

The Formation Mechanism of Abnormal Overpressure in Depositional Basins and Its Controlling Effect on Hydrocarbon Accumulation

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Abstract: Abnormal overpressure is commonly encountered in depositional basins and is considered a key factor influencing the efficiency, safety, and assessment of hydrocarbon accumulation dynamics in drilling projects. Research indicates the following: (1) The genesis of abnormal overpressure in depositional basins can be broadly classified into five types, including disequilibrium compaction, fluid expansion, diagenesis, tectonic squeezing, and pressure transmission; (2) For specific geological conditions in depositional basins, the mudstone logging curve chart method is employed to assess abnormal overpressure; (3) The impact of abnormal overpressure in depositional basins on hydrocarbon accumulation is manifested in four aspects: its influence on hydrocarbon generation from source rocks, its effect on reservoir connectivity, its impact on seal integrity of cap rocks, and its influence on hydrocarbon migration. These research findings provide crucial guidance for a deeper understanding of abnormal overpressure in depositional basins and its significance in the evaluation of hydrocarbon exploration.

Keywords: Abnormal Overpressure; Causes of Overpressure; Controlling Effect on Hydrocarbon Accumulation.

1. Preface

In oil and gas-bearing basins, the phenomenon of abnormal overpressure in subsurface fluids is a widespread natural occurrence. This phenomenon is closely linked to the generation, migration, accumulation, and preservation of oil and gas [1]. Its formation signifies that within sedimentary basins, the fluid pressure in rock pores is higher than the surrounding hydrostatic pressure. This unique geological condition provides a favorable environment for the formation and long-term preservation of oil and gas reservoirs. Specifically, the formation of abnormal overpressure is closely related to the hydrocarbon generation process in source rocks, marking the starting point of oil and gas formation. Simultaneously, abnormal overpressure influences the complex relationship between the hydrocarbon source and the reservoir, alters the sealing conditions of cap rocks, and thereby affects the direction and speed of oil and gas migration. In-depth research into the causes and evolutionary characteristics of abnormal overpressure is crucial for a deeper understanding of the formation processes in sedimentary basins. Furthermore, resolving the assessment of abnormal overpressure's controlling effect on oil and gas fields is of significant importance. Therefore, our study aims to comprehensively elucidate the formation mechanisms of abnormal overpressure in sedimentary basins and discuss effective methods for its assessment. Through a thorough analysis of the role abnormal overpressure plays in the hydrocarbon accumulation process, we hope to provide more comprehensive guidance and insights for oil and gas exploration and development.

2. Mechanism of Overpressure Formation

The formation of abnormal overpressure occurs due to the development of a relatively sealed system within rock layers, where fluids in the pores cannot be expelled normally. As

pressure, temperature, and stress increase, the confined fluid undergoes expansion and compression, leading to overpressure (Hu Jing, 2004). Abnormal overpressure is widely developed in sedimentary basins, and its formation mechanism is complex and diverse. Currently, the recognized mechanisms for overpressure formation primarily include disequilibrium compaction (Magara, 1968), hydrothermal pressuring (Barker, 1972), tectonic pressuring (Frederick et al., 1973), hydrocarbon generation pressuring (Meissner, 1976), clay mineral dehydration (Powers, 1967; Bruce, 1984), and others.

2.1. Disequilibrium Compaction

"Disequilibrium Compaction" refers to the phenomenon where during the compaction process of mudstone, the compaction fluid is not able to be expelled in a timely manner or is obstructed, leading to a situation where the pore volume cannot decrease with the increasing overburden load [4]. This results in the fluid in the pores bearing part of the load from the overlying strata, causing the porosity to be higher than the normal compacted porosity, and the pore fluid pressure higher than the corresponding hydrostatic pressure. According to previous research (Li et al., 2023), it has been shown that in the Permian mudstone of the Jimusaer Depression in the Junggar Basin, abnormal overpressure commonly occurs due to disequilibrium compaction. This is identified as one of the most common causes of overpressure formation in that region.

2.2. Fluid Expansion

Hydrothermal pressuring occurs due to the increase in formation temperature with burial depth, leading to the expansion of pore water and rocks [7]. Especially when the volume expansion of pore water exceeds that of the rocks, and if the pore water cannot escape, the pore pressure is inevitably elevated. According to previous research (Zhou et al., 2023), hydrothermal pressuring was identified by scholars such as Barker. They proposed that in a closed water-containing system with a fixed volume, for every 0.56°C change in

temperature, the internal pressure can vary from 0.76 MPa (saturated saline water) to 0.86 MPa (freshwater). In such a scenario, taking a formation with freshwater as an example, a temperature increase of 4.4°C could generate excess pressures up to 6.90 MPa. Therefore, hydrothermal pressuring is considered one of the most common causes of abnormal overpressure in geological formations. This phenomenon has profound implications for processes such as the generation, migration, accumulation, and preservation of oil and gas in formations. The study provides important clues for understanding the mechanisms of abnormal overpressure formation in sedimentary basins.

2.3. Diagenesis

The diagenetic process is due to the hydration of montmorillonite during the sedimentation process. In this process, montmorillonite, which adsorbs a large amount of free water, transforms into interlayer bound water. With increasing burial depth, the temperature of the strata gradually rises[8]. When the temperature reaches the rupture temperature of the montmorillonite lattice, the interlayer bound water is released as free water. This free water is expelled from the already compacted strata, and under the influence of the increased strata temperature, it undergoes expansion, resulting in abnormally high pressure. The uneven compaction of mudstone is the most common mechanism for abnormal overpressure formation in sedimentary basins. This process plays a crucial role in the abnormal overpressure in the strata, significantly affecting processes such as the generation, migration, accumulation, and preservation of oil and gas[9]. Understanding this mechanism contributes to a deeper study of geological processes in sedimentary basins and provides guidance for exploration and development.

2.4. Tectonic squeezing

The fundamental reason for the formation of abnormal high pressure due to tectonic activity lies in the compressional stress exerted by tectonic squeezing on the formation's pores[11]. On one hand, tectonic squeezing leads to the development of strong overpressure in the foreland strata, forming fracture channels that communicate between the upper and lower sealing formations. In this environment, hydrocarbons in the deep source rocks migrate upward along fractures driven by overpressure. On the other hand, the uplift, erosion, and fault activity resulting from tectonic squeezing determine the preservation conditions of the cap rock. The uplift and erosion of the cap rock promote fault activity, while rapid sedimentation within the basin accelerates the thermal maturation process of source rocks. These intertwined processes collectively contribute to the formation of abnormal high pressure. This tectonic activity has profound implications for the evolution of strata, the generation and migration of oil and gas in sedimentary basins, and other geological processes.

2.5. Pressure transmission

Pressure transmission refers to the process whereby high-pressure flowing fluids released or leaked from a high-pressure system in subsurface layers lead to elevated pressure in a normal-pressure system[12]. Under the driving force of excess pressure, fluids move laterally from deep to shallow along the reservoir until pressure equilibrium is achieved, resulting in lateral overpressure transmission. Previous studies suggest three mechanisms for overpressure

transmission[14]: first, the injection of high-pressure fluids; second, the migration of high-pressure fluids along permeable formations (such as sandstone layers, fracture systems, salt structures, etc.); and third, the expansion of fluids in an overpressure-sealed compartment. Additionally, in the presence of fracture effects, they may cause the overpressure-sealed compartment to experience leakage and migrate upwards, forming anomalous high-pressure strata. The uneven compaction of mudstone is the most common mechanism for overpressure formation in sedimentary basins.

3. Methods for Overpressure Identification

3.1. Log Curve Combination Analysis Method

The rock physics properties of overpressured formations formed by different mechanisms exhibit distinct characteristics[16]. Therefore, overpressure origins can be identified based on the relationship between the log response in the overpressured interval and effective stress, as well as the response relationship between acoustic velocity and density. When employing the log curve combination analysis method for overpressure origin analysis, it requires acoustic log, resistivity log, and density log data. Acoustic logs can be used to determine the distribution of overpressured intervals, resistivity logs are used to discern fluid properties (water or hydrocarbons) or the effects of lateral squeezing, and density logs primarily reflect changes in porosity.

Hydrocarbon generation and expansion-induced pressure increase are manifested in log curves as asynchronous reversals in acoustic velocity, resistivity, and rock density, with the reversal in rock density lagging. Some scholars propose the following viewpoints[19]: (1) if the overpressured interval shows an increase in acoustic travel time or a decrease in velocity, a decrease in resistivity, and a significant decrease in density with increasing burial depth, then the overpressure may be due to the mechanism of uneven compaction; (2) if the overpressured interval exhibits an increase in acoustic travel time or a decrease in velocity, an increase in resistivity, and little or no decrease in density with increasing burial depth, then the overpressure may be due to the mechanism of hydrocarbon generation and expansion; (3) if the overpressured interval shows an increase in acoustic travel time or a decrease in velocity and an increase in density with increasing burial depth, then the overpressure may be due to the mechanism of montmorillonite-illite transformation; (4) if the overpressured interval exhibits a normal decrease in acoustic travel time or an increase in velocity, along with increases in resistivity and density, then the overpressure may be due to the mechanism of tectonic squeezing. However, the above are preliminary identifications based on the log curve combination characteristics of overpressure origins, and determining specific causes requires comprehensive analysis using various other methods.

3.2. Overpressure Formation Mechanism Recognition Chart Method

On the basis of previous research, four main mechanisms for the formation of overpressure have been identified through a comprehensive recognition model (Figure 1)[22]. These four types of pressurization mechanisms exhibit significant differences in the curves of the relationship between acoustic velocity and vertical effective stress, as well

as density and acoustic velocity. However, it is challenging to distinguish between the pressurization mechanisms of fluid expansion and overpressure transmission using this model. Therefore, when making specific judgments, it is essential to

fully consider the actual geological conditions of the research area. Combining this consideration, the two mechanisms can be distinguished effectively.

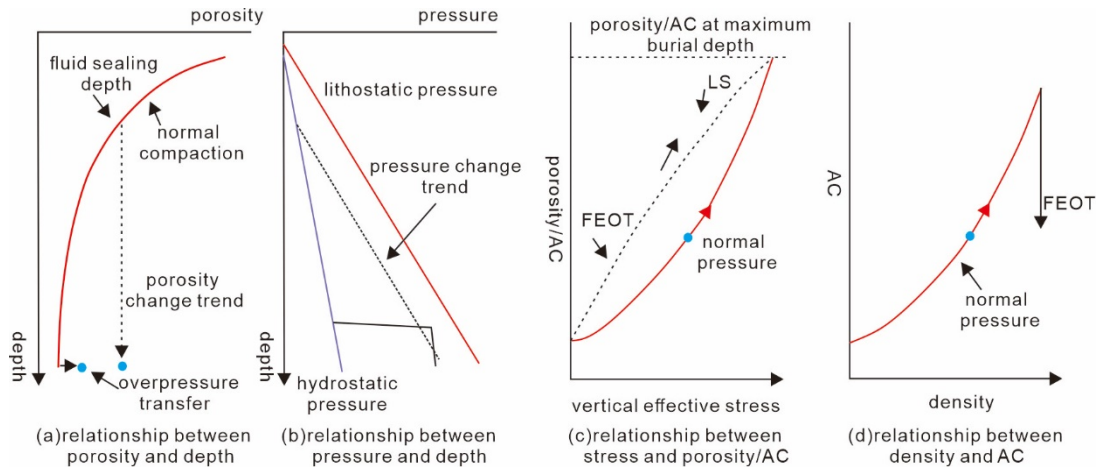
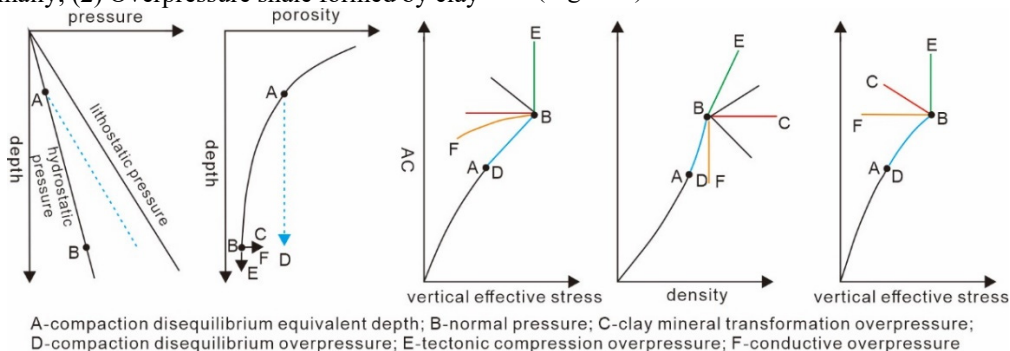


Fig 1. Comprehensive Identification Model Diagram of Overpressure Formation Mechanisms

3.3. Acoustic Velocity-Density Crossplot Method

Some scholars believe that overpressure formed by unbalanced compaction falls on the loading curve, similar to normal pressure. In contrast, overpressure formed by other mechanisms is located outside the loading curve. Zhao Jingzhou and others specifically studied three cases, including: (1) Overpressure generated by fluid expansion mechanisms such as gas generation, where acoustic velocity decreases with increasing overpressure, but density remains unchanged or changes minimally; (2) Overpressure shale formed by clay

diagenesis or chemical compaction, where density increases with overpressure, but acoustic velocity either does not decrease or decreases minimally; (3) Overpressure formed by load transfer mechanisms or mixed-genesis mechanisms, with density-velocity changes lying between the two aforementioned cases. This is characterized by a decrease in acoustic velocity and an increase in density with increasing overpressure. Lahann and others, using density-velocity crossplot analysis, were among the first to observe the transformation of montmorillonite to illite and fluid expansion mechanisms such as hydrocarbon generation (Figure 2).



A-compaction disequilibrium equivalent depth; B-normal pressure; C-clay mineral transformation overpressure; D-compaction disequilibrium overpressure; E-tectonic compression overpressure; F-conductive overpressure

Fig 2. Density-Acoustic Velocity Crossplot

4. Quantitative Assessment Method for Overpressure

4.1. Numerical Simulation

The numerical simulation technique was initially not used to predict pore fluid pressure. Instead, it was originally employed for the quantitative study of various complex migration processes of oil and gas from generation to the occurrence of secondary migration. However, by delving into the physical and chemical mechanisms of oil and gas and applying expertise in geology, fluid dynamics, geophysics, geochemistry, and other related fields, numerical simulation techniques can better transform the conceptual models of geologists into mathematical models in computers[31]. This enables quantitative calculations to reconstruct the basin's history of stratigraphic evolution, hydrocarbon generation, oil

and gas migration, and accumulation history[24]. This includes aspects of sedimentation (formation, lithology, thickness, and age), non-sedimentation (unconformities and ages), erosion events (thickness and age).

The simulation of the age, thickness, and lithology of the strata is obtained through standard stratigraphic age tables, well log data, and logging information, with a particular emphasis on determining erosion thickness. Currently, the PetroMod software is widely used for simulating sedimentary basins, providing key outputs such as burial history charts, thermal histories, maturity histories, and hydrocarbon generation histories. The burial history chart reflects and reconstructs the sedimentary and tectonic history of oil and gas-bearing basins. The methods mainly include forward modeling and backstripping. Both methods are based on the principle of sediment compaction, assuming that with increasing burial depth, only the pore volume decreases while

the thickness of the stratum framework remains constant[26].

Thermal history is used to reflect and reconstruct the paleo-heat flow and paleo-temperature history of oil and gas-bearing basins, thus reconstructing the thermal maturity history of organic matter. Determination methods include geothermal methods, and a combination of geothermal and geochemical methods. Maturity history can reflect and reconstruct the maturity history and hydrocarbon generation history of oil and gas-bearing basins. Hydrocarbon generation history models include generation rate models and volume method models, ultimately yielding the amount of oil and gas generated in different periods in different source rocks. The hydrocarbon expulsion history reflects and reconstructs the expulsion and expulsion direction history of oil and gas-bearing basins, i.e., the history of initial migration.

4.2. Pressure Calculation Methods

Pressure calculation by reverse deduction method refers to the use of various methods to calculate the formation pressure in the overpressure interval. The calculated results are then compared with the measured formation pressure, and the similarity between the two is observed. The method that yields results closest to the measured pressure is likely to be the cause of overpressure in the formation. The equilibrium depth method is a formation pressure calculation method based on the assumption that overpressure is caused by unbalanced compaction. Therefore, if the pressure calculated by this method closely matches the measured pressure, it can be inferred that the overpressure is caused by unbalanced compaction. Conversely, if the calculated results deviate significantly from the measured pressure, it suggests that overpressure may not be caused by unbalanced compaction. Since the equilibrium depth method is based on porosity, and overpressure caused by fluid expansion and other unloading mechanisms generally does not exhibit significant porosity anomalies, the overpressure calculated by the equilibrium depth method often tends to be lower than the measured pressure.

The Eaton method involves using different Eaton indices in the Eaton formula to calculate formation pressure. The calculated results are then compared with the measured formation pressure to determine the cause of overpressure. The calculation formula for the Eaton method is[33]:

$$P = P_{ov} - (P_{ov} - P_w)/(\Delta t_n/\Delta t)^n \quad (1)$$

the Eaton index "n" carries intrinsic implications regarding the causative factors. Generally, it is believed that pressure calculated with an "n" value of 3.0 is attributed to unbalanced compaction, while a value of approximately 6.5 suggests pressure resulting from fluid expansion or pressure transmission.

In summary, no single method can guarantee its accuracy. Therefore, in practical work, researchers should employ multiple methods, examine the deviations in their results, and analyze potential scenarios in conjunction with actual conditions. For instance, considerations may include the presence of source rocks in the study area. If absent, there may be no need to consider hydrocarbon-induced overpressure. Other factors to assess could be the presence of intense tectonic compression or indications of shale compaction phenomena.

5. Overpressure-Controlled Reservoir Accumulation

According to the impact of overpressure on hydrocarbon generation, the generation of microfractures to improve reservoir storage performance, enhancement of the sealing capacity against oil and gas, as well as the promotion of the initial migration of oil and gas, these effects fully demonstrate the controlling role of overpressure on oil and gas reservoirs in sedimentary basins[34].

5.1. The Impact of Overpressure on Source Rocks

Previous studies suggest that the impact of overpressure on hydrocarbon generation is primarily manifested in three aspects:(1) Overpressure can influence hydrocarbon generation products. Experimental simulations under isothermal and pressurized conditions have confirmed that overpressure can lead to a relative increase in liquid hydrocarbon yield and a relative decrease in gaseous hydrocarbon yield;(2) Overpressure can affect the maturity of source rocks. Through the analysis of the relationship between the acoustic travel time and the Ro value in typical wells, it has been observed that abnormal segments of Ro values deviate from the normal curve. This confirms that Ro values in the overpressure interval are significantly lower than the normal trend;(3) Overpressure can impact the hydrocarbon generation threshold and the lower limit of the oil generation window. Experimental simulations have revealed that under geological overpressure conditions, the hydrocarbon generation threshold and the lower limit depth of the oil window increase. The cracking of liquid hydrocarbons with high carbon numbers is constrained, indicating the possibility of liquid hydrocarbon occurrence in the deep layers of high-pressure formations.

5.2. Impact of Overpressure on Reservoir

The development of overpressured formations can slow down the mechanical compaction and diagenesis of overlying formations, enhancing the reservoir performance of mid-deep layers. This is mainly reflected in having better physical parameters (porosity and permeability) compared to the normal compaction trend. On the one hand, the generation of overpressured formations partially offsets the overlying formation pressure, reducing the effects of mechanical compaction. As a result, primary pores occupied by high-pressure fluids are preserved during further burial, leading to higher porosity compared to the corresponding burial depth.

On the other hand, the development of overpressured formations is conducive to reservoir dissolution. As diagenesis progresses to a certain stage, the rapid increase in fluid pressure in the formation pores, accompanied by the generation of a large amount of organic acids, promotes the transition of the diagenetic environment to an acidic medium. Most of the generated organic acids dissolve in the formation pore water. Under high-temperature and high-pressure conditions after deep burial, the dissolution capacity of carbonate cement and acid-sensitive minerals (such as feldspar) is significantly enhanced, indirectly leading to the formation of numerous secondary dissolution pores in the deep formations.

5.3. The impact of overpressure on the oil and gas reservoir cap rock

The overpressure in shale cap rock relies on the dual sealing mechanisms of capillary pressure closure and overpressure closure, playing a significant role in effectively sealing the underlying oil and gas reservoirs[28]. It is a key factor in the formation and maintenance of two sets of ultra-high-pressure systems, namely, the middle combination and lower combination. In both top-seal retention and closure-type high-pressure systems, dense sealing layers serve as ideal cap rocks. They act not only as physical boundaries but also as excellent thermal interfaces. Under high-temperature and high-pressure conditions, they become effective seals for oil and gas, while under normal conditions, oil and gas can pass through various types of rock layers. This is because the thermal conductivity of hydrocarbon-bearing formations (especially gas-bearing formations) is much lower than that of water-bearing formations under high-temperature and high-pressure conditions, resulting in negative thermal dynamic gradients at the boundaries. At this point, the reservoir cap rock becomes a thermal cap rock.

The clay mineral transformation and diagenetic chemical changes during the formation of cap rock in high-pressure systems can yield various results: (1) Precipitation of ions such as Si, Ca, Fe, Mg can accumulate on the surface of argillaceous rocks, forming a closure effect; (2) Crystallization of authigenic minerals can lead to pore blockage; (3) Transformation of clay minerals can create numerous bound-type pathways, reducing the permeability of the rock formation. These effects contribute to effective closure, preventing the escape of oil and gas. The high-pressure closure in shale is a form of physical closure. The high-potential surface in the central part of the high-pressure layer can prevent the migration of oil and gas, causing them to accumulate beneath the shale (Hunt, 1990). Additionally, it protects the porosity and permeability of the middle and deep layers, enhances resistance to structural deformation, and improves the sealing capability of faults. Compared to physical closure, physical closure is effective not only for solute-phase fluids but also for free-phase fluids. In areas with intense tectonic activity, such as the Sichuan Basin and the Ordos Basin, the high-pressure closure in shale plays a crucial role in the formation of oil and gas reservoirs[29].

5.4. The impact of overpressure on the migration of oil and gas

Overpressure formations not only influence the evolution of organic matter and hydrocarbons but can also serve as a driving force for the migration and accumulation of oil and gas in hydrocarbon-bearing basins. Research has shown that overpressure formations play a crucial role in both the initial migration of hydrocarbons and their secondary migration in oil and gas basins[32].

On one hand, during the initial migration of hydrocarbons, they predominantly move in a free state, with the main resistance coming from capillary resistance in small pores and throats. When abnormal high-pressure conditions in shale exceed the capillary resistance, the resulting pressure difference can drive hydrocarbon substances out of the source rocks.

On the other hand, at the top of overpressure systems, sealing layers with high density are often present. When the formation pressure generated by high-pressure fluids in the

reservoir exceeds the fracture pressure of the sealing layer, localized microfractures can form. Under high-pressure driving forces, this can lead to the secondary migration of oil and gas, creating new accumulations in other traps.

After the generation of hydrocarbons in source rocks, some may require long-distance secondary migration to reach reservoir layers. The magnitude of overpressure is closely related to the amount of hydrocarbon generation in source rocks. The pressure in the rock pores sharply increases during the process of soluble organic matter and kerogen turning into oil, leading to abnormal high-pressure conditions. According to the principle of pressure balance, the formation pressure in source rocks should be greater than the sandstone breakthrough pressure and greater than 50% saturation pressure for efficient migration of high-pressure fluids (hydrocarbon substances) through the conduits driven by pressure differences.

6. Conclusion

(1) The genesis of overpressure in sedimentary basins can be roughly categorized into five types: disequilibrium compaction, fluid expansion, diagenesis, tectonic compression, and pressure transmission;

(2) The identification of overpressure in sedimentary basins primarily relies on the use of mudstone log curve charts, combined with specific geological conditions of the sedimentary basin;

(3) The impact of sedimentary basins on hydrocarbon accumulation can be broadly divided into four aspects: the influence on hydrocarbon generation in source rocks, the impact on reservoir transport, the effect on cap rock sealing of oil and gas, and the influence on the migration of oil and gas.

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