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Conventional–Unconventional Hydrocarbon Accumulation Within a Tectonically Reworked Whole Petroleum System: Insights from the Kuqa Depression, Tarim Basin, NW China

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Abstract

Understanding hydrocarbon accumulation in deep and ultra-deep tectonically active basins demands an integrated evaluation of conventional and unconventional petroleum systems. The Kuqa Depression, a gas-prone foreland basin along the northern margin of the Tarim Basin, serves as an ideal case for investigating hydrocarbon enrichment mechanisms within a tectonically reworked Whole Petroleum System. Through burial and thermal history reconstruction, structural analysis, and petroleum-system evaluation, this study elucidates the evolution of hydrocarbon generation, redistribution, and retention. The results reveal that rapid Neogene-Quaternary burial accelerated the maturation of Triassic–Jurassic source rocks, triggering concentrated gas generation and widespread overpressure development. Successive foreland deformation has persistently modified reservoirs, migration pathways, and trap geometries, resulting in large-scale hydrocarbon redistribution via fault–fracture networks. Conventional and unconventional accumulations share common source kitchens, burial histories, pressure systems, and tectonic controls, but differ in hydrocarbon retention mechanisms. Conventional accumulations are dominated by migration processes, whereas unconventional accumulations are governed by retention processes. A generation–redistribution–retention framework is proposed to explain hydrocarbon enrichment within a tectonically reworked Whole Petroleum System. This framework provides a unified interpretation of conventional–unconventional hydrocarbon accumulation in the Kuqa Depression and offers insights for deep and ultra-deep petroleum exploration in tectonically active basins.

Keywords: whole petroleum system; tectonic reworking; source–reservoir coupling; conventional–unconventional accumulation; Kuqa Depression

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1. Introduction

Conventional and unconventional hydrocarbon accumulations have traditionally been investigated as independent system during exploration. However, growing geological evidence demonstrates that the two types of accumulations generally share source kitchens, burial histories, pressure systems, and tectonic controls, and therefore should be evaluated

within an integrated petroleum-system framework [1–3]. Updated advances in the theories of Whole Petroleum Systems and integrated conventional–unconventional petroleum systems further clarify that diverse hydrocarbon accumulations are alternative geological expressions of a unified petroleum system, rather than discrete resource categories.

Integrated petroleum systems in tectonically active basins exhibit particularly complex evolutionary characteristics, such as hydrocarbon generation, reservoir modification, structural deformation, and fluid migration typically occur simultaneously and spatially overlapped. In such settings, petroleum-system architecture may be continuously modified by tectonic reworking, leading to significant changes in hydrocarbon distribution and preservation. Understanding the control mechanisms of tectonic activities on hydrocarbon generation, redistribution, and retention remains a key challenge in petroleum geology.

The Kuqa Depression, located along the northern margin of the Tarim Basin, is one of the most prolific gas-producing regions in China [4]. The basin hosts giant conventional gas accumulations in the Keshen–Kela Deep Gas Province and also contains abundant unconventional hydrocarbon resources, including tight-gas, shale-gas, and coal-derived gas systems [5–7]. Previous studies have focused on source-rock evolution, structural deformation, overpressure development, reservoir quality, and hydrocarbon accumulation. Nevertheless, most previous studies focus on isolated petroleum-system elements or single reservoir types, and the relationships between conventional and unconventional accumulations within a unified petroleum-system framework remain inadequately understood [8–10].

This study integrates quantitative to semi-quantitative techniques, including burial and thermal history reconstruction, structural kinematic and geometric analysis, fluid inclusion dating, reservoir diagenetic sequence analysis, and quantitative evaluation of hydrocarbon migration and redistribution. In addition, this study transcends the conventional petroleum geology approach of "generation–migration–accumulation" and proposes, from the perspective of "source–reservoir coupling and sequential accumulation," an investigation into the enrichment patterns of both conventional and unconventional resources within the framework of the Tectonically Reworked Whole Petroleum System [11–14]. Special emphasis is placed on the effects of rapid burial, multi-stage tectonic reworking, hydrocarbon redistribution, and differentiated retention processes. Based on these analyses, a generation–redistribution–retention framework is proposed to provide a unified interpretation of hydrocarbon enrichment in the basin and to offer insights for deep and ultra-deep petroleum exploration in tectonically active basins.

2. Geological Setting

2.1. Tectonic Framework

The Kuqa Depression is located along the northern margin of the Tarim Basin and forms part of the foreland basin system developed along the southern flank of the Tianshan Orogenic Belt (Figure 1). The depression is bounded by the Southern Tianshan fold-and-thrust belt to the north and transitions southward into the central uplifted regions of the Tarim Basin.

The present-day structural architecture of the Kuqa Depression is predominantly shaped by late Cenozoic intracontinental shortening, driven by far-field tectonic responses to the ongoing collision between the Indian and Eurasian Plates. Since the Miocene, strong latitudinal compression has produced a series of longitudinal-trending fold-and-thrust belts, resulting in one of the most intensely deformed foreland basin systems in western China [15,16].

Structurally, the depression can be subdivided into several tectonic unit subdivisions, including the northern monocline belt, the Kelasu structural belt, the Baicheng Sag, the

Yangxia Sag, the Qiulitage structural belt, the Yiqikelike Tectonic Belt and the South Slope Belt (Figure 1). Among these units, the Kelasu structural belt hosts the giant gas accumulations of the Keshen–Kela Deep Gas Province and represents the most important hydrocarbon exploration domain within the basin.

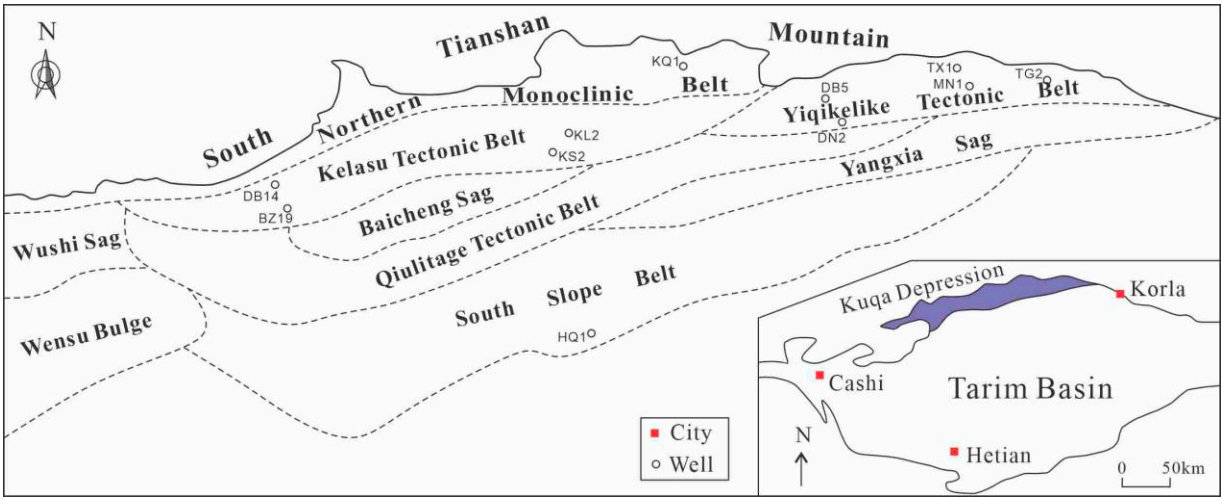

Figure 1. Structural framework and tectonic subdivision of the Kuqa Depression, northern Tarim Basin (modified from [17]).

The Kuqa Depression is typified by well-developed thin-skinned thrust structures and controlled by regional evaporite detachment horizons. Multi-stage compressional tectonic events have produced complex structural geometries, including fault-propagation folds, fault-bend folds, imbricate thrust systems, duplex structures, and faulted anticlines. These structures exert fundamental controls on hydrocarbon migration pathways, trap development, reservoir fracturing, and hydrocarbon preservation [18,19].

2.2. Stratigraphic Framework

The sedimentary succession of the Kuqa Depression records the complete tectonic transition from a Mesozoic intracontinental basin to a Cenozoic foreland basin (Figure 2). The basin preserves a relatively continuous Triassic–Quaternary stratigraphic successionn with a maximum local sedimentary thickness exceeding 12 km [20].

Triassic strata are dominated by fluvial, deltaic, and lacustrine deposits. Organic-rich mudstones developed during this period constitute one of the major hydrocarbon source-rock intervals in the basin. Jurassic successions comprise extensive coal-bearing fluvial and lacustrine deposits, including thick coal seams, carbonaceous mudstones, and dark mudstones that represent the principal source rocks for natural gas generation.

Cretaceous strata consist predominantly of continental clastic deposits, including sandstones, mudstones, and locally developed conglomerates. These units form important reservoir intervals in some structural domains. During the Paleogene, extensive evaporite sequences were deposited in restricted lacustrine environments. These evaporites subsequently played significant roles in structural deformation and conventional hydrocarbon preservation.

Neogene deposits are dominated by thick continental clastic successions. Particularly noteworthy are the Pliocene Kuqa Formation and the Quaternary Xiyu Formation, which locally exceed several kilometers in thickness. Rapid accumulation of these sediments during late Cenozoic foreland subsidence provided the principal burial load responsible for the deep burial and accelerated maturation of Triassic–Jurassic source rocks [21,22].

Overall, the integrated stratigraphic succession records long-term sedimentation and progressive tectonic subsidence during foreland basin evolution, laying the geological foundation for the evolution of a deeply buried petroleum system.

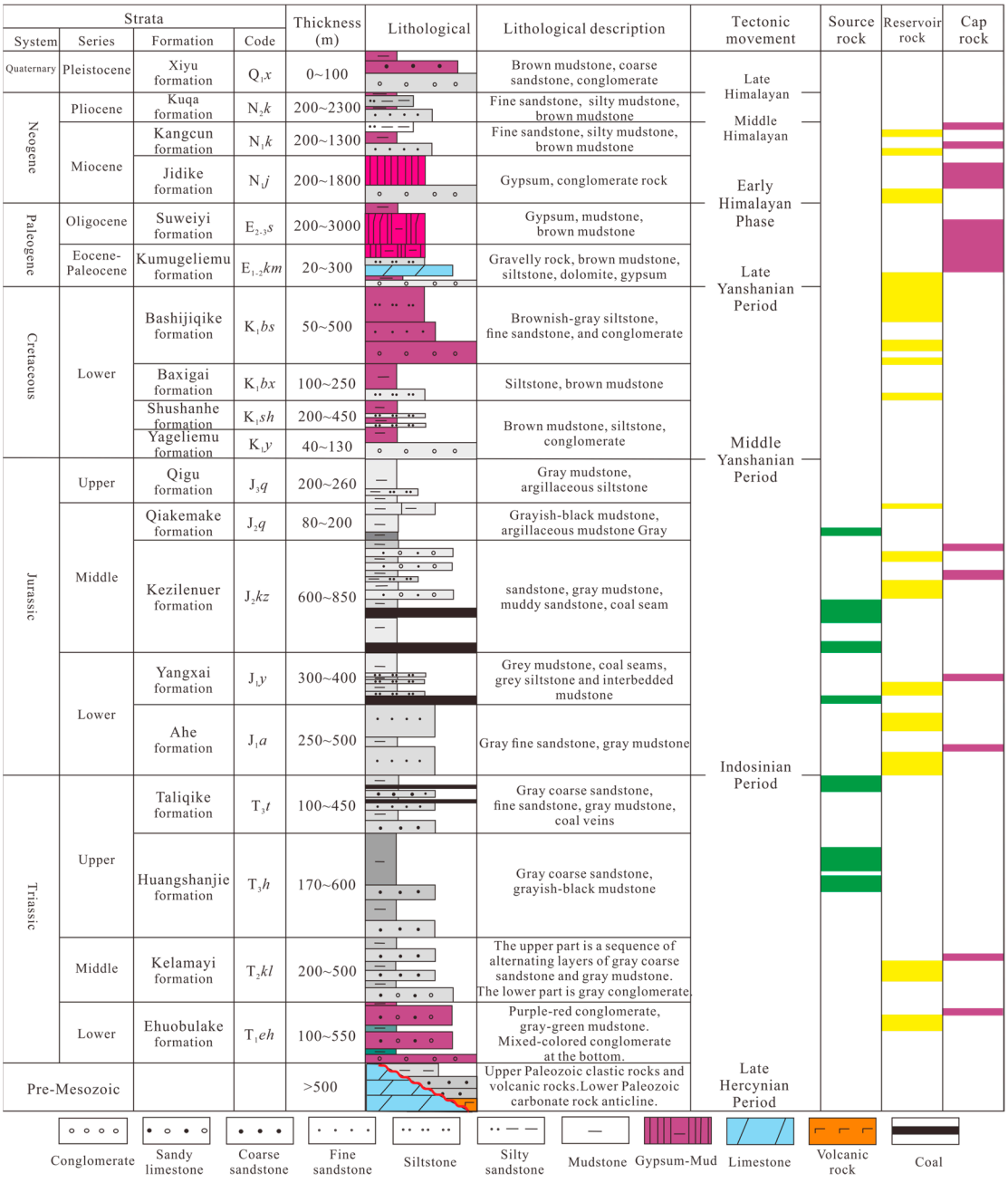

Figure 2. Generalized Triassic–Quaternary stratigraphic framework and petroleum-system elements of the Kuqa Depression (modified from [23]).

2.3. Petroleum Geological Characteristics

2.3.1. Source Rocks

Hydrocarbon generation within the Kuqa Depression is primarily sourced from Triassic and Jurassic source rocks [24]. The Triassic source rocks are dominated by lacustrine mudstones and carbonaceous mudstones, whereas the Jurassic source-rock system includes thick coal measures, carbonaceous mudstones, and dark lacustrine mudstones [25].

Organic matter within these sequences is dominated by Type II and Type III kerogens, implying mixed terrestrial and lacustrine organic inputs. Total organic carbon (TOC)

content generally ranges from 1% to 8%, with notably higher values in coal-bearing intervals. These source rocks possess substantial hydrocarbon-generation potential and constitute the principal gas source for both conventional and unconventional accumulations in the study area.

Thermal evolution studies indicate that most Triassic–Jurassic source rocks have reached high-maturity to over-mature stages, particularly within the deep depocenters and structural belts affected by rapid burial in the Cenozoic (Figure 3). Consequently, the basin is characterized by widespread gas generation and gas-prone hydrocarbon systems.

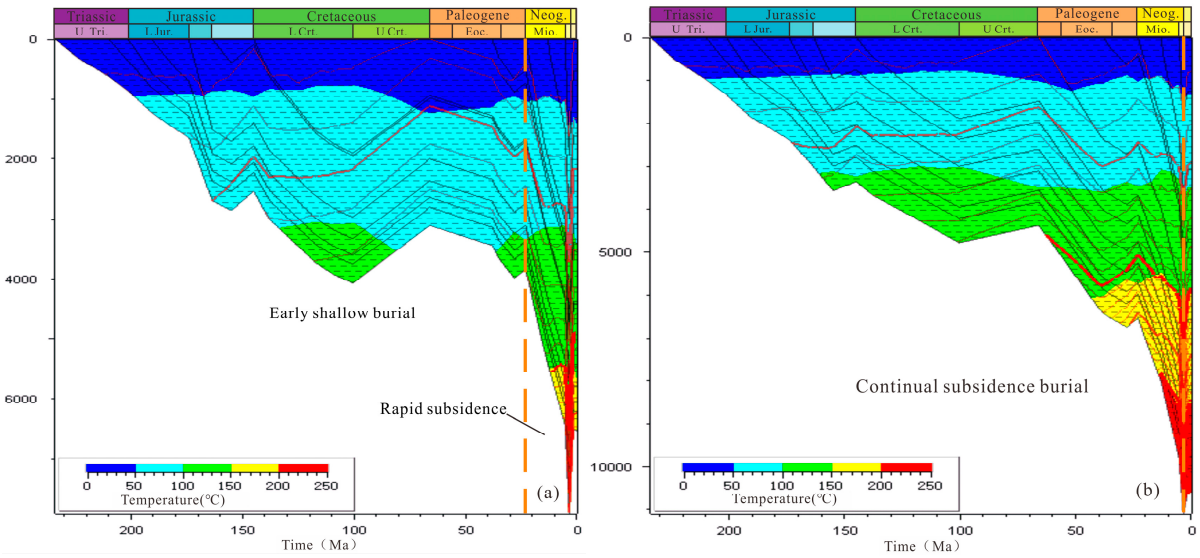

Figure 3. Burial history of representative wells in the northern structural belt of the Kuqa Depression. (**a**) Well Dibei-5, Dibei segment; (**b**) Well Keshen-2, Kubei segment.

2.3.2. Reservoir Systems

Reservoirs within the Kuqa Depression are highly diverse and include both conventional and unconventional systems (Table 1).

Table 1. Classification Table of Conventional and Unconventional Reservoir Types in Kuqa Depression.

Reservoir Type	Formation Mechanism	Physical Property Characteristic	Example
Conventional tight gas reservoir	Fracture network development zone	Porosity of 5–12% Permeability < 0.1 mD	Tuge2
Unconventional shale gas reservoir	Dense matrix sealing	Porosity < 6% Permeability < 0.01 mD	Yishen1
Transitionary reservoir	Fracture-matrix composite	Porosity of 8–18% High heterogeneity	Mingnan1

Conventional reservoirs are primarily developed in deeply buried sandstone strata of the Triassic, Jurassic, Cretaceous, and Paleogene sequences. These reservoirs have experienced extensive compaction and cementation during deep burial and are generally characterized by low porosity and low permeability [22]. However, tectonic fractures significantly improve local reservoir quality, providing effective storage space and migration conduits for hydrocarbon charging.

Unconventional reservoirs include tight sandstones, organic-rich shales, coal seams, and associated low-permeability intervals. Storage space within these systems is dominated by micropores, nanopores, organic-matter pores, and microfractures. These unconventional

intervals typically exhibit source–reservoir paragenesis, with hydrocarbons retained within low-permeability rock matrices without long-distance migration.

As a result, reservoir development in the basin forms a continuous spectrum extending from fracture-enhanced tight conventional reservoirs to in situ self-sourced unconventional reservoirs.

2.4. Integrated Petroleum System

The depression accommodates multiple hydrocarbon accumulation types during multi-stage tectonic movement [18,19], including large-scale conventional gas fields, tight gas, coal-derived gas, shale gas, and composite hybrid accumulations. Advancements in petroleum-system research increasingly infer that conventional and unconventional hydrocarbon accumulations commonly represent different manifestations of a single petroleum system rather than independent geological entities [13,14]. This perspective is particularly applicable to the Kuqa Depression.

Both conventional and unconventional hydrocarbons within the Kuqa Depression are predominantly sourced from the same Triassic–Jurassic source-rock system and share a consistent burial history, thermal evolution pathway, pressure regime, and tectonic framework. Hydrocarbons generated within deep source kitchens may either migrate into structurally controlled traps to form conventional accumulations or remain within source rocks and adjacent tight intervals to form unconventional accumulations. From this perspective, the Kuqa Depression contains a unified hydrocarbon system characterized by three interconnected components: (1) pervasive hydrocarbon generation from deeply buried, high-maturity Triassic–Jurassic source rocks, (2) large-scale hydrocarbon migration and secondary redistribution via overpressure-driven fault–fracture systems, and (3) differential hydrocarbon retention within migration-dominated conventional traps and in situ retention-dominated unconventional reservoirs. The coexistence of these processes indicates that conventional and unconventional accumulations should be evaluated within the Whole Petroleum System framework.

3. Evolution of the Petroleum-System Elements

The evolution of the petroleum system in the Kuqa Depression is fundamentally controlled by the interplay between long-term basin subsidence and late-stage foreland deformation. Unlike relatively stable petroleum systems that evolve progressively under continuous burial, the Kuqa Depression experienced significant tectonic reorganization during the late Cenozoic.

3.1. Burial and Thermal Evolution

The burial and thermal evolution of Triassic–Jurassic source rocks represent the primary driving mechanisms for petroleum-system development in the Kuqa Depression. Reconstructed burial histories reveal a two-stage evolutionary pattern for source rock sequences, comprising prolonged moderate burial in the early stage and rapid deep burial in the late Cenozoic (Figure 4).

During the Triassic and Jurassic, the basin developed as an intracontinental depression dominated by fluvial, deltaic, and lacustrine sedimentation. Source rocks accumulated under relatively stable tectonic conditions and experienced gradual burial. Although heat flow was comparatively high during this stage (approximately 40–55 mW/m^2), the limited burial depth restrained thermal maturation. Most source rocks remained within the immature to early mature stages ($Ro < 0.6\%$) and yielded only minor quantities of hydrocarbons.

From the Early Cretaceous to the Paleogene, continuous burial processes were interrupted by multiple episodes of tectonic uplift and erosion, leading to prominent spatial

heterogeneity in thermal evolution across the depression. Source-rock burial depths fluctuated between approximately 2 km and 4 km, while maximum paleotemperatures reached 120–140 °C. In the eastern part of the basin, including the Dibei–Tugeerming area, earlier uplift and erosion slowed thermal maturation. These events produced periods of reduced thermal evolution and delayed the onset of extensive hydrocarbon generation. In comparison, the western Kelasu–Baicheng region experienced sustained burial and locally entered the mature stage (Ro ≈ 0.7–1.0%). Consequently, hydrocarbon generation during this stage was dominated by oil generation and early gas generation, although total hydrocarbon yields remained relatively limited.

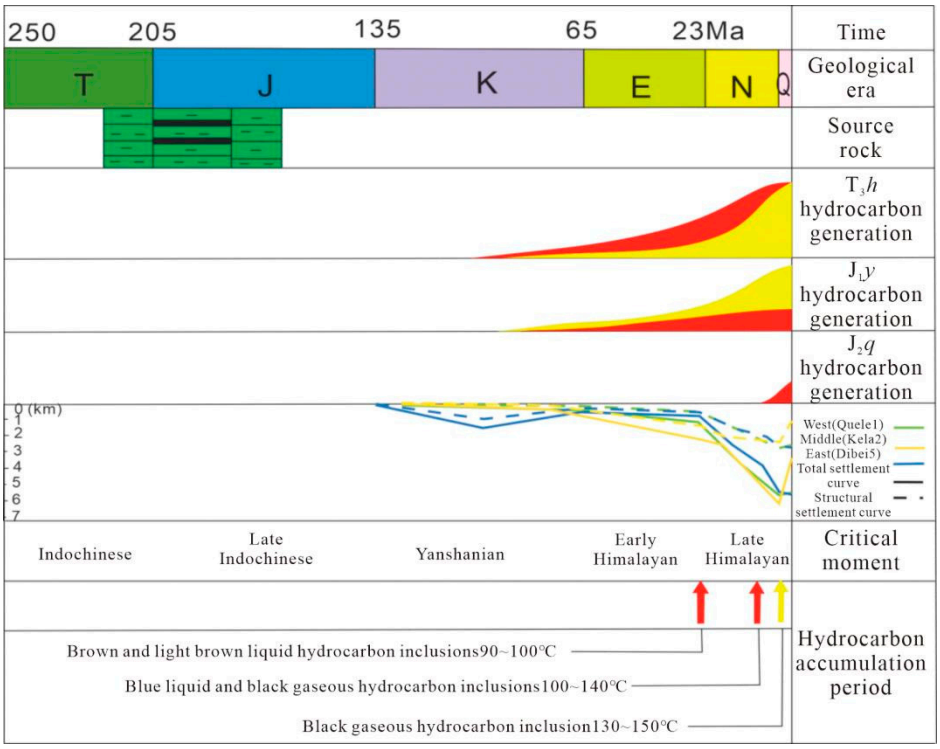

Figure 4. Thermal evolution history of Triassic–Jurassic source rocks in the Kuqa Depression. Accelerated thermal maturation and concentrated gas generation induced by late tectonic burial.

A fundamental transition occurred during the late Cenozoic. Rapid uplift of the Southern Tianshan Mountains triggered intense foreland subsidence, accompanied by the rapid accumulation of extraordinarily thick Neogene and Quaternary clastic successions. In most parts of the depression, cumulative Neogene burial exceeded several kilometers, with local thickness exceeding 5 km within a relatively limited geological interval. Such rapid subsidence drove the Triassic–Jurassic source rocks to extreme burial depths of 6–10 km. The increase in burial depth dramatically accelerated thermal maturation and resulted in maximum paleotemperatures ranging from 180 °C to 230 °C. Within a short period (less than 5 Ma), source rocks entered into high-maturity and over-mature stages and experienced large-scale gas generation. Vitrinite reflectance values commonly exceed 1.5–2.0% within the principal hydrocarbon kitchens, indicating extensive gas-prone thermal evolution.

Rapid burial exerts a critical control on hydrocarbon generation during the Late Neogene and Quaternary. Rather than following a prolonged history of gradual hydrocarbon generation, the Kuqa Depression experienced a relatively short but highly efficient phase of gas generation. This process established the material foundation for the giant gas accumulations currently discovered throughout the basin.

In summary, the burial and thermal evolution of Triassic–Jurassic source rocks in the Kuqa Depression display pronounced temporal and spatial heterogeneity. Late-stage

rapid burial not only accelerated thermal maturation but also fundamentally controlled large-scale gas generation and near-source accumulation. This mechanism provides the geological basis for ongoing exploration of ultra-deep gas resources beneath existing discoveries in the Kelasu structural belt and elsewhere within the Kuqa Depression.

3.2. Reservoir Tightening and Storage Evolution

Reservoir evolution in the Kuqa Depression reflects the combined effects of deep burial diagenesis and tectonic deformation. Progressive burial resulted in substantial reduction in reservoir porosity and permeability, transforming a large proportion of primary sandstone reservoirs into typical tight reservoirs. Meanwhile, tectonic fracturing generated additional storage space and fluid-flow pathways, producing a complex storage continuum that includes conventional pores, microfractures, and nanoscale storage domains (Figure 5).

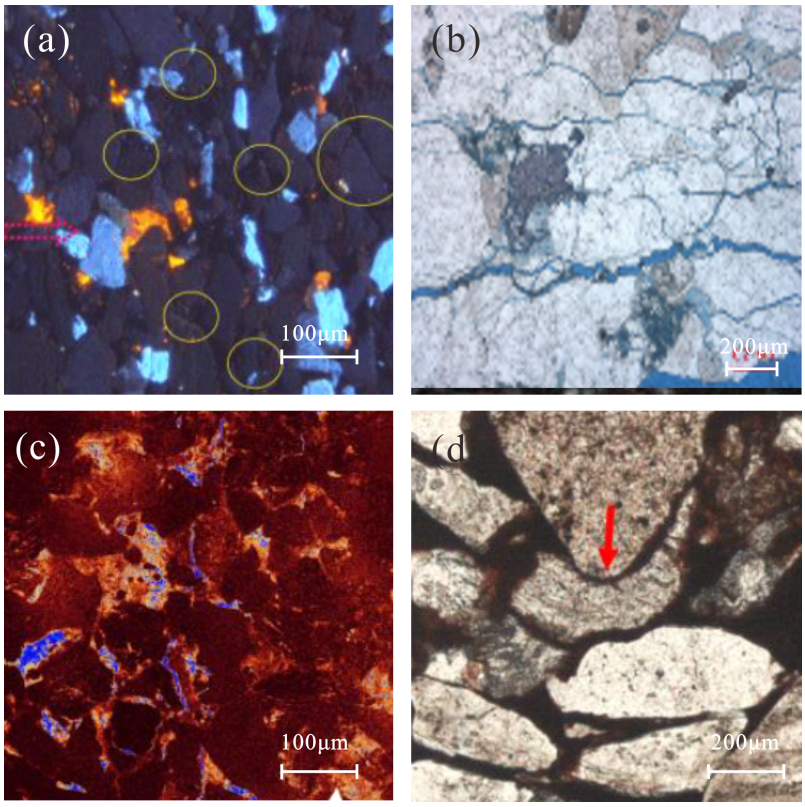

Figure 5. Tectonically induced pore-fracture systems generated during compressional deformation in the Kuqa Depression. Notes: (**a**) tight contacts between grains (yellow cicle); (**b**) Fractures improve reservoir connectivity; (**c**) intergranular dissolution pores; (**d**) Grain-scale flexure (red arrow).

Mechanical compaction serves as the dominant factor controlling reservoir deterioration during burial. Quantitative evaluations indicate that mechanical compaction alone can reduce primary porosity by over 12% when burial depth exceeds 5000 m. At greater burial depths, chemical compaction and cementation further reduced pore volume through quartz overgrowth and carbonate precipitation. In addition to vertical overburden pressure, intense horizontal compressional stresses associated with the Himalayan tectonic orogeny further intensified reservoir deterioration. Maximum principal stresses reached approximately 75–100 MPa, causing grain rotation, preferred orientation, grain breakage, and additional pore collapse. The combined influence of compaction, tectonic stress, and cementation ultimately produced deeply buried sandstone reservoirs characterized by extremely low porosity (<8%) and ultra-low permeability (<0.1 mD), representing typical tight-reservoir systems (Figure 6).

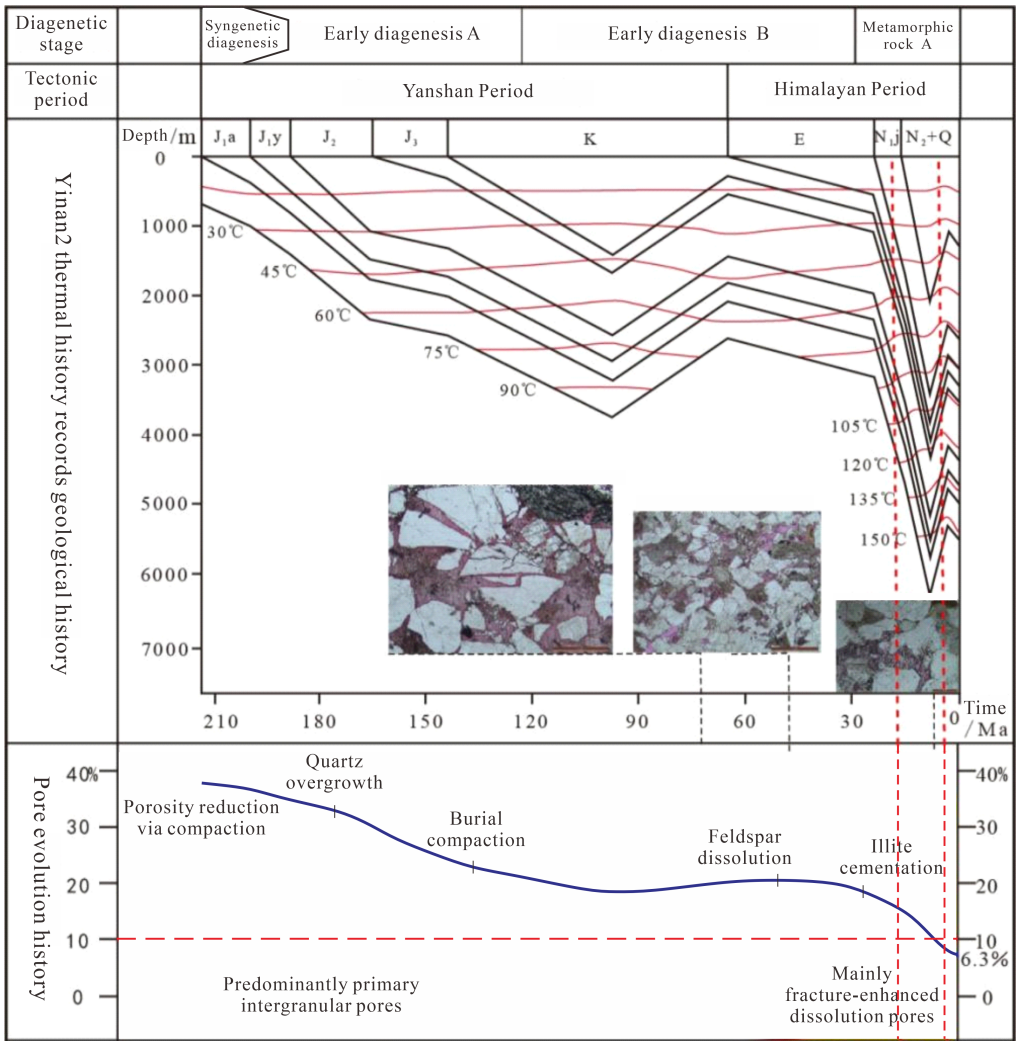

Figure 6. Evolutionary model of the Ahe Formation tight sandstone reservoir in the Dibei area.

However, reservoir evolution cannot be interpreted solely as a process of progressive quality degradation. Late-stage tectonic compression generated extensive fracture systems that partially compensated for matrix deterioration. Fracture porosity commonly contributes approximately 12–18% of total storage capacity in fractured reservoir intervals. Representative examples include the Tuge-2 well area, where porosities range from 5% to 12%, reservoir performance is primarily controlled by fracture systems and reservoir productivity is predominantly governed by fracture development. Moreover, fracturing may increase permeability by one to two orders of magnitude. In fracture-developed zones within the ultra-deep Kelasu structural belt, local permeabilities could exceed 1 mD even under extreme burial depths.

In addition to conventional sandstone reservoirs, organic-rich mudstones, coal-bearing strata, and associated tight intervals also evolved into important storage media. Hydrocarbon storage within these unconventional reservoirs occurs primarily in micropores, nanopores, organic-matter pores, adsorption sites, and microfractures, such as those encountered in the Yishen-1 well area (Figure 7).

The storage continuum concept is particularly important for understanding hydrocarbon accumulation mechanisms in the Kuqa Depression because it bridges the traditional distinction between conventional and unconventional reservoir systems. From a petroleum-system perspective, storage space in the Kuqa Depression forms a continuous spectrum extending from fracture-improved tight sandstone reservoirs to self-sourced unconven-

tional reservoirs. These storage domains are genetically related and evolved under a common burial and tectonic history.

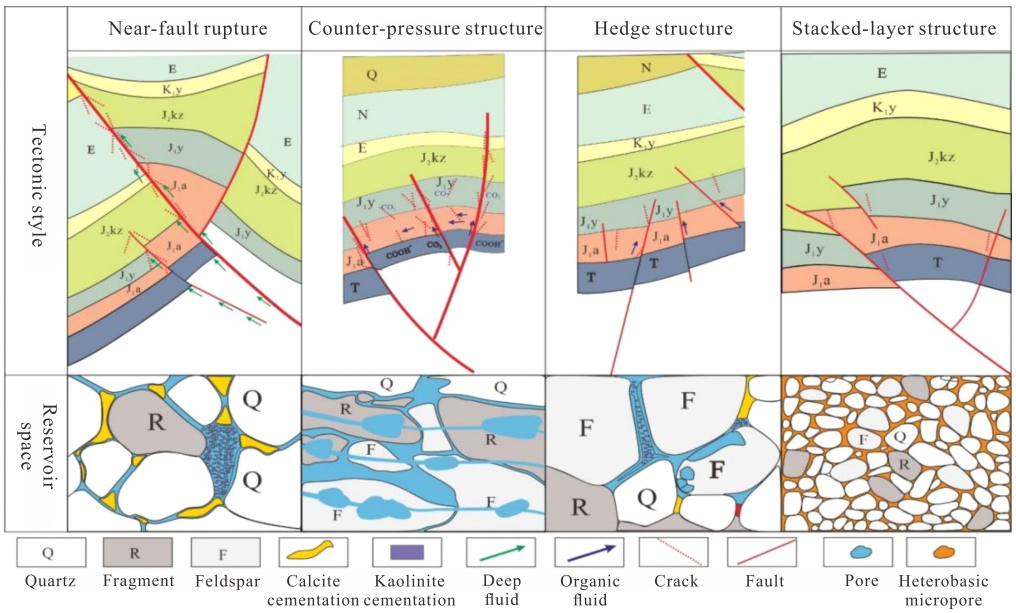

Figure 7. Structural styles, fracture systems, and their controls on reservoir development in the Kuqa Depression.

3.3. Structural Evolution and Trap Reorganization

The structural architecture of the Kuqa Depression underwent profound modification during late Cenozoic foreland deformation. Progressive shortening associated with the uplift of the Southern Tianshan Orogen generated large-scale fold-and-thrust systems that fundamentally altered the geometry of the petroleum system.

Prior to intense compression, the basin was characterized by relatively simple structural configurations controlled mainly by depositional and subsidence processes. However, continued shortening during the Neogene and Quaternary resulted in widespread development of thrust faults, fault-propagation folds, fault-bend folds, and faulted anticlines. Structural deformation had several important consequences for petroleum-system evolution.

First, tectonic deformation produced abundant structural traps that subsequently became major hydrocarbon accumulation sites. Many giant gas fields discovered in the basin occur within faulted anticlines formed during late-stage deformation. Second, tectonic deformation modified pre-existing traps and hydrocarbon accumulations. Earlier accumulations were subjected to structural adjustment, remigration, leakage, and even destruction. Consequently, present hydrocarbon distribution represents the cumulative result of repeated trap modification rather than simple preservation of original accumulations. Third, fault systems generated during compression established an important hydraulic network between source rocks and reservoirs. These structures significantly enhanced vertical hydrocarbon migration and promoted fluid redistribution throughout the basin.

Overall, structural evolution not only created hydrocarbon traps but also continuously reorganized petroleum-system architecture. The present hydrocarbon distribution pattern can be viewed as the final expression of long-term structural reorganization superimposed upon ongoing hydrocarbon generation and migration.

3.4. Hydrocarbon Migration and Redistribution

Hydrocarbon migration within the Kuqa Depression was jointly governed by overpressure evolution, fault activity, fracture and structural reorganization. Given the synchronous

occurrence of intense tectonic deformation and petroleum-system evolution, hydrocarbon migration is more appropriately described as redistribution rather than simple migration.

During the principal gas-generation stage, rapid maturation of deeply buried source rocks generated substantial volumes of natural gas and associated fluid overpressure. The elevated pore pressures reduced capillary resistance and enhanced hydrocarbon expulsion efficiency. Faults and fracture networks created during compressional deformation provided effective migration pathways connecting source kitchens with overlying reservoirs. Major thrust faults acted as regional conduits for vertical migration, whereas fracture networks facilitated local hydrocarbon transport and reservoir charging.

Hydrocarbon migration in the basin is characterized by the coexistence of short-distance and long-distance transport processes. Conventional gas accumulations generally formed through focused migration into structurally favorable traps, whereas unconventional accumulations commonly retained a substantial proportion of generated hydrocarbons within source rocks or adjacent low-permeability intervals. Progressive tectonic deformation triggered multiple phases of hydrocarbon remigration and redistribution. Early-expelled hydrocarbons were displaced into newly formed traps, while previous accumulations could be partially remobilized by fault reactivation and pressure evolution.

The present hydrocarbon distribution in Kuqa Depression reflects a dynamic redistribution process driven by the interaction among hydrocarbon generation, overpressure development, tectonic deformation, and reservoir evolution (Figure 8). This redistribution process provides the critical link between petroleum-system evolution and the formation of both conventional and unconventional hydrocarbon accumulations.

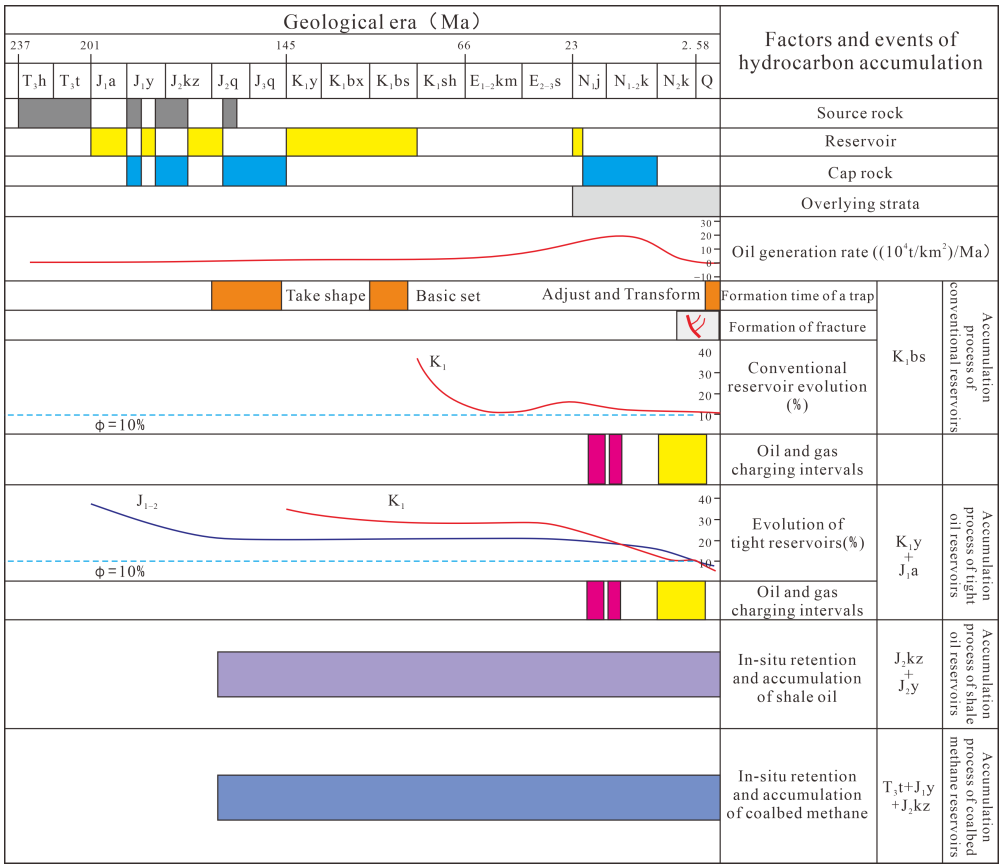

Figure 8. Hydrocarbon generation and accumulation events within the Whole Petroleum System of the Kuqa Depression.

4. Discussion

4.1. Tectonic Reworking as a Driver of Petroleum-System Evolution

Petroleum-system evolution in the Kuqa Depression demonstrates that tectonic deformation exerted far more comprehensive controls than merely forming structural traps. Rapid foreland subsidence associated with uplift of the Southern Tianshan Mountains accelerated the burial and thermal maturation of Triassic–Jurassic source rocks, ultimately inducing concentrated gas generation and widespread overpressure development. At the same time, compressional deformation modified reservoir properties through compaction and fracture formation, reorganized migration pathways through fault growth and reactivation, and continuously altered trap geometries during structural evolution.

As a consequence, source rocks, reservoirs, traps, migration pathways, and accumulation domains did not evolve independently. Instead, all geological elements were progressively modified during basin deformation. The present hydrocarbon distribution pattern therefore reflects the cumulative effects of tectonic reworking superimposed on ongoing hydrocarbon generation and migration (Figure 9).

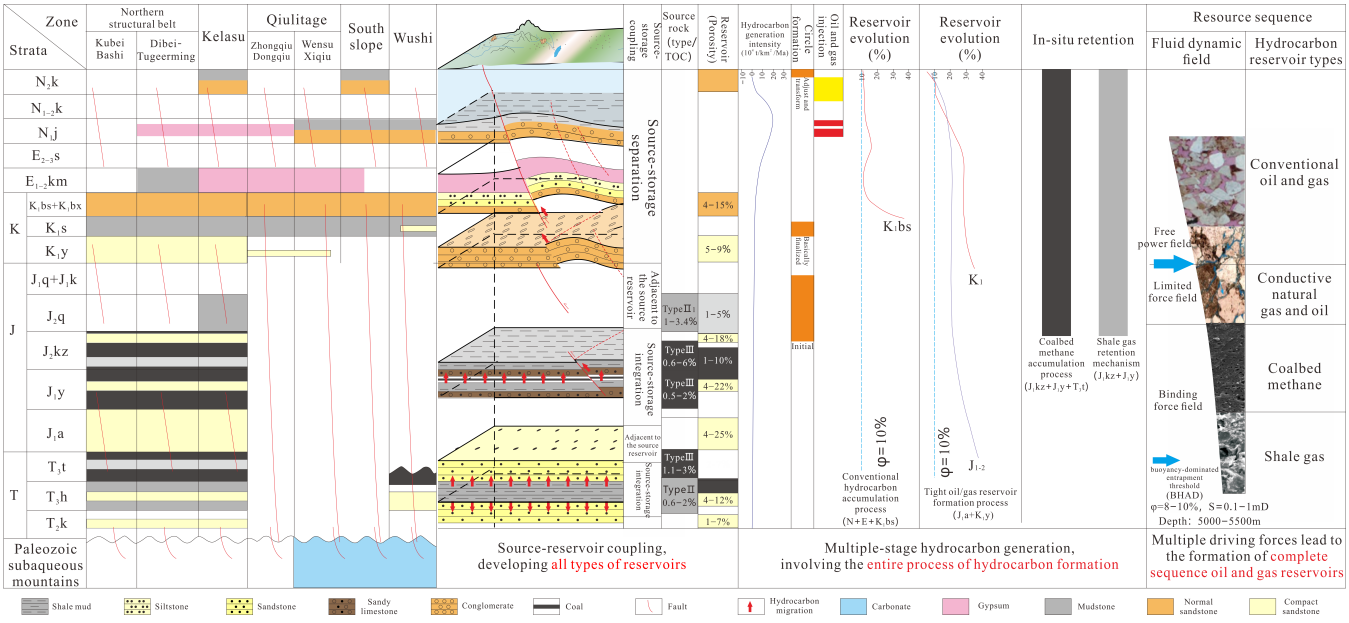

Figure 9. Full-spectrum hydrocarbon accumulation model of the Whole Petroleum System in the Kuqa Depression.

This evolutionary pattern differs significantly from that of relatively stable cratonic basins, where hydrocarbon generation, migration, and accumulation are commonly treated as sequential processes. In the Kuqa Depression, tectonic deformation acted as a dynamic force that continuously reshaped petroleum-system architecture. Tectonic reworking should therefore be regarded as a primary driver of petroleum-system evolution rather than a late-stage overprint on pre-existing hydrocarbon accumulations.

4.2. Mechanisms Controlling Conventional–Unconventional Hydrocarbon Accumulation

The coexistence of conventional and unconventional hydrocarbon accumulations is one of the most distinctive characteristics of the Kuqa petroleum system. Although these accumulations exhibit contrasting storage and preservation styles, they share common source kitchens, burial histories, pressure systems, and tectonic controls.

Rapid late-stage burial generated large volumes of natural gas and established extensive overpressure systems that enhanced hydrocarbon expulsion and migration efficiency. Simultaneously, deep burial and tectonic deformation caused widespread reservoir tighten-

ing while generating fracture networks that locally improved storage capacity and fluid connectivity. Structural reorganization further promoted hydrocarbon redistribution by linking source rocks, reservoirs, and accumulation domains through fault–fracture systems (Figure 10).

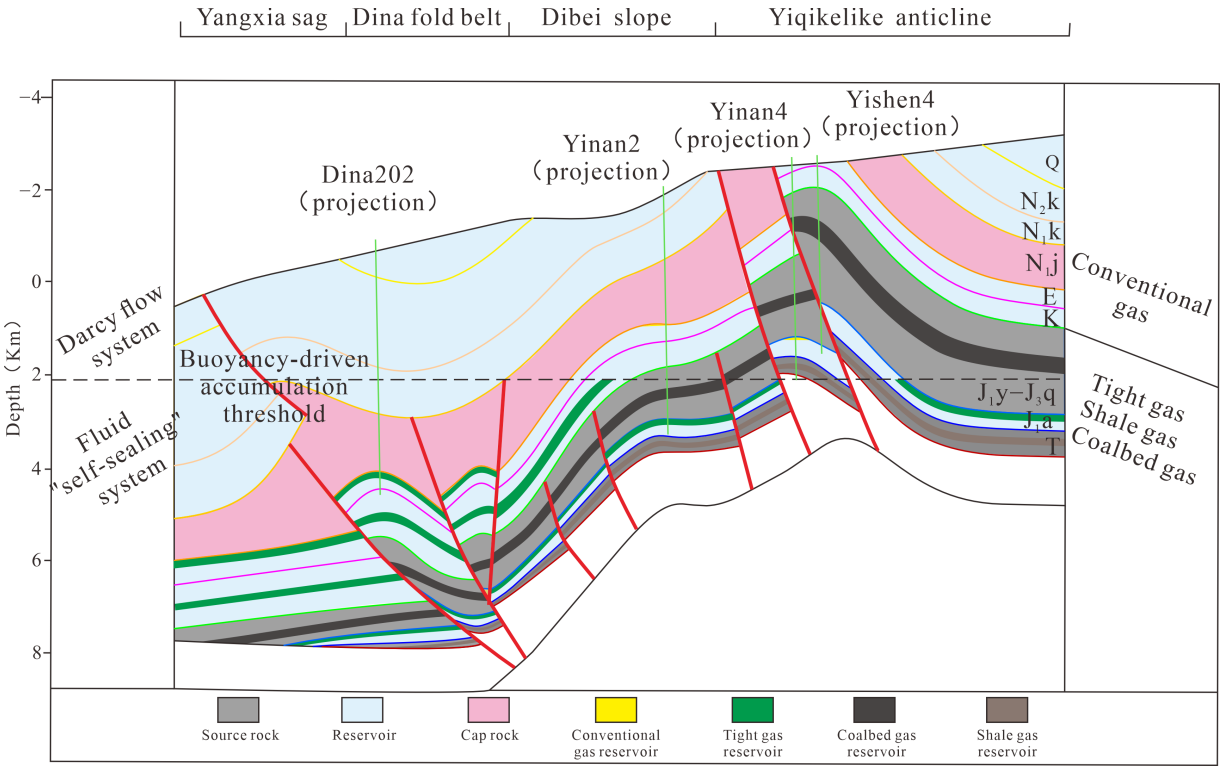

Figure 10. Structural cross-section of the Triassic–Jurassic Whole Petroleum System in the Dibei area, Kuqa Depression.

Under this common geological framework, hydrocarbons followed two principal accumulation pathways. The first pathway involved hydrocarbon migration into structurally favorable reservoirs, leading to conventional gas accumulations controlled by structural trapping and seal effectiveness. The second pathway involved hydrocarbon retention within source rocks and adjacent low-permeability reservoirs, resulting in unconventional accumulations controlled by self-sourcing, self-storage, capillary sealing, adsorption, and overpressure preservation.

The essential distinction between conventional and unconventional accumulations therefore lies not in hydrocarbon origin, but in the degree of hydrocarbon migration and the mechanisms of hydrocarbon retention. Both accumulation styles represent different expressions of a single petroleum system that evolved under common geological constraints.

4.3. Framework for Tectonically Reworked Whole Petroleum System

The results of this study suggest that hydrocarbon enrichment in the Kuqa Depression can be understood within a generation–redistribution–retention framework.

Hydrocarbon generation was initiated by rapid late-stage burial, which accelerated thermal maturation of Triassic–Jurassic source rocks and produced large volumes of methane-rich gas together with widespread overpressure. This process established the material foundation of the petroleum system.

Subsequent tectonic deformation continuously reorganized petroleum-system architecture. Fault growth, fracture development, trap modification, and pressure evolution promoted repeated hydrocarbon migration, remigration, and fluid redistribution. As

a result, present-day hydrocarbon accumulations represent the cumulative outcome of long-term structural reorganization and dynamic fluid movement.

Hydrocarbon retention ultimately determined the distribution of conventional and unconventional resources. Conventional accumulations developed where hydrocarbons migrated into structurally favorable reservoirs and were preserved by effective trapping mechanisms. In contrast, unconventional accumulations formed where hydrocarbons remained within source rocks or adjacent low-permeability reservoirs and were retained through self-sealing and overpressure-assisted preservation.

Accordingly, hydrocarbon enrichment in the Kuqa Depression can be interpreted as a dynamic generation–redistribution–retention process operating within a tectonically reworked Whole Petroleum System. This framework integrates conventional and unconventional accumulations into a unified petroleum-system model and provides a conceptual basis for understanding hydrocarbon occurrence in deeply buried tectonically active basins (Figure 11).

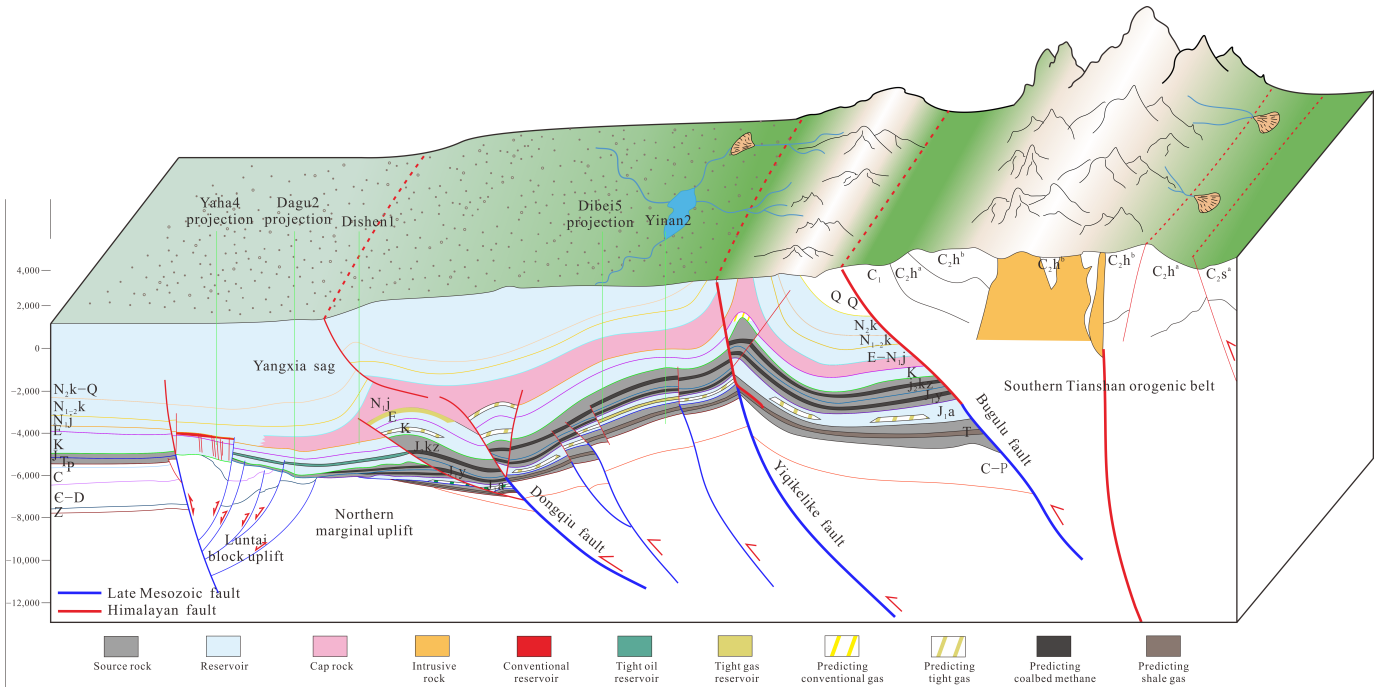

Figure 11. Conceptual model of the Triassic–Jurassic Whole Petroleum System in the Kubei–Dibei segment of the Kuqa Depression.

4.4. Implications for Deep and Ultra-Deep Hydrocarbon Exploration

Deep and ultra-deep hydrocarbon exploration is increasingly becoming a major frontier for petroleum resource development worldwide. However, exploration success in these environments remains challenging because reservoir quality commonly deteriorates with increasing burial depth and tectonic complexity often obscures petroleum-system relationships.

The Kuqa Depression provides a typical case illustrating how tectonic reworking fundamentally modifies the evolution of the petroleum system at the base scale. The results of this study demonstrate that deep and ultra-deep hydrocarbon enrichment is not simply controlled by burial depth or reservoir quality, but by the coupled evolution of hydrocarbon generation, tectonic deformation, fluid redistribution, and hydrocarbon retention. Rapid burial and widespread overpressure can sustain efficient hydrocarbon generation and migration even under extreme burial conditions, whereas tectonically induced fracture systems may significantly enhance the effectiveness of otherwise tight

reservoirs. Consequently, deeply buried petroleum systems should be evaluated as dynamically evolving systems rather than through isolated assessments of source rocks, reservoirs, or structural traps.

The integrated petroleum-system perspective developed in this study also highlights the importance of joint evaluation of conventional and unconventional resources. In tectonically active basins, hydrocarbons may be redistributed into both structurally trapped reservoirs and adjacent low-permeability storage domains, forming a continuous accumulation spectrum rather than discrete resource types. Therefore, future exploration strategies should focus on the dynamic interactions among hydrocarbon generation, redistribution, and retention, particularly in deeply buried foreland basins characterized by rapid burial, strong tectonic reworking, and widespread overpressure development. Future exploration programs should therefore consider the entire hydrocarbon continuum rather than focusing solely on discrete structural traps.

5. Conclusions

The Tectonically Reworked Whole Petroleum System (TRWPS) differs fundamentally from conventional Whole Petroleum Systems (WPS) developed in stable subsidence settings. Its distinctive geological characteristics are refined as follows:

Multi-stage tectonic reworking represents the core driver governing the evolution of the Whole Petroleum System in the Kuqa Depression. Tectonic activities not only create structural traps but also comprehensively reshape all essential petroleum-system elements. As a persistent dynamic factor throughout hydrocarbon generation, migration, accumulation, and preservation, multi-phase tectonic reworking ultimately controls differential hydrocarbon enrichment in the basin.

Intense tectonic reworking during the late Cenozoic triggered rapid burial, providing an indispensable material basis and dynamic conditions for large-scale ultra-deep gas enrichment in the Kuqa Depression. This distinctive model of late-stage concentrated gas generation fundamentally differentiates the Kuqa petroleum system from those of stably subsiding basins, establishing a critical geological foundation for the extensive co-accumulation of deep conventional and unconventional natural gas resources.

The proposed "generation–redistribution–retention" theoretical framework takes dynamic tectonic reworking as its primary controlling constraint. It clarifies the coupled geological relationships whereby rapid burial principally accounts for the differential distribution of conventional and unconventional hydrocarbon reservoirs. This framework effectively elucidates the coexisting and differential enrichment mechanisms of diverse hydrocarbons within tectonically reworked petroleum systems, further improving and enriching the Whole Petroleum System theory.

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