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Original Paper

Multi-spherical interactions driving the generation, accumulation and distribution of natural gases and CO_2 resources in the Changling Fault Depression, Songliao Basin, China

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ABSTRACT

This study systematically investigates the genesis, migration, accumulation, and distribution patterns of natural gas and CO_2 in the Changling Fault Depression of the Songliao Basin through an interdisciplinary Earth system framework, focusing on multi-sphere interactions. Integrated analyses employing gas geochemistry, numerical simulations, and core observations reveal that deep magmatic-hydrothermal processes (lithosphere) provide

$_2$ influx through volcanic activity and fault system development, whereas climate-sedimentation coupling under Ferrel circulation and global eustatic cycles regulates organic matter enrichment. This integrated analysis establishes a comprehensive framework for volcanic gas reservoir exploration and CO_2 geological sequestration, contributing to the synergistic advancement of carbon neutrality and energy security strategies.

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1. Introduction

The Earth system constitutes a dynamically coupled framework comprising the lithosphere, hydrosphere, atmosphere, and biosphere, whose interactions govern geological evolution and resource distribution through material and energy exchange (Bowring et al., 2022; Jin et al., 2023; Zhang et al., 2024b; Zhu et al., 2024). Recent advances have highlighted the critical role of multi-

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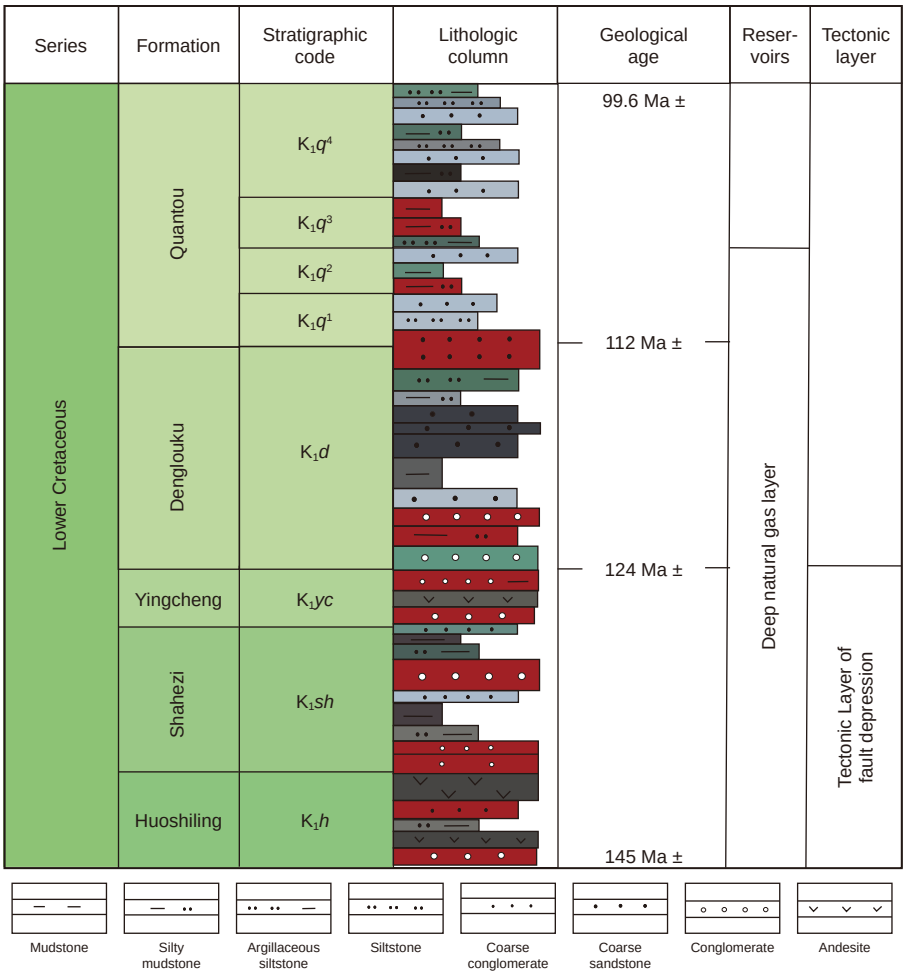

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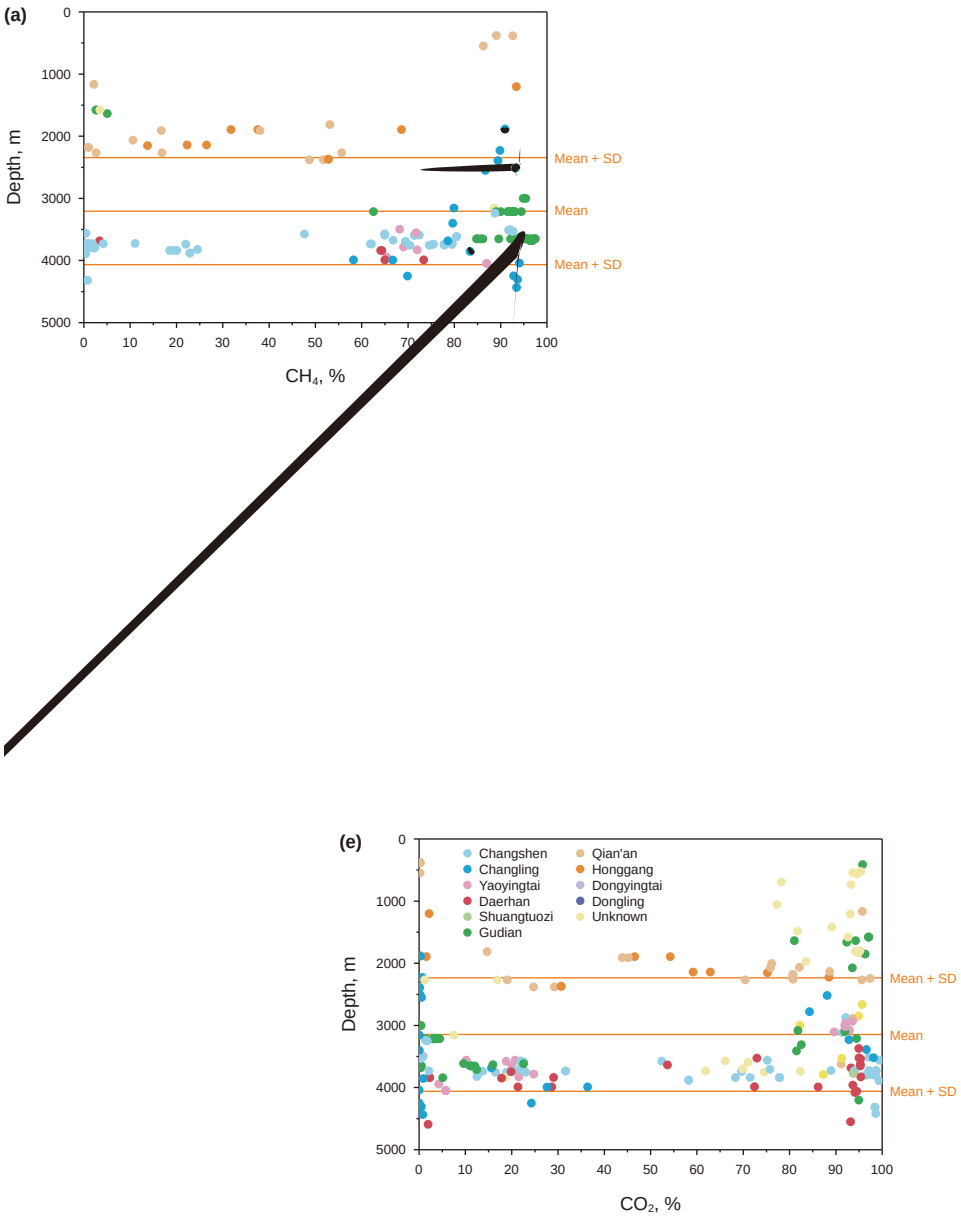

Fig. 3. Variation of natural gases components with depth in the Changling Fault Depression, Songliao Basin. Natural gas components: **(a)** CH_4, **(b)** C_2H_6, **(c)** C_3H_8, **(d)** C_4H_{10}, and **(e)** CO_2.

4.1.2. Carbon isotopic characteristics of natural gases

$\delta^{13}C_1$ display significant depth-dependent variability (Fig. 4(a)). In deeper intervals (3000–4130 m), $\delta^{13}C_1$ values range from 30 to 16.54 , corresponding to the Changshen, Yaoyingtai, Daerhan, and Gudian regions. Shallower depths (380–2540 m) exhibit bimodal isotopic trends: a narrow range (11.9 to 1.7) in the Changling area and a broader distribution (56.8 to 23.2) in Qian'an, Honggang, and Dongling areas. Carbon isotopic sequences show both normal ($\delta^{13}C_1 < \delta^{13}C_2 < \delta^{13}C_3$) and reversed patterns (Fig. 4(c)), including partial reversals ($\delta^{13}C_1 > \delta^{13}C_2$ or $\delta^{13}C_2 > \delta^{13}C_3$) and complete reversals ($\delta^{13}C_1 > \delta^{13}C_2 > \delta^{13}C_3$). These anomalies likely reflect mixing of thermogenic and abiogenic gas sources.

4.1.3. Compositional characteristics of CO_2

CO_2 in the Changling Fault Depression displays bimodal enrichment zones at 400–2550 m and 2850–4550 m, exhibiting significant concentration differentiation (Fig. 3(e)). High CO_2 concentrations (50%–99.45%) dominate across multiple regions, with ultrahigh values (>80%) predominantly occurring at 2660–4550 m. Moderate-high CO_2 contents (60%–80%) are concentrated in the Changshen and Daerhan areas at 3520–4000 m, while similar ranges are observed in Qian'an and Honggang areas at shallower depths (2000–2270 m). Low-to-moderate CO_2 concentrations (0%–30%) are widely distributed, with intermediate values (10%–30%) prevalent at 3550–4000 m. Notably, low CO_2 concentrations (<10%) are localized in the Changshen, Changling, Daerhan, and Gudian areas at 3000–4590 m, as well as in the Changling and Honggang areas at 1890–2550 m.

4.1.4. Carbon isotopic characteristics of CO_2

The $\delta^{13}C_{CO_2}$ values range from 18.9 to 0.6 , with the majority of samples clustered between 3470 and 4050 m (Fig. 4(b)). These isotopic characteristics are primarily associated with the Changling, Yaoyingtai, Qian'an, and Gudian areas. The narrow isotopic range and positive $\delta^{13}C_{CO_2}$ values (> 8) in

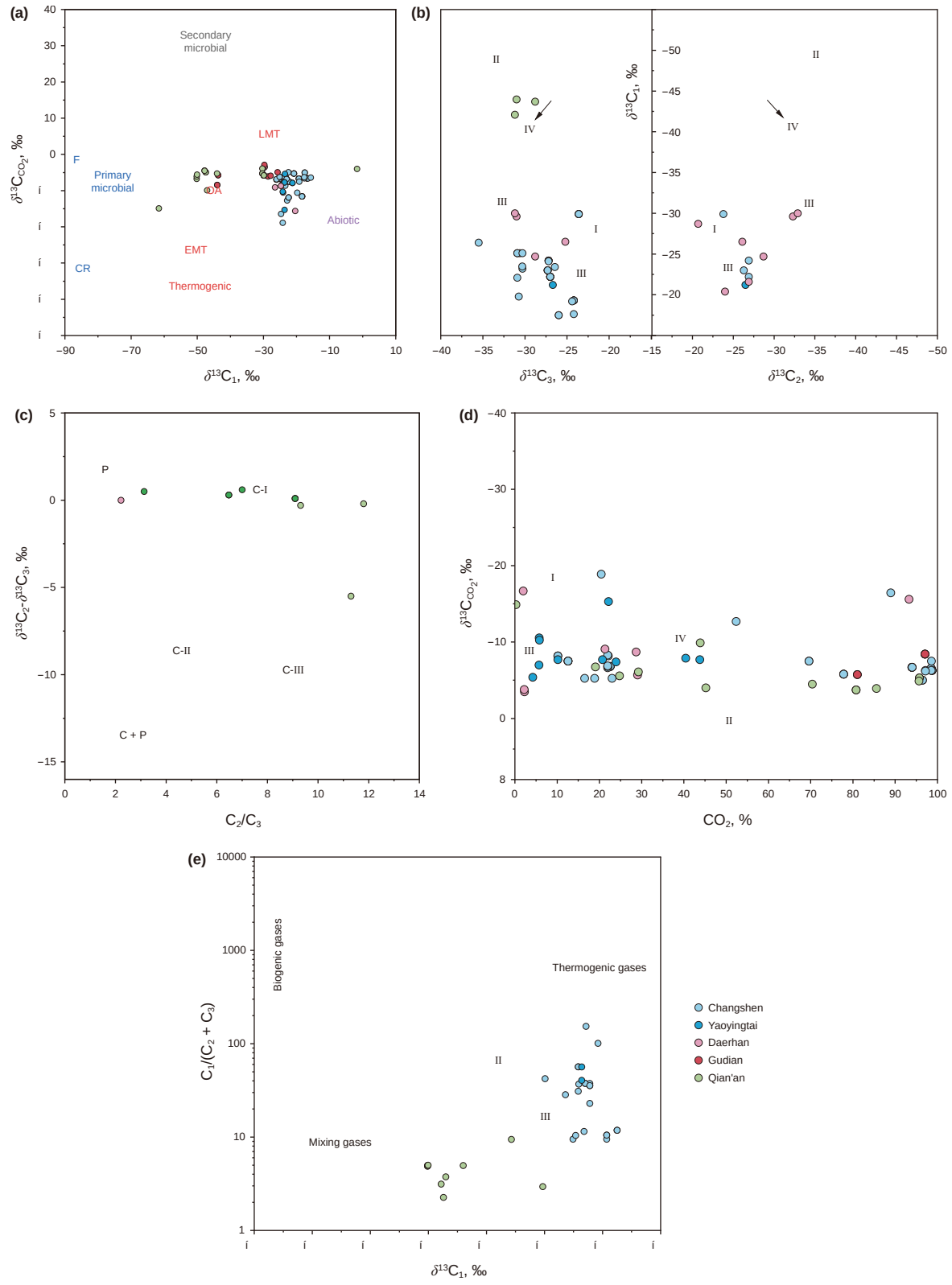

Fig. 7. Origins of CH_4 and CO_2 gases in the Changling Fault Depression. **(a)** Relationship between $\delta^{13}C_1$ and $\delta^{13}C_{CO_2}$, modified from Milkov and Etiope (2018). Abbreviations: CR, carbon dioxide reduction; F, fermentation; EMT, early mature thermogenic gas; OA, oil-associated thermogenic gas; LMT, late mature thermogenic gas; **(b)** Gas type identification based on $\delta^{13}C_1$-$\delta^{13}C_2$-$\delta^{13}C_3$, modified from Dai et al. (2014). Zones: I, coal-derived gas; II, oil-type gas; III, reversal carbon isotopes of mixed gas; IV, coal-derived or oil-type gas; **(c)** Gas type identification based on cracking processes, modified from Lorant et al. (1998). Zones: P, kerogen cracking gas; C-I, oil cracking gas; C-II, condensate oil cracking gas; C-III, cracking gas; C ‡ P, mixture of kerogen cracking gas and oil cracking gas; **(d)** Genetic identification of CO_2 sources, modified from Dai (1992). Zones: I, organic CO_2; II, inorganic CO_2; III, coexistence of organic and inorganic CO_2; IV, mixed organic and inorganic CO_2; **(e)** Natural gas type identification base on $\delta^{13}C_1$ and the $C_1/(C_2 ‡ C_3)$ ratio, modified from Bernard et al. (1978).

through deep-seated faults into reservoirs (Fig. 8). High-concentration inorganic CO_2 dominates the Changshen and Qian'an regions (Fig. 7(d)), while minor organic contributions from organic matter thermal degradation are observed in Daerhan and Qian'an areas. Mixed organic-inorganic CO_2 signatures occur in Yaoyingtai and Changshen areas, reflecting interactions between biogenic carbon recycling and mantle inputs.

The accumulation of CO_2 reservoirs is primarily attributed to: (1) mantle-derived magma underplating and crustal remelting, generating CO_2-rich hybrid magmas; (2) basement fault reactivation driving multi-phase volcanic eruptions (Fig. 8), where early syn-rift volcanics formed reservoir-seal assemblages, while late-stage eruptions injected CO_2 into pre-existing volcanic conduits, with microporosity and fracture networks in volcaniclastics enhancing storage capacity (Fig. 9); (3) post-Yingcheng cessation of basement fault activity, enabling preservation of CO_2 within self-sourced volcanic reservoirs. Notably, the Qianshenzi Fault as a syn-depositional structure controlling fissure-type eruptions dictates reservoir distribution by regulating volcanic vent geometry and fracture permeability (Fig. 8). This fault-mediated accumulation mechanism highlights the critical role of tectono-magmatic coupling in creating spatially constrained, high-purity CO_2 reservoirs with exceptional seal integrity. The coexistence of magmatic degassing pulses and fault-sealing episodes establishes favorable conditions for long-term carbon sequestration in volcanic systems.

5. Discussion

5.1. Influence of tectonic evolution

The Songliao Basin initiated its tectonic evolution during the Jurassic, progressing through four distinct phases that differentially influenced volcanic reservoir development and CO_2 charging (Figs. 10 and 11).

The volcanic reservoir formation stage comprised: (1) Huoshiling-Yingcheng rift phase (192–110 Ma), characterized by high-angle normal faulting under rapid Pacific Plate subduction, which induced asthenospheric upwelling and crustal extension (Chen et al., 2017; Cheng et al., 2020; Lou et al., 2022). This phase generated mafic volcanics during the Huoshiling stage and bimodal (mafic-felsic) volcanic suites during the Yingcheng stage, with peak volcanism occurring at 130–110 Ma (Cheng et al., 2020). (2) Denglouku-Nenjiang sag phase (110–80 Ma), marked by reduced volcanic activity as Pacific subduction decelerated, culminating in maximum lake transgression during the Nenjiang stage with deposition of kilometer-thick lacustrine mudstones and multiple hydrocarbon source beds (Jia et al., 2013; Zhang et al., 2013; Cheng et al., 2020; Liu et al., 2023b).

CO_2 charging occurred during: (1) Sifangtai-Paleocene uplift phase (80–50 Ma, Fig. 10(a)), featuring intensified mafic magmatism with widespread dolerite dikes and basaltic eruptions under persistent extensional regimes (Cao et al., 2018; Cheng et al., 2020). (2) Oligocene-Miocene inversion phase (40–10 Ma, Fig. 10(b)), dominated by NE-trending folding, thrust faulting, and structural modification of strata from Huoshiling to Mingshui stages (Huang et al., 2004; Cheng et al., 2020). This phase coincided with a Pacific Plate subduction direction shift from NNW to NWW and subduction angle reduction from steep to shallow.

Throughout these phases, the Changling Fault Depression experienced NNW-SSE compression, with stress dissipation concentrated along southeastern uplift zones and intra-basinal basement faults, diminishing northwestward (Fig. 8) (Ming et al., 2009; Dong et al., 2014). Structural inversion effects exhibited vertical stratification, influencing progressively shallower strata

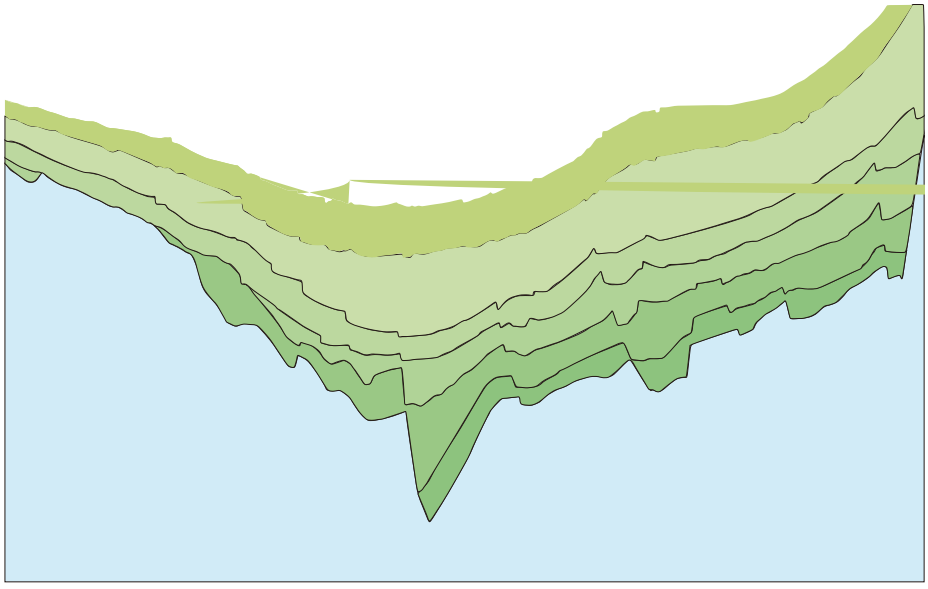

Fig. 8. The stratigraphic profile of mantle fluids intrusion along deep faults in the Changling Fault Depression, Songliao Basin.

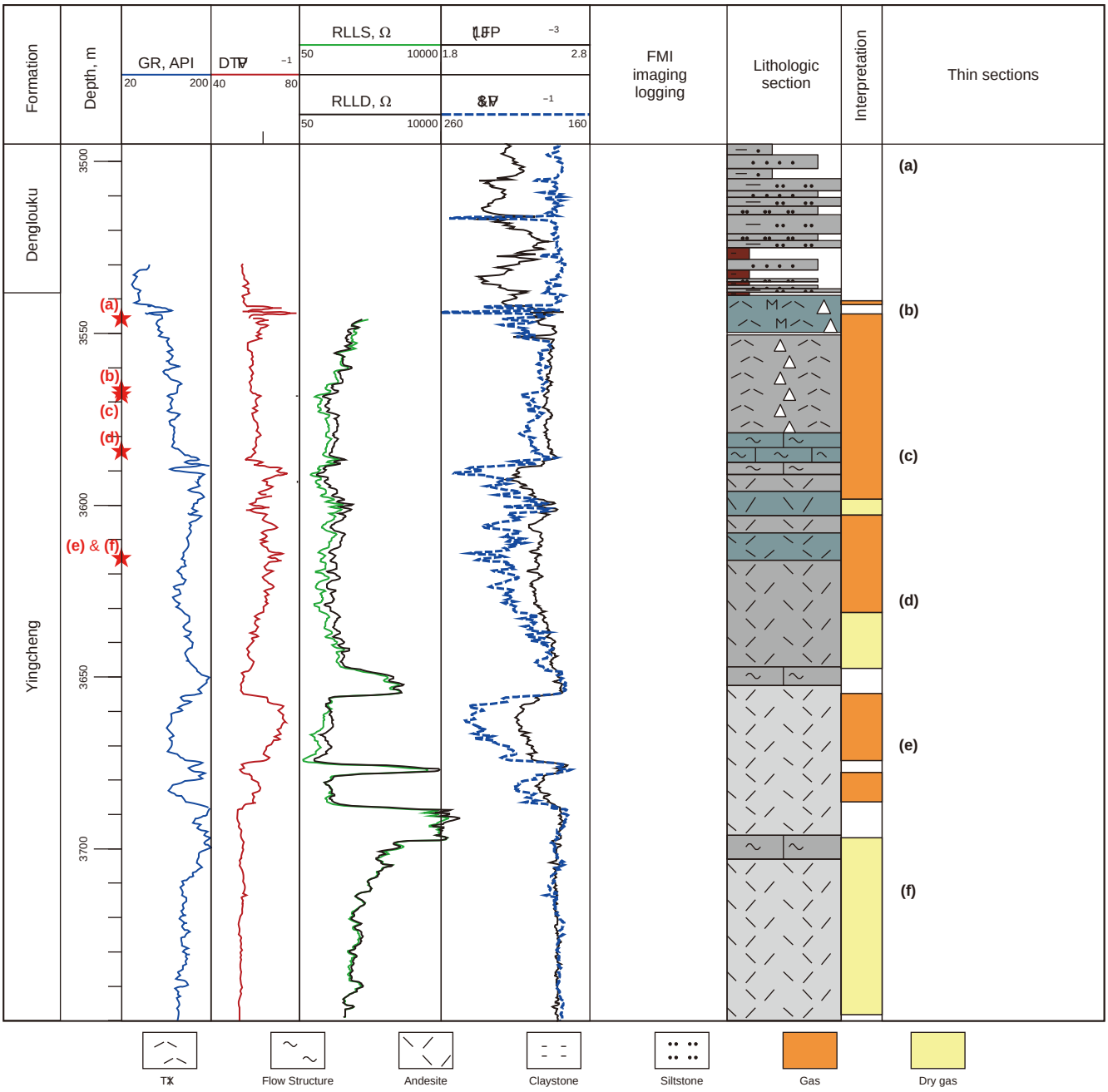

Fig. 9. Well logging curves, lithology, and core thin-section photomicrographs of Well YS1. **(a)** Tuff, 3546 m; **(b)** Tuff breccia, 3567.2 m; **(c)** Tuff breccia, 3568.2 m; **(d)** Flow structures in volcanic rocks, 3584 m; **(e)** Andesite, 3615 m; **(f)** Andesite, 3615 m.

from southeast to northwest. The Oligocene-Miocene inversion ultimately established the current reservoir distribution patterns, where compressional anticlines and fault-sealed traps govern hydrocarbon accumulation, while CO_2 reservoirs are preferentially localized along reactivated volcanic conduits and fracture networks. This spatiotemporal coupling between tectonic reorganization and magmatic-tectonic cycles created vertically stacked, laterally partitioned fluid systems-shallow biogenic methane reservoirs overlying deep thermogenic-abiotic hybrid systems with mantle-derived CO_2 plumes.

Additionally, tectonic evolution exerts a coupled control on the charging and distribution of CH_4 and other non-hydrocarbon gases. Reactivated basement faults and fracture networks not only provided conduits for mantle-derived CO_2 but also governed vertical migration of thermogenic methane expelled from Shahezi Formation source rocks (see vertical/plannar CH_4-CO_2 complementarity in Fig. 6 and migration pathways in Fig. 7). Noblegas signatures (He) and depth-stratified N_2 distributions further indicate that faults act as selective conduits: deep, high-connectivity faults favor ascent of mantle-sourced volatiles (CO_2, He), while low-permeability or laterally extensive carrier beds permit lateral CH_4 migration and trap accumulation. Therefore, as supported by the planar maps in Fig. 6, noble gas and N_2 depth profiles, and the discussion in Section 6, a coupled tectonic-migration model is needed to account for (a) upward advective flux of deep volatiles during magmatic/tectonic pulses, and (b)

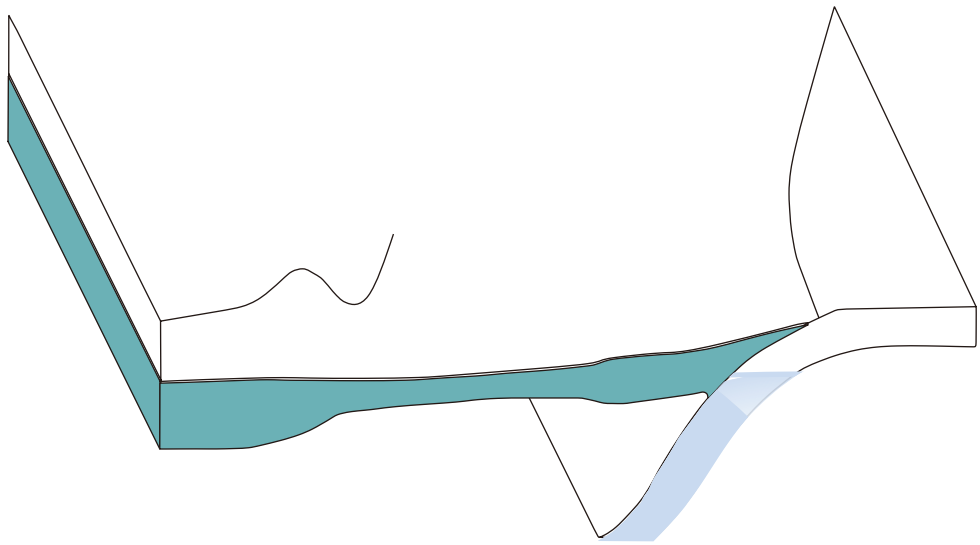

Fig. 10. Three-dimensional model of the tectonic-thermal evolution stages of the Songliao Basin after the Late Cretaceous, modified from Cheng et al. (2020). **(a)** Stage I: Late Cretaceous–Early Paleogene (~80–50 Ma). **(b)** Stage II: Oligocene–Miocene (~40–10 Ma).

simultaneous lateral redistribution of thermogenic CH_4 controlled by carrier-bed architecture and caprock integrity.

It is worth noting that numerous sub-seismic faults were generated during the tectonic evolution of the basin. Although their influence is not the primary focus of this study, it does not imply they are insignificant; on the contrary, they are likely key factors controlling hydrocarbon preservation and migration (Jiang et al., 2023, 2024, 2025a, 2026).

5.2. Influence of climatic evolution

The formation is intrinsically linked to Early Cretaceous rift events, with its unique petroleum system development strongly influenced by mid-latitude Ferrel circulation-driven climatic controls (Figs. 11 and 12). Investigations demonstrate that the Ferrel circulation belt not only played a pivotal role in global polar ice-melt dynamics (Zhu et al., 2024) but also regulated precipitation patterns between 40 and 60 N/S latitudes, fostering organic carbon enrichment in temperate humid zones. This climatic regime, coupled with Cretaceous global oceanic anoxic events (OAEs: OAE1a, OAE1b, OAE2, OAE3) (Barclay et al., 2010; Jenkyns, 2010), jointly facilitated the development of premium source rocks through by enhancing terrestrial nutrient influx and lacustrine primary productivity under Ferrel circulation-induced humid climates, improving organic carbon burial efficiency via water column stratification during OAEs (McArthur et al., 2020), and spatiotemporal coupling of these factors that maintained optimal organic matter production-preservation conditions from mid-Albian to early Late Cretaceous (~110–90 Ma).

From the Huoshiling to Shahezi and Yingcheng stages, the basin evolved from deeper, humid freshwater to shallower, semi-arid and more brackish conditions, with a gradual decline in water-column reducing capacity. High TOC values (>2 wt%) correlate positively with redox-sensitive elements (V, Ni, Cr, V/Cr, Ni/Co) and with humid-climate indicators (Cu enrichment, high paleoclimate index, low Sr/Cu < 6), suggesting that strongly reducing and semi-humid conditions favored the formation of high-quality source rocks. Paleosalinity proxies (Sr, Sr/Ba, Sr/Ca) show weaker

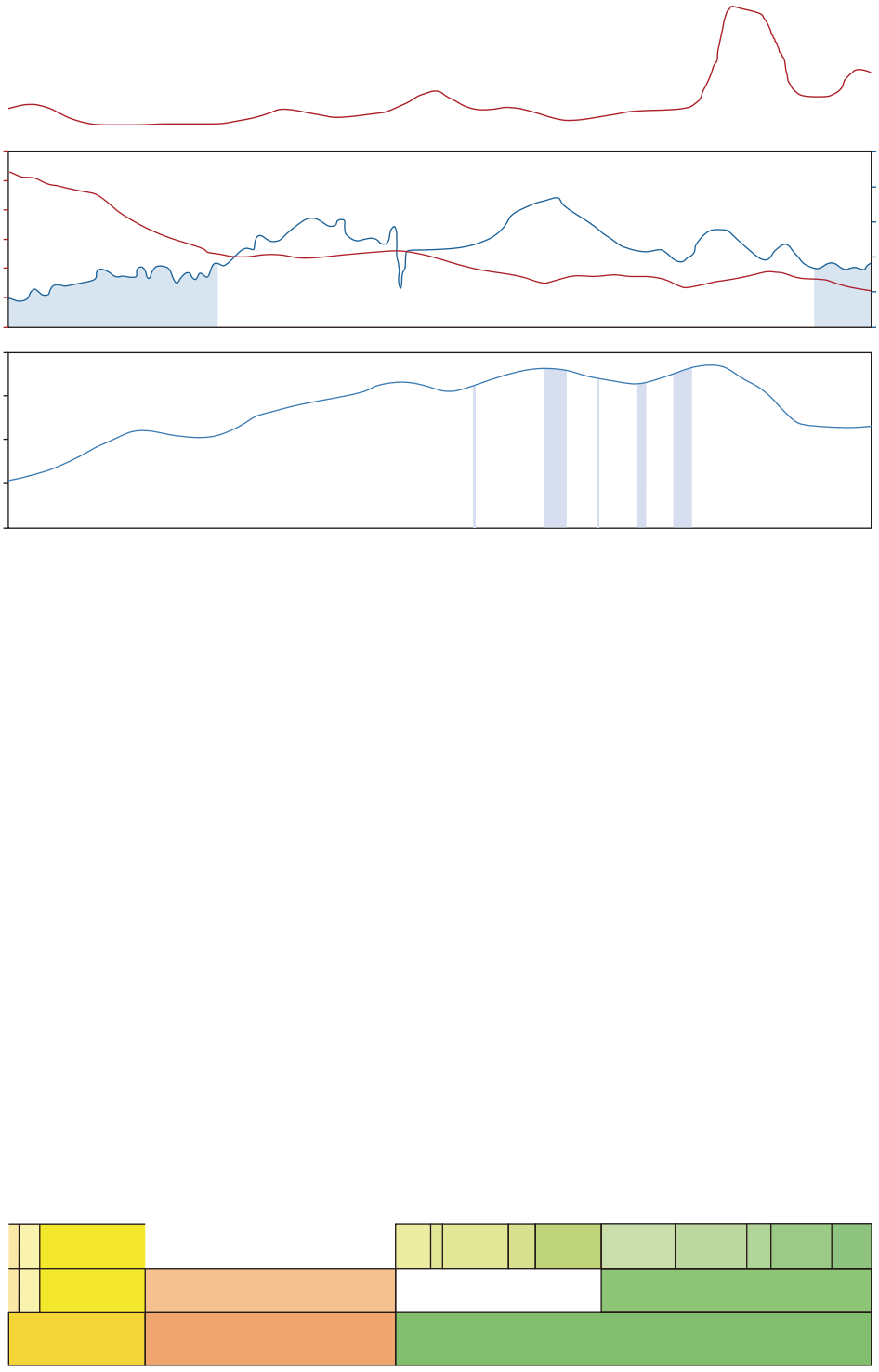

Fig. 11. Multi-sphere interactions and hydrocarbon system evolution in the Changling Fault Depression, Songliao Basin. **(a)** Tectonic chronology (Cheng et al., 2020). **(b)** Global average temperature curve (Scotese, 2021) and global marine $^{87}Sr/^{86}Sr$ curve (McArthur et al., 2020). **(c)** Global sea-level variations (Boulila et al., 2021) and regional transgression events (Wu et al., 2024). **(d)** Source-reservoir-seal systems and hydrocarbon charging stages, modified from Yu et al. (2013). **(e)** CO_2 charging episodes. **(f)** The hydrocarbon generation history curve of Yingcheng Formation and Shahezi Formation, modified from Huang et al. (2012). **(g)** Chronostratigraphic framework of the Songliao Basin. Note on colored blocks and legend: In panels (b)–(e) the colored blocks are time intervals referenced to the stratigraphic/time axis shown in panel (g); the horizontal length of each block corresponds to its duration on the panel(g) time axis. The meaning of each color is indicated by the left-side panel headings and by the legend box plotted on the figure. For clarity, the primary color key used in panels (d)–(e) is: the first charging period is represented in blue, and the second charging period is represented in orange.

subduction of the Pacific Plate triggered large-scale volcanism coinciding with >100 m global sea-level rise and stable 15 C climatic conditions, forming premium volcanic reservoirs exemplified by the Yingcheng, Shahezi, and Huoshiling Formations. (ii) Late Cretaceous to present (73.3–5.1 Ma) shallow-angle, accelerated subduction facilitated mantle-derived magma emplacement and CO_2 charging. Notably, limited CO_2 degradation during this phase, coupled with progressive sea-level fall and global cooling, established unique gas preservation conditions.

The two major marine transgressions synchronously responded to global eustatic cycles (Liu et al., 2011; Bai et al., 2023; Wang et al., 2024a). This tripartite coupling mechanism, comprising tectonic activation, sea-level fluctuation, and climatic variation, not only shaped pore evolution in volcanic reservoirs but also determined the spatial distribution and resource abundance of petroleum systems by modulating anoxic event frequency and organic carbon burial efficiency (Bjerrum and Canfield, 2004; Irwin et al., 1977). Specifically, Early Cretaceous hydrothermal alteration enhanced secondary porosity in volcaniclastics through zeolitization and chloritization, while Late Cretaceous tectonic inversion created fracture networks that optimized reservoir permeability (Liu et al., 2017b). The temporal coincidence of enhanced organic productivity during oceanic anoxic events (OAEs) and optimal reservoir diagenesis during tectonic quiescence periods created a unique configuration, positioning the Songliao Basin as a global benchmark for studying continental rift petroleum systems under greenhouse climate regimes.

Based on the geochemical data from the Lower Cretaceous source rocks in Well SL3, the paleoenvironmental evolution profile of the study area during the Early Cretaceous were reconstructed (Fig. 12). The reconstruction indicates that from the Huoshiling to the Shahezi and Yingcheng depositional stages, the Changling Fault Depression experienced a progressive transition from deep to shallow water depth, from humid to semi-arid climate conditions, from freshwater to brackish environments, and from increasing to decreasing water column reducing capacity (Li et al., 2017). Overall, the paleoenvironment during the Shahezi and Yingcheng stages showed significant stratified variation, which directly controlled the heterogeneity in hydrocarbon generation potential across different source rock intervals.

A significant positive correlation is observed between total organic carbon (TOC) content and redox-sensitive elements such as Cr, Ni, V, Ni/Co, and V/Cr (Fig. 13(a)–(e)). Samples with TOC greater than 2.0% are notably enriched in V, Ni, and Cr (Fig. 13(a)–(c)), indicating that the formation of high-quality Lower Cretaceous source rocks was primarily controlled by strongly reducing water column conditions. Meanwhile, TOC also correlates well with paleoclimate-sensitive indicators, including Cu, Fe/Cu, and Sr/Cu ratios (Fig. 13(f)–(i)), as well as the paleoclimate index (Li et al., 2017). Most samples with TOC > 2.0% are Cu-enriched (Fig. 13(f)), show paleoclimate index values above 0.7, and Sr/Cu ratios below 6 (Fig. 13(i)), all pointing to a semi-humid to humid climate regime. In contrast, TOC shows a weaker correlation with paleosalinity indicators such as Sr, Sr/Ba, and Sr/Ca (Fig. 13(j)–(l)), suggesting that paleosalinity had a limited impact on the development of high-quality source rocks in this region (Li et al., 2017). These observations collectively demonstrate that redox conditions and paleoclimate were the dominant environmental factors controlling source rock quality in the Lower Cretaceous.

There is a strong coupling relationship among paleoproductivity, redox conditions, and paleoclimate, which directly influenced organic matter enrichment (Wang et al., 2024b; Zhao et al., 2025). TOC content is positively correlated with paleoproductivity indicators such as Al_2O_3/K_2O, Al/Ti, and Ba concentrations (Fig. 13(m)–(o)). Source rocks from the Shahezi and Huoshiling formations display higher paleoproductivity levels (Figs. 11(d) and 12), while those from the Yingcheng Formation exhibit relatively lower values.

During the early depositional stage (Shahezi Formation), tectonic activity and volcanism were relatively weak, resulting in limited accommodation space and shallow water depths. Under humid to semi-humid climatic conditions, intensified river inflow delivered abundant terrestrial organic matter, primarily from higher plants. However, the injection of large volumes of freshwater reduced salinity and weakened water column stratification, leading to poor preservation conditions and consequently low organic matter abundance (Fig. 14(a)). In contrast, during the Yingcheng Formation stage, enhanced rifting and volcanic activity expanded the basin accommodation space and deepened the water column. Inputs of volcanic materials stimulated the proliferation of algae and other lower aquatic organisms. Under semi-arid conditions, terrestrial input decreased, while higher salinity strengthened stratification and reducing capacity, greatly improving organic matter preservation (Fig. 14(b)). The co-evolution of lake basin settings under tectonic control, coupled with volcanic influence, jointly regulated the spatial and temporal distribution of high-quality source rocks in the study area.

5.4. Integrated multi-sphere coupling: mechanisms and evidences

The interactions among the lithosphere, atmosphere, and hydrosphere are key to understanding the spatiotemporal distribution of both natural gas and CO_2 in the Changling Fault Depression. To strengthen the coupling discussion, we integrate the available geochemical, isotopic, and paleoenvironmental evidence into three major pathways that reveal how multi-spherical processes jointly influenced gas generation, migration, and preservation.

Volcanic and magmatic activities during the Huoshiling–Yingcheng periods supplied abundant heat and nutrient-rich detritus to the lacustrine system. These pulses enhanced primary productivity and, combined with stratification and rapid burial, promoted organic carbon accumulation and preservation. This interpretation is supported by elevated TOC contents and higher V/Cr and Sr/Cu ratios observed in the Yingcheng Formation (Figs. 12 and 13), indicating a more reducing and saline depositional environment compared with the Shahezi Formation.

Episodes of mantle-derived CO_2 injection, identified by $\delta^{13}C_{CO_2}$ values ranging from 18.9 to 0.6 and by deep CO_2 enrichment zones (2.66–4.55 km), altered the local carbon equilibrium, redox state, and carbonate precipitation potential (Section 4.2). These CO_2 pulses, likely linked to syn-magmatic degassing, influenced both the geochemical environment of the source rocks and the diagenetic evolution of reservoirs, thus modifying gas accumulation efficiency and phase distribution.

Tectonic inversion and episodic fault reactivation not only regulated hydrocarbon generation timing but also determined the connectivity between deep mantle reservoirs and shallower sedimentary systems. Deep, high-permeability faults served as conduits for upward migration of mantle-sourced CO_2 and He, while shallower carrier beds facilitated lateral migration and trapping of thermogenic CH_4. This complementary spatial pattern is evident from the planar distribution of CH_4 and CO_2 (Fig. 6) and the noble-gas enrichments near deep faults (Supplementary Material). The interplay between vertical and lateral migration establishes the structural foundation for the observed partitioning of CH_4-rich and CO_2-rich zones (Fig. 11).

This synthesis reinforces the integrated nature of the system, showing that lithospheric tectono-magmatic activities provided both the energy and materials driving hydrocarbon generation and

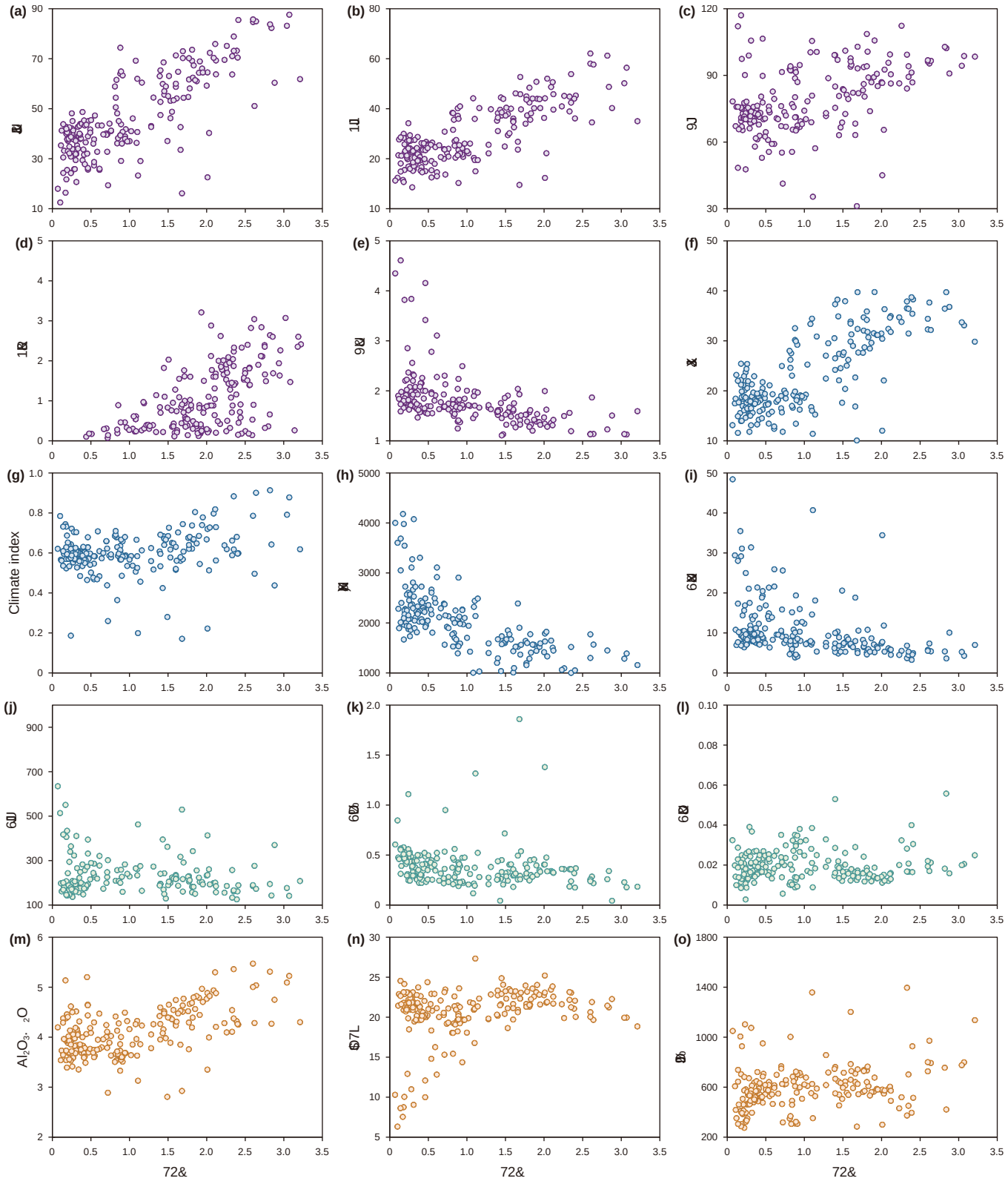

Fig. 13. Relationships between element contents (or their ratios) and TOC in Lower Cretaceous hydrocarbon source rocks of Changling Fault Depression, Songliao Basin. This integrated analytical framework encompasses four paleoenvironmental indicator modules: redox-sensitive elements (**a)** Cr, **(b)** Ni, **(c)** V concentrations) with their diagnostic ratios **(d)** Ni/Co and **(e)** V/Cr for redox conditions; paleoclimate proxies including **(f)** Cu concentration, **(g)** Paleoclimate index, and elemental coupling ratios **(h)** Fe/Cu and **(i)** Sr/Cu; paleosalinity indicators featuring **(j)** Sr concentration combined with **(k)** Sr/Ba and **(l)** Sr/Ca ratios; and paleoproductivity parameters demonstrated by **(m)** Al_2O_3/Ti, **(n)** Al/Ti ratios, and **(o)** Ba concentration.

Fig. 14. Schematic model of tectonic-climatic-sedimentary interactions. **(a)** Rifting and volcanic activity are weak, resulting in limited lacustrine accommodation space and shallow water depth. **(b)** Enhanced rifting and volcanic activity lead to rising base level, increasing sedimentary accommodation space and deepening of the water body.

CO_2 enrichment, while hydrospheric and atmospheric factors modulated organic preservation and post-generation redistribution.

5.5. Comparison of multi-sphere interactions in Songliao and other basins

The formation and evolution of hydrocarbon systems in rift basins are increasingly recognized as outcomes of dynamic interactions among internal Earth processes, climatic conditions, and sedimentary environments (Liu et al., 2024; Zhang et al., 2024b; Jiang et al., 2025b; Jiang and Liu, 2025; Wang et al., 2025). A comparative analysis of the Songliao Basin, the North Sea Basin, and the Bohai Bay Basin highlights both the diversity and commonality of multi-sphere interactions under different tectonic and climatic regimes (Hao and Chen, 2024; Shan et al., 2023; Xie et al., 2024; Zhao et al., 2025; Zhu et al., 2024).

In the Songliao Basin, the development of petroleum systems was controlled by two distinct episodes of Pacific Plate subduction (Chen et al., 2017; Li et al., 2019). The Early Cretaceous stage involved steep-angle subduction, large-scale volcanism, and widespread thermal activity, while the Late Cretaceous stage was dominated by shallower subduction that facilitated CO_2 migration from mantle sources (Cao et al., 2018; Liu et al., 2018; Liu et al., 2023a; Shan et al., 2023). These internal processes coincided with global climate stability and sea level rise during the Early Cretaceous, and with sea level fall and cooling during the Late Cretaceous. The combined influence of tectonic activity, climate variation, and sea level change created favorable conditions for hydrocarbon generation and preservation (Zhang et al., 2024b). Oceanic anoxic events promoted organic carbon accumulation, while hydrothermal alteration and faulting enhanced secondary porosity and permeability in volcaniclastic reservoirs (Li et al., 2018; Liu et al., 2023; Zhang et al., 2024b). This convergence of processes resulted in a unique match between source rock development, reservoir formation, and hydrocarbon charging periods.

In the North Sea Basin, the petroleum systems evolved through multiple phases of crustal extension and thermal subsidence from the Paleozoic to the Cenozoic (Zhu et al., 2024). Deep mantle activity and slab rollback shaped the architecture of basin, while surface climate patterns and marine transgressions controlled source rock deposition (Zhu et al., 2024). The Jurassic and Cretaceous successions, including the Draupne and Kimmeridge formations, were formed through the overlap of tectonic subsidence, anoxic bottom waters, and regional shale deposition. Although the North Sea lacks significant volcanic activity, its long-term geodynamic and climatic interactions show a different but equally effective form of multi-sphere coupling. Both the Songliao and North Sea basins share a critical characteristic which is temporal alignment between hydrocarbon generation and reservoir development.

The Bohai Bay Basin, especially the Kongdian 2nd Member of the Cangdong Sag, represents another variation of sphere interaction. The hydrocarbon accumulation of basin follows a layered configuration controlled by lithospheric deformation, hydrological evolution, biological productivity, and sediment supply (Zhao et al., 2025). This resulted in a vertically differentiated system, with microbial gas in the upper zone, oil in the middle, and deep thermogenic gas at the bottom (Zhao et al., 2025). Unlike the temporally synchronized system of the Songliao Basin, the Bohai Basin case shows how multiple petroleum systems can coexist in a stratified structure formed by repeated tectonic and climatic cycles. Despite differences in lithology and burial history, both basins exhibit the importance of vertical structural control and fluid partitioning across geological time.

Together, these comparisons demonstrate that although the geological expressions of multi-sphere interactions vary, the underlying principles remain consistent. The coordination of tectonic events, climatic phases, and sedimentary dynamics is a powerful driver of petroleum system evolution (Shan et al., 2023; Hao and Chen, 2024; Xie et al., 2024; Zhu et al., 2024; Zhao et al., 2025). The Songliao Basin, with its volcanic reservoir systems and deep CO_2 inputs, offers a globally relevant case for understanding greenhouse-driven hydrocarbon accumulation in continental rift settings. Recent studies have emphasized that hydrocarbon generation and enrichment represent a complex geodynamic process involving multi-spheric material cycles, energy transfer, and coupled evolutionary mechanisms. Research in this direction is still in its early stage and requires integrated approaches that combine deep lithospheric dynamics, multi-spheric interactions, petroleum system evolution, and emerging tools such as machine-learning–based predictive analysis. The recently proposed multi-spheric interaction-driven hydrocarbon formation theory (Zhu et al., 2025) further highlights the necessity of linking deep Earth processes with surface environmental responses to fully understand spatiotemporal variations in hydrocarbon systems. The findings from the Changling Fault Depression are consistent

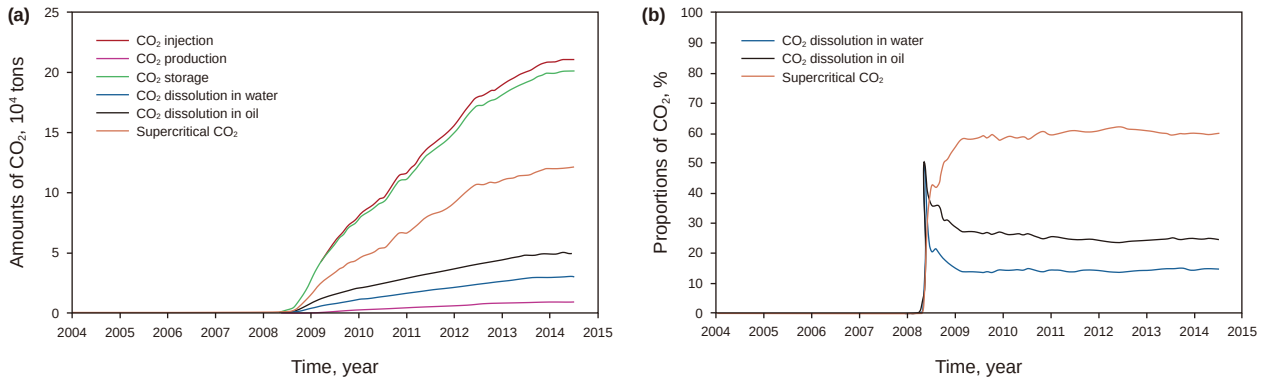

Fig. 15. Amounts **(a)** and proportions **(b)** of CO_2 trapped in various forms in the H-59 block, modified from Zhang et al. (2016).

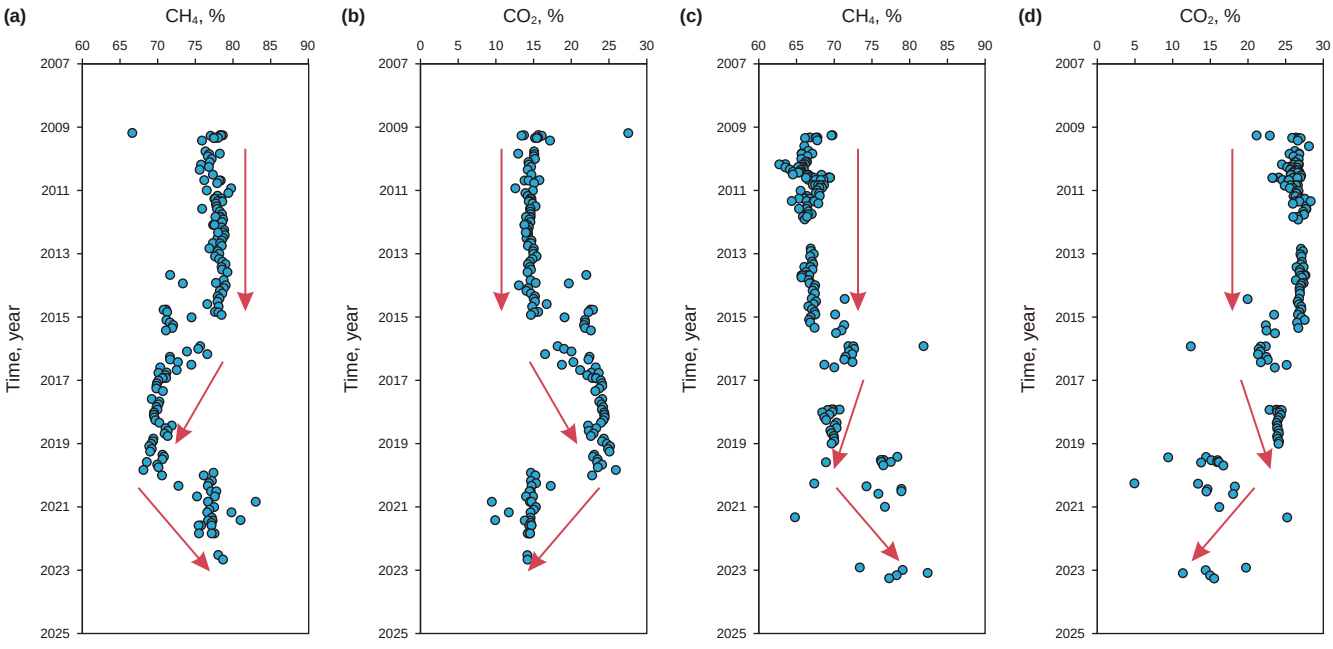

Fig. 16. Temporal variation of gas content in the Changling Fault Depression, Songliao Basin. **(a)** CH_4 and **(b)** CO_2 in Well CS1-1. **(c)** CH_4 and **(d)** CO_2 in Well CS103.

with this emerging framework, while also providing basin-scale evidence that complements observations from other volcanic-rifted systems in East Asia.

5.6. Implications for CO_2 sequestration

A representative case study from the H-59 block, located in the western part of the Daqingzi subregion within the central Changling Fault Depression of the southern Songliao Basin, was used to validate the applicability of the integrated CO_2 sequestration potential area (Fig. 1(b)). The block covers an area of approximately 3.1 km^2, with an estimated original oil in place of about 1.6 million tonnes. The primary oil-bearing interval is hosted in the Qingshankou Formation (Qing I-III members), which is overlain by a regionally continuous 500–550 m thick mudstone caprock. The reservoir is oil-dominated (Dong et al., 2014; Liu et al., 2017b; Huo et al., 2020; Liu et al., 2023a).

To date, a total of 210,800 tonnes of CO_2 has been injected into the reservoir, resulting in cumulative oil production of 126,400 tonnes (Zhang et al., 2016) (Fig. 15(a)). The oil recovery factor during the CO_2 injection stage increased from 5% to 14.7%. Concurrently, cumulative water injection and production volumes reached 109,600 and 119,300 tonnes, respectively, while 9600 tonnes of CO_2 have been recovered (Fig. 15(a)). The current effective CO_2 storage volume is estimated at 201,200 tonnes (Zhang et al., 2016).

Reservoir simulation and material balance analyses indicate the partitioning of stored CO_2 as follows (Zhang et al., 2016) (Fig. 15(b)): 42.68%–60.15% (~121,000 tonnes) is trapped in a supercritical state, 24.85%–41.8% (~50,000 tonnes) is dissolved in residual oil, and the remaining 15% (~30,200 tonnes) is dissolved in formation water. Based on the reservoir's physical characteristics and current performance, the estimated maximum effective storage potential is 263,700 tonnes, leaving a residual capacity of 62,500 tonnes (Zhang et al., 2016).

These results confirm that the geological setting of the Changling Fault Depression is highly favorable for long-term CO_2 sequestration, and that the integrated evaluation model can effectively predict high-potential zones with substantial CO_2 storage capacity (Du et al., 2016; Zhang et al., 2016; Dou et al., 2023; Song et al., 2023; Wang, 2023; Wang et al., 2023). The H-59 case thus provides real-world validation for the practical applicability of models.

5.7. Limitation of data

Significant temporal variations in gas composition were identified during the analysis of natural gas and CO_2 distribution characteristics. Comparative longitudinal analysis of gas samples collected across different drilling years revealed distinct compositional evolution patterns: CH_4 concentrations exhibited a three-phase stable-decline-rise trend (Fig. 16(a) and (c)), while CO_2 displayed an inverse stable-rise-decline trajectory (Fig. 16(b) and (d)), with final steady-state compositions remaining below initial production levels. This temporal dependency implies dynamic compositional re-equilibration during gas field development.

It is hypothesized that before production began, the reservoir maintained a natural equilibrium where CH_4 with a molecular weight of 16.04 was concentrated in the upper part and CO_2 with a molecular weight of 44.01 was enriched in the lower part of the reservoir. This balance may have been disturbed by continued extraction but other mechanisms could also be involved. Engineering factors such as gas injection or pressure maintenance were ruled out through audits of operational protocols. The observed compositional variations are therefore more likely caused by pressure decline and fluid redistribution during production activities.

6. Conclusions

Natural gas in the Changling Fault Depression is dominated by CH_4 (60%–97.4%) with low $C_2‡$ contents, while $\delta^{13}C_1$ values (56.8 to 1.7) indicate mixed thermogenic and abiogenic origins locally influenced by coal-derived gas. CO_2 displays ultra-high concentrations (up to 99.45%) and $\delta^{13}C_{CO_2}$ values (18.9 to 0.6) confirming a predominant inorganic mantle-derived source with minor organic input in Daerhan. Carbon isotope reversals and fractionation patterns reflect multi-source mixing and post-accumulation alteration.

Spatially, CH_4 preferentially accumulates in volcanic reservoirs of the Quantou and Yingcheng Formations, whereas CO_2-rich zones (>80%) dominate the eastern Changshen area, complementary to CH_4 distributions. N_2, H_2, and He enrichments are fault-controlled, indicating deep fluid connectivity through basement structures. Hydrocarbon accumulation followed two pathways: near-source vertical migration via Shahezi faults and lateral migration along Yingcheng carrier beds. Mantle-derived CO_2 migrated upward along reactivated basement faults during Late Cretaceous–Paleogene magmatism, while later tectonic inversion (40–10 Ma) enhanced reservoir preservation by sealing fractures and generating microporosity in volcaniclastics.

Integrating these results, we propose a tectonic-climatic-sedimentary multi-sphere coupling model, wherein lithospheric processes (Pacific Plate subduction, basement faulting, and volcanism) controlled reservoir architecture and CO_2 charging; hydrospheric lacustrine fluctuations and atmospheric Ferrel circulation modulated organic enrichment via climate-sedimentation coupling; and biospheric productivity governed organic burial efficiency enhanced by volcanic ash. Paleoenvironmental evolution from the Huoshiling to Yingcheng stages-characterized by shallowing lake levels, semi-arid transition, and decreasing redox capacity-regulated source rock quality, with the Shahezi Formation showing stronger productivity and hydrocarbon generation potential.

This synthesis reveals that hydrocarbon enrichment in the Changling Fault Depression results from the interplay of magmatic, climatic, and depositional factors across multiple Earth spheres. The proposed model provides a new conceptual framework for understanding gas-CO_2 coexistence in volcanic basins and supports deep unconventional exploration and carbon-neutral strategies through integrated CO_2 sequestration-reservoir management approaches.

CRediT authorship contribution statement

Ming-Ming Jiang: Writing – review & editing, Writing – original draft, Software, Methodology, Funding acquisition, Conceptualization. **Si-Shuo Zhou:** Writing – original draft, Visualization. **Xin Yan:** Writing – original draft, Data curation. **Quan-You Liu:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they rd that ig