ISSN: 2688-8645

Characteristics, Genetic Mechanisms and Hydrocarbon Accumulation Control of Abnormal High Pressure in the Northwestern Qaidam Basin

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Abstract

Abnormal high-pressure systems are widely developed within the Cenozoic strata of the northwestern Qaidam Basin (NW Qaidam), which is a key geological factor constraining hydrocarbon exploration and drilling safety. This study systematically investigates their distribution characteristics, genetic mechanisms, and controlling effects on hydrocarbon accumulation by comprehensively utilizing a large amount of geological, geophysical, and basin modeling data. The results indicate that the abnormal pressure in the NW Qaidam exhibits a four-segment vertical zonation: low pressure in shallow sections, normal pressure in middle sections, overpressure in mid-deep sections, and strong overpressure in deep sections. The top interface of overpressure lies between 1000 and 2500 m. On a planar scale, the overpressure centers are highly coupled with sedimentary centers. From the Upper Member of the Lower Ganchaigou Formation (E32) to the Upper Youshashan Formation (N22), the overpressure centers migrated eastward along with the sedimentary centers. Analysis of genetic mechanisms reveals that the overpressure in the study area results from the combined effects of undercompaction, tectonic compression, and hydrocarbon generation. The widely developed gypsum-salt rocks played a crucial indirect role in the formation and preservation of the overpressure system by enhancing sealing capacity and promoting organic matter enrichment and hydrocarbon generation. The evolution of abnormal high pressure is highly coupled with hydrocarbon charging episodes. The source-reservoir excess pressure difference (up to 10-20 MPa) provided the key driving force for hydrocarbon migration. The overpressure system itself constitutes an effective seal, forming an "overpressure compartment" together with the gypsum-salt caprocks. This compartment controls hydrocarbon accumulation and distribution, leading to primary high-pressure reservoirs within the compartment and secondary normal-pressure reservoirs outside it. This research deepens the theoretical understanding of overpressure systems in saline lacustrine basins under strong tectonic compression and provides a scientific basis for hydrocarbon exploration and drilling engineering safety in the NW Qaidam.

Keywords

Northwestern Qaidam Basin; Abnormal High Pressure; Genetic Mechanism; Overpressure Evolution; Hydrocarbon Accumulation.

1. Introduction

Formation pressure is one of the most fundamental fluid dynamic parameters in sedimentary basins. Its anomalies, especially abnormal high pressure (overpressure), are closely related to hydrocarbon generation, migration, accumulation, and preservation processes, and are also key constraints on drilling engineering safety and efficiency [1][2]. Global petroleum exploration practice shows a close relationship between abnormal high pressure and hydrocarbon enrichment. According to incomplete statistics, among over 180 discovered abnormal high-pressure basins worldwide, more than 160 are hydrocarbon-rich basins [3]. In China, abnormal high pressure has been identified in 29 petroliferous basins [4].

The Qaidam Basin is an important plateau inland petroliferous basin in western China, with its western part (West Qaidam) being the main hydrocarbon production area where abnormal high pressure is widely developed within the Cenozoic (Paleogene–Neogene) strata [4][5]. The northwestern Qaidam Basin (NW Qaidam), as an important tectonic unit of West Qaidam, is a key and potential exploration zone in recent years. This area has undergone multiple tectonic movements during the Cenozoic, depositing a thick sequence of saline lacustrine facies, forming complex "lower generation, upper storage, multi-stage accumulation" petroleum geological conditions [6]. Studies confirm that abnormal high pressure is widely developed in the Paleogene–Neogene of NW Qaidam, with the overpressure top interface depth ranging from about 1500-2500 m, playing an important controlling role in hydrocarbon distribution and accumulation [7][8].

Research on abnormal pressure in the Qaidam Basin has achieved a series of results. Early studies preliminarily discussed the characteristics of abnormal pressure in the basin, attributing its origin to undercompaction and hydrothermal effects [5]. Subsequently, Guo Zeqing et al. (2005) systematically elaborated the distribution, genesis, and controlling effects on hydrocarbon migration of abnormal high pressure in the Cenozoic of West Qaidam, pointing out that disequilibrium compaction, tectonic compression, and hydrothermal pressurization are the main causes [4]. In recent years, with deepening exploration, scholars have begun to focus on the differences in overpressure genetic mechanisms among different tectonic units. For example, Liu Chenglin et al. (2019), studying the Paleogene–Neogene in NW Qaidam, indicated that its overpressure results from the combined effects of undercompaction, tectonic compression, and hydrocarbon generation, with quantitative evaluation showing undercompaction has the highest contribution (>60%), followed by tectonic compression (20%~30%) [7]. Fan Changyu et al. (2015), studying the Eboliang structural belt on the northern margin of the Qaidam Basin, emphasized the importance of overpressure transfer mechanisms [9]. Furthermore, as a typical saline lacustrine basin, the widely developed gypsum-salt rocks in NW Qaidam have a special and significant impact on the formation and preservation of overpressure [10][11].

However, existing research still lacks fine characterization of the spatial distribution (especially vertical zonation and planar migration) of abnormal high pressure in NW Qaidam, and understanding of the quantitative contribution proportions of multiple genetic mechanisms and dynamic evolution processes remains controversial. In particular, the specific role and mechanism of the saline environment (high salinity, gypsum-salt rocks) in the formation and preservation of the overpressure system need further deepening. Therefore, this paper selects the northwestern Qaidam Basin as the study object. Based on systematically reviewing previous research results and comprehensively utilizing multi-source data including geology, well logging, testing, and basin modeling, it aims to: (1) finely characterize the vertical and planar distribution characteristics of abnormal high pressure in NW Qaidam; (2) deeply analyze and quantitatively evaluate the contribution mechanisms of key factors such as undercompaction, tectonic compression, hydrocarbon generation, and the saline environment to overpressure formation; (3) explore the relationship between abnormal high pressure and hydrocarbon accumulation. This study not only helps deepen the theoretical understanding of the overpressure system in this special plateau saline lacustrine basin of the Qaidam Basin but also provides direct scientific basis for hydrocarbon exploration deployment, favorable zone prediction, and drilling engineering safety in this area.

ISSN: 2688-8645

2. Regional Geological Setting

The Qaidam Basin is located in the northeastern part of the Tibetan Plateau and is China's largest inland plateau intermontane basin. Tectonically, the NW Qaidam belongs to the western Qaidam Basin (West Qaidam) region. It is bounded by the Altun Mountains to the west and north, roughly by the Yingbei Fault to the south adjacent to the southwestern Qaidam region, and by the Pingdong Fault to the east adjacent to the Yiliping Depression [7][8] The study area is mainly located within two secondary tectonic units of the West Qaidam Depression: the Mangya Depression and the Dafengshan Uplift, developing a series of NW-SE trending anticlinal structural belts, which are key targets for hydrocarbon exploration.

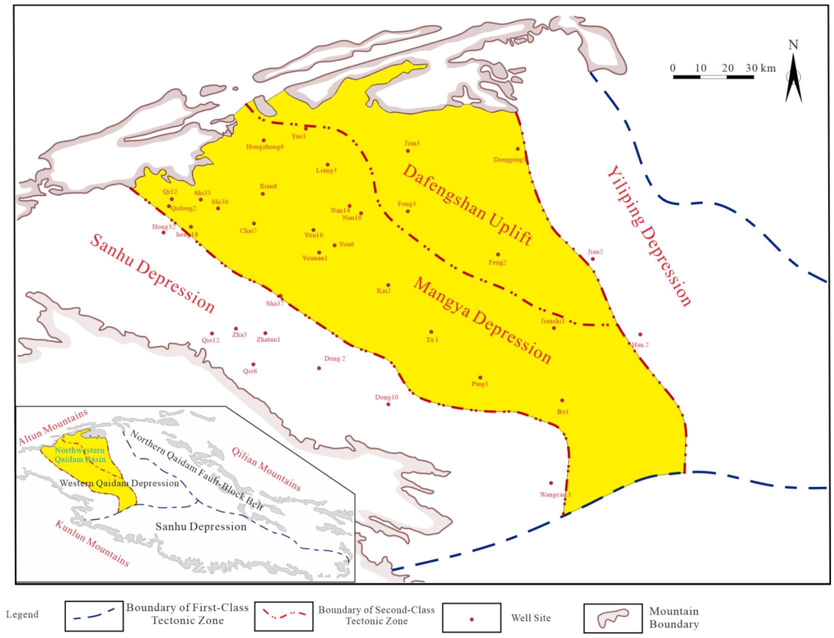

Figure 1. Regional Geological Overview Map of the Northwestern Qaidam Basin

The formation and evolution of the Qaidam Basin are controlled by the remote effects of multiple tectonic actions, including the collision of the Indian and Eurasian plates, the phased uplift of the Tibetan Plateau, and the left-lateral strike-slip of the Altun Fault [12]. During the Cenozoic, the NW Qaidam was long in a large saline lake environment ranging from shore-shallow lake to semi-deep–deep lake, depositing a sequence dominated by fine-grained sediments [13]. The Cenozoic strata are complete from bottom to top, mainly including the Paleogene Lulehe Formation (E_{1+2}), Lower Ganchaigou Formation (E_3, divided into the lower member E_3^1 and upper member E_3^2), Upper Ganchaigou Formation (N_1), Youshashan Formation (N_2, divided into the Lower Youshashan Member N_2^1 and Upper Youshashan Member N_2^2), Shizigou Formation (N_2^3), and Quaternary Qigequan Formation (Q_{1+2}) [14]. Among them, the Upper Member of the Lower Ganchaigou Formation (E_3^2) is the most important source rock layer and overpressure development layer in the study area. Its lithology consists of interbedded dark gray, gray-black mudstone, calcareous mudstone, marlstone, and siltstone, locally intercalated with gypsum-salt rocks, belonging to semi-deep–deep lake facies deposits [15].

The sedimentary evolution of the Cenozoic lake basin in the Qaidam Basin is controlled by both tectonics and climate, with clear migration patterns of the sedimentary center and salinization center [16]. During the Oligocene (E_3^2 deposition period), the lake basin expanded to its maximum extent, with the salinization center located in the Yingxi area, developing gypsum-salt rocks [11]. Since the Miocene, influenced by tectonic compression, the sedimentary center has continuously migrated southeastward. This sedimentary background of a saline lacustrine basin determines that the strata in NW Qaidam have unique lithological assemblage characteristics such as high salinity, carbonate-rich, fine-grained sediments-dominated, and high sedimentation rates, providing an important geological foundation for the development of abnormal high pressure.

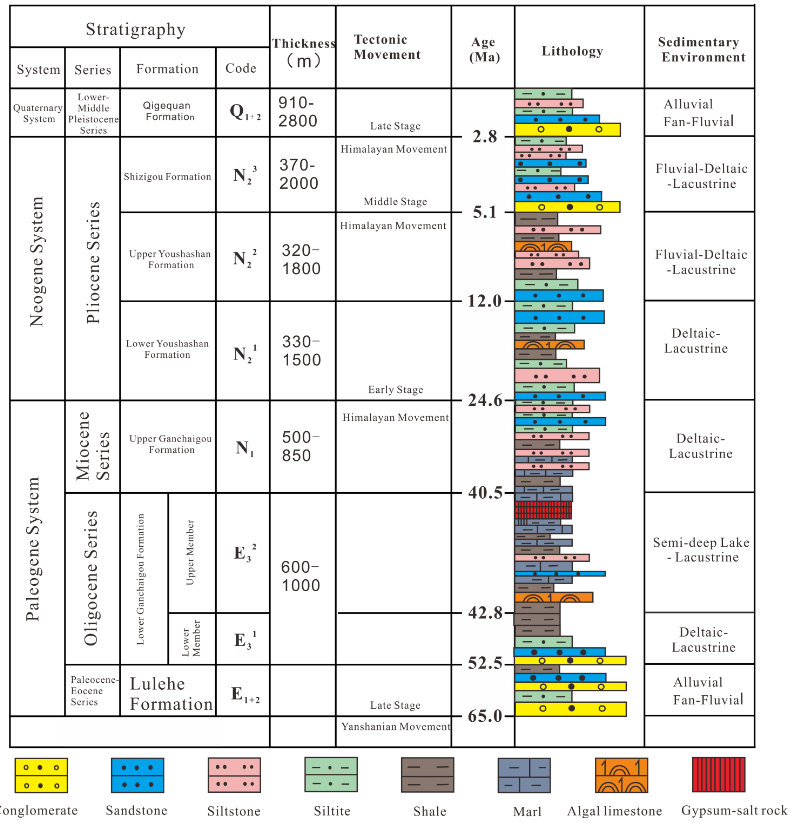

Figure 2. Comprehensive Stratigraphic Column of the Northwestern Qaidam Basin

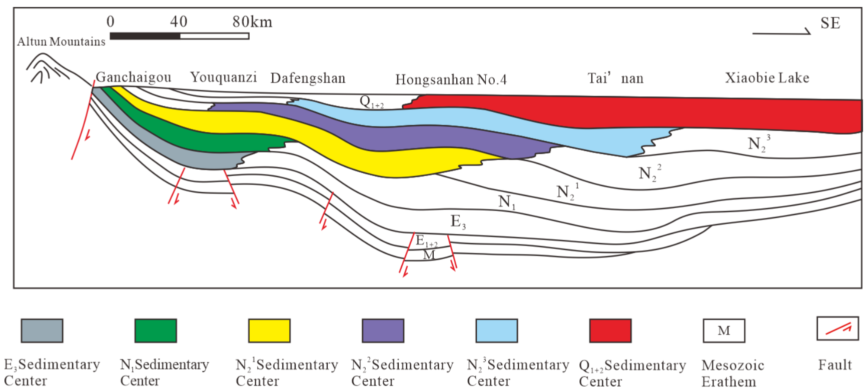

Figure 3. Schematic diagram of the migration of sedimentary centers in the Qaidam Basin (modified after Fu Suotang et al., 2015[397])

3. Characteristics of Abnormal High Pressure Distribution

3.1. Data and Methods

This study systematically collected 158 valid measured pressure data points (DST, RFT, MDT) from 82 key exploration wells in NW Qaidam, as well as conventional well logging curve datasets from 65 key exploration wells. The pressure coefficient (Pc = measured pressure / hydrostatic pressure at the same depth) was used as the core indicator for pressure type classification. Combined with statistical characteristics of measured points, pressure types were divided into: abnormal low pressure (Pc < 0.90), normal pressure (0.90 ≤ Pc < 1.20), weak overpressure (1.20 ≤ Pc < 1.40), overpressure (1.40 ≤ Pc < 1.60), and strong overpressure (Pc ≥ 1.60).

For a large number of intervals without measured pressure data, formation pressure prediction was conducted using the equivalent depth method based on acoustic transit time (AC) logs. A normal compaction trend line model of shale acoustic transit time (AC) versus depth was established for each well, and the true overburden pressure gradient varying with depth was calculated using the density log integration method, improving calculation accuracy. Through this method, calculated pressure data for over 180,000 depth points were obtained, forming a gridded pressure dataset covering the entire study area. Simultaneously, the Eaton method was used for comparative verification, optimizing and determining the best Eaton exponent x value for the study area as 3.2.

3.2. Vertical Distribution Characteristics

The relationship diagrams of formation pressure and pressure coefficient versus depth plotted based on measured and calculated data clearly reveal the systematic variation pattern of formation pressure in the vertical direction within the study area, showing a refined "four-segment" zonation feature (Figure 4):

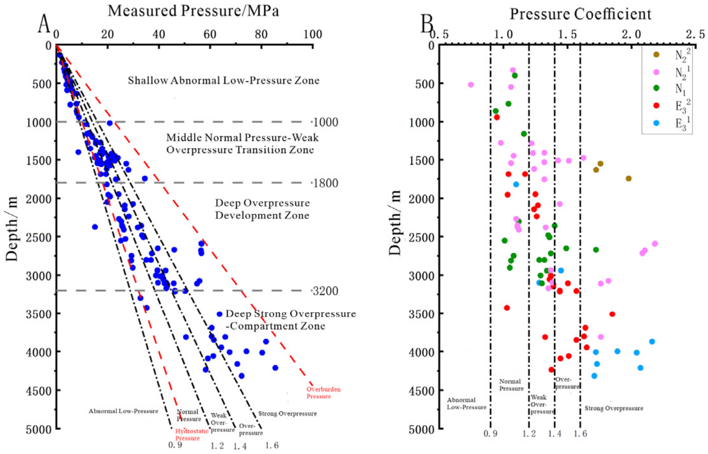

Figure 4. Scatter plot of vertical distribution of formation pressure and pressure coefficient in the northwestern Qaidam Basin

Shallow Abnormal Low-Pressure Zone (Burial Depth <1000m): Pressure coefficients are concentrated between 0.75-0.90, with an average level of about 0.82. Mainly related to later tectonic uplift and erosion and fluid pressure release.

Middle Normal Pressure-Weak Overpressure Transition Zone (Burial Depth 1000-1800m): Pressure coefficient span ranges from 0.95 to 1.20, with an average of about 1.05, indicating a fluid dynamic system close to normal compaction. A small number of weak overpressure points begin to appear at the bottom of this zone.

Deep Overpressure Development Zone (Burial Depth 1800-3200m): Pressure coefficients are mainly concentrated in the range of 1.30 to 1.80. It can be further subdivided into the main overpressure development sub-zone (1800-2500m, pressure coefficient 1.30-1.60) and the strong overpressure increasing sub-zone (2500-3200m, pressure coefficient 1.60-1.80). The heterogeneity of overpressure increases, reflecting the composite superposition of multiple pressurization mechanisms.

ISSN: 2688-8645

Deep Strong Overpressure-Compartment Zone (Burial Depth >3200m): Mainly distributed beneath thick gypsum-salt rocks in deep sag areas, pressure coefficients are generally greater than 1.80, with the highest measured value reaching 2.20. The pressure-depth gradient approaches the lithostatic pressure gradient, exhibiting "pressure compartment" characteristics.

The overpressure top interface (the depth at which the pressure coefficient first continuously exceeds 1.2) exhibits distinct zonation. In structural belts located within sedimentary centers (such as Nanyishan), the overpressure top interface is relatively shallow (2200m), with a younger initial stratigraphic horizon (N_2^1). In structural belts at the basin margin (such as Dafengshan), the overpressure top interface is deeper (2500m), with an older initial stratigraphic horizon (E_3^2). In the Yingxi area, where gypsum-salt rocks are well-developed, the overpressure top interface occurs at a relatively shallow depth (1800 m), but beneath it, there exists a strong overpressure abrupt change zone formed by the sealing of gypsum-salt rocks [11]. From west to east, the stratigraphic horizon of the overpressure top interface shows a trend of gradually becoming younger, which is completely consistent with the eastward migration history of the sedimentary center since the Cenozoic [4, 17].

3.3. Planar Distribution Characteristics

The planar contour maps of pressure coefficients for different stratigraphic horizons reveal the spatial heterogeneity and evolutionary patterns of overpressure (Figure 5):

Upper Youshashan Formation (N_2^2) and above: Primarily a normal pressure system.

Lower Youshashan Formation (N_2^1): The overpressure range expands but remains mainly concentrated in local structures.

Upper Ganchaigou Formation (N_1): The overpressure range further expands, with multiple, relatively weak overpressure centers emerging, and their positions shifting eastward.

Upper member of the Lower Ganchaigou Formation (E_3^2): This is the horizon with the most extensive and strongest overpressure development. On the plane, it exhibits a distinct ring-like or quasi-ring-like distribution. The overpressure and strong overpressure centers (Pc > 1.6) are stably located within the sedimentary center areas, primarily including three centers: Yingxi-Shizigou, Youquanzi-Xianshuiquan, and Dafengshan. The pressure coefficient gradually decreases from these centers towards the basin margins.

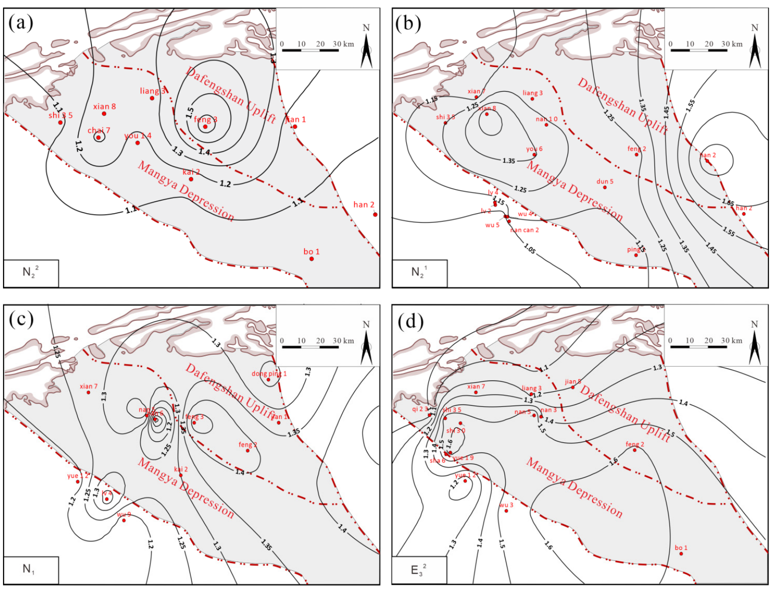

Figure 5. Planar contour maps of formation pressure coefficients for different stratigraphic horizons

ISSN: 2688-8645

By comparing the planar positions of overpressure centers across different stratigraphic horizons, a clear spatiotemporal migration pattern emerges: from E_3^2 to N_2^2, the high-value overpressure zones progressively shift from southwest to northeast. This migration trajectory is entirely consistent with the migration history of the sedimentary-subsidence center of the western Qaidam Basin lake basin [16-17], profoundly revealing that the formation and preservation of overpressure are primarily controlled by the spatiotemporal evolution of the sedimentary center.

4. Genetic Mechanisms and Quantitative Evaluation of Abnormal High Pressure

4.1. Geological Conditions for Overpressure Formation

The abnormal overpressure in the northwestern Qaidam Basin is the result of the coupling and superposition of multiple geological processes, primarily characterized by the following conditions:

Rapid Sedimentation and Undercompaction Conditions: The Cenozoic sedimentation rate in the study area is generally high, reaching 400-700 m/Ma during the E_3^2 depositional period [7]. Rapid deposition of thick mudstone and gypsum-salt rocks (with a mud-to-sand ratio generally exceeding 75% in E_3^2) impedes the expulsion of pore fluids, providing the material basis for undercompaction-induced overpressure.

Tectonic Compression Conditions: The Qaidam Basin has been under a strong compressional tectonic setting since the Neogene [6]. Lateral tectonic stress directly compresses rock pore volume and, within a closed system, leads to an increase in fluid pressure.

Hydrocarbon Generation Conditions: The main source rocks, E_3^2 and N_1, have entered the mature to highly mature stage [8]. Hydrocarbon generation from organic matter (especially gas generation) causes expansion of pore fluid volume, generating a pressurization effect within a closed system.

Special Role of Salt Minerals: Widely developed gypsum-salt rocks possess high plasticity and low permeability, serving as excellent sealing layers. The high-salinity environment is conducive to the preservation of organic matter, and the high thermal conductivity of gypsum-salt rocks can promote the thermal evolution of source rocks. Diagenetic processes such as gypsum dehydration and transformation can also increase fluid volume [10-11].

4.2. Comprehensive Identification of Genetic Mechanisms

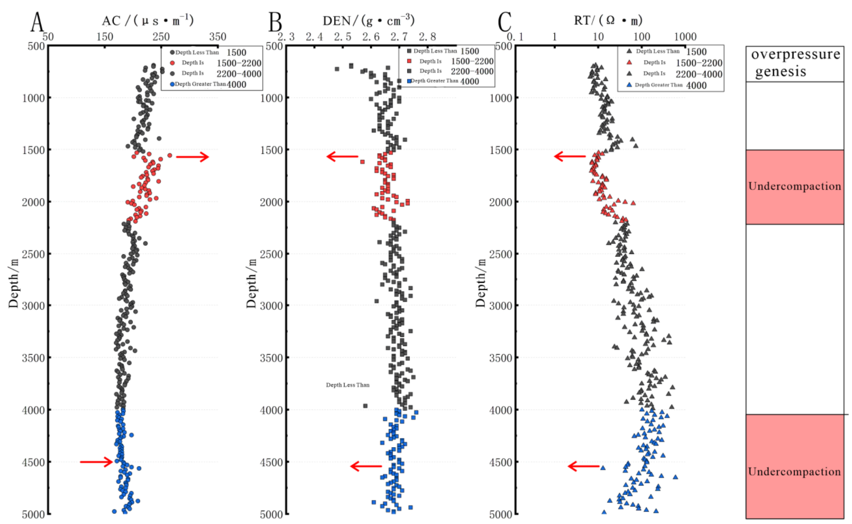

Figure 6. Logging curve combination analysis of mudstone in Well YN1

Comprehensively apply the logging curve combination analysis method and the acoustic velocity-density-effective stress crossplot method (Bowers method) to identify the causes of overpressure in typical wells.

Logging response characteristics: Undercompaction causes are characterized by a significant increase in acoustic transit time and a marked decrease in density; hydrocarbon generation pressurization causes are characterized by an increase in acoustic transit time, a significant increase in resistivity, and little change in density; tectonic compression causes are characterized by normal or decreased acoustic transit time and increased density [7-8]. For example, well YN1 (Figure 6).

Crossplot analysis: Crossplots of vertical effective stress versus acoustic velocity and acoustic velocity versus density were constructed for the typical well K2. The results show that the data points are scattered in distribution. Some deep points deviate significantly from the normal loading trend line towards the unloading direction, indicating the superposition of hydrocarbon generation pressurization. Other points exhibit high acoustic velocity and high density characteristics, consistent with tectonic compression. The crossplot analysis confirms that the overpressure in the study area is a composite genesis resulting from multiple mechanisms, primarily hydrocarbon generation and tectonic compression.

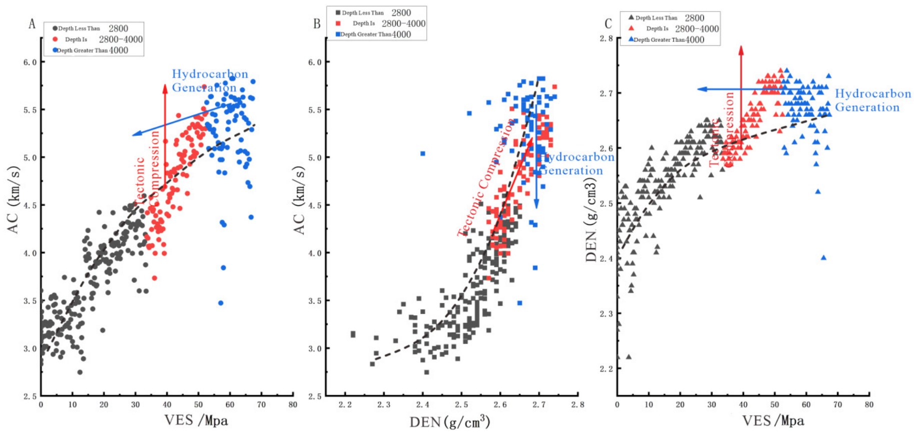

Figure 7. Identification of overpressure genesis in well K2

The overpressure genesis mechanism combinations vary across different stratigraphic horizons and structural positions: In the E_3^2 layer, undercompaction superimposed with hydrocarbon generation pressurization dominates in the depression areas, while tectonic compression contributes significantly in the compressional belts. The overpressure in the middle-shallow layers (N_1, N_2^1) mainly originates from their own undercompaction and tectonic compression, and may also involve pressure transmission from deeper sources. In areas where gypsum-salt rocks are well-developed, the characteristics are "undercompaction-dominated within the salt intervals, and a composite of undercompaction and hydrocarbon generation pressurization beneath the salt" [11].

4.3. Quantitative Evaluation of Genesis

Estimating the contribution rates of major overpressure mechanisms based on geological models:

Undercompaction contribution (ΔP_1): Calculated using the principle of the equivalent depth method. Studies show that undercompaction is the most important controlling factor for overpressure formation in the northwestern Qaidam Basin, with an average contribution rate of approximately 60% [7].

ISSN: 2688-8645

Tectonic compression contribution (ΔP_2): Estimated under the assumption of a completely closed system. The contribution rate is about 20%–30% [7].

Hydrocarbon generation contribution (ΔP_3): Estimated based on hydrocarbon generation volume and sealing models. Most studies suggest its contribution is relatively small, generally below 10%–15%. However, in areas with high-quality source rocks sealed by gypsum-salt layers (e.g., beneath the salt in Yingxi), its contribution can increase significantly [7-8, 11].

Therefore, the abnormal overpressure in the northwestern Qaidam Basin results from the superposition of multiple factors—"sedimentation-hydrocarbon generation-tectonics"—with undercompaction as the dominant mechanism, and tectonic compression and hydrocarbon generation serving as important superimposed and enhancing factors.

5. Evolution of Abnormal High Pressure and its Controlling Effects on Hydrocarbon Accumulation

5.1. Restoration of Pressure Evolution History

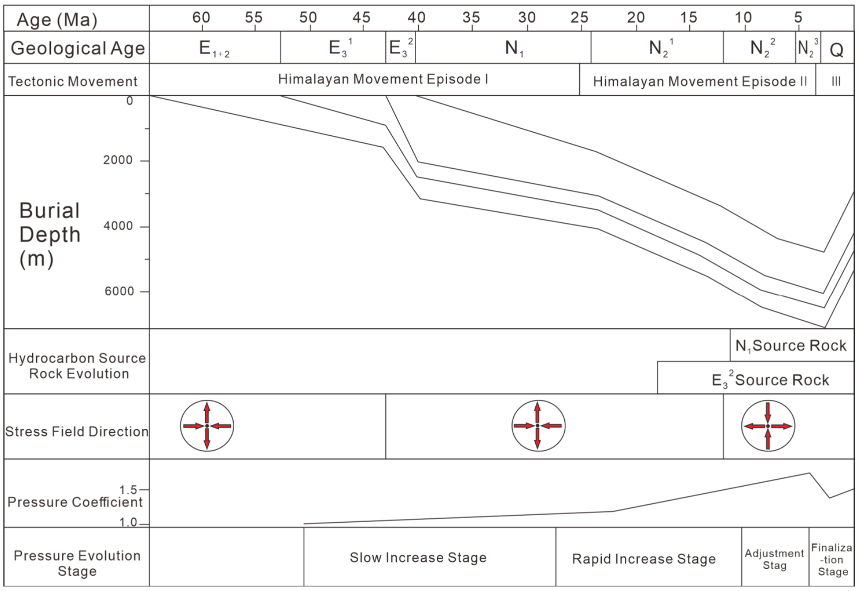

Figure 8. Pressure Evolution Model Diagram

Using the PetroMod 1D basin modeling software, the pressure evolution history was restored for four key wells: Jian-3 (Mangya Depression), Liang-3 (Xiaoliangshan Depression), Nan-10 (Nanyishan Structure), and You-6 (Altun Mountain Front Belt). The model input complete stratigraphic sequences, lithology, paleo-heat flow models, source rock geochemical parameters, and key erosion events, and was calibrated using measured Ro and pressure data.

Simulation results indicate that the overpressure evolution in the northwestern Qaidam Basin can be divided into four stages: 1) Early slow-increase stage (E_3^2-N_1): Dominated by undercompaction, forming initial weak overpressure. 2) Mid-term rapid-increase stage (N_2^1-N_2^3): Hydrocarbon generation becomes fully activated, compounding with ongoing compaction, leading to a rapid increase in overpressure intensity and extent. This is the main formative period of the overpressure system. 3) Late adjustment stage (end of N_2^3-early Q): Intense tectonic uplift causes local pressure release. 4) Finalization stage (Q-present): Late-stage sedimentary loading combined with ongoing hydrocarbon generation/compression leads to the final stabilization of the overpressure system following the adjusted framework. Different structural units exhibit distinct evolutionary paths: depression areas show continuous pressurization; uplift areas exhibit an episodic cycle of "pressurization - pressure release -

repressurization"; and strong compressional belts in the foreland area are characterized by late-stage compression-dominated rapid pressurization.

5.2. Controlling Effects on Hydrocarbon Accumulation

The overpressure system plays a crucial controlling role in hydrocarbon migration and accumulation in the northwestern Qaidam Basin:

Providing migration driving force: Overpressure is the core driving force for hydrocarbon migration. The accumulation of overpressure within source rocks can lead to episodic micro-fracture hydrocarbon expulsion; the excess pressure difference between source and reservoir (simulations show it can reach 10-20 MPa) provides ample driving force for secondary hydrocarbon migration.

Controlling accumulation space: Overpressure compartments control the vertical distribution of hydrocarbons. Gypsum-salt rocks and tight mudstones form the compartment top seal, while the strong overpressure within the compartment itself constitutes an efficient pressure seal, facilitating the formation of high-pressure primary hydrocarbon reservoirs (e.g., the deep reservoirs in Nanyishan). The episodic opening of compartment boundaries (faults) allows hydrocarbons to accumulate in secondary reservoirs within the normal-pressure system outside the compartment, forming a distribution pattern of "overpressure below, normal pressure above" [8, 13].

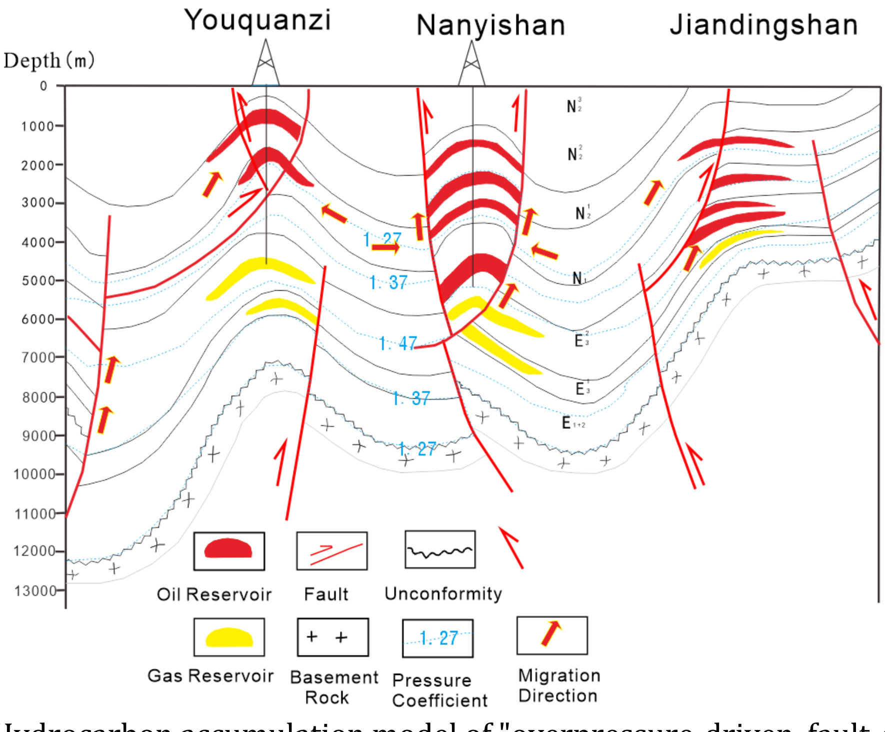

Figure 9. Hydrocarbon accumulation model of "overpressure-driven, fault-conducted, compartment/trap accumulation" in the northwestern Qaidam Basin

Improving reservoir properties: Overpressure inhibits mechanical compaction by reducing effective stress, preserving primary porosity; the high-pressure fluid environment may promote dissolution; when overpressure accumulates to the rock fracture pressure, it can generate micro-fractures, effectively improving the flow capacity of deep tight reservoirs.

Coupling to form accumulation models: Overpressure evolution is highly coupled with hydrocarbon charging episodes. The main pressurization period due to hydrocarbon generation (N_2^1-N_2^3) is also the main hydrocarbon charging period. Overpressure accumulation triggers episodic fault opening, forming preferential migration pathways. Ultimately, driven by overpressure, hydrocarbons migrate along faults and are trapped in reservoirs protected by overpressure, either within overpressure compartments or structural traps, forming the composite accumulation model in the study area: "overpressure-driven, fault-conducted, compartment/trap accumulation".

6. Conclusion

Abnormal overpressure is widely developed in the Cenozoic strata of the northwestern Qaidam Basin. Vertically, it exhibits a four-segment zoning pattern: "shallow low pressure, middle normal pressure, middle-deep overpressure, and deep strong pressure." Horizontally, the overpressure centers are coupled with sedimentary centers and migrate eastward following the eastward migration of the sedimentary center since the Cenozoic. The upper member of the Lower Ganchaigou Formation (E_3^2) is the main horizon for overpressure development.

The overpressure in the study area results from the composite effects of multiple factors, including undercompaction, tectonic compression, and hydrocarbon generation. Quantitative evaluation indicates that undercompaction is the dominant factor (contribution rate 60%), followed by tectonic compression (20%-30%), with hydrocarbon generation also contributing (<10%-15%). The widely developed gypsum-salt rocks play a key indirect role in the formation and preservation of the overpressure system by enhancing sealing and promoting hydrocarbon generation.

The overpressure evolution has undergone a dynamic process of early compaction-induced pressurization, mid-term rapid increase due to hydrocarbon generation, and late-stage adjustment and finalization, controlled by key tectonic episodes. The abnormal overpressure provides a crucial driving force for hydrocarbon migration. The pressure compartments formed by overpressure control hydrocarbon accumulation space and improve the physical properties of deep reservoirs. Ultimately, this couples to form a hydrocarbon accumulation model characterized by "overpressure-driven, fault-conducted, compartment/trap accumulation."

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