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He, Q., Liu, B., Shi, K. et al. (2026) Sequence-stratigraphic evolution and controlling factors of Lower Cambrian carbonate clinoforms on a distally steepening ramp, Tarim Basin, China. *Marine Geoscience and Energy Resources*, 192. 207789. ISSN: 3117-5783

<https://doi.org/10.1016/j.marger.2026.207789>

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Sequence-stratigraphic evolution and controlling factors of Lower Cambrian carbonate clinoforms on a distally steepening ramp, Tarim Basin, China

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Abstract

Clinofoms, as fundamental components in sedimentary basin fills, represent the preserved stratal expression of slope systems that link shallow-water and deep-water environments in carbonate depositional systems. Although large-scale carbonate clinoforms developed extensively in the Tarim Basin during the Early Cambrian, their geometry, sedimentary evolution, and controlling factors have not yet been systematically studied. This research integrates 3-D seismic, drilling and well-logging data to perform a quantitative and systematic analysis of the seismic facies, geometrical characteristics, and depositional evolution of the Cambrian (Stage 3) Xiaoerbulake Formation clinoforms. A high-resolution sequence stratigraphic framework is constructed using the Integrated Prediction Error Filter Analysis (INPEFA) method. Seven distinctive seismic facies (SF1-SF7) are identified in the study area; these correspond to seven facies belts distributed in three depositional environments: mixed tidal flats, inner ramp and middle ramp. The analysis recognizes five higher-order composite clinothems (CC1–CC5) and seventeen subordinate clinoforms (C1–C17). Collectively, these record an overall progradation from southwest to northeast. Clinoform-edge trajectory patterns initially exhibit an aggradational trend that progressively transitions to a predominantly progradational trend. Two 3rd-order sequences (SQ1 and SQ2) are distinguished within Stage 3, each containing multiple 4th- and 5th-order sequences. SQ1 comprises CC1–CC3 (C1–C10), whereas SQ2 comprises CC4–CC5 (C11–C17). The early depositional system is characterized by a gently inclined carbonate ramp system, whereas the later stage evolves into a distally-steepening ramp. The development of these clinoforms was controlled by the interplay of several factors. Relative sea-level fluctuations directly controlled available accommodation and the resultant geometry of developed clinoforms. The spatial variability of paleogeomorphological features, such as a central depression surrounded by elevated margins, governed accommodation and controlled clinoform trajectory, progradation distance, and aggradation thickness. Moreover, paleoclimate and paleoceanographic conditions indirectly influenced clinoform development by modulating carbonate production and hydrodynamic energy. This study addresses the knowledge gap concerning the sequence-stratigraphic evolution of carbonate clinoforms on a ramp and clarifies the main controlling factors on clinoform growth. These findings provide valuable insights into the

evolution of ancient carbonate ramps and contribute to a more comprehensive understanding of global carbonate clinoform systems.

Key words: Early Cambrian, Carbonate ramp, Clinoforms, Sequence stratigraphy, depositional evolution, Tarim Basin

1 Introduction

The Cambrian Period represents a critical interval in Earth's history, marked by rapid biological diversification and extensive carbonate deposition (Rowland and Shapiro, 2002; Marshall, 2006; Fan et al., 2020). During this time, carbonate depositional systems were common in low-latitude tropical seas, providing valuable insights into paleoenvironments, ocean evolution, and the global carbon cycle (Rowland and Shapiro, 2002). The depositional processes of carbonate system development were governed by an interplay among various physical, chemical, and biological factors, including seawater chemistry, temperature, paleoclimate, paleo-ocean currents, and the evolution of biological communities (Hallock, 1987; Pomar et al., 2005; Lukasik and Simo, 2008; George et al., 2009). Within preserved carbonate successions, clinoforms record the evolution of slope systems that linked together shallow-water and deep-water depositional environments. Preserved clinoforms occur widely in both ancient and modern basin fills around the world (Olariu et al., 2020; Pellegrini et al., 2020). Clinoforms not only record dynamic sediment transport processes from nearshore to deep water, but also capture the integrated effects of global sea-level changes, sediment supply, paleogeomorphological features and tectonic activity, and exert a primary control on depositional facies distribution (Henriksen et al., 2009; Anell et al., 2014; Patruno and Helland-Hansen, 2018; Pellegrini et al., 2020). Although research on factors that govern the development of clinoforms in siliciclastic systems is well established (Patruno et al., 2015; Patruno and Helland-Hansen, 2018), studies of factors that control clinoform development in carbonate systems remain relatively few in number, albeit a small number of successions, such as the extensive outcrops of the Permian of the Guadalupe Mountains have been studied in detail (Saller, 1996; Hunt et al., 2003; Kerans et al., 2013; Playton and Kerans, 2018). Unlike the skeletal-dominated factories of the Late Paleozoic (Xu et al., 2023), Lower Cambrian platforms were dominated by microbial communities following the profound environmental changes of the Ediacaran-Cambrian transition (Zhuravlev and Wood, 2018; Wood et al., 2019). While the study of Guadalupe Mountains has established fundamental models (Kerans et al., 2013), mechanisms driving clinoform evolution in the Early Cambrian remain distinct. This is largely because carbonates predominantly form rapidly in situ via chemical and biochemical precipitation (Pomar and Hallock, 2008; Pomar et al., 2012), resulting in more complex and diverse clinoform geometries and architectures, with depositional patterns and sedimentary evolution that have not been systematically investigated (Pellegrini et al., 2020). Consequently, clinoforms and their complex internal architectures record important aspects of the depositional evolution of carbonate systems. Moreover, they hold critical geological significance for the formation and distribution of subsurface resources.

Recent research in the Lower Cambrian of the Tarim Basin has achieved significant breakthroughs in the Xiaerbulake Formation (or Stage 3) (Du and Pan, 2016; Zheng et al., 2020). Research advances have been made in areas such as sedimentology, microbiology, reservoir

characterization, and clinoform analysis. [Hu et al. \(2019a\)](#), [Ji et al. \(2020\)](#) and [Zhu et al. \(2019\)](#) integrated intra-basin drilling and field outcrop data to investigate tectono-sedimentary paleogeography, thereby providing general insights into sedimentary facies associations and their spatial distribution. [Song et al. \(2014b\)](#), [Bai et al. \(2017a\)](#). [Chen et al. \(2024\)](#) examined microbial classification, microbial rock types, and their controlling factors. [Jiang et al. \(2021\)](#) and [Zheng et al. \(2020\)](#) explored reservoir geological models, diagenetic processes, and reservoir genesis. [Song et al. \(2014b\)](#), [Bai et al. \(2017a\)](#) identified multiple phases of microbial mound clinoforms in the field. [Liu et al. \(2016\)](#) and [Zhu et al. \(2023\)](#) identified several generations of clinoforms within the basin. However, most prior studies have solely focused on field sections, single-well analyses, or large-scale seismic interpretation, lacking systematic, high-resolution, multi-well integrated quantitative analyses of clinoform geometries and depositional architectures ([Zhu et al., 2019](#); [Zhu et al., 2023](#)). Moreover, comprehensive evaluations of external controls—such as global sea-level fluctuations, paleogeomorphology, paleoclimate, and paleoceanography—on carbonate clinoform formation and evolution are still limited. Regional comparative studies are also relatively scarce, hindering a comprehensive understanding of the sedimentary evolution and reservoir development patterns in the Xiaoerbulake Formation carbonates ([Li et al., 2017](#); [Wei et al., 2021](#)).

To address these knowledge gaps, this study investigates the Lower Cambrian Xiaoerbulake Formation in the Tarim Basin by integrating high-resolution three-dimensional seismic data with drilling and well-logging information. The geometries and internal architectures of carbonate clinoforms and their associated stratal packages are systematically characterized, and their spatial distribution patterns and trajectory evolution are comprehensively analyzed. A high-resolution sequence stratigraphic framework was established to reconstruct the depositional evolution during different stages. This framework allows for a comprehensive assessment of the interplay among paleogeomorphology, relative sea-level fluctuations, paleoceanographic dynamics, and paleoclimatic conditions in controlling clinoform growth and sediment accumulation processes.

2 Geological setting

The Tarim Basin is one of the largest and oldest cratonic basins in northwestern China (Fig. 1a). It is bounded by the Tianshan Mountains to the north and the Kunlun-Altyn Mountains to the south (Fig. 1b) ([Lin et al., 2011](#); [Zhang et al., 2013](#); [Shi et al., 2018](#); [Shang et al., 2020](#)). The basin covers an area of approximately 56×10^4 km², with significant subsurface resource potential ([Lu et al., 2008](#); [Gao and Fan, 2015](#)). During the Neoproterozoic, the region underwent extensive extensional tectonism associated with the breakup of the Rodinia supercontinent ([Jia, 1997](#); [Jia et al., 2004](#); [He et al., 2005](#)). By the late Ediacaran, the Keping tectonic event uplifted the basin, resulting in a widespread regional unconformity ([He et al., 2019](#)). Subsequently, gradual subsidence during the early Paleozoic facilitated widespread marine transgressions in the Cambrian ([Lin et al., 2012](#); [Shang et al., 2020](#); [He et al., 2025](#)). The present study focuses on the central and northern parts of the Tarim Basin, encompassing major tectonic units such as the eastern Tabei Uplift, Aman Depression, Tazhong Uplift, and western Manjiaer Depression (Fig. 1b). This region exhibits a complex depositional paleogeomorphology, typified by a general southwest-high to northeast-low paleorelief ([Wei et al., 2021](#)).

Internationally, the Cambrian System is subdivided into four series and ten stages ([Geyer and](#)

121 Shergold, 2000; Babcock et al., 2005). However, in the Tarim Basin, the Cambrian succession is
122 routinely divided into three series (Lower, Middle, and Upper Cambrian) and six stages (Fig. 2) (Jia
123 et al., 2004; Zhang et al., 2020). This regional division is broadly time-equivalent and correlatable
124 with the international scheme. The Lower Cambrian in the Tarim Basin corresponds to the
125 international Terreneuvian and Series 2. The Xiaoerbulake Formation, the focus of this study, is
126 assigned to the Lower Cambrian and is equivalent to international Stage 3 (Jia et al., 2004; Zhang
127 et al., 2020; Wu et al., 2021b). Stratigraphically, the Xiaoerbulake Formation overlies the Yuertusi
128 Formation (Fortunian to Stage 2) and is succeeded by the Wusonggeer Formation (Stage 4) (Jiang
129 et al., 2021). The Lower Cambrian successions in the Tarim Basin exhibit significant regional
130 variability between the southern and northern area (Liu et al., 2022b; Cheng et al., 2023).

131 The Yuertusi Formation is largely absent or extremely thin in the southern region due to
132 extensive exposure of the paleocontinent (Liu et al., 2022b). By contrast, in the north this formation
133 comprises deep-water black shale and argillaceous limestone, which have been interpreted as
134 deposits of a shelf depositional environment (Gao et al., 2022; Zhu et al., 2024). The Xiaoerbulake
135 Formation is dominated by mixed siliciclastic-carbonate rocks and crystalline dolomite in the
136 southern region (Cheng et al., 2023) and the northern region is characterized by relatively deep-
137 water limestone and dolomitic limestone, indicating a ramp depositional environment (Zheng et al.,
138 2019; He et al., 2025). The Wusonggeer Formation is characterized by thick evaporites in the
139 southern region, which formed under intense evaporitic conditions (Zhang et al., 2023), while the
140 northern region is dominated by argillaceous dolomite and gypsum dolomite deposited in a tidal flat
141 environment, indicative of a rimmed platform depositional environment (He et al., 2025).

142 3 Data and methods

143 This study uses a diverse set of data to support a systematic analysis of the geometry and
144 depositional evolution of Stage 3 clinoforms of the Tarim Basin. The dataset comprises 3D seismic
145 volumes, wells, and both wireline and mud logging data. The high-resolution 3D seismic survey
146 covers approximately 13×10^4 km² (Fig. 1). Well data include records from 11 wells, with core,
147 cuttings and thin-section interpretations primarily acquired from prior studies (Peng et al., 2022;
148 Zhu et al., 2024; He et al., 2025). Mud logging data provide insights into dolomite and calcite
149 content, whereas gamma-ray (GR) and Resistivity (RD) logs serve as the primary wireline log
150 dataset.

151 Seismic interpretation utilizes high-resolution profiles extracted from the seismic volume and
152 analyzed using standard interpretation techniques (Mitchum et al., 1977). Key seismic boundaries,
153 facies types, and clinoform geometries were identified and mapped using the Move™ software
154 (Midland Valley). Seismic facies were classified based on reflection amplitude, frequency, and
155 continuity, calibrated against lithological data from multiple wells. Vertical seismic calibration was
156 applied to integrate well-log data with seismic datasets. To analyze clinoform architecture, the
157 seismic profiles were flattened on the surface representing the base of the Lower Cambrian (cf.
158 Huang et al., 2020; He et al., 2025). Clinoform edge (i.e., breaks of slope) and lower rollover points
159 were identified and traced across the sections to delineate spatial distribution and edge locations of
160 successive clinoform sets (Anell et al., 2014; Berton and Vesely, 2016; Pellegrini et al., 2020).

Several geometric parameters were quantitatively extracted, including progradation distance, aggradation thickness, trajectory angle, foreset dip, clinoform height, and width (Fig. 3) (cf. Anell et al., 2014; Paumard et al., 2019). Progradation distance reflects basinward migration trends, whereas aggradation thickness and trajectory angle provide constraints on sediment supply and relative sea-level change. Foreset dip, height, and width inform interpretations of sedimentation rates and accommodation space variability (Anell et al., 2014; Paumard et al., 2019; Gamberi et al., 2020). Residual thickness analysis was applied to evaluate thickness differentials (cf. Feng, 2004; Zhang et al., 2021b), revealing that the central part of the study area was a paleogeomorphic depression, and enabling a preliminary delineation of its spatial extent. Due to the proprietary nature of the 3D seismic data, only owner-approved profiles are presented.

Generally, each depositional sequence can be subdivided into four systems tracts: lowstand systems tract (LST), transgressive systems tract (TST), highstand systems tract (HST) and falling stage systems tract (FSST) (Van Wagoner et al., 1987; Posamentier and Vail, 1988; Catuneanu et al., 2009). However, in many cases, lowstand and falling stage systems tracts tend to be only poorly developed and represented in carbonate depositional systems (Burchette and Wright, 1992). Herein, a transgressive–regressive (T-R) sequence model is selected to subdivide the Stage 3 strata of the studied Cambrian succession (cf. Embry, 1993; Catuneanu et al., 2006; Catuneanu et al., 2009): Regressive Systems Tracts (RST) and Transgressive Systems Tracts (TST) are identified. Maximum flooding surfaces (MFS) are used to define systems tract boundaries (Embry, 1993).

For well-log analysis, Integrated Prediction Error Filter Analysis (INPEFA) was applied to GR curves. This method utilizes the Burg spectral approach to calculate autoregressive coefficients and derive a maximum entropy spectrum prediction. The Prediction Error Filter Analysis (PEFA) curve is generated by subtracting these predicted values from the original GR data (Nio et al., 2005; Behdad, 2019). The PEFA curve is then integrated to produce the INPEFA curve, which reflects relative changes in water depth (Behdad, 2019; Akbarzadeh et al., 2025). An increasing INPEFA trend upward indicates a transgressive phase, whereas a downward trend denotes regression (Yuan et al., 2018; Hu et al., 2021). Turning points in the INPEFA curve often correspond to sequence boundaries (Abedi et al., 2025). However, INPEFA is sensitive to non-stationary signals, where long- and medium-term trends—driven by tectonic subsidence or long-period climatic variation—may obscure finer-scale stratigraphic signals (Li et al., 2019). According to Magalhaes et al. (2020), apparently low-resolution signals may reflect the superposition of high-resolution signals upon broader trends. To improve resolution and eliminate trend bias, wavelet transform or INPEFA-based multi-scale decomposition techniques have been proposed (Behdad, 2019). In this study, we applied the L1 trend filtering algorithm (cf. Kim et al., 2009) to the GR data for detrending. The L1 trend filtering algorithm is a regularization-based method that decomposes a time series into a long-term trend component and a short-term residual component. It solves an optimization problem that balances fidelity to the original data with an L1 penalty on the second differences of the estimated trend. This approach yields a piecewise linear trend that adapts to changes in the data while preserving sharp breakpoints. By applying L1 trend filtering, we effectively removed low-frequency background trends and enhanced recognition and delineation of high-resolution stratigraphic sequences.

4 Results

4.1 Seismic facies description and interpretation

The seismic reflections are predominantly characterized by clinoform-related facies. Based on reflection configuration, amplitude, frequency, and continuity observed on seismic profiles, seven typical seismic facies types have been identified within the clinoforms. These facies are closely associated with specific depositional environments (Fig. 4).

Seismic Facies One (SF1). *Composition:* SF1 is defined by parallel, highly continuous reflections with strong amplitude and low frequency. It exhibits a relatively thin thickness of approximately 15–30 ms TWT (22.5–45 m). *Interpretation:* SF1 is interpreted as corresponding to mixed tidal flat deposits (Fig. 4) (Peng et al., 2022). This facies is restricted to the southwestern portion of the study area, specifically the Tazhong Uplift, and displays limited spatial extent (Yang et al., 2021).

Seismic Facies Two (SF2). *Composition:* SF2 is characterized by subparallel reflections of moderate to low continuity, moderate to strong amplitude, and moderate frequency, with a thickness of approximately 30–40 ms TWT (45–60 m; Fig. 4). *Interpretation:* SF2 is interpreted as dolomite flat deposits developed within the inner ramp (Yang et al., 2018; Peng et al., 2022) and is mainly present in the Tazhong Uplift.

Seismic Facies Three (SF3). *Composition:* SF3 displays parallel reflections with moderate to high continuity, moderate amplitude, and moderate to low frequency. Its maximum thickness reaches up to 270 ms TWT (approximately 405 m) and is interpreted as representative of depression-fill deposits within the middle ramp (Fig. 4) (Hu et al., 2019b; Hendry et al., 2021). *Interpretation:* SF3 is widely distributed throughout the central and western regions of the study area.

Seismic Facies Four (SF4). *Composition:* SF4 is characterized by arch-shaped, low-continuity reflections with moderate to weak amplitude and high frequency (Fig. 4). *Interpretation:* SF4 is interpreted as representing inner-ramp shoal deposits (Liu et al., 2020; Peng et al., 2022) and is mainly observed in the southern Tazhong Uplift.

Seismic Facies Five (SF5). *Composition:* SF5 exhibits subparallel reflections with moderate continuity, moderate to weak amplitude, and moderate to high frequency. It has a moderate thickness ranging from 60 to 140 ms TWT (90–210 m). *Interpretation:* SF5 corresponds to deposits from the inner middle ramp (Fig. 4) (Zhang et al., 2021c; He et al., 2025). This facies shows clear spatial and temporal variability. It is continuously distributed in the southwestern Awati Depression, the Tazhong Uplift, and the Aman Depression, but occurs only in the upper stratigraphic levels in the eastern Tabei Uplift.

Seismic Facies Six (SF6). *Composition:* SF6 presents subparallel to parallel reflections with moderate to high continuity, moderate to strong amplitude, and moderate to low frequency. It reaches a maximum thickness of approximately 230 ms TWT (345 m). *Interpretation:* SF6 is interpreted as associated with outer middle ramp (Fig. 4) (Zhang et al., 2021c; Zeng et al., 2022; He et al., 2025). This facies is continuously developed in the eastern part of the study area, showing a rapid west-to-east thinning trend.

Seismic Facies Seven (SF7). *Composition:* SF7 is distinguished by chaotic, low-continuity

reflections with weak amplitude and high frequency. It has a relatively thin thickness of approximately 20–50 ms TWT (30–70 m) and typically appears between intervals of the fifth seismic facies (Fig. 4). *Interpretation*: SF7 is interpreted as middle-ramp shoal deposits, primarily occurring in the upper strata of the eastern Tabei Uplift (Hu et al., 2019b; Huang et al., 2020). Its distribution is scattered and discontinuous, and it is not discernible in some seismic profiles.

4.2 Trajectory description and three-dimensional architecture

In the study area, the thickness of Stage 3 strata increases from ~50 meters in the south to ~500 meters in the north, and is relatively thin in the east, ~100 meters (Fig. 5). This study presents five 2D seismic profiles selected from a larger 3D dataset, each with varying orientations to systematically characterize the geometry, internal architecture, and spatial distribution of clinoforms in the study area. A total of five composite clinothems (Composite Clinothem one to Composite Clinothem five, CC1–CC5) are identified, which are further subdivided into seventeen individual clinoforms (C1–C17; Fig. 5-9).

Given the tectonically stable setting of the Tarim Basin, we identified five major onlap surfaces through seismic tracking of the composite clinothem boundaries. These composite clinothems correspond closely with the five major maximum flooding surfaces recognized globally by Haq and Schutter (2008) for this time period, providing a reliable framework for constraining the temporal boundaries of each clinoform package (Fig. 2). This correlation is proposed as a working hypothesis for discussing the depositional duration of the composite clinothems, given the absence of independent absolute age control from the study area. The subsequent discussions on depositional timing are therefore based on this hypothesized framework. Nevertheless, the broader chronostratigraphic framework of the study interval (Stage 3) has been constrained by previous studies (Chen et al., 2024). Line 1 is oriented southwest-to-northeast across the central study area and images the full suite of clinoforms (Fig. 5). Line 2 is oriented west-to-east through the northern sector, imaging CC2–CC5 (Fig. 6). Line 3 is a short west-to-east-oriented profile in the northeastern portion of the study area, where only CC3–CC5 are identified (Fig. 7). Each composite clinothem itself hosts three or four smaller clinoform units nested within it. Line 4 is oriented southwest to northeast and demonstrates the lateral variability of the clinothem geometries (Fig. 8). In addition, a strike-oriented (northwest-to-southeast) profile (Line 5) has been extracted to illustrate lateral stratigraphic continuity and correlation across the study area (Fig. 9), and to tie key stratal surfaces between all the presented lines.

Based on analyses of the clinoform edge (i.e., breaks of slope) trajectory angle (Tse) and the ratio of progradation to aggradation (Pse/Ase), three trajectory types are defined (Table 1-3): (1) Descending: $Tse < 0^\circ$ and $Pse/Ase < 0$, indicating negative aggradation and a downward trajectory characteristic of retrogradational clinoform stacking; (2) Flat: $0^\circ < Tse < 0.1^\circ$ and $Pse/Ase > 500$, suggesting a stable, progradational edge with minimal aggradation; (3) Ascending: $Tse > 0.1^\circ$ and $0 < Pse/Ase < 500$, reflecting combined aggradational and progradational stacking trends. It is noteworthy that the seismic profiles are not precisely orthogonal to the regional clinoform strike. Consequently, to obtain accurate spatial dimensions in map view, corrections for apparent distance are required. Such corrections have been implemented using standard trigonometric correction methods.

4.2.1 Seismic profile characteristics

4.2.1.1 CC1 (C1 to C3)

The lower surface boundary of CC1, deposited between 521 Ma and 518.8 Ma, *sensu* Haq and Schutter (2008), corresponds to the boundary between the Terreneuvian and Series 2 of the Lower Cambrian (Wang et al., 2024). This surface boundary is represented by an onlap surface (SB0; Fig. 5a-b) characterized by strong seismic amplitude, attributed to the pronounced acoustic impedance contrast between the Terreneuvian and Series 2 strata (Zeng et al., 2022). CC1 overlies thin-bedded deep-water deposits of the Yuertusi Formation (Wei et al., 2021). It is primarily composed of mixed tidal flat (seismic facies SF1), dolomite flats (SF2), and middle-ramp depression deposits (SF3; Fig. 5c). In some wells, this clinoform unit is associated with relatively thin successions of terrigenous detritus (Yang et al., 2021), exhibiting strong-amplitude, moderate- to low-frequency reflections up to 30 ms TWT (approx. 45m; Fig. 5c).

Composite Clinothem One (CC1) is only observed in Line 1 and Line 5. It displays a distinctly ascending edge (i.e., breaks of slope) trajectory, shaped by both aggradation and progradation (Fig. 5b and Fig. 9b). The clinoform edge of CC1 progrades approximately 38 km into the basin and thickens by 180 m. The trajectory angle reaches 0.27° , while the foreset dip remains relatively low ($\sim 0.53^\circ$). During the initial development stage, the C1 deposits downlap onto Terreneuvian strata and onlap the paleocontinent, forming a steep edge trajectory ($\sim 0.58^\circ$) and attaining a maximum aggradational thickness of approximately 95 m. This relationship indicates a period of rapid relative sea-level rise. In the subsequent stage, the C2–C3 clinoforms record reduced aggradation (~ 51 m), while substantial topset accumulation was maintained. These deposits continue to onlap the paleocontinent and prograde basinward over a distance of up to 15 km (Table 1). This progradational pattern records a slower but sustained episode of sea-level rise that gradually inundated (i.e., transgressed) the paleocontinental surface.

4.2.1.2 CC2 (C4 to C6)

The lower surface boundary of CC2, dated between 518.8 Ma and 517.8 Ma, *sensu* Haq and Schutter (2008), is defined by surface boundary SB1, which sharply separates the overlying reflections characterized by moderate- to strong- amplitude, weak continuity, and moderate- to low-frequency from underlying reflections with moderate amplitude, high continuity, and low frequency (Fig. 5a). In proximal areas, SB1 behaves as a transgressive surface and extends basinward. Seismic profiles show that CC1 onlap the CC2 package (Fig. 5b). Compositionally, CC2 resembles CC1; it is dominated by inner-ramp dolomite flat deposits (SF2) and middle-ramp depression deposits (SF3; Fig. 5c and Fig. 6c). The thickest interval of SF3 reaches up to 250 ms TWT (approximately 375 m), making it one of the most significant records of accommodation creation and sedimentation rate. In the proximal part of CC2, an approximately 20 ms TWT (~ 30 m) strong-amplitude reflection is also observed, indicating the mixed tidal flat deposits (Fig. 6c).

Composite Clinothem Two (CC2) is fully preserved in Line 1 and Line 5 (southern study area) but only partially observed in Line 2 (northern area). The clinoform edge trajectory evolves from an ascending to a descending pattern, displaying pronounced progradation with minor aggradation (Fig. 5b, Fig. 6b and Fig. 9b). In Line 1 and Line 2, the clinoform edge progrades ~ 28 km and ~ 23 km basinward, respectively. The trajectory angle remains gentle ($\sim 0.02^\circ$), while the foreset dip increases significantly to $\sim 1.51^\circ$. In the southern area, C4 shows ~ 49 m of aggradation, suggesting a moderately rapid sea-level rising, resulting in accommodation space increase. In contrast, the edges

of C5–C6 exhibit descending trajectories, and their progradation distances (~10 km) are shorter than those in CC1. In the north, C5–C6 show steeper trajectory angles and more extensive progradation (~27 km; Table 1 and Table 2). The rollover points of the clinoforms shift markedly basinward, resulting in downlap onto thin-bedded outer ramp to basin deposits.

4.2.1.3 CC3 (C7 to C10)

The lower surface boundary of CC3 (517.8–517 Ma), *sensu* Haq and Schutter (2008), marked as surface boundary SB2, is defined by seismic reflections with medium to weak amplitude, moderate continuity, and moderate- to low- frequency. This surface represents a prominent downlap surface that separates overlying reflectors—characterized by moderate amplitude and continuity—from underlying reflections with medium to strong amplitude and poor continuity (Fig. 6a-b). CC3 is distinct from earlier clinoforms in that inner-ramp shoal facies (SF4) are sporadically developed within inner ramp dolomite flats (SF2), while middle-ramp depression deposits (SF3) reach a thickness of 150 ms TWT (approximately 225 m; Fig. 6c).

Composite Clinothem Three (CC3) is fully developed in Line 1 and Line 4 across the central study area and is also observed in Lines 2 and 3 farther north. The trajectory of the ramp edge transitions from ascending to descending (Fig. 6b-8b). Compared to CC2, CC3 is characterized by a steeper foreset dip and a smaller trajectory angle. The ramp edge progrades basinward by approximately 30 km and 39 km along Lines 1 and 2, respectively. In Line 3, where the clinoform is incomplete, progradation reaches only ~19 km, indicating that northern progradation distances exceed those in the south. The foreset dip of CC3 increases to 2.2°. In the northern sector, C7 exhibits an aggradation thickness of ~80 m, substantially greater than the 23 m observed in the central area. Correspondingly, the trajectory angle in the north (~1.59°) is also larger than that in the central part (~0.60°). From C8 to C10, progradation distances in the north increase from 8 km to 11 km. Although the horizontal distance between the ramp-edge and the basal rollover point gradually decreases, the overall clinoform height remains constant (~230 m), resulting in an increase in dip to 1.76°. In contrast, the central zone shows a rise in progradation distance (~8 km) followed by a reduction (~7 km), with a much gentler trajectory angle (~0.13°). Meanwhile, the foreset dip rapidly increases from 1.36° to 2.22° (Table 1 and Table 2).

4.2.1.4 CC4 (C11 to C13)

Surface boundary SB3, which defines the base of CC4 (517–515.5 Ma), *sensu* Haq and Schutter (2008), is readily identifiable on seismic profiles by its moderate amplitude, moderate continuity, and moderate frequency reflections, along with a characteristic downlap geometry (Fig. 6a-8a). Above this surface boundary, the clinoform foreset dip increases, and the overlying CC4 package is marked by moderate to strong amplitude, high continuity, and high-frequency reflections (Fig. 7b). The mixed tidal flat facies (SF1) is either absent or only weakly developed. Instead, the clinoform set is dominated by inner middle ramp (SF5) and outer middle ramp (SF6) deposits (Fig. 5c and 6c). Locally, some middle ramp shoal facies (SF7) are developed near the tops of the clinoform sets (6c).

Composite Clinothem Four (CC4) is observed in all three seismic profiles and is consistently located in the northern part of the study area (Fig. 5-7). The ramp-edge trajectory of CC4 varies: it is descending in Line 1 (~-0.06°), but displays ascending trends in Line 2 (0.14°) and Line 3 (0.04°). Compared to CC1–CC3, the progradation distance of CC4 is considerably reduced—approximately 15 km in Line 1 (Table 1) and about 18 km in Lines 2 and 3 (Table 2-3). C11 exhibits an ascending

trajectory, with significant aggradation in Lines 2 and 3 (~62 m and ~32 m, respectively), while in Line 1 the vertical aggradation is limited (~16 m). Additionally, progradation in Line 1 is only ~4 km, indicating a rapid relative sea-level rise that generated substantial accommodation space (Table 1-3). C12–C13 exhibit descending trajectories with limited landward migration of the basal rollover point. The magnitude of descent decreases from -0.24° to -0.10° in Lines 1 and 2, but increases from -0.76° to -1.09° in Line 3 (Table 1-3).

4.2.1.5 CC5 (C14 to C17)

CC5 (515.5–514 Ma) *sensu* Haq and Schutter (2008), is positioned above surface boundary SB4, a prominent onlap surface that clearly separates overlying reflectors—characterized by moderate to weak amplitude, low continuity, and high frequency—from underlying units (Fig. 5a-8a). The top of CC5, marked by SB5, signifies the termination of clinoform deposition. This surface boundary distinctly separates strong-amplitude, continuous, low-frequency reflectors from those of CC5 (Huang et al., 2020; Zeng et al., 2022). The clinoform set displays well-developed downlap reflections and convergence of foreset reflections toward the underlying clinoforms, forming a complete envelope with the underlying clinoforms (Fig. 5b-8b). The inner-ramp mixed tidal flat facies (SF1) is absent in proximal parts of this clinoform (Fig. 5a). The distal forset of CC5 shows seismic characteristics similar to CC4, but middle-ramp shoal facies (SF7) are more extensively developed near the top (Fig. 5c and Fig. 6c).

Composite Clinothem Five (CC5) is observed across all three seismic profiles, though its spatial orientation varies. In Line 1, the clinoform edge trajectory is parallel to descending (Fig. 5b), while in Lines 2 and 3 it transitions from ascending to descending (Fig. 6b-8b). Overall, CC5 displays a more pronounced progradational pattern than CC1–CC4, with steeper dips and greater descent in its edge trajectories. Progradation distances in Lines 1 and 2 reach approximately 34 km and 33 km, respectively (Table 1-2), whereas Line 3 records a slightly shorter distance of ~28 km (Table 3). C14 shows limited progradation (~5–7 km) and a gently sloping edge trajectory that is mostly parallel to slightly ascending. From C15 to C17, progradation distances increase progressively from 8 km to 10 km, indicating an expansion in the scale of clinoform deposition. The trajectory descent becomes more pronounced—for example, in Line 3 the trajectory angle decreases from -0.72° to -4.77° (Table 1-3).

4.2.2 Plan view distribution

By identifying the clinoform edge (i.e., breaks of slope) on five seismic profiles (Line 1, Line 2, Line 3, Line 4 and Line 5), the plan-view distribution of each composite clinothem (CC1–CC5) was reconstructed (Fig. 10). Overall, the clinoform sets in the study area exhibit a general migration trend from southwest to northeast. For more detailed spatial analysis, each clinoform was divided into three segments: northern ($N43^{\circ}$ – $N40^{\circ}$), middle ($N40^{\circ}$ – $N37^{\circ}$), and southern ($N37^{\circ}$ – $N34^{\circ}$) zones. Line 1 reveals middle segments of CC1–CC3 and northern segments of CC4–CC5) whereas Lines 2 and 3 mainly represent northern segments (Fig. 10). The analysis in this study focuses primarily on the northern and middle zones.

Composite Clinothem One (CC1) is mainly distributed in the southwest, trending WNW–EES. The northern segment exhibits significantly greater migration than the middle. The northern clinoform edge is relatively straight, oriented approximately $N45^{\circ}$ E, with a migration distance of ~80 km. In contrast, the middle segment exhibits a northeastward shift with a more curved edge

(~N30°E) and a shorter migration distance of ~50 km, which decreases rapidly from north to south (Fig. 10a). CC2 is predominantly located in the northwest and trends NW–SE. The northern edge is slightly curved, with a similar orientation to CC1 and a migration distance of ~40 km. The middle segment is deflected southward to ~N70°E, with a north-to-south decrease in migration from ~35 km to ~10 km (Fig. 10b). CC3 shows a clear northeastward shift from CC2, trending NW–SSE. In the northern segment, the clinoform edge is notably curved, with migration distances ranging from ~30 to 25 km. A distinct inflection point is observed: to the north of the inflection, the trend is ~N50°E, while to the south it approaches ~N85°E. The middle segment edge is straighter, trending NNW–SSE, with a shorter migration distance of ~15 km (Fig. 10c). The areal extent of CC4 is more limited, with its main body confined to the northeast. It shares a similar orientation with CC3, though its migration distances are significantly shorter ~18 km in the north and ~10 km in the south (Fig. 10d). CC5 spans a broader area than CC4 and trends generally NNW–SSE, with its edges oriented nearly E–W. The northern segment exhibits a straight edge with a trend of ~N60°E and a migration distance of ~35 km. South of the inflection point, the trend shifts to ~N95°E with a migration distance of ~15 km. In the middle segment, the clinoform edge trends ~N80°E, and the migration distance increases relative to the southern part of the northern segment (Fig. 10e).

In summary, the orientations of successive clinoforms reveal a progressive shift from WWS–NNE to NW–SE. Spatial extent and migration distances tend to decrease from early to late stages. Additionally, clinoform migration distances are greater in the northern segments compared to the middle, whereas edge orientation changes more sharply in the middle than in the north.

4.3 High-resolution sequence stratigraphic framework

4.3.1 3rd order stratigraphic sequences

Two third-order sequences (SQ1 and SQ2) are identified within the Stage 3 strata based on both seismic profiles and well data (Fig. 11 and Fig. 12a), consistent with previous sequence stratigraphic frameworks developed from both outcrop and subsurface studies (Bai et al., 2017a; He et al., 2025). In outcrop sections, SQ1 generally displays relatively dark-colored deposits, whereas SQ2 is characterized by lighter-colored strata (Song et al., 2012; Bai et al., 2017b). Within the basin interior, the sequence boundaries that define these sequences are identified by large-scale onlap and downlap surfaces in seismic profiles, and by marked lithologic transitions in wells. The previously identified surfaces SB0, SB3, and SB5 correspond, respectively, to the base of the first third-order sequence, the base of the second third-order sequence, and the top of the second third-order sequence of Stage 3 strata. These two third-order sequences show distinct differences in seismic reflection characteristics and ramp-edge (i.e., breaks of slope) trajectories. In SQ1, CC1–CC3 were respectively deposited during TST1–RST1, RST2, and RST3, and are primarily composed of seismic facies corresponding to inner ramp, outer middle ramp, and outer ramp facies. The associated clinoform edge (i.e., break of slope) trajectories are predominantly ascending to flat. In contrast, SQ2 includes CC4 and CC5, which developed during TST2–RST4 and RST5, and are dominated by seismic facies associated with inner middle ramp, outer middle ramp, and outer ramp facies. SQ2 exhibits steeper ramp-edge geometries and preserves clear onlap terminations, along with a transition from flat to descending edge trajectories.

4.3.2 4th order stratigraphic sequences

Within the third-order sequences, multiple fourth-order sequences can be identified through the integration of seismic profiles, drilling data, and well-log curves. In seismic sections, these fourth-order sequences are typically marked by local onlap or downlap geometries, whereas in well logs they correspond to abrupt changes in lithology and electrical-log signature. The fourth-order sequence boundaries align closely with clinoform boundaries (Fig. 11 and Fig. 12b). No distinct unconformities are observed at these boundaries; instead, they are primarily characterized by lithologic transition surfaces. Log responses below the boundary typically show upward-increasing trends, whereas those above exhibit decreasing trends. Furthermore, high-resolution division of fourth-order sequences is achieved by comparing detrended INPEFA curve variations across different systems tracts within each third-order sequence using selected well data. The tops of fourth-order sequences are often marked by decreasing GR values, elevated dolomite content, relatively low INPEFA values, and notably low resistivity value—indicative of high-energy, grain-dominated carbonate deposition. In contrast, the base is commonly associated with increased GR values and higher calcite content, reflecting the deposition of low-energy micritic limestone. Well-to-seismic calibration results demonstrate that intervals represented by high-energy deposits correspond to seismic troughs, with trough amplitude strength reflecting the development intensity of such sediments. For instance, in Well 6, the uppermost strata consist of a very shallow-water, high-energy grain-dominated carbonate unit. This interval is expressed seismically as moderate–weak amplitude, moderately continuous, high-frequency, low-polarity reflections, consistent with sedimentological interpretations.

4.3.3 5th order stratigraphic sequences

Due to the relatively low resolution of the available seismic data, fifth-order sequences observed in well logs cannot be reliably identified directly from seismic profiles. In contrast, natural GR logs provide indications of lithologic changes within the stratigraphy. However, GR signals are inherently composite, integrating multiple stratigraphic signatures and thus remain vulnerable to interpreter subjectivity. To minimize such bias, this study builds upon the fourth-order sequence framework and applies detrended INPEFA analysis for high-resolution delineation of fifth-order sequences (Fig. 11 and Fig. 12c). Detailed analysis focuses on the uppermost fourth-order sequence within CC5, a key target interval in subsurface resources exploration. Based on lithologic observations and log responses, each fifth-order sequence displays a vertically upward-shallowing regressive pattern. Typically, the base consists of low-energy micritic limestone. As sea level falls and salinity increases, high-energy peloidal limestone and dolomitic limestone become more abundant, transitioning upward into argillaceous dolomite and intraclastic dolo-grainstone. When sea level rises abruptly, dolomite is rapidly replaced by micritic and dolomitic limestone, forming a distinct lithologic transition surface that marks the fifth-order sequence boundary (Fig. 11 and Fig. 12c) (Zhu et al., 2024; He et al., 2025). INPEFA curves closely correspond to these depositional patterns. During periods of lower sea level, the INPEFA curve shows a negative trend, consistent with low-GR and low-RD dolomite deposition. In contrast, the curve trends positively, corresponding to high-GR and high-RD limestone intervals. Notably, upward inflection points in the INPEFA curve align closely with fifth-order sequence boundaries.

5 Discussion

5.1 Paleogeomorphology analysis and restoration

This study integrates seismic profiles and previous research (Chen et al., 2015; Hu et al., 2019a), to reconstruct the paleogeomorphologic characteristic of the study area. The Stage 3 strata exhibit a typical pattern of greater thickness in the central basin, thinning progressively toward the margins, with the thinnest accumulation in the western sector (Fig. 13a). To ensure the reliability of the residual thickness analysis, the top of the Stage 3 strata was selected as the flattening datum (Fig. 13b), providing a more accurate restoration of depositional paleotopography. A two-dimensional seismic profile trending from southwest to northeast across the central basin (flattened to the Stage 3 strata top) similarly shows thicker strata in the basin center and thinner deposits toward the flanks. As regional tectonic subsidence was relatively stable during this period (Gao et al., 2017; Huang et al., 2020), the observed thick central accumulations suggest that deposition within a depression with high initial accommodation.

In the southwest, reduced thicknesses is primarily controlled by the pre-existing paleo-uplifts (Zhu et al., 2019), as supported by the seismic onlap terminations that indicate elevated paleotopography. In contrast, reduced thicknesses in the east are attributed to deep-water depositional settings within the Manjiaer Depression (Hu et al., 2019a). Additionally, localized structural highs in the north (Fig. 13) may be the result of tectonic reactivation during the late Caledonian orogeny (Gao, 2015; Huang et al., 2020; Liu et al., 2022a), which caused regional uplift and complicated paleogeomorphologic restoration. However, analysis of thickness distribution still suggests that the northern region was a paleogeographic low during deposition, with relatively deeper water and evidence of underfilled sedimentation (Guan et al., 2019; Wu et al., 2021a). Overall, the depositional pattern of Stage 3 inherited of the paleogeomorphology from the late Terreneuvian, with a regional trend of high relief in the southwest and lower topography to the northeast. A central depression is observed in the basin, with a subtle submarine paleo-high developing along its eastern margin (Fig. 13c).

5.2 Depositional evolution and models

Based on the established sequence stratigraphic framework, this study integrates seismic-based geometries and sedimentological data from wells to analyze the depositional facies architecture of the Stage 3 succession (Fig. 11 and Fig. 12) and establish a depositional evolution model (Fig. 14-15). During the early Fortunian of the Cambrian, a rapid transgression resulted in the widespread deposition of deep-water shales across the Tarim Basin (Wei et al., 2021). Extensive paleo-uplifts were present throughout the basin. The southern part of the study area was dominated by exposed paleo-continent, whereas the central and northern regions represented shelf environment, and the eastern area developed into a deeper basin environment (Fig. 14a and Fig. 15a) (He et al., 2025). As sea level began to fall during Stage 2, the Tarim Basin entered a prolonged period of regression that persisted into Stage 4 (Bai et al., 2017a).

During the early development of SQ1, the basin developed a gentle ramp system with a central depression (Fig. 14a). In the early SQ1 (TST1 + RST1), an episode of rapid sea-level rise caused a transgression and a retreat of the shoreline of the southern paleo-continent. Along the margins of

the paleo-continent, narrow and continuous mixed tidal flats developed, characterized by the interfingering of terrigenous clastics and carbonates (Hu et al., 2019a; Zhu et al., 2019). Erosional processes dominated in the paleocontinental interior, resulting in sparse or absent sediment accumulation. Northeastward, the system transitioned into dolomite flats and inner middle ramp deposits dominated by argillaceous dolomite and micritic dolomite (Peng et al., 2022), which formed the foreset of CC1. Oolitic dolomite-dominated inner-ramp shoals developed on paleogeomorphic highs, locally containing minor amounts of terrigenous quartz grains (Cheng et al., 2023). The central region was characterized by a depositional environment of a middle-ramp depression. In the northeast, relatively shallow water conditions favored the development of outer middle ramp deposits dominated by peloidal limestone and dolomitic limestone (Fig. 14b and Fig. 15b) (Zhu et al., 2024; He et al., 2025), which gradually transitioned eastward into an outer ramp depositional environment.

During the later development of SQ1 (RST2 + RST3), sustained relative sea-level rise led to continued submergence of the southern paleocontinent, driving the southward migration of mixed tidal flats. Meanwhile, as the rate of sedimentation significantly exceeded the rate of relative sea-level rise, early-formed shallow-water inner-ramp shoals, dolomite flats, and inner middle ramp deposits progressively prograded northward, resulting in a substantial expansion of the inner-ramp depositional zone. The middle-ramp depression in the central region constitute the primary foreset development zone of CC2–CC3 (Fig. 14b and Fig. 15b). The gradual reduction in the spatial extent of the depression suggests a falling sea level. In the northeast, outer middle ramp deposits show a bidirectional migration toward the southwest and east.

During the early development of SQ2, the depositional system continued to reflect a ramp characteristic, but exhibited more pronounced development of high-energy shoals and restricted dolomite flats. The distal ramp became steeper, resulting in a depositional architecture characterized by distally steepened slopes with a central low (Fig. 14c and Fig. 15c). In the early SQ2 (TST2 + RST4), the southern study area was almost entirely submerged, leading to the development of mixed tidal flats, dolomite flats and small-scale inner-ramp shoals deposits. The extent of the central depression gradually decreased due to progressive sediment infilling. Surrounding inner middle ramp facies migrated toward the depression area, forming the principal foreset zone of CC4. In the northeast, Due to the continued sea-level fall, the northeast developed inner middle ramp deposits dominated by calcareous dolomite and dolomitic limestone (Fig. 15c) (Zhu et al., 2024; He et al., 2025). Inner middle ramp were distributed along the eastern margin of the central depression and were associated with small-scale middle ramp shoals forming near the tops of clinoform foresets on the basinward side. Toward the basin center, the depositional environments gradually transitioned into outer middle ramp, outer ramp, and ultimately deep-water basin (Fig. 14c).

During the later development of SQ2 (RST5), only limited mixed tidal flat deposits developed in the south, while the southwestern area was dominated by inner-ramp dolomite flats. As sea level continued to fall, large-scale inner-ramp shoals began to form along the southwestern margin of the central depression, acting as a barrier to seawater circulation. This promoted the development of gypsum dolomite flat deposits in the south (Jiang et al., 2018). In the northeast, nearly the entire area transitioned into inner middle ramp facies, with an expanded distribution (Fig. 15c). As clinoforms continued to prograde basinward, the middle-ramp shoals near the clinoform edges also migrated accordingly, exhibiting increased areal extent and enhanced continuity. The inner and outer

middle ramp deposits in the northeast constitute the primary foreset development zone of CC5. (Fig. 14c and Fig. 15d).

5.3 Controlling factors on architecture and evolution

The architecture of carbonate ramps is governed by the interplay between the rate of accommodation creation and the production efficiency of the carbonate factory (Scholle et al., 1983; Webster et al., 2004; Pedley and Carannante, 2006; Pomar et al., 2012). The former is directly controlled by tectonic activity (Watney et al., 2008) and global sea-level fluctuations (Lukasik and Simo, 2008; Bergman et al., 2010), whereas the latter is strongly influenced by nutrient availability (Lukasik and Simo, 2008), hydrodynamic energy (Bergman et al., 2010), water temperature, paleo-oceanic circulation, and paleoclimate conditions (Shahzad et al., 2018). Additionally, inherited paleotopography plays a critical role in defining the initial accommodation space (Catuneanu et al., 2006). The combined influence of these factors accounts for the significant variability observed in the architecture and depositional evolution of the shallow-water carbonate clinoforms in the study area.

5.3.1 Paleogeomorphology

Paleogeomorphic variation in the study area exerted a primary control on the migration direction, geometric characteristics of clinoforms, and sediment distribution. The undulation of paleotopography governed the amount of accommodation space available (Schlager, 2005), thereby influencing clinoform geometry. As paleotopography decreased from high to low, the increase in accommodation generally lead to longer clinoform progradation distances, steeper foreset angles, and greater clinoform widths. Conversely, these geometric parameters tend to be reduced overall. For example, in the C1–C4 of middle segment (N40°–N37°), increasing paleotopographic dip enhanced clinoform progradation. In contrast, the paleotopographic dip sharply decreased and even became negative in the C5–C10, resulting in a rapid reduction in geometric dimensions. Meanwhile, the gentler dips in the C11–C13 of northern segment (N37°–N34°) corresponded to larger all clinoform geometric parameters. In the C14–C17, increasing paleotopographic dip in the northern segment produced steeper edge (i.e., breaks of slope) trajectories, indicating the strong influence of paleogeomorphology on clinoform architecture (Fig. 16a-b). Additionally, paleogeomorphology relief determined depositional water depth, which exerted differential control on sediment types. In the southwest, paleotopographic highs favored the accumulation of high-energy shallow-water deposits such as intraclastic dolo-grainstone (Hu et al., 2019a; Zhu et al., 2019), whereas paleotopographic lows were dominated by deeper-water, low-energy deposits including limestones and calcareous dolomite in the northeast (Zhu et al., 2024; He et al., 2025). In the eastern paleotopographic highs, the development of clinoforms significantly promoted the accumulation of shallow-water, high-energy grain-dominated carbonates (Fig. 15). In contrast, the lower paleotopographic areas near the central depression remained dominated by deep-water, low-energy deposits such as micritic limestone, indicating that initial topographic highs were more susceptible to modification by clinoform progradation.

5.3.2 Sea-level changes

During the Early Cambrian Series 2 (including Stage 3 and Stage 4), the Tarim Basin

experienced relatively stable tectonic conditions and entered a phase of slow thermal subsidence (Gao et al., 2017). The depositional process was unaffected by syndepositional faulting (Huang et al., 2020), and variations in accommodation were primarily controlled by in relative sea-level changes (RSL), which can be categorized into low-frequency and high-frequency fluctuations.

5.3.2.1 Low-frequency sea-level changes

Low-frequency relative sea-level changes exerted a control on long-term accommodation trends, significantly influencing the geometry, sediment composition, and depositional environments of the composite clinothems (CC1–CC5). The relative sea level evolved through two transgressive–regressive (TST–RST) cycles, characterized by relatively short-term rapid rises followed by prolonged, gradual falls (He et al., 2025). During periods of relatively rapid sea-level rise, accommodation increased substantially, resulting in composite clinothems with thicker aggradation, steeper edge (i.e., breaks of slope) trajectory angles, and reduced progradation distances and dips (Table 1-3 and Fig. 16c-g), reflecting localized sediment accumulation under relatively deep-water, low-energy outer middle ramp deposits dominated by micritic and dolomitic limestones. In contrast, during periods of rapid sea-level rise or gradual fall, accommodation was generated only relatively slowly. Composite clinothems exhibit thinner aggradation and gentler edge trajectories, while progradation distances and clinoform dips increase, producing steeper clinoform geometries overall (Table 1-3 and Fig. 16c-f). These trends reflect a greater degree of basinward sediment redistribution and the evolution toward shallow-water inner middle ramp and shoal composed of grainstones and dolo-grainstones.

5.3.2.2 High-frequency sea-level changes

High-frequency relative sea-level changes significantly modulated the availability of accommodation over shorter timescales, thereby controlling the geometric attributes and sedimentary characteristics of clinoforms (C1–C17). During rapid, high-frequency sea-level rise, accommodation increased abruptly, leading to greater aggradation thickness, steeper edge trajectory angles, and increased ramp relief (Fig. 16c-g). These conditions favored the accumulation of deeper-water, low-energy facies and produced upward-shallowing stacking patterns. Subsequent slow sea-level fall reduced accommodation, resulting in increased progradation distances and clinoform dips, accompanied by decreased aggradation thickness and ramp relief (Fig. 16c-g). This drove a transition to shallow-water, high-energy sedimentation and the formation of upward- shallowing depositional cycles. By contrast, high-frequency sea-level fluctuations primarily controlled lithologic cyclicity within fourth-order sequences. These cycles are characterized by high-frequency vertical stacking of micritic limestone, dolomitic limestone, and grainstone, superimposed on the fourth-order sequences. The deposits exhibit multiple short-term upward-shallowing rhythmic cycles (He et al., 2025).

5.3.3 Paleoclimate and Paleoceanography

The geometries and depositional architecture of the Stage 3 clinoforms provide stratigraphic evidence to link depositional processes to Early Cambrian paleoclimatic and paleoceanographic trends. During the Early Cambrian, an accelerated rate of global mid-ocean ridge spreading and intensified submarine volcanic activity (Maloof et al., 2010; Wang et al., 2020) led to the widespread release of calcium, phosphorus, and carbon dioxide via hydrothermal vents (Fig. 17a-b). These processes drove the climatic transition from the Ediacaran Icehouse to the Cambrian Hothouse

period and triggered widespread ocean eutrophication (Cook and Shergold, 1984; Tucker, 1992; Ganino and Arndt, 2009; Zhang et al., 2021a). The great thickness of the Stage 3 strata (up to 700 m; Fig. 13) and the extensive basinward progradation of clinothems indicate a high-efficiency carbonate factory, commensurate with the global “Hothouse” conditions and intensified siliciclastic input. During Stage 3, the Tarim Block was located near the paleoequator (Hoffman and Li, 2009; Zhao et al., 2011; Song et al., 2014a), and experienced a global stepwise temperature trend, reaching ~25°C (Fig. 17c) (Scotese et al., 2021). With warming temperatures, widespread continental weathering intensified, increasing inputs of Ca²⁺ and HCO₃⁻ to the ocean, thereby promoting carbonate production (cf. Li and Elderfield, 2013; Zhai et al., 2018; Knapp and Tipper, 2022).

Although elevated phosphorus concentrations may have initially inhibited carbonate deposition due to nutrient-driven eutrophication (Riding and Liang, 2005). However, the marked progradation events observed in our seismic profiles (CC1-CC3) suggest that in the Tarim Basin (Table 1-3), the carbonate factory was thriving, potentially aided by the biological fixation of phosphorus during the Cambrian explosion (Laing et al., 2019; Tarhan et al., 2023). This fixation likely resulted in a gradual decrease in P levels, thereby weakening its inhibitory effect on carbonate production. Eventually, the carbonate production rate showed an overall increasing trend through time, consistent with the scale of Stage 3 clinothems (Fig. 17e). Additionally, the spatial distribution of clinothems (Fig. 10) reveals a consistent progradation from southwest to northeast. The trajectory strongly correlates with the reconstructed paleowind patterns for the Tarim Block, which indicate a prevailing wind direction of ~226° ± 42 and a persistent westward drift of paleowind (Fig. 17f) (Hu et al., 2023). This suggests that wind-driven surface currents played a physical role in transporting carbonate sediments basinward, thereby controlling the dominant direction of clinoform stacking. The vertical evolution of lithologies supports an interpretation of intensifying hydrodynamic energy linked to regional climate warming. Although early composite clinothems (CC1-CC3) are dominated by high-energy grainstone of inner-ramp shoal (SF4) in the shallow depositional facies, the later composite clinothems (CC4-CC5) are mainly composed of extremely high-energy grainstone and rudstone with significantly increased content of middle-ramp shoal (SF7; Fig. 11). Meanwhile, the Tarim Block migrated from ~15°N to ~10°N during Stage 3 (Fig. 17d) (Li et al., 2014; Wang et al., 2024), further enhancing regional temperature. These conditions likely intensified tropical storm activity, resulting in the increased frequency and scale of storm-reworked rudstones observed in the upper part of stage 3 strata in wells 5 (Fig. 11), consistent with outcrop records (Song et al., 2014a).

6 Conclusions

Based on the integrated analysis of seismic facies, clinoform characteristics, and high-resolution sequence stratigraphy using drilling, well logging, mud logging, and 3D seismic data of Stage 3 succession in the central and northern Tarim Basin, the following main conclusions can be drawn.

1. Seven seismic facies types (SF1–SF7) are identified in the Stage 3 strata, corresponding to distinct depositional environments including mixed tidal flats, inner-ramp dolomite flats and shoals, inner middle ramp, middle-ramp depression, middle-ramp shoals, and outer middle ramp facies. Five composite clinothems (CC1–CC5) are recognized, which correlate with five

major onlaps documented globally during the same time interval. These composite clinothem are further subdivided into 17 subordinate clinoforms (C1–C17), each comprising three to four individual clinoforms. Early-stage clinoforms are dominated by ascending trajectories, whereas subsequent clinoforms transited to flat and descending trajectories. Laterally, clinoforms consistently prograded from the southwest to the northeast, while vertically they exhibit clear stacking. In map view, clinoforms expanded progressively northeastward from the initial southwestern position.

2. Two third-order sequences (SQ1 and SQ2) are identified within Stage 3, each comprising a transgressive systems tract (TST) and a regressive systems tract (RST). 3rd-order sequences contain multiple 4th-order sequences, which in turn include 5th-order sequences. Sequence stratigraphic framework construction is based on INPEFA analysis of GR logs. CC1 to CC3 were deposited during TST1–RST1, RST2, and RST3, respectively, whereas CC4 and CC5 correspond to TST2–RST4 and RST5. Each composite clinothem aligns with specific systems tracts. The 17 subordinate clinoforms (C1–C17) represent 4th-order sequences. 3rd-order sequence boundaries are marked by onlap and downlap truncations in seismic profiles, indicative of relative sea-level fluctuations. 4th-order sequence boundaries align with clinoform boundaries and are often characterized by abrupt lithological and log responses. Fifth-order sequences are delineated by changes in lithology and inflection points in the INPEFA curve.
3. The paleogeomorphology of the study area is characterized by a southwest-to-northeast gradient, with elevated highs in the southwest, a central depression, and gradually declining terrain toward the northeast. The depositional system was characterized by a gently inclined ramp in SQ1. In contrast, the system evolved into a distally steepened ramp in SQ2. Clinoform progradation exerted a modifying effect on the original paleogeomorphology, with extensive shoal development emerging over pre-existing paleotopographic highs. The architecture and stratigraphic evolution of clinoforms within the carbonate ramp were primarily governed by the combined influence of inherited paleogeomorphology, relative sea-level changes, and variations in paleoclimate and paleoceanography. Paleotopographic relief controlled the initial accommodation space and influenced clinoform edge (i.e., breaks of slope) trajectory angles and progradation distances. Low-frequency relative sea-level changes determined the geometry and depositional setting of composite clinothems, while high-frequency sea-level changes directly impacted the stacking pattern and facies transitions within individual clinoforms. Meanwhile, temporal shifts in paleoclimate and oceanographic conditions affected the productivity of the carbonate factory, thereby influencing both clinoform scale and sediment composition.
4. This study establishes a quantitative workflow for analyzing carbonate ramp clinoforms, integrating facies interpretation, seismic-based clinoform identification, geometric parameter extraction, and sequence stratigraphic correlation. This approach offers a valuable framework for interpreting the sedimentary dynamics, enhances understanding of ramp evolution, and provides guidance for subsurface resources exploration in similar carbonate systems

Author contribution statement

Author contributions: Qing He: Conceptualization, writing-original draft, writing-review &

editing, methodology, investigation, funding acquisition; Bo Liu: project administration, writing-review & editing, supervision, resources; Kaibo Shi: writing-review & editing, validation, resources; Nigel P. Mountney: writing-review & editing, validation; Adam D. McArthur: writing-review & editing, validation; Zongjie Li: resources; Chun Wu: writing-review & editing; Jun Li: data curation; Jiaming Deng: data curation; Xichuan Men: data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the Science and Technology Major Project of Northwest Exploration and Production Company of SINOPEC. Number: 344400000-24-ZC0607-0041. In addition, we gratefully acknowledge financial support from the Graduate School of Peking University. Grant Number: 202401003. Thanks to Senior Engineer Yancheng Song (Research Institute of Petroleum Exploration & Development, PetroChina) for the insightful discussions on high-frequency sequence stratigraphic subdivision. We would like to express our sincere thanks to the editorial staff for their assistance. We also thank the anonymous reviewers for their constructive comments and valuable suggestions, which have significantly improved this work.

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Fig. 6. Un-interpreted (a), and interpreted (b, c) seismic profiles of Line 2 in the north of the study area (see location on Fig. 1b). Fm. is Formation; C1 is clinoform one; CC1 is Composite clinothem one; Synth. Seis. is synthetic seismogram.

Fig. 7. Un-interpreted (a), and interpreted (b, c) seismic profiles of Line 3 in the north of the study area (see location on Fig. 1b). Fm. is Formation; C1 is clinoform one; CC1 is Composite clinothem one; Synth. Seis. is synthetic seismogram.

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Fig. 9. Un-interpreted (a), and interpreted (b, c) seismic profiles of Line 5 in the central study area (see location on Fig. 1b). Fm. is Formation; C1 is clinoform one; CC1 is Composite clinothem one.

Fig. 10. Maps representing the migration of the ramp-edge during different time intervals, as recorded by the five composite clinothems (CC1–CC5) identified in this study.

Fig. 11. Correlation of well logs and lithology within the high-resolution sequence stratigraphic framework of wells 5, 6 and 7 of Stage 3 strata in the study area.

Fig. 12. High-resolution well correlation along Line 2, integrating INPEFA curves and clinoform division to illustrate 3rd, 4th and 5th sequence stratigraphic framework of the stage 3 succession, Tarim Basin. Lithologies in the drilling columns are based on published data from [He et al. \(2025\)](#) and [Tian et al. \(2018\)](#).

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Fig. 17. Compilation of paleoclimate and paleoceanographic parameters relevant to clinoform development and facies distribution during Stage 3 in the Tarim Basin. (a) Changes in seawater calcium concentrations over time ([Stanley and Hardie, 1998](#)); (b) Atmospheric CO₂ concentration expressed as the ratio of past CO₂ mass to the present pre-industrial level (RCO₂) ([Bernier and](#)

Kothavala, 2001); (c) Global average temperature variation (Scotese et al., 2021); (d) Latitudinal drift of the Tarim Plate during the early Cambrian (Li et al., 2014), with yellow areas indicating the outline of the Tarim Basin; (e) Variations in prevailing paleowind directions over the Tarim region during Stage 3 (Hu et al., 2023); (f) Evolution of clinoform scale in the study area, derived from an integrated assessment of clinoform relief, progradation distance, and plan-view extent.

Table 1 Summary of measured and calculated parameters describing each clinoform (C1 to C17) architecture for composite clinothems (CC1 to CC5) identified along Lines 1 (see Fig. 5 and see location on Fig. 1b). The table includes sequence and systems tract assignments interpreted within the sequence stratigraphic framework (see Fig. 12). Geometric parameters were extracted from seismic profiles and converted from two-way travel time (TWT, ms) to depth (m).

Table 2 Summary of measured and calculated parameters describing each clinoform (C5 to C17) architecture for composite clinothems (CC2 to CC5) identified along Lines 2 (see Fig. 6 and see location on Fig. 1b). The table includes sequence and systems tract assignments interpreted within the sequence stratigraphic framework (see Fig. 12). Geometric parameters were extracted from seismic profiles and converted from two-way travel time (TWT, ms) to depth (m).

Table 3 Summary of measured and calculated parameters describing each clinoform (C9 to C17) architecture for composite clinothems (CC3 to CC5) identified along Lines 3 (see Fig. 7 and see location on Fig. 1 b). The table includes sequence and systems tract assignments interpreted within the sequence stratigraphic framework (see Fig. 12). Geometric parameters were extracted from seismic profiles and converted from two-way travel time (TWT, ms) to depth (m).

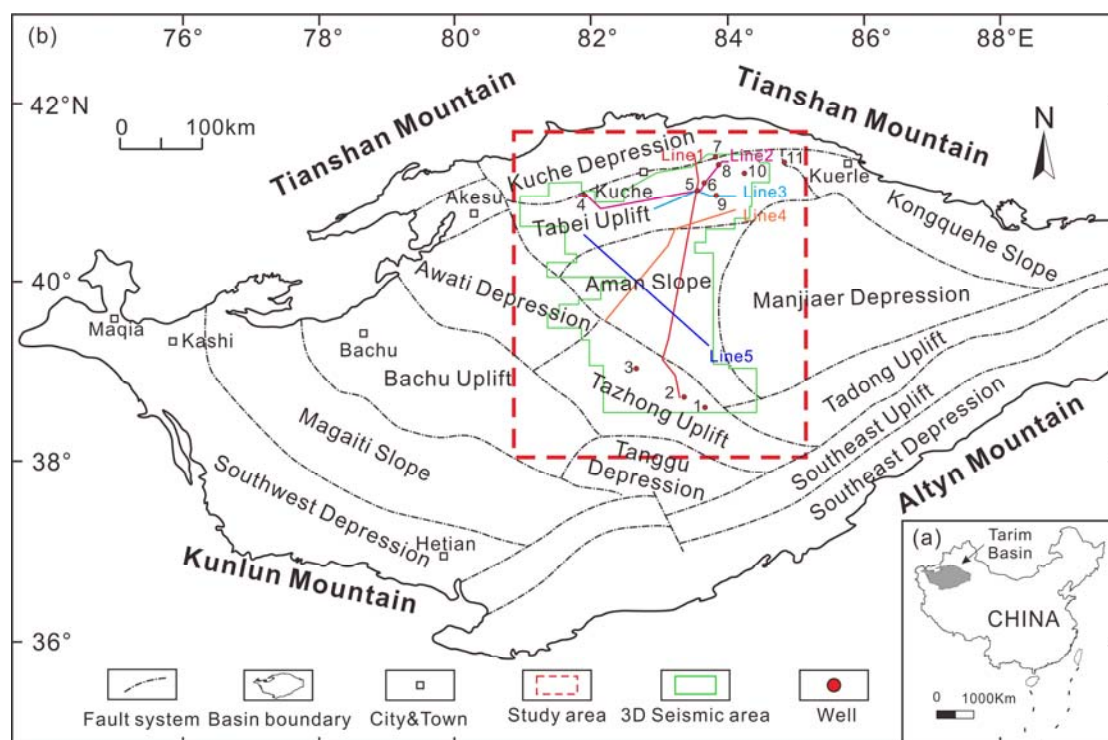


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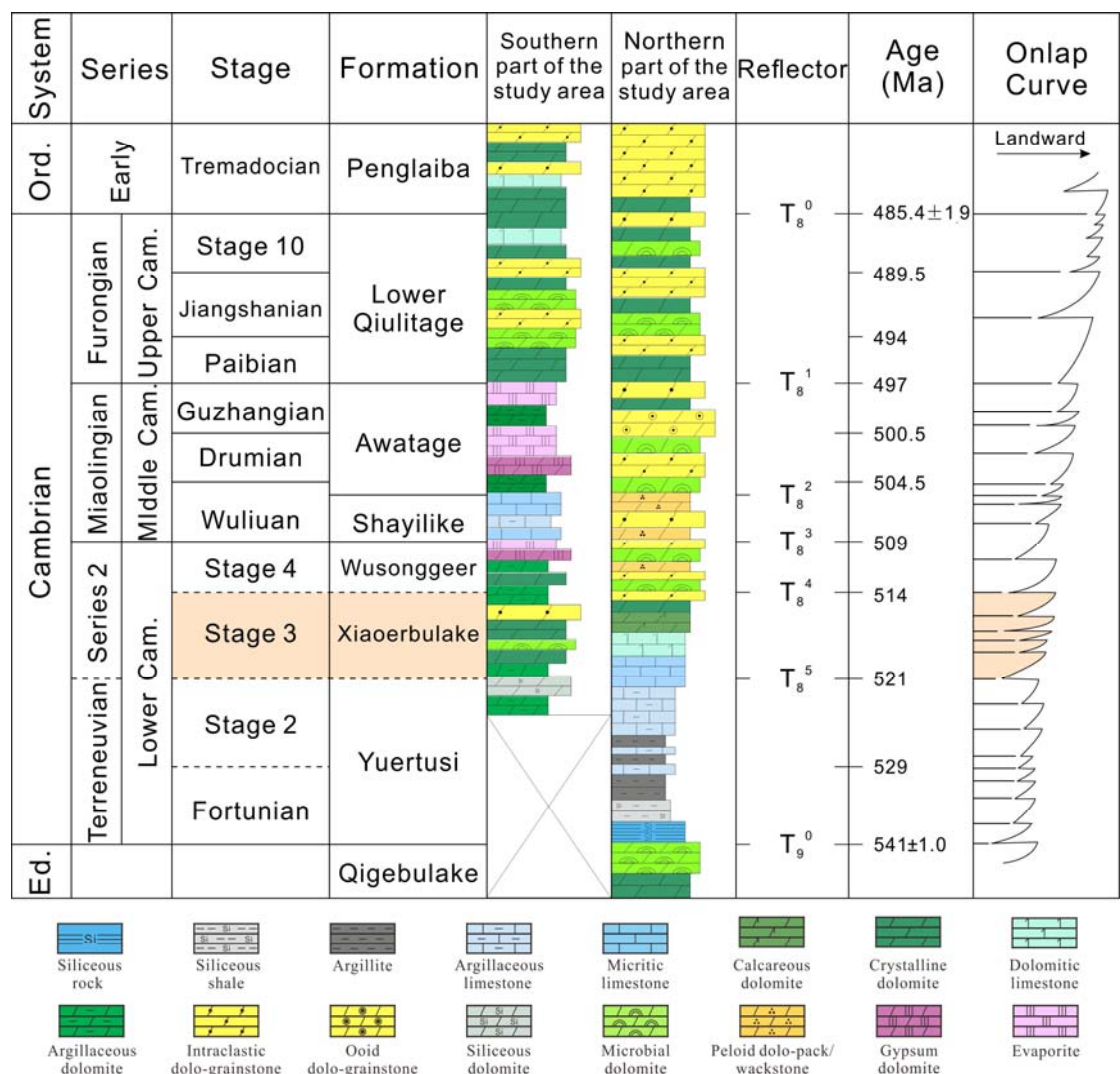
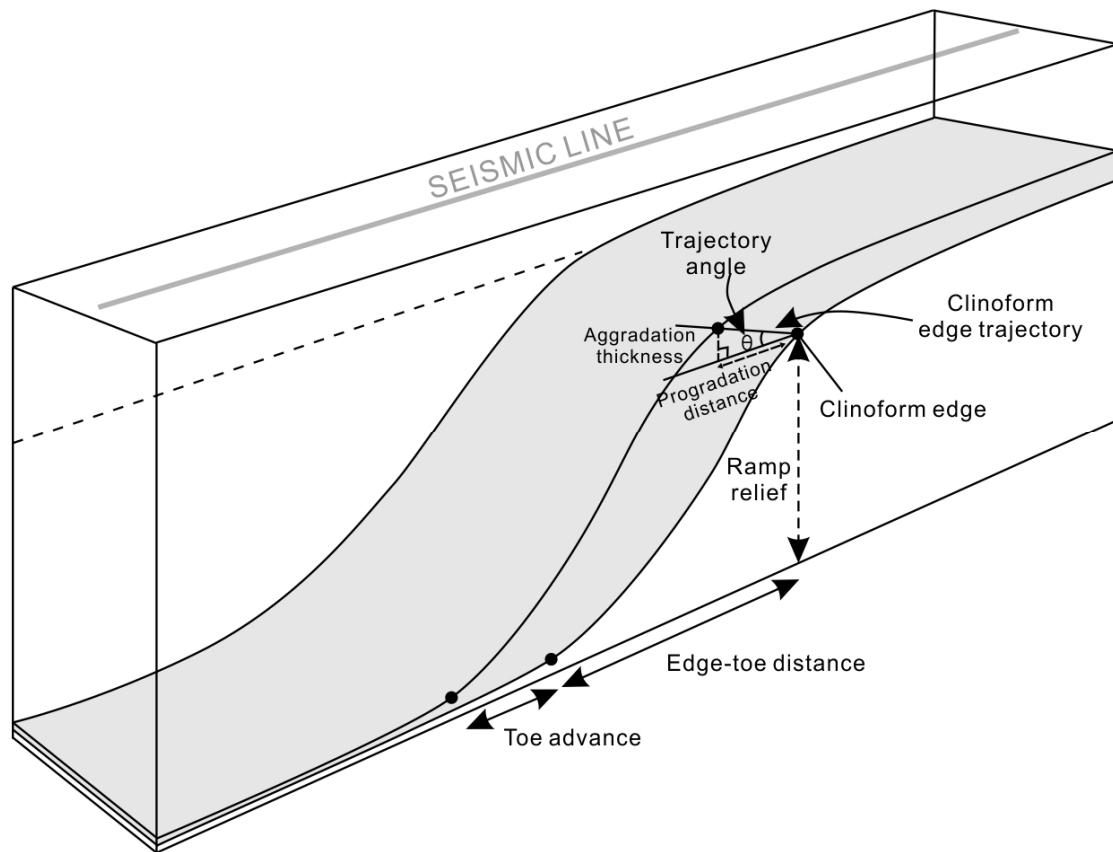


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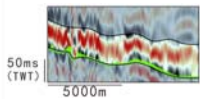
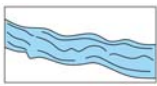
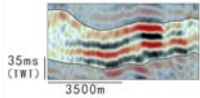
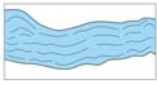
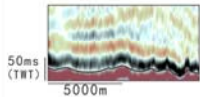
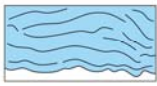
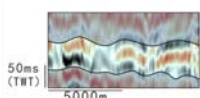
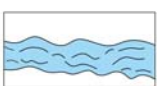
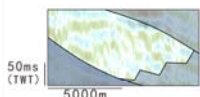
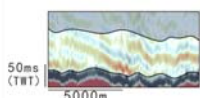
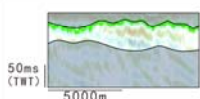
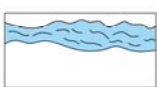
Seismic facies type	Seismic profile	Reflection line drawing	Reflection characteristics	Interpretations of environment
SF1			Parallel reflections High continuous Strong amplitude Low frequency	Mixed tidal flat
SF2			Sub parallel reflections Moderate-low continuous Moderate-strong amplitude Moderate frequency	Inner-ramp dolomite flat
SF3			Parallel reflections Moderate-high continuous Moderate amplitude Moderate-low frequency	Middle-ramp depression
SF4			Arch-shaped reflections Low continuous Moderate-weak amplitude Low-moderate frequency	Inner-ramp shoal
SF5			Sub parallel reflections Moderate continuous Moderate-weak amplitude Moderate-high frequency	Inner middle ramp
SF6			Sub parallel-parallel reflections Moderate-high continuous Moderate-high amplitude Moderate-low frequency Downlap reflection terminations	Outer middle ramp
SF7			Chaotic reflections Low continuous Weak amplitude High frequency	Middle-ramp Shoal

Fig. 4. Seismic facies identified on the seismic data and their interpreted depositional environments within the stage 3 succession. Modified after Yang et al. (2018), Hu et al. (2019), Liu et al. (2020), Huang et al. (2020), Zhang et al. (2021c), Hendry et al. (2021), Peng et al. (2022), Zeng et al. (2022), and He et al. (2025).

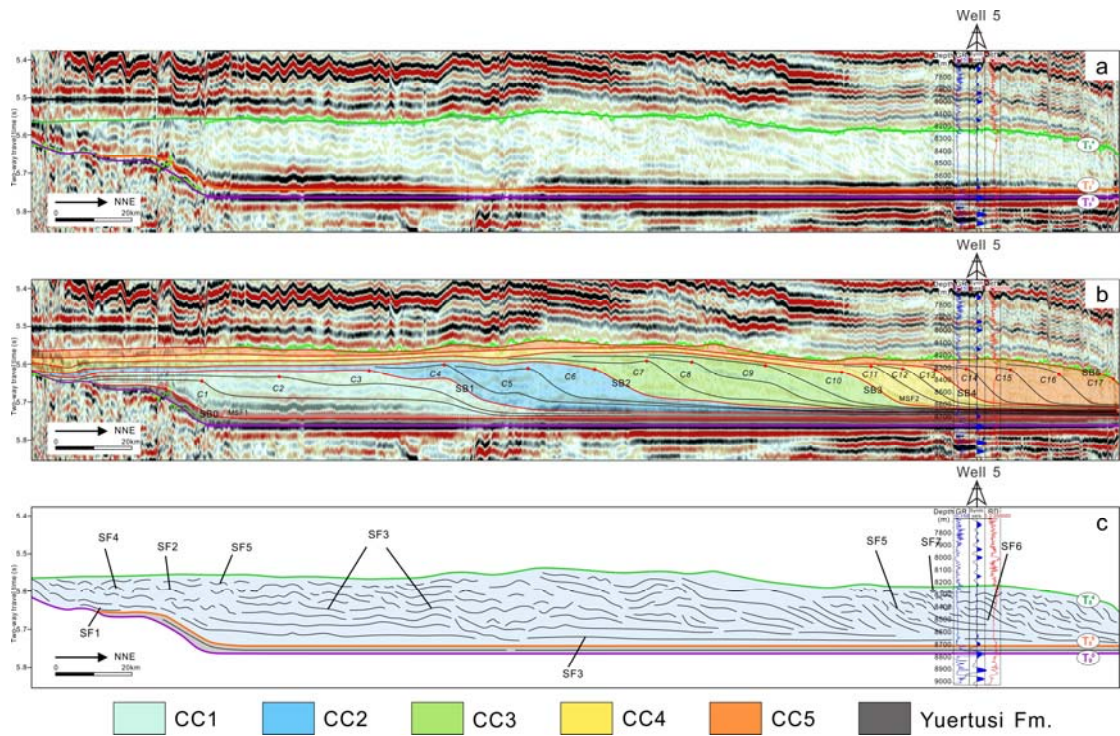


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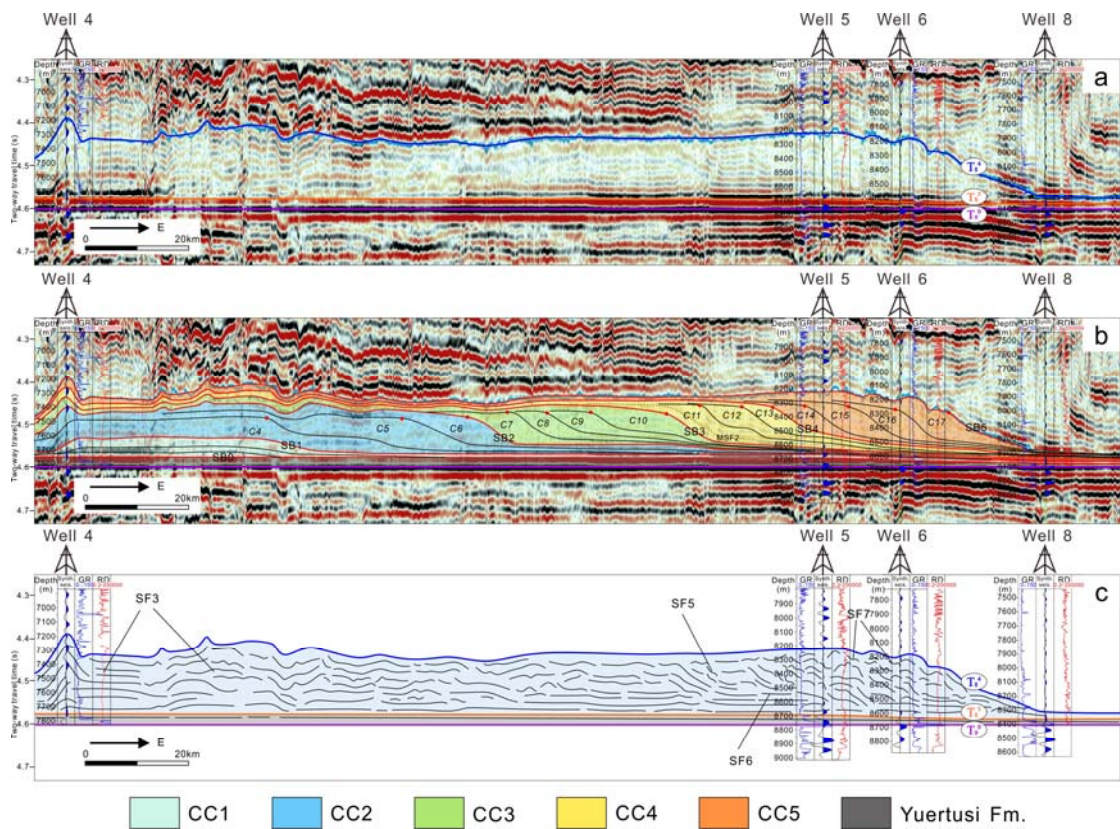
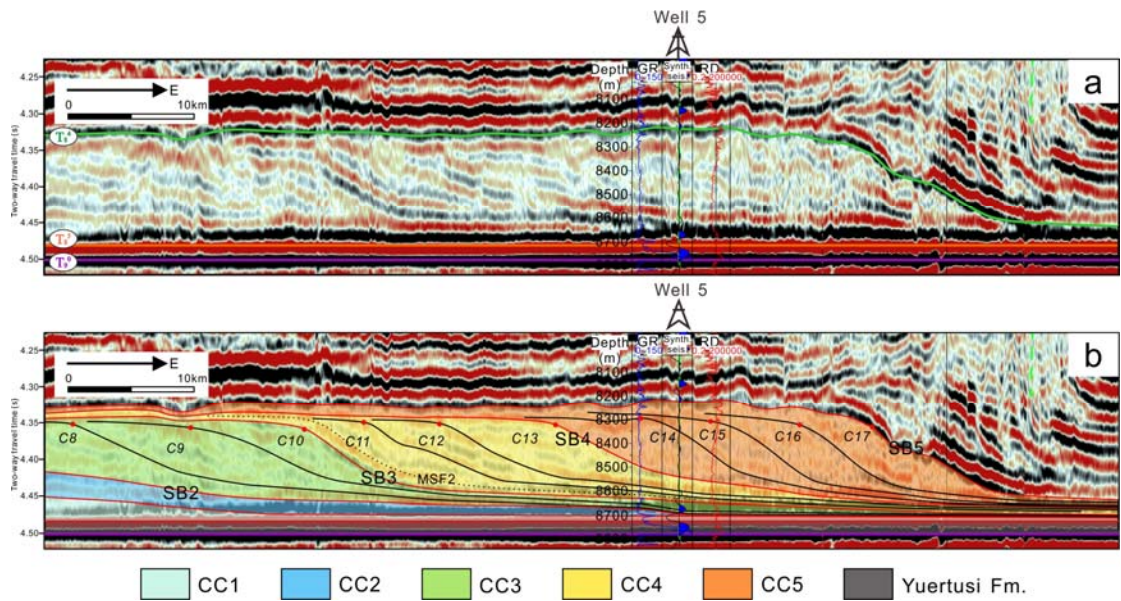


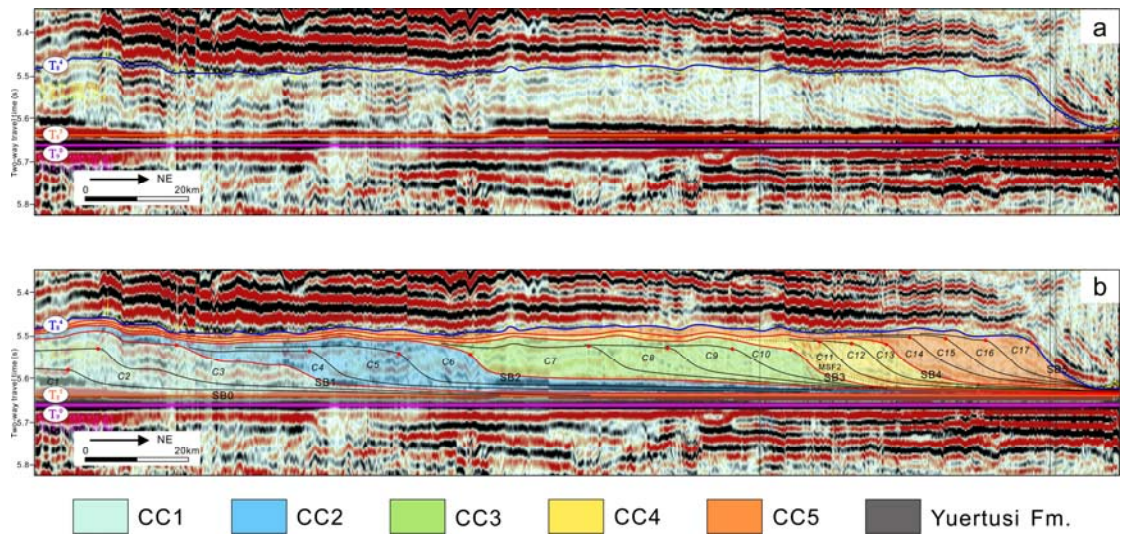
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31 Fig. 8. Un-interpreted (a), and interpreted (b) seismic profiles of Line 4 in the central study area (see
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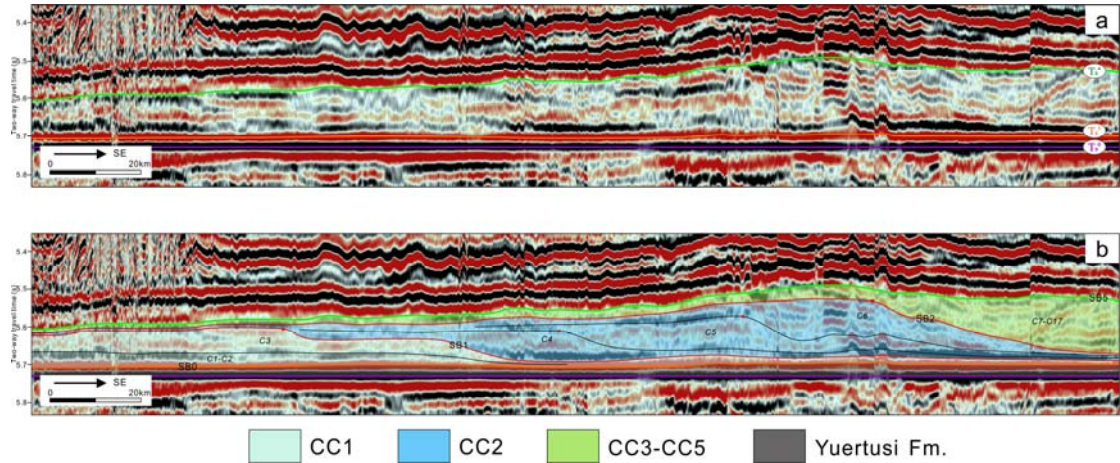


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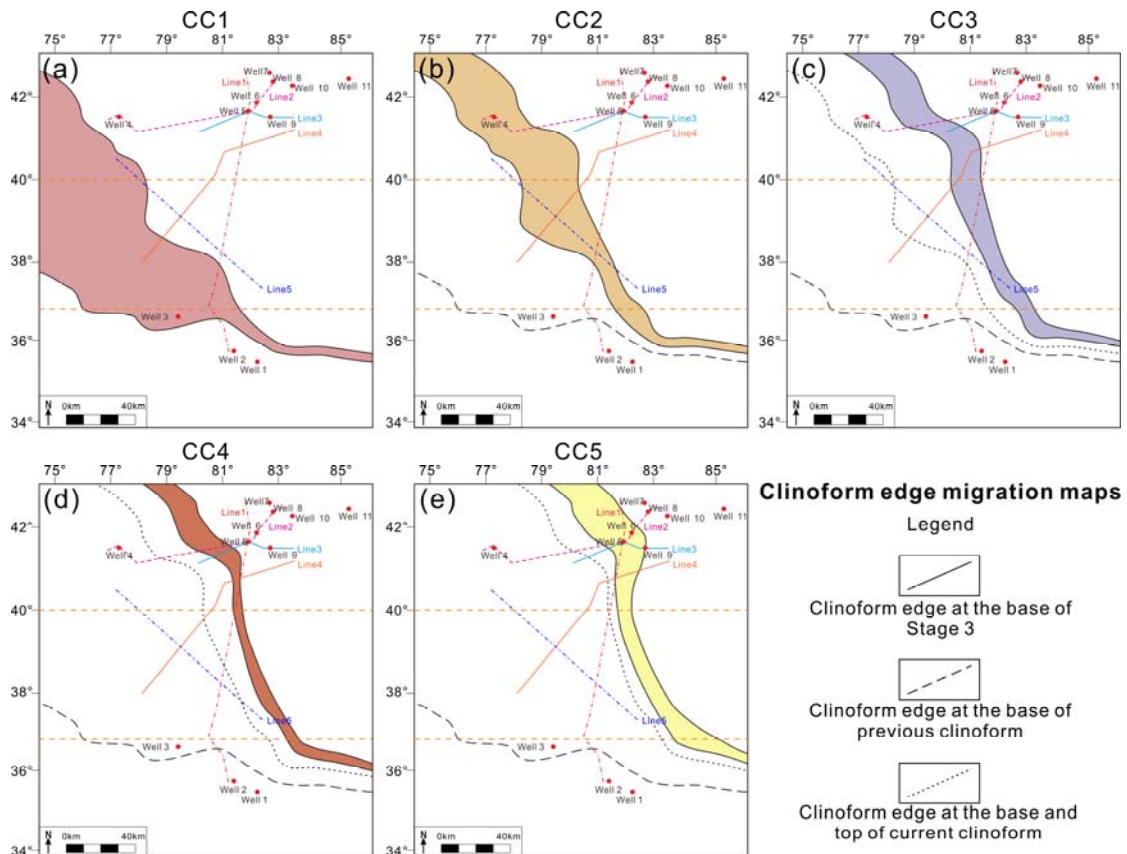


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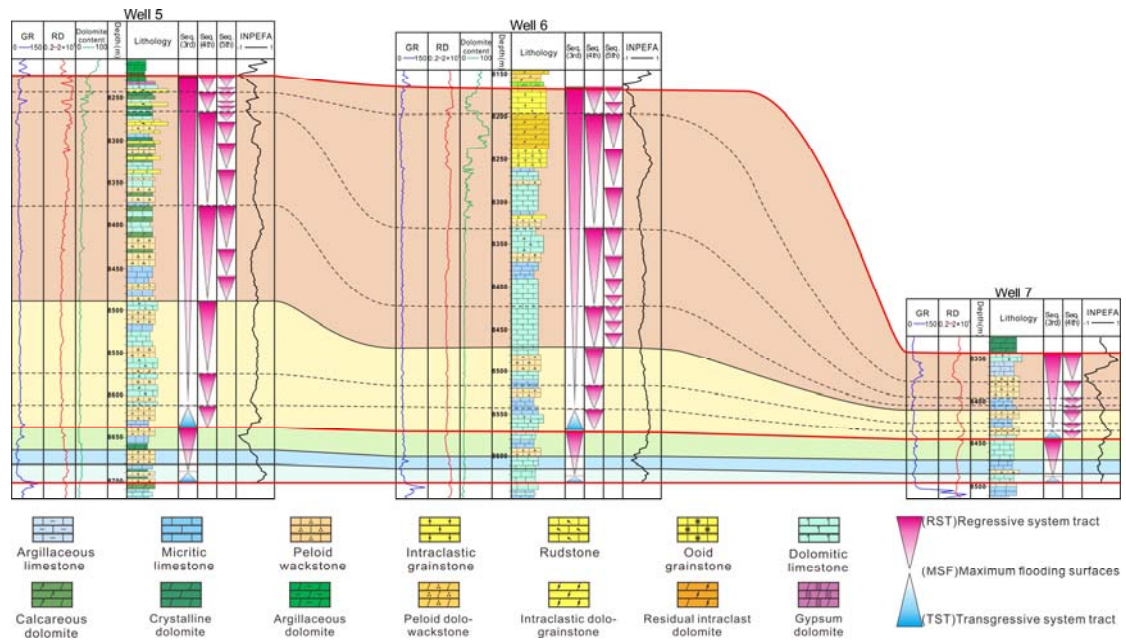


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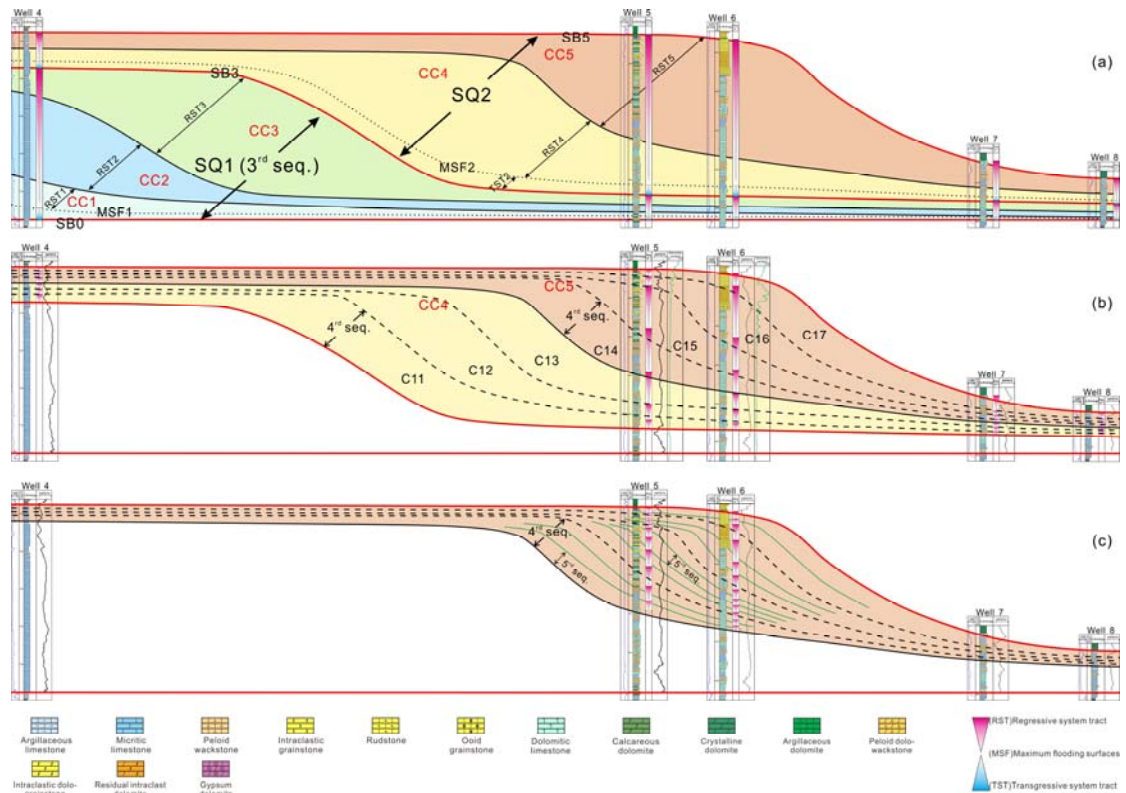


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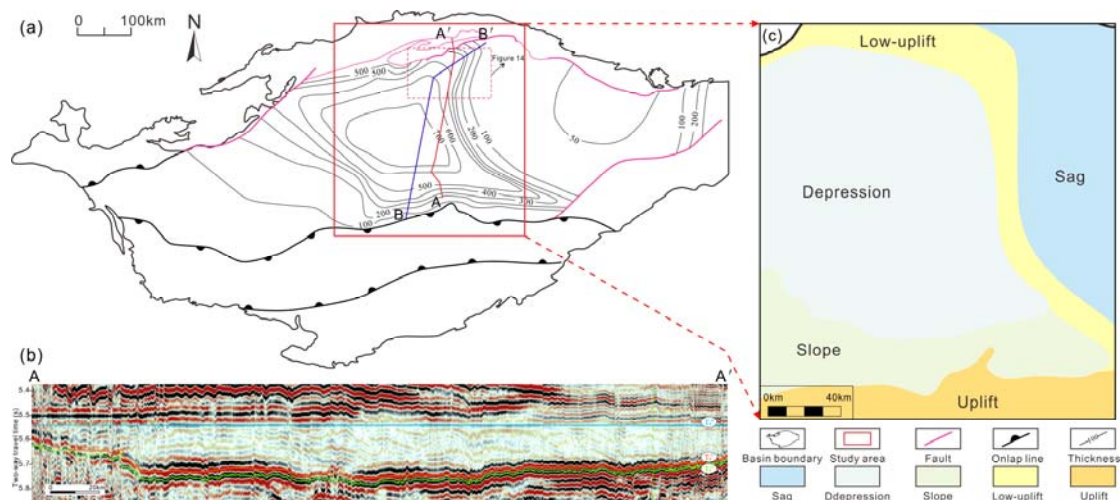


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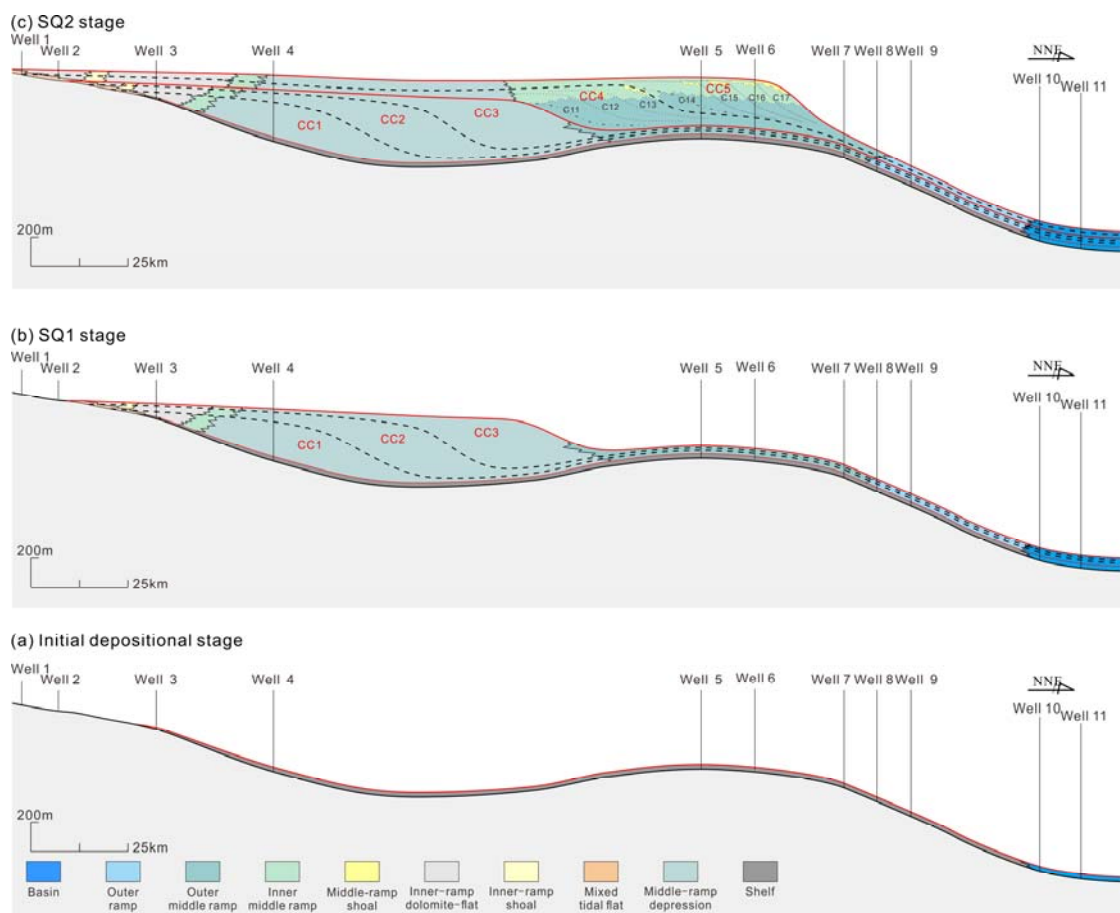
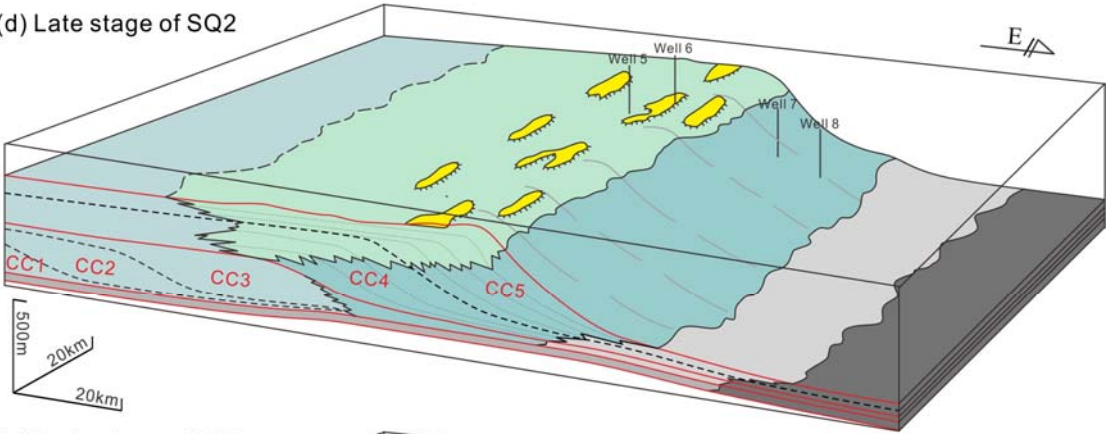


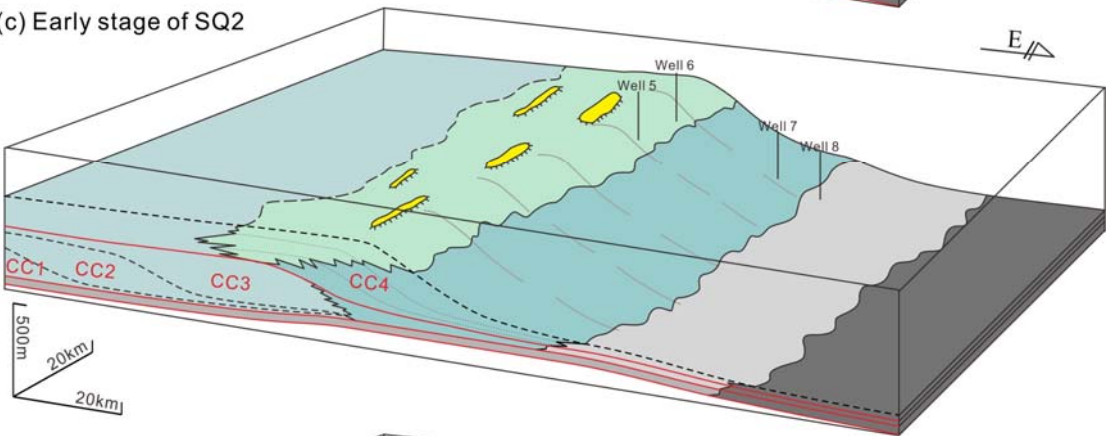
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58 development.

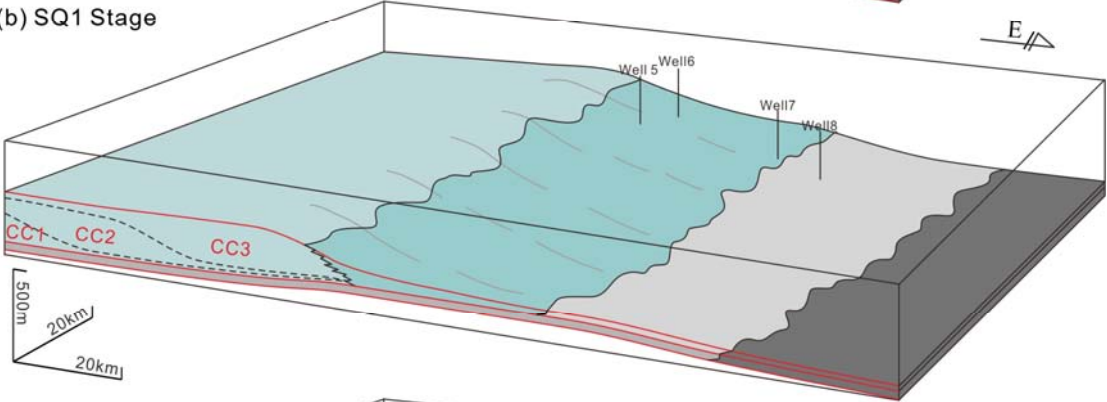
(d) Late stage of SQ2



(c) Early stage of SQ2



(b) SQ1 Stage



(a) Initial depositional stage

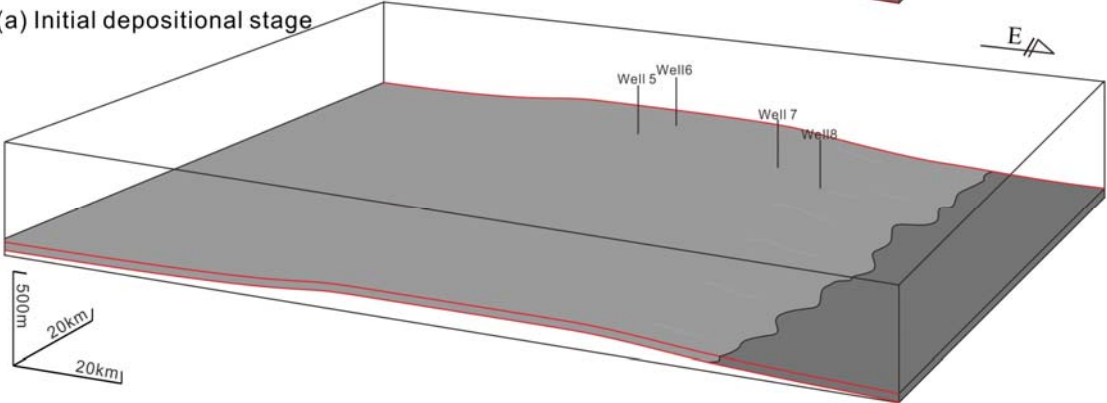


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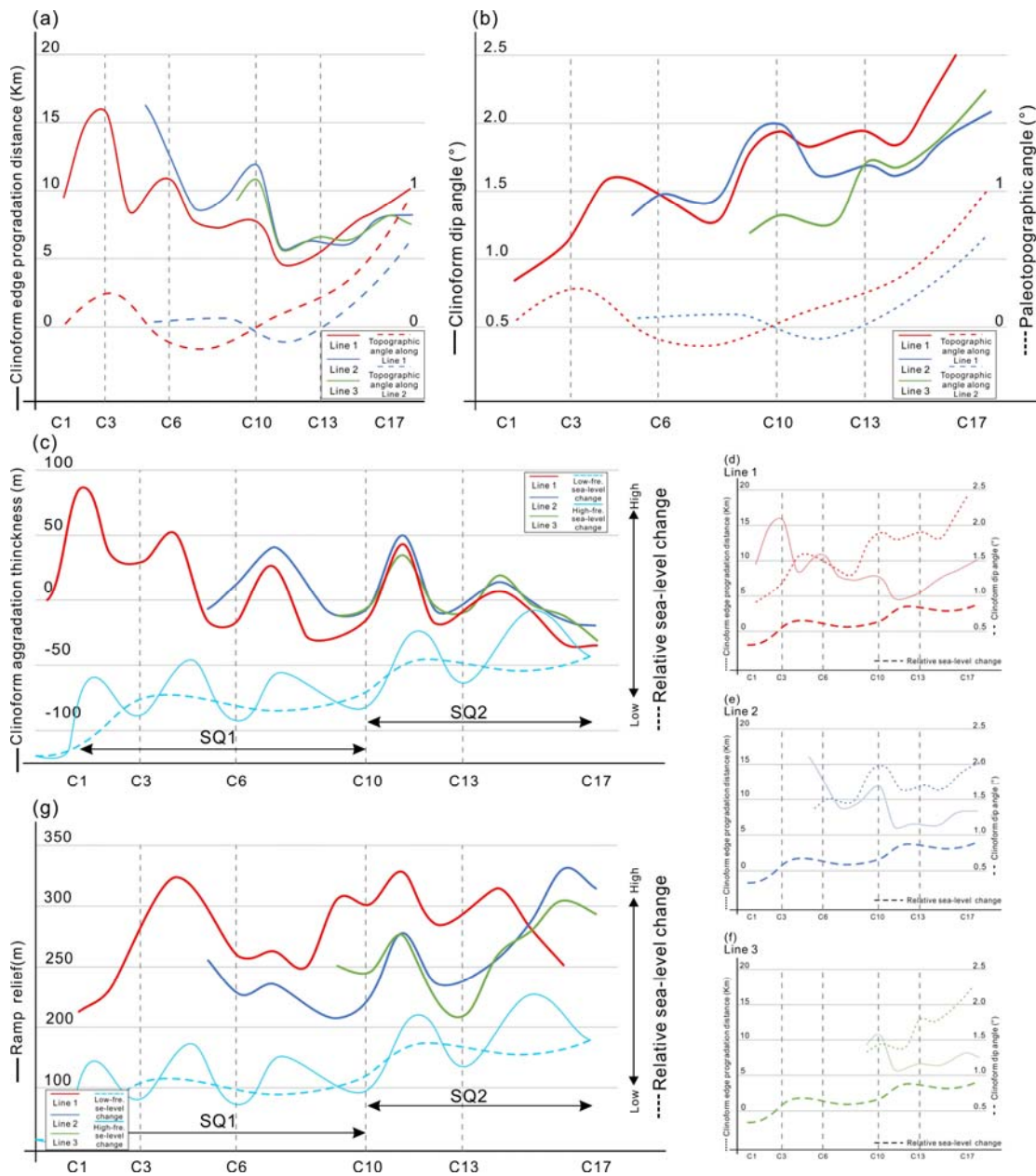


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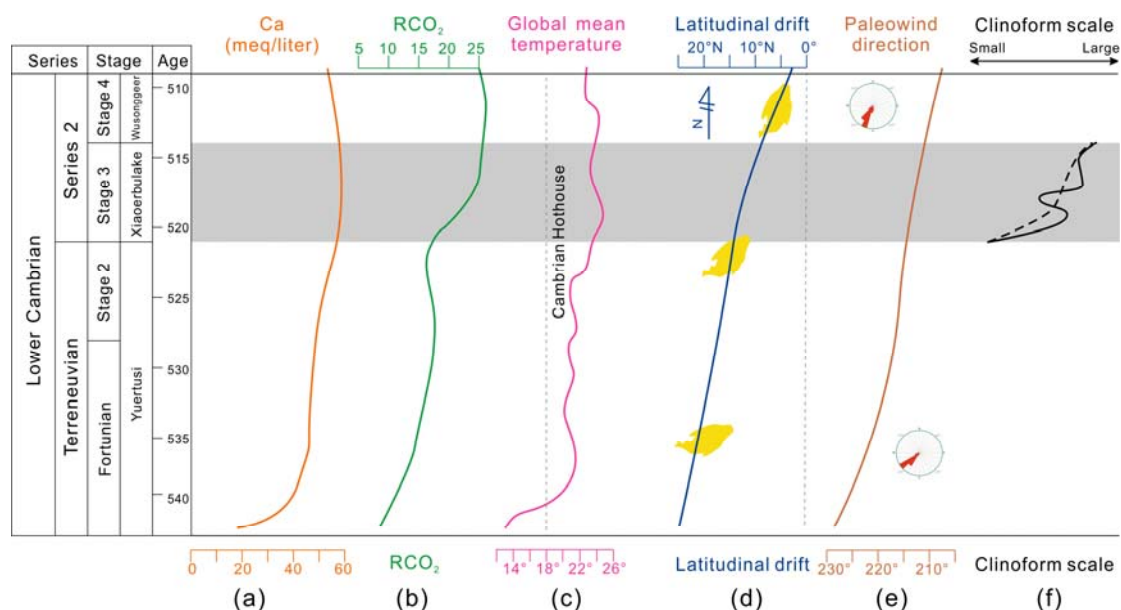


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