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Distribution and Genesis of Permian Overpressure in the Eastern Fukang Sag, Junggar Basin

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Abstract

Overpressure is widely distributed in the Permian strata of the eastern Central Depression in the Junggar Basin and is closely related to hydrocarbon reservoirs. However, its genesis, evolution process, and controlling effects on reservoir formation remain unclear. Using comprehensive mudstone compaction curves and vertical effective stress-density crossplots, the formation mechanisms of abnormal high pressure in the Permian strata of the study area were analyzed. On this basis, the basin modeling method was applied to reconstruct the overpressure evolution for different lithologies in the Permian strata, summarize its planar distribution patterns, analyze the impact of overpressure on hydrocarbon reservoirs within the area, and further summarize the hydrocarbon accumulation models under the control of Permian overpressure in the study area. The results indicate: (1) The Permian strata in the study area develop weak to strong overpressure, with significant differences in the magnitude of overpressure developed in different structural locations. The overpressure is strongest in the sag area, followed by the slope zone, and relatively weak in the uplift area. (2) The genesis of overpressure varies significantly among different lithologies. The overpressure in the source rocks of the Lucaogou Formation is attributed to hydrocarbon generation and undercompaction; the overpressure in the reservoir of the Upper Wuerhe Formation is attributed to overpressure transfer and undercompaction; the overpressure in the mudstone caprock of the Upper Wuerhe Formation is attributed to undercompaction.

Keywords

Junggar Basin; Fukang Sag; Permian; Overpressure Genesis.

1. Introduction

Overpressure (abnormally high pore fluid pressure) is a common phenomenon in petroliferous basins[1]. The formation and evolution of overpressure not only significantly impact hydrocarbon accumulation[2] but are also closely related to drilling and production engineering[3]. Globally, 180 sedimentary basins are known to develop overpressure[4]. Since its first discovery in 1878, scholars both domestically and internationally have gradually begun to emphasize the influence of abnormal fluid pressure on hydrocarbon accumulation during petroleum exploration. Nearly a century of exploration and research has revealed that formation overpressure is closely related to the generation, evolution, migration, and accumulation of hydrocarbons, affecting to some extent the essential elements of hydrocarbon accumulation (source rock, reservoir, caprock, and overburden) and the accumulation process (generation, expulsion, migration, and accumulation of hydrocarbons); it also plays an important role in accumulation dynamics, controlling the distribution of hydrocarbons to a certain extent[5].

Research on overpressure-controlled reservoir formation is one of the forefront topics in petroleum geology. Studying overpressure-controlled reservoir formation can reveal how overpressure influences the migration pathways, velocity, and accumulation modes of hydrocarbons, clarify the development of overpressure in different strata and regions, accurately predict the distribution and enrichment patterns of hydrocarbon resources, improve the success rate of hydrocarbon exploration, provide a more solid theoretical basis for hydrocarbon exploration and development, and is of great significance for advancing petroleum geology. Therefore, this paper will conduct an in-depth analysis of the genesis of overpressure in the Junggar Basin and its relationship with the formation and distribution of hydrocarbon reservoirs, laying the foundation for establishing hydrocarbon accumulation models.

2. Geological Setting of the Study Area

The Junggar Basin is a multi-stage superimposed basin rich in hydrocarbon resources in northwestern China. It is surrounded on three sides by Paleozoic sutures and fold belts: to the west by the NE-trending West Junggar Fold-Thrust Belt, including the Zayier Mountains, Hala'ate Mountains, and Delun Mountains, which represent the suture zone formed by the collision and amalgamation of the Junggar Block with the Tacheng and Balkhash blocks; to the northeast by the Kalamaili Suture Zone and the East Junggar Block, including the SW-trending Qinggelidi Mountain and Kalamaili Mountain; to the north by the North Tianshan Fold-Thrust Belt, which is the fold suture zone between the Junggar Block and the Tarim Plate, including the Yilinheibiergen Mountains and Bogda Mountains[6] (Figure 1). The interior of the basin consists of six first-order structural units: the Southern Junggar Thrust Belt, the Central Depression Belt, the Luliang Uplift Belt, the Wulungu Depression Belt, the Eastern Uplift Belt, and the Western Uplift Belt[7][8].

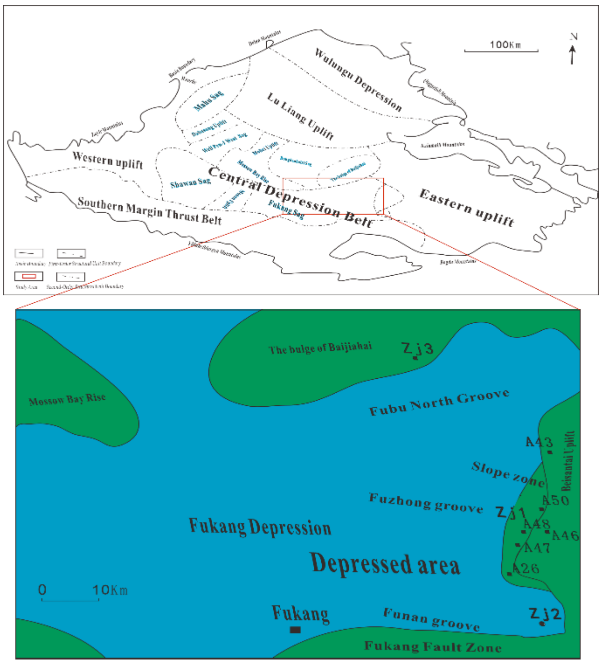

Figure 1. Tectonic Location of the Fukang Sag, Junggar Basin

The first-order structural unit, the Central Depression Belt of the Junggar Basin, is located in the central part of the basin, widely distributed, with a total area of approximately 38,200 km^2. Its structure is relatively stable compared to other structural units in the Junggar Basin. The northern part of the Central Depression Belt adjoins the Luliang Uplift, and the southern part is adjacent to the North Tianshan Thrust Belt. It features alternating uplifts and sags from west to east, including five sheet-like sags and five band-like uplifts. The five sheet-like sags are the Mahu Sag, Shawan Sag, Well Pen-1 West Sag, Dongdaohaizi Sag, and Fukang Sag. The five band-like uplifts are the Dabasong Uplift, Mobei Uplift, Mosuowan Uplift, Monan Uplift, and Baijiahai Uplift. The Central Depression Belt contains the most important hydrocarbon-generating sags in the basin. Currently, most of the hydrocarbons discovered in the Eastern Uplift Belt, Western Uplift Belt, and Luliang Uplift Belt are sourced from the source rocks within the Central Depression Belt, including multiple sets of source rocks from the Jurassic, Permian, and Carboniferous. The hydrocarbon reservoirs identified in the early exploration stages are mostly distributed around the Central Depression Belt[9].

The Fukang Sag is located in the southeastern part of the Central Depression Belt of the Junggar Basin and is one of the important hydrocarbon-generating sags in the basin, with an exploration area of approximately 9,000 km^2. It is bounded by the Monan Uplift to the west, the Beisantai Uplift and Xiquan Nose to the east, the Baijiahai Uplift and Dongdaohaizi Sag to the north, and the Huomatu Anticline and Fukang Fault Zone to the south[10]. From north to south, the Fukang Sag develops three trough areas: North Fukang, Central Fukang, and South Fukang (Figure 1). The north and south flanks of the Xiquan Nose develop the South Fukang and Central Fukang troughs, respectively. The South Fukang Trough on the south flank has a gentler slope, while the Central Fukang Trough on the north flank has a steeper slope[11].

3. Characteristics of Formation Pressure in the Study Area

This study selected drilling fluid density data and measured formation pressure data from 10 wells penetrating the target layers in the eastern Fukang Sag of the Junggar Basin. Due to the scarcity of measured pressure points in the target layers of the study area, which only include 4 measured points from two wells (A47 and ZJ1) in the Central Fukang Trough area, and since most wells in the study area have drilling fluid density data, although drilling fluid density is generally greater than the corresponding measured formation pressure, it can, to some extent, reflect the distribution characteristics of formation pressure. Considering these conditions, this study also utilized the variation trend of drilling fluid density to reflect the characteristics of formation pressure variation.

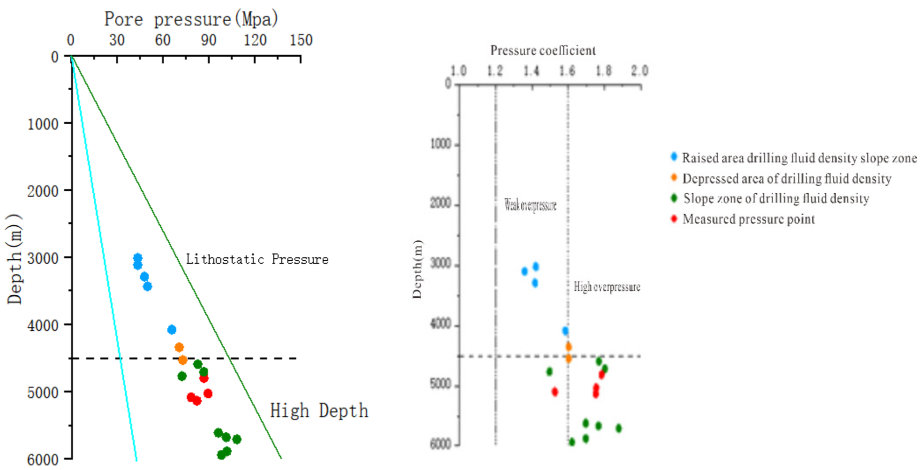

Figure 2. Relationship between Pressure Coefficient, Formation Pressure, and Burial Depth in the Fukang Sag, Junggar Basin

The Permian strata in the eastern Fukang Sag are buried at depths of 3000-6000m, with formation pressure coefficients ranging from 1.3 to 1.9 and excess pressure distributed between 12-49 MPa. Based on the classification method of Li Wei et al.[12], the relationship between pressure coefficient, formation pressure, and burial depth in the eastern Fukang Sag was plotted, showing that the study area develops weak to strong overpressure (Figure 2). The Permian formation pressure coefficient in the uplift area ranges from 1.36 to 1.59, with an excess pressure of 12-23 MPa; in the slope zone, it ranges from 1.52 to 1.79, with an excess pressure of 24-37 MPa; in the sag area, it ranges from 1.5 to 1.88, with an excess pressure of 23-49 MPa. Based on the above, it can be concluded that the Permian overpressure in different structural parts of the eastern Fukang Sag, Junggar Basin, varies significantly. The overpressure developed in the Permian of the sag area is the strongest, followed by the slope zone, and is relatively weak in the uplift area (Figure 3). The characteristics of Permian overpressure development in the study area are that the overpressure developed in the eastern uplift is relatively lower than that within the western Fukang Sag, showing a characteristic of "low in the east, high in the west".

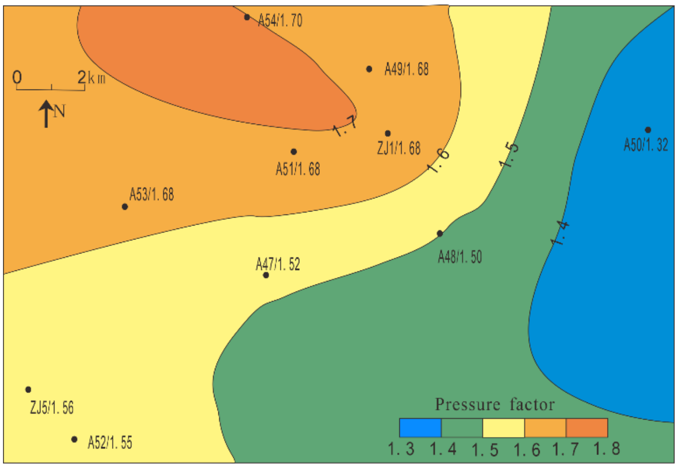

Figure 3. Distribution of Pressure Coefficient in the Upper Wuerhe Formation, Eastern Fukang Sag, Junggar Basin

4. Methods for Discriminating Overpressure Genesis

The formation and distribution of formation overpressure are controlled by multiple factors. Scholars generally believe that the genesis of overpressure mainly includes five types: disequilibrium compaction (undercompaction), fluid expansion, diagenesis, tectonic compression, and pressure transfer. Among them, fluid expansion includes hydrocarbon generation expansion and aquathermal expansion[13]. Zhao Jingzhou[13] et al. believe that in deeply buried medium-to-high temperature environments (>70°C), the main causes of overpressure are non-undercompaction factors such as hydrocarbon generation expansion and diagenesis.

4.1. Disequilibrium Compaction

Disequilibrium Compaction (Undercompaction): During the burial process of sedimentary rocks, as the burial depth increases, the loading from overlying sediments causes a gradual increase in vertical stress, making clastic particles more compact and reducing the pore volume between clastic particles, thereby expelling pore fluids. If the burial rate of the sediment is slow, and the volume of fluid expelled from the pores equals the volume of pore reduction between clastic particles with increasing burial depth, the pore fluid pressure is in a normal pressure state[14]. If the sediment undergoes rapid subsidence after deposition, during rapid burial, the pore volume between clastic particles decreases rapidly while the expulsion of pore fluid from the sediment is slow. The volume of pore reduction exceeds the volume of pore fluid expulsion, causing the pore fluid to bear part of the load stress from the pore reduction, resulting in an increase in pore fluid pressure. This compaction state is called disequilibrium

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compaction[13][15]. Disequilibrium compaction-induced overpressure primarily forms in Cenozoic sedimentary basins characterized by rapid burial and thick mudstone development[13].

4.2. Fluid Expansion

4.2.1. Hydrocarbon Generation Expansion

The prerequisite for overpressure formation by hydrocarbon generation is the development of thick mudstones in the sedimentary basin, where the mudstone acts as source rock containing abundant organic matter, and the organic matter has entered the main stage of oil and gas generation upon thermal maturation. When kerogen matures, it generates oil and gas (including formation water). In this process, high-density organic matter is converted into low-density hydrocarbons. The pores created by the consumption of organic matter are smaller than the volume of hydrocarbons generated, causing relative expansion of the pore fluid volume and forming overpressure. Harwood's research found that the volume expansion generated during kerogen hydrocarbon generation can reach 25%. Additionally, hydrocarbons generated from organic matter can transform the single-phase flow of formation water into multi-phase flow, thereby reducing the relative permeability of water in the mudstone, leading to a decrease in the expulsion rate of pore water, which favors the formation of overpressure.

4.2.2. Aquathermal Expansion

The basic principle of aquathermal expansion is that as the formation temperature increases, the volume of fluid in the formation pores expands. Although the pore volume of rock grains also increases with temperature, the expansion rate of the pore fluid volume is significantly greater than that of the rock grain pore volume. If the formation is well sealed, the expanded portion of the pore fluid volume cannot be expelled from the formation, leading to an increase in pore fluid pressure and the formation of abnormally high pore fluid pressure. The formation of overpressure by aquathermal expansion requires the following conditions: 1) an abnormally high formation temperature; 2) sealing conditions[16]. The scale of overpressure formed by the thermal expansion of formation water is influenced by the properties of the formation fluid; generally, the expansion amplitude of hydrocarbon fluids due to heating is significantly stronger than that of ordinary formation water. Furthermore, due to differences in the sealing capacity of different lithologies, the magnitude of overpressure generated by aquathermal expansion also varies. Evaporites, having better sealing conditions, can develop significant overpressure under the influence of abnormally high formation temperatures if they contain certain pores.

4.3. Diagenesis

Diagenesis mainly includes: the release of interlayer water from montmorillonite and the transformation of montmorillonite to illite[17]-[18]. Early sediments often contain clay minerals like montmorillonite with abundant interlayer water in their crystal structure. As burial depth and formation temperature increase, clay minerals undergo changes, and chemical reactions occur between different clay minerals. During burial, interlayer water within the crystal structure of clay minerals is released into the formation pores. This released interlayer water has a lower density, causing the pore fluid volume to expand and form overpressure. Osborne and Swarbrick's research suggests that the scale and magnitude of overpressure formed during different stages of clay mineral evolution vary. The percentage increase in pore fluid volume due to clay mineral dehydration is about 4%. In the early diagenetic stage, clay mineral dehydration is relatively concentrated, but at this time, due to the low degree of sediment compaction and strong compaction-driven dewatering, the effect of clay mineral dehydration on overpressure formation can be neglected. In the late diagenetic stage, the scale

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of overpressure formed by clay mineral dehydration is about 0.05-0.1 Pa, having a relatively small impact on overpressure generation.

The depth range of clay mineral dehydration varies in different basins. Pearson and Small calculated in 1988 that the depth range for clay mineral dehydration in the Gulf of Mexico shelf area is 2.0-3.8 km, and the depth for montmorillonite-to-illite transformation dehydration in the North Sea area is about 2.5-4.0 km. The magnitude of overpressure formed by clay mineral dehydration differs significantly at different depth intervals[19]. Simultaneously, due to ongoing debates regarding the transformation mechanisms of clay minerals with increasing temperature, the magnitude of pore fluid volume increase varies under different transformation mechanisms, leading to differences in the magnitude of overpressure formed. In 1997, Osborne and Swarbrick calculated the changes in formation pore fluid volume during 10 major clay mineral transformation mechanisms. Combined with different simulation experiments, they concluded that if the original montmorillonite content in the sediment is 20%, under a geothermal gradient of 35°C/km, the percentage increase in pore fluid volume is about 0.2%. However, when the geothermal gradient increases to 40°C/km, the percentage increase in pore fluid volume can reach 1.82%. Therefore, overpressure formation from clay mineral transformation is also influenced by the heating rate.

4.4. Tectonic Compression

Tectonic compression can generate significant overpressure[20][23]. There are two main viewpoints regarding the mechanism of overpressure generation by tectonic compression: 1) Tectonic compression causes rapid uplift or even erosion of the formation, reducing the overburden load pressure on the uplifted sealed formation and decreasing the effective stress between clastic particles. However, since the formation fluid pressure within the closed system remains unchanged, the pressure coefficient increases, forming overpressure. 2) Tectonic compression causes changes in the stress field. Clastic particles in the formation are compressed, leading to a reduction in pore volume between particles. If the pore fluid cannot be expelled, the pore fluid pressure increases. Although the mechanism for overpressure generation by tectonic compression is debated, examples of overpressure formed by tectonic compression are relatively common[24]. The formation of overpressure by tectonic compression is based on two prerequisites: 1) The compressed rock layer must contain a large amount of fluid; 2) During compression, the fluid environment must be closed or semi-closed, meaning the fluid cannot flow out freely.

4.5. Pressure Transfer

Pressure transfer includes lateral transfer and vertical transfer[25][26]. Tingay et al.[27], using effective stress-acoustic velocity and density-acoustic velocity crossplots, determined that the widespread overpressure in the inner shelf deltaic sequence of the Baram Basin, Brunei, was of fluid expansion origin. Then, based on analyses such as the lack of good source rocks in the deltaic sequence, the irrelevance of overpressure formation to smectite-illite transformation, and the good correspondence between the distribution of fluid expansion/transfer overpressure and the outer boundaries of Pliocene inversion structures, they concluded that the overpressure in the inner shelf delta system resulted from the transfer of overpressure from prodelta shales through faults.

Reports on pressure transfer in China are found in the Yinggehai Basin in the east, and the southern Junggar, Kuqa, Qaidam basins or areas in the west.

Currently, the main qualitative discrimination methods for overpressure genesis include well log combination analysis, Bowers' method, acoustic velocity-rock density crossplot method, porosity comparison method, pressure calculation back-analysis method, and comprehensive overpressure genesis analysis[13]. The genetic mechanisms of overpressure vary in sedimentary basins of different ages, and the relationship between overpressure of different origins and hydrocarbon accumulation differs, as do the pressure prediction methods.

5. Identification of Permian Overpressure Genesis in the Eastern Fukang Sag

This study primarily utilizes measured formation pressure data from Well A47 and Well ZJ1 in the slope zone of the Central Fukang Trough to identify the genesis of Permian overpressure in the eastern Fukang Sag. The comprehensive mudstone compaction curve of Well A47 shows that at a depth of about 4000m, the acoustic interval transit time, density, and resistivity begin to reverse, deviating from the normal compaction trend. The drilling fluid density increases from 1.2 g/cm^3 to 1.6 g/cm^3. The measured formation pressure at a depth of 5094m is 76.78 MPa, with a pressure coefficient of 1.51. Comprehensively, it is identified that overpressure develops in the bottom of the Karamay Formation (T_2k) and the underlying strata in this well. The Permian sedimentary thickness in Well A47 is 480m, with a mudstone-to-strata ratio of 43.4%. Furthermore, the density porosity and acoustic porosity of the mudstones below the overpressure top surface are higher than those in the normally compacted section, exhibiting characteristics of abnormal high porosity indicative of undercompaction (Figure 4). The undercompacted overpressure mudstone points from the Upper Wuerhe Formation deviate from the normal compaction trend line on the acoustic velocity-density crossplot (Figure 5a), indicating that the overpressure in the Upper Wuerhe Formation mudstone section is due to both undercompaction and fluid expansion. The measured pressure points in the reservoir adjacent to mudstones project onto the unloading curve position on the density-vertical effective stress crossplot, with a significant decrease in vertical effective stress (Figure 5b), showing that besides undercompaction, overpressure transfer is also an important cause of overpressure in the Upper Wuerhe Formation reservoir.

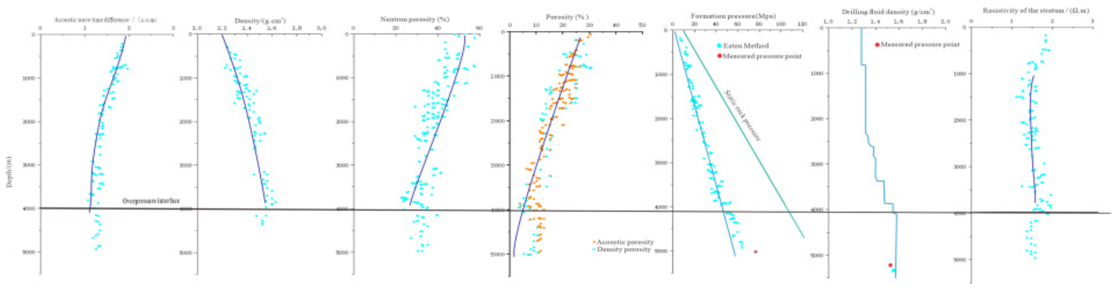

Figure 4. Comprehensive Mudstone Compaction Curve of Well A47, Fukang Sag

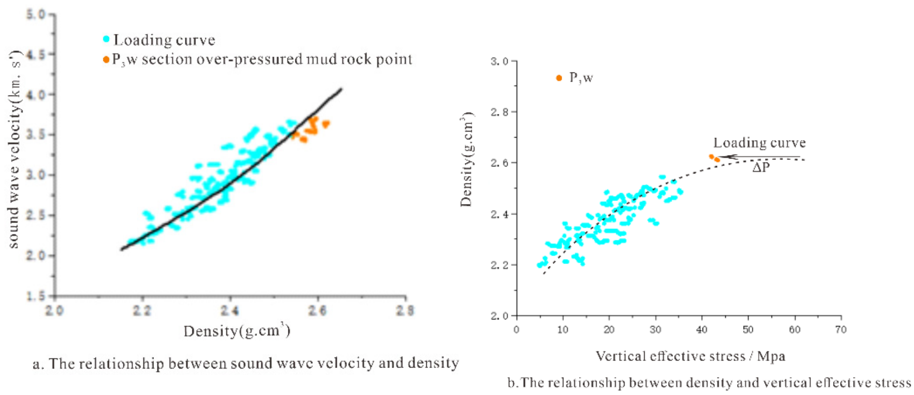

Figure 5. Identification of Overpressure Genesis using Crossplot Methods in Well A47, Fukang Sag, Junggar Basin

The comprehensive mudstone compaction curve of Well ZJ1 shows that at a burial depth of about 4000m, the acoustic interval transit time, density, and resistivity begin to reverse, deviating from the normal compaction trend. The drilling fluid density gradually increases from 1.4 g/cm^3 to 1.6 g/cm^3, indicating the development of an overpressure system in the bottom of the Haojiagou Formation (T_3hj) and the underlying strata. During the Permian deposition period, the Middle-Upper Permian sedimentary thickness in Well ZJ1 was 598m, with a mudstone-to-strata ratio of 43.2%, providing the geological conditions for undercompaction. Additionally, the density porosity and acoustic porosity of the mudstones below the overpressure top surface are higher than those in the normally compacted section, exhibiting characteristics of abnormal high porosity indicative of undercompaction (Figure 6). On the acoustic velocity-density crossplot, the undercompacted mudstone points of the Lucaogou Formation fall below the normal compaction curve (Figure 7a), indicating a significant increase in acoustic interval transit time and decrease in acoustic velocity for the Lucaogou Formation mudstones. Furthermore, the Lucaogou Formation in the eastern area is a set of fair to good source rocks. Thus, it can be determined that the overpressure in the Lucaogou Formation mudstone section is due to both undercompaction and hydrocarbon generation. The mudstone points from the Upper Wuerhe Formation section lie on the loading curve on the acoustic velocity-density crossplot (Figure 7a), characteristic of undercompaction-induced overpressure. The measured pressure points in the reservoir section of the Upper Wuerhe Formation, adjacent to mudstones, project onto the unloading curve position on the density-vertical effective stress crossplot (Figure 6), with a significant decrease in vertical effective stress, indicating overpressure transfer in the Upper Wuerhe Formation reservoir. Additionally, combined with geological conditions, it is found that primary pores develop within the reservoir, indicating that undercompaction is also a cause of overpressure in the Upper Wuerhe Formation reservoir.

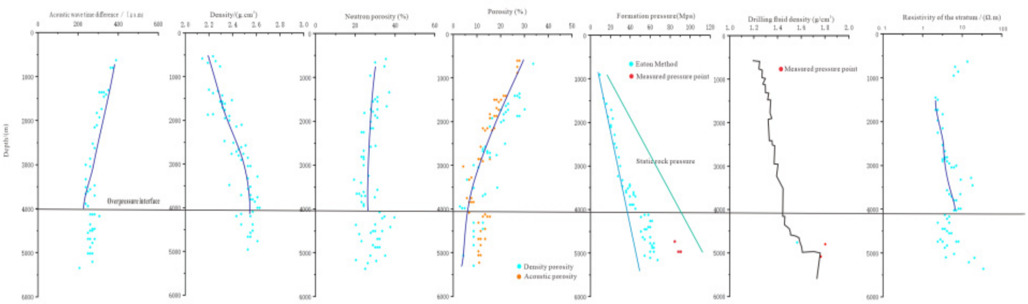

Figure 6. Identification of Overpressure Genesis using Crossplot Methods in Well ZJ1, Fukang Sag, Junggar Basin

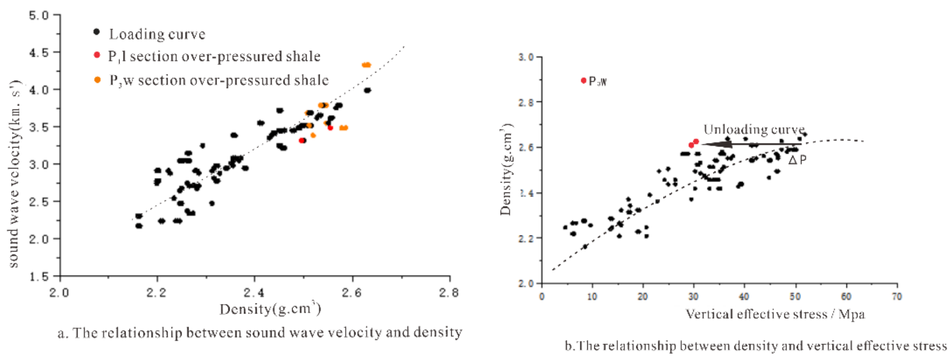

Figure 7. Identification of Overpressure Genesis using Crossplot Methods in Well ZJ1, Fukang Sag, Junggar Basin

Based on the identification results from these two typical wells, the overpressure genesis in the source rocks of the Lucaogou Formation includes undercompaction and hydrocarbon generation; the overpressure genesis in the reservoir of the Upper Wuerhe Formation results from the combined effects of overpressure transfer and undercompaction; the overpressure genesis in the caprock mudstone of the Upper Wuerhe Formation is undercompaction.

6. Conclusion

This study focused on the eastern Fukang Sag within the Central Depression Belt of the Junggar Basin. Using comprehensive mudstone compaction curves and vertical effective stress-density crossplots, the formation mechanisms of abnormal high pressure in the Permian strata of the study area were analyzed. On this basis, the basin modeling method was applied to reconstruct the overpressure evolution for different lithologies (source rock, reservoir, caprock) within the area, and their planar distribution patterns were summarized. The evolution of overpressure is closely related to the generation, migration, accumulation, and preservation of oil and gas. Therefore, by utilizing the reconstructed overpressure evolution characteristics of different lithologies and combining them with the actual geological conditions of the area, the relationship between overpressure evolution and hydrocarbon accumulation in the area was analyzed. The following understandings were obtained:

(1)The distribution of present-day measured pressures in the Permian strata of the eastern Fukang Sag has the following characteristics: the overpressure developed in the Permian of the sag area is the strongest, followed by the slope zone, and is relatively weak in the uplift area. Overall, it exhibits a distribution characteristic of "high in the west, low in the east".

(2)Based on the identification of overpressure genesis for different Permian lithologies in two typical wells on the eastern slope of the Fukang Sag, the comprehensive results indicate the respective overpressure genesis for different lithologies as follows: the overpressure genesis in the source rocks of the Lucaogou Formation includes undercompaction and hydrocarbon generation; the overpressure genesis in the reservoir of the Upper Wuerhe Formation results from the combined effects of overpressure transfer and undercompaction; the overpressure genesis in the caprock mudstone of the Upper Wuerhe Formation is undercompaction.

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