficient to form a perfect seal which can hold overpressure for a long geological period. Additional sealing mechanisms are needed for isolating the Palaeozoic reservoirs.

The Astrakhan gas field is located in the southwestern part of the Precaspian Basin and is currently considered to be the largest sour gas field in the world. The content of H_2S in the gas varies from 16% to 31%. The subsalt carbonate reservoir consists of broad, thick packages of porous, shallow-water platform limestones deposited during the Middle Carboniferous. The hydrocarbons of the Astrakhan Field are structurally trapped in the dome part of the Astrakhan Arch. The field is approximately 110 km long by 40 km wide, with a reservoir thickness of 225 m. Seismic data indicate that the height of the Astrakhan Arch is more than 1000 m but the fluids fill only 15–20% of the volume of the trap. The gas–water contact in the west is at −4134 m subsea and in the east at −4073 m subsea. The principal source of the gas is located in the Sarpin rift zone, where the subsalt formations are below 8000 m. Gas flow from the northwest to the southeast may be one of the reasons why the gas–water contact in the west is deeper than in the east.

The seal of the principal gas accumulation is the Lower Permian bituminous shale, with a thickness up to 200 m. Above the Permian seal, two small oil accumulations have been discovered in the basal anhydrites of the Kungurian salt

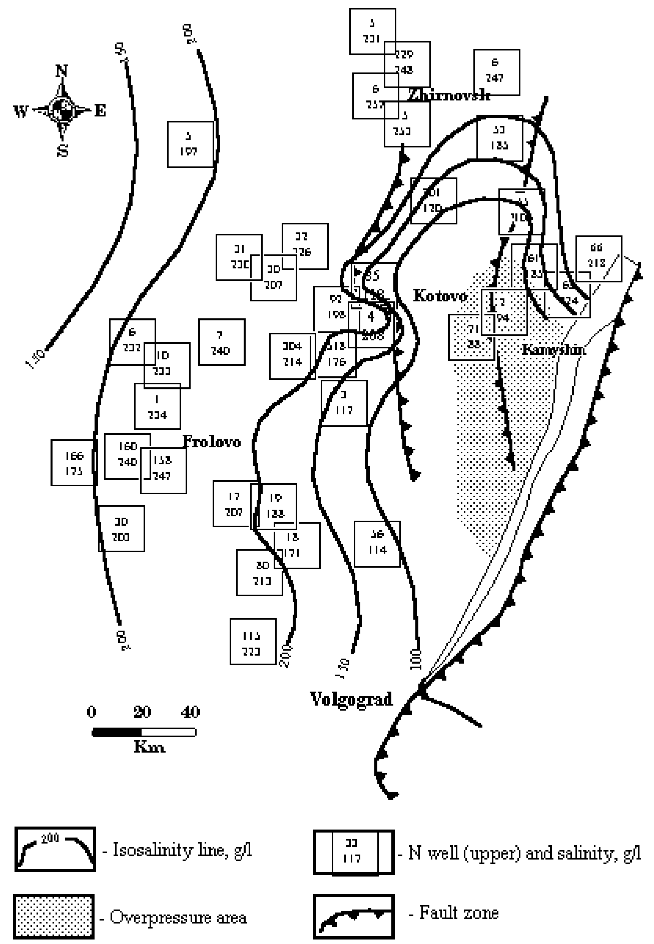

Fig. 7. Water salinity and overpressured reservoirs in the terrigeneous Devonian in the Volgograd Region. Area of low salinity waters is wider than the overpressured zone.

formation (Fig. 8). The first reservoir is 3–6 m thick and the second one is 14–20 m thick. Oil accumulations in these reservoirs are very limited and flow rates decrease rapidly. Oil indications are present in the Kungurian salts but there are no indications of the presence of H_2S, inspite of the fact that a lot of lenses with brine have been encountered during the penetration of salt rocks. Some very small oil accumulations (Beshkul, Raznochinovka, Kirikili) have been discovered in Mesozoic deposits in the upper part of the sedimentary section. In these oil accumulations the absence of direct and indirect indications of H_2S is remarkable. The principal sour gas reservoir is overpressured, with a formation pressure of 60 MPa at depths of 4000 m.

Oil, gas and solid bitumen distributions within the sedimentary section provide the most important data on the history of hydrocarbon accumulation. Sakhibgareev & Kuryshev (1990) carried out a detailed investigation of solid bitumen and oil patches in the productive gas reservoir and concluded that there had previously been a great oil accumulation in the Astrakhan carbonate reservoir. This oil accumulation had an oil–water contact 37–40 m below the modern gas–water contact. Based on the bitumen distribution in the productive gas reservoir, from 8 to 10 palaeo-oil-water contacts formed during the destruction of this huge oil accumulation (Fig. 9). The destruction of the oil accumulation was, according to Sakhibgareev & Kuryshev (1990), caused by the combined effects of tectonic activity and poor seal quality.

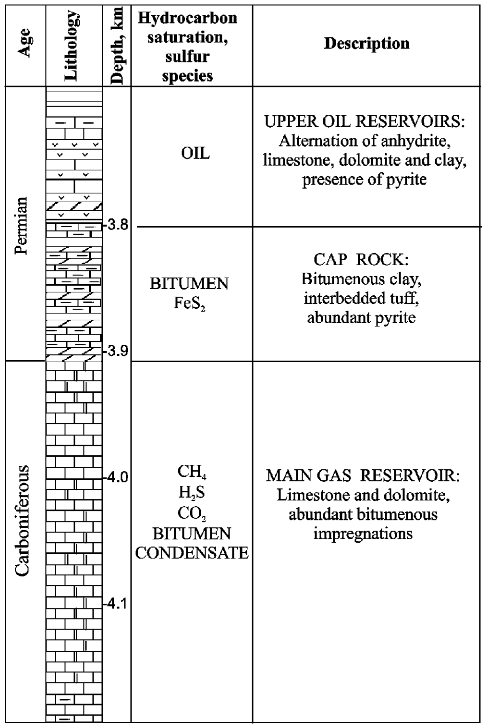

Fig. 8. Stratigraphic column, hydrocarbon saturation and secondary mineralization of the subsalt reservoirs and seals of the Astrakhan Field.

The weakness of this model is the absence of essential oil accumulation in the shallow suprasalt formations in the Astrakhan zone. Some very small oil accumulations have been discovered in Mesozoic deposits but their cumulative reserves are less than 1 million tons. It is difficult to imagine that some billion tons of oil could disappear in the 2000 m thick Mesozoic terrigeneous formations. A modification of this model is presented here (Fig.10).

- In the first stage, a relatively small oil accumulation formed in the Middle Carboniferous (C_2) subsalt reservoir and some oil migrated through the Lower Permian seal to the basal anhydrite of Kungurian salt and post-salt sediments. As a result, pores and fissures in the Permian shales became saturated with oil; some small oil accumulations formed in the basal anhydrite and oil inclusions traced the migration pathways in salt.
- In the second stage, sour gas invasion in the main subsalt reservoir formed the gas accumulation and an oil rim, which descended concurrently with reservoir filling by gas. Light hydrocarbons of oil were transformed into condensate. Heavy components of oil and bitumen were smeared in the reservoir. Pulsed invasions of gas were marked by the relatively continuous periods of the constant oil–water contacts with abundant bitumen precipitation. Vertical gas migration through the Permian oil-saturated shale led to bitumen precipitation in the pores, fissures and interlayer spaces, forming a perfect seal.
- In the third stage, sour gas filled the trap, oil was divided into condensate and solid bitumen. Isolated oil accumulations in the basal anhydrite above the main reservoir existed since the first stage.

This model can explain the principal features of gas, oil and bitumen distribution in the subsalt rock sequence of the Astrakhan Field. These data suggest that the holding capacity of

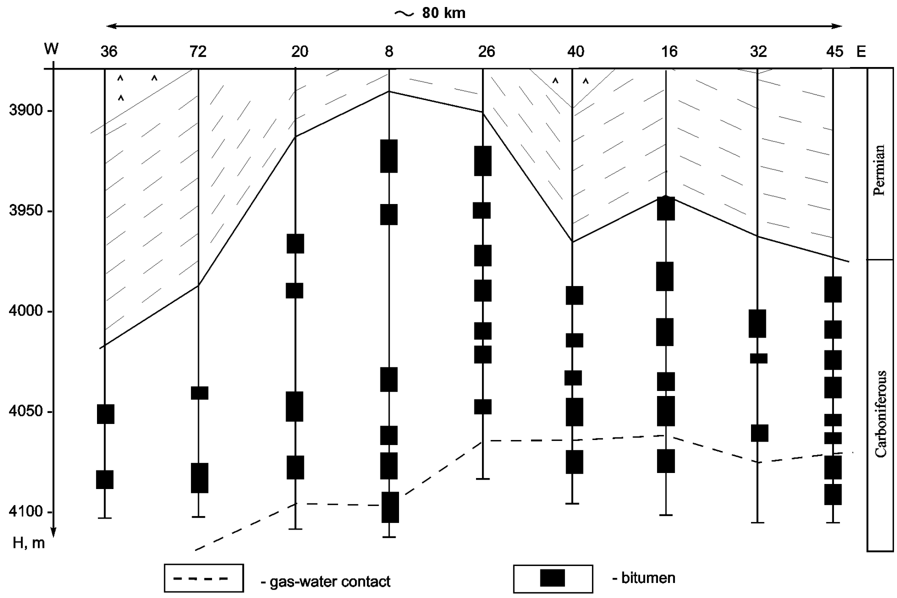

Fig. 9. Simplified cross-section of the Astrakhan reservoir and position of the main solid bitumen impregnations (Sakhibgareev & Kuryshev 1990).

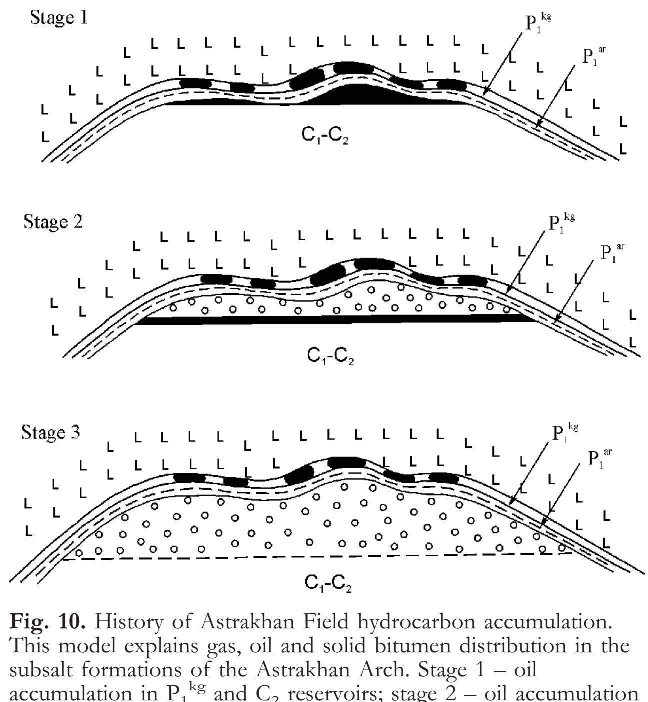

Fig. 10. History of Astrakhan Field hydrocarbon accumulation. This model explains gas, oil and solid bitumen distribution in the subsalt formations of the Astrakhan Arch. Stage 1 – oil accumulation in P_1^{kg} and C_2 reservoirs; stage 2 – oil accumulation in P_1^{kg} and oil–gas accumulation in C_1–C_2 reservoir; stage 3 – oil accumulation in P_1^{kg} reservoir and gas accumulation in C_1–C_2 reservoir.

a seal for gas may be changed by incorporation of bitumen in shale. Sour gas entered in the oil-saturated shale played an active role to form the most perfect seal for the great gas accumulation.

CONCLUSION

The oil window stage in the Precaspian Basin is marked by the appearance of an abnormal pressure zone with increasing clay porosity, formation water demineralization, secondary calcite and silica minerals and solid bitumen generation. These processes are realized in the completely compacted shale zones. It seems that two-phase shale saturation and capillary pressure are insufficient to hold overpressure over a long time period. Forming perfect seals is the most important factor in creating overpressure zones in ancient rocks and it can be connected with two-stage fluid generation or two-stage fluid migration through the seal. Two-stage hydrocarbon saturation within the seal (oil and, later, gas) accompanied by deasphalting and bitumen precipitation in shales is the most probable process involved in forming a perfect seal in the Precaspian Basin.

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