

# Facies-dependent response of reef–shoal development to orbital pacing in the Changxing Formation, Sichuan Basin

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## Research Article

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# Abstract

Orbital forcing can produce contrasting stratigraphic expressions across carbonate-platform facies. We integrated lithology, thin-section microfacies, and high-resolution gamma-ray records from wells PS10 and PS2 in the Changxing Formation, Sichuan Basin, and applied spectral, time–frequency, COCO/eCOCO, band-pass filtering, and amplitude-modulation analyses to construct floating astrochronologies. PS10 records an intraplatform reef–shoal system dominated by MF1 grainstone and FA2 grain-shoal deposits, including three major shoal units and a reef-base–reef-core–reef-cap/grain-shoal complex. PS2 records three shallowing-upward alternations between FA2 grain shoals and FA4 intershoal–tidal-flat fine-grained deposits. Whole-interval COCO indicates mean sedimentation rates of 7.7 cm kyr<sup>−1</sup> for PS10 and 11.2 cm kyr<sup>−1</sup> for PS2. Both wells preserve 405-kyr long eccentricity, 125/95-kyr short eccentricity, 41-kyr obliquity, and 23.7-kyr precession rhythms. Precession-amplitude envelopes contain dominant 109–110-kyr modulation and show strong coherence with short eccentricity, indicating eccentricity-paced bundling of high-frequency depositional rhythms. Stepwise eCOCO Best SR changes coincide with facies transitions. Long-term warming, carbon-cycle change, and progressive deoxygenation defined the environmental context, whereas orbital pacing regulated buildup windows and growth pulses. Facies position filtered this forcing: the intraplatform high at PS10 favored sustained vertical aggradation, whereas the platform-margin setting at PS2 favored repeated shoal expansion, retreat, and fine-grained deposition. Thus, identical orbital rhythms generated different stratigraphic architectures across facies belts.

## 1. Introduction

During the Late Permian Changhsingian, marine carbonate platforms were widespread across South China. The Sichuan Basin and adjacent regions preserve transitions among platform-margin reef–shoal, intraplatform-shelf, and deeper-water deposits. These transitions are documented by Wu et al. (2012), Chen et al. (2012), Deng et al. (2023), and Wang et al. (2023). This interval records the late stage of the Late Paleozoic climatic transition. Long-term ice-volume decline, sea-level fluctuations, and orbital-scale environmental changes continually regulated accommodation, fine-grained sediment input, and carbonate production (Fielding et al. 2008; Rygel et al. 2008; Haq and Schutter 2008). Reef–shoal development was therefore episodic. Biogenic buildups and grain shoals aggraded when shallow-water accommodation, hydrodynamic energy, and carbonate production were favorable. After environmental conditions changed, reef–shoal deposition was replaced by open-platform or fine-grained shelf sedimentation.

Previous studies have mainly attributed the spatial distribution of carbonate reef–shoal bodies to water depth, paleotopography, hydrodynamic conditions, and argillaceous dilution. These studies established models centered on platform-margin high-energy belts and carbonate-factory migration (Read 1985; Burchette and Wright 1992; Schlager 2003, 2005; Pomar and Hallock 2008; Flügel 2010). Such models explain platform-margin reef–shoal complexes and their lateral migration. Outcrop and subsurface studies of the Changxing Formation also document diverse platform-margin reef–shoal, intraplatform

grain-shoal, and local biogenic-buildup associations (Chen et al. 2018, 2024; Tan et al. 2020). However, reef–shoal complexes on local intraplatform highs experienced different hydrodynamic, sediment-supply, and accommodation conditions. Their vertical aggradation and cyclic organization cannot be treated as simple extensions of platform-margin models. Existing studies explain the spatial differentiation of Changxing reef–shoal deposits, but direct comparisons of their vertical recurrence and cyclic organization across facies belts remain limited.

Facies differences and vertical rhythms are commonly superimposed within the same lithologic and well-log responses in subsurface Changxing reef–shoal successions. Platform margins commonly contain high-energy bioclastic shoals, reef–shoal complexes, and frequent transitions to fine-grained deposits. Local intraplatform highs may instead support vertically aggrading patch reefs or local reef–shoal bodies. Both settings can contain low-GR carbonate intervals and bioclastic–framework limestone associations. However, their facies stacking, continuity, and preservation differ markedly. The same external rhythm can therefore produce sustained carbonate buildup, repeated facies migration, or alternations between carbonate and fine-grained deposition.

Gamma-ray logs are sensitive to argillaceous input, natural radioactive-element enrichment, and lithologic heterogeneity in carbonate successions. They continuously record vertical changes in carbonate production, fine-grained sediment input, and depositional conditions (Weedon 2003; Hinnov 2000, 2013; Strasser et al. 2006). An established orbital chronology for the Lopingian of South China identifies stable 405-kyr long eccentricity and subordinate orbital rhythms. This framework provides a regional temporal context for Changhsingian depositional cycles (Wu et al. 2013). Within the age constraints of the Changxing Formation, a floating astronomical timescale links GR cycles, microfacies successions, and reef–shoal stacking. The initiation, interruption, and recovery of reef–shoal growth can thus be compared across consistent temporal scales.

The Pengxi–Wusheng intraplatform shelf and the Jiange–Langzhong platform margin preserve contrasting depositional records. The former contains a local biogenic reef and multiple grain shoals, whereas the latter records transitions between platform-margin grain shoals and intershoal–tidal-flat fine-grained deposits. Wells PS10 and PS2 represent these respective settings. This study integrates lithology, thin-section microfacies, and GR records from both wells to reconstruct facies associations, sequence architecture, and vertical reef–shoal configuration. Multitaper method (MTM), evolutionary fast Fourier transform (eFFT), evolutionary harmonic analysis (EHA), wavelet, correlation coefficient (COCO), and evolutionary correlation coefficient (eCOCO) analyses establish age-constrained floating astronomical timescales. Precession-band amplitude modulation, coherence, and phase relationships test whether short eccentricity organized high-frequency rhythms. Local Best SR variations are then compared with global Changhsingian paleotemperature, carbon-cycle, and marine redox trends. This comparison evaluates how global environmental boundaries, orbital modulation, and facies filtering jointly controlled reef–shoal development. The study addresses three linked questions. How were successive reef–shoal growth windows organized by orbital pacing? Why did identical rhythms produce

different stratigraphic expressions on the intraplatform shelf and platform margin? How did local carbonate factories respond to the Late Permian environmental transition?

## 2. Geological background

During the Late Permian Changhsingian, the Sichuan Basin occupied the northwestern part of the South China marine carbonate province. The basin contained intraplatform-shelf, carbonate-slope, platform-margin, and interreef depositional units. Platform-margin reef–shoal bodies formed belts, whereas isolated biogenic reefs and grain-shoal patches occurred across the intraplatform shelf (Fig. 1; Wu et al. 2012; Chen et al. 2012; Deng et al. 2023; Wang et al. 2023). This paleogeography produced a depositional system containing both continuous platform-margin high-energy belts and local intraplatform buildups. Hydrodynamic energy, fine-grained sediment input, and carbonate production differed markedly between these settings.

PS10 is located on the intraplatform shelf in the Pengxi–Wusheng area, near an isolated biogenic-reef patch. Its Changxing Formation records a local biogenic reef and several grain shoals above an intraplatform calcareous–argillaceous background. PS2 is located along the Jiange–Langzhong platform-margin belt. It preserves repeated vertical transitions between intraplatform-to-platform-margin bioclastic grain shoals and intershoal–tidal-flat fine-grained deposits. The two wells represent a local intraplatform reef–shoal system and a platform-margin grain-shoal–intershoal system, respectively. They provide a paleogeographic basis for comparing reef–shoal architectures and depositional responses across facies belts.

The studied Changxing Formation intervals consist mainly of limestone, bioclastic limestone, micritic limestone, and argillaceous limestone. Shale, mudstone, and siliceous limestone occur locally. These assemblages resemble reported intraplatform grain shoals, local reefs, and platform-margin reef–shoal–fine-grained systems in the Sichuan Basin. Relevant examples include Wu et al. (2012), Chen et al. (2012), Tan et al. (2020), Wang et al. (2023), and Deng et al. (2023). Vertical changes in skeletal components, grain-supported fabrics, micrite, and argillaceous material record transitions among reef cores, grain shoals, intraplatform limestone backgrounds, and platform-margin intershoal–tidal-flat fine-grained deposits. PS10 contains a local reef core and three superimposed grain-shoal units on the intraplatform shelf. PS2 records repeated migration between platform-margin grain shoals and intershoal–tidal-flat fine-grained facies.

## 3. Materials and methods

### 3.1 Petrographic and lithofacies framework

Sedimentary-facies analysis used bed-by-bed lithologic logs, original composite columns, and thin-section data from 5420.000–5592.500 m in PS10 and 5961.500–6183.218 m in PS2. Thin-section observations documented rock texture, grain type, biotic components, micritic matrix, cement, and

supporting fabric. Microfacies were named using the carbonate classifications of Dunham (1962) and Embry and Klovan (1971). Standard microfacies, facies-belt position, and skeletal-framework characteristics supported further subdivision (Wilson 1975; Tucker and Wright 1990; Flügel 2010). Dissolution pores, dolomitization, and silicification were described separately as diagenetic features rather than depositional microfacies. Chert nodules were treated as silicification features. A sample was assigned to MF7 only when siliceous limestone formed the dominant lithology.

Thin-section depths were matched to their corresponding lithologic intervals. Microfacies were assigned using grain-support fabrics, skeletal frameworks, micrite content, and the continuous facies context in the original lithologic columns. Bioclastic–intraclastic limestones with clear grain support or within continuous grain-shoal intervals were assigned to MF1. Bioclastic limestones dominated by micritic matrix were assigned to MF2. In situ framework-building limestones were assigned to MF3, and ordinary limestones lacking evidence of grain support were assigned to MF4. Facies associations were grouped by dominant microfacies, vertical stacking, and bounding assemblages rather than by mechanically subdividing every microfacies bed. Environmental interpretations followed established criteria for carbonate-platform facies belts, carbonate factories, and reef–shoal buildups (Wilson 1975; Schlager 2003; Pomar and Hallock 2008; Flügel 2010). FA1 represents the reef core. In PS10, FA2 represents reef-cap or intraplatform grain-shoal deposits. In PS2, FA2 represents intraplatform-to-platform-margin bioclastic grain shoals. FA3 represents reef-flank–reef-base–open-platform limestone backgrounds. FA4 represents an intraplatform calcareous–argillaceous shelf in PS10 and platform-margin intershoal–tidal-flat fine-grained deposits in PS2. FA5 represents a siliceous calcareous shelf association.

Within this microfacies–facies-association framework, the PS10 composite column was used to identify third- and fourth-order sequences. The interpretation integrated lithologic stacking, long- and short-term GR envelopes, GR wavelet energy, and transgressive-to-highstand cyclic architecture. Sequence boundaries were placed where lithologic shifts, GR-envelope inflections, and facies-stacking changes occurred together. Maximum flooding surfaces correspond to greater fine-grained input, higher GR values, and transitions from transgressive to highstand aggradation. Sequence subdivision followed established multiscale stacking principles in carbonate sequence stratigraphy and cyclostratigraphy (Schlager 2005; Strasser et al. 2006). This sequence framework links facies-association evolution, depositional cycles, and orbital-filtering results.

## **3.2 Well-log proxies and stratigraphic dataset**

This study used GR logs from 5420.0–5592.5 m in PS10 and 5961.5–6183.125 m in PS2. The original curves were checked for increasing depth and resampled at a uniform spacing of 0.125 m. The processed GR intervals are 172.5 m thick in PS10 and 221.625 m thick in PS2. Microfacies and facies-association statistics for PS2 extend to 6183.218 m in the original lithologic record. The resulting interval for facies analysis is therefore 221.718 m thick.

Gamma-ray responses in carbonate rocks are mainly controlled by argillaceous components, potassium-bearing minerals, and natural radioactive elements such as uranium and thorium. These responses

continuously reflect carbonate purity, fine-grained sediment input, and lithologic transitions (Asquith and Krygowski 2004; Ellis and Singer 2007; Rider and Kennedy 2011). The uniformly sampled GR series were used for spectral and time–frequency analyses, sedimentation-rate estimation, and construction of floating astronomical timescales.

### **3.3 Cyclostratigraphic analysis and age-constrained floating astronomical timescales**

Cyclostratigraphic analyses of both GR series were performed in Acycle. The workflow included MTM, eFFT, wavelet, EHA, and COCO/eCOCO sedimentation-rate searches. It also included Gaussian band-pass filtering, amplitude modulation, and coherence–phase analysis (Li et al. 2019). Depth-domain spectral peaks, time–frequency energy, orbital-period ratios, sedimentation rates, and modulation frequencies formed the evidence chain for orbital-cycle identification and hierarchical validation. Sedimentation-rate matching and red-noise tests followed established statistical procedures for deep-time astrochronology (Meyers and Sageman 2007; Meyers 2012; Hinnov 2013).

Before spectral analysis, the uniformly sampled GR series were demeaned. MTM identified the principal depth-domain cycles, and spectral significance was evaluated against an AR(1) red-noise background and by F-tests (Thomson 1982; Mann and Lees 1996). The time-bandwidth product was 2, and the smoothing window was 0.2. The nfft values were 32,768 for PS10 and 65,536 for PS2. The eFFT, EHA, and wavelet analyses characterized the persistence, energy variation, and vertical migration of major frequency components. These patterns were tracked along depth and relative-time axes (Torrence and Compo 1998; Kodama and Hinnov 2015). The analysis tracked 405-kyr long eccentricity, 125/95-kyr short eccentricity, approximately 41-kyr obliquity, and approximately 23.7-kyr precession. Orbital hierarchies followed long-term orbital solutions and stable deep-time frequency relationships (Laskar et al. 2004, 2011).

COCO/eCOCO matched candidate orbital-period combinations to corresponding sedimentation rates. The search ranged from 0.1 to 12.0 cm kyr<sup>−1</sup> at 0.1 cm kyr<sup>−1</sup> increments, producing 120 rate nodes. Correlation significance was evaluated using 3,000 Monte Carlo simulations (Li et al. 2018, 2019). Whole-interval COCO estimated the equivalent mean sedimentation rate for the Changxing Formation and supported depth–time conversion. A sliding-window eCOCO analysis recovered local sedimentation-rate changes. Window lengths were 69 m for PS10 and 80 m for PS2, with steps of approximately 1.5 m. These settings produced 70 local windows for PS10 and 95 for PS2. The rate with the highest correlation in each window was defined as the Best SR. The resulting continuous local sedimentation-rate trajectory was used to identify facies transitions and carbonate-factory reorganization.

The published age range of the Changxing Formation provided the external temporal boundary for each floating astronomical timescale. Internal cycle hierarchies comprised 405-kyr long eccentricity, 125/95-kyr short eccentricity, approximately 41-kyr obliquity, and approximately 23.7-kyr precession (Laskar et al. 2004, 2011; Wu et al. 2013). Time frameworks for both wells were based on whole-interval dominant sedimentation rates, period ratios, cycle counts, and relative durations. Local eCOCO Best SR values

characterized segmented sedimentation-rate changes within each mean temporal framework. Gaussian band-pass filters extracted the main candidate cycles. The filtered cycles were projected onto lithologic and facies-association columns for subdivision and counting.

Amplitude-modulation analysis treated the approximately 23.7-kyr precession component as the high-frequency carrier. Its amplitude envelope was extracted using the Hilbert transform and then analyzed spectrally. Coherence and phase analyses compared the amplitude envelope with the 125/95-kyr short-eccentricity filter. Peaks within the short-eccentricity band, high coherence at corresponding frequencies, and stable phase structure jointly verified modulation across orbital hierarchies. These criteria follow the astronomical relationship between eccentricity and precession amplitude and its cyclostratigraphic applications (Hinnov 2000; Laskar et al. 2004, 2011).

### **3.4 Global environmental records and local response comparison**

To identify the long-term environmental context of local reef–shoal development, this study compiled global Changhsingian paleotemperature,  $\delta^{13}\text{C}_{\text{carb}}$ , and marine redox records. The paleotemperature reconstruction follows Wang et al. (2020), and the global carbon-cycle record uses  $\delta^{13}\text{C}_{\text{carb}}$  data from Gliwa et al. (2020). Marine redox change follows the ocean-deoxygenation proxy and local linear trend of Zhang et al. (2024). All records were projected onto a numerical age axis. Calibration used high-precision end-Permian geochronology and the integrated Changhsingian timescale from South China (Shen et al. 2011; Burgess et al. 2014; Yuan et al. 2014). Key markers include the base of the late Wuchiapingian, the onset of marine deoxygenation at approximately 252.8 Ma, the end-Permian mass extinction, and the Permian–Triassic boundary. The PS10 eCOCO Best SR trajectory was converted to the age domain using the floating astronomical timescale. It was aligned with the global records to compare local sedimentation-rate reorganization with global warming, carbon-cycle change, and ocean deoxygenation.

## **4. Results**

### **4.1 Sedimentary microfacies, facies associations, and vertical distribution**

Seven sedimentary microfacies were identified in the Changxing Formation of wells PS10 and PS2. Bioclastic–intraclastic grainstone (MF1) contains abundant bioclasts or intraclasts, clear grain-supported fabrics, and little micrite. It also includes bioclastic limestone intervals that occur continuously within grain-shoal units in the original columns (Fig. 2c). Bioclastic wackestone (MF2) contains dispersed bioclasts in a micritic matrix and lacks clear grain support. Interparticle pores and interparticle dissolution pores occur locally (Fig. 2b, d). Skeletal framework limestone (MF3) preserves in situ reef-building frameworks of sponges, corals, and algae, with sponge frameworks being particularly characteristic (Fig. 2a). Micritic limestone (MF4) is micrite- or mud-supported and contains few grains. It includes ordinary limestone without clear evidence of grain support (Fig. 2e). Argillaceous limestone–

marl (MF5) and shale–mudstone (MF6) record argillaceous fine-grained deposition. Siliceous limestone (MF7) contains a substantial siliceous component within the rock framework (Fig. 2f). Limestone containing chert nodules was assigned according to its dominant primary fabric.

The co-occurrence and vertical stacking of microfacies define five facies associations. Intervals dominated by skeletal framework limestone constitute the reef-core association (FA1). Intervals dominated by bioclastic–intraclastic grainstone form the reef-cap–grain-shoal association (FA2). FA2 includes reef caps and isolated intraplatform grain shoals in PS10, and intraplatform-to-platform-margin bioclastic grain shoals in PS2. Intervals dominated by MF2 and MF4, with local MF5, form the reef-flank–reef-base–open-platform association (FA3). MF4, MF5, and MF6 form the calcareous–argillaceous fine-grained association (FA4). FA4 represents an intraplatform calcareous–argillaceous shelf in PS10 and platform-margin intershoal–tidal-flat fine-grained deposition in PS2. Intervals dominated by siliceous limestone form the siliceous calcareous shelf association (FA5).

MF1 grainstone is the most abundant microfacies in the Changxing Formation of PS10 and accounts for 44.06%. MF4 micritic limestone is second and accounts for 31.30%. FA2 grain shoals are the dominant facies association and account for 44.06%. FA3, FA4, and FA1 account for 24.93%, 18.26%, and 12.75%, respectively. These proportions show that PS10 is neither a uniform open-platform succession nor a continuous reef. It records a reef–shoal system comprising a local biogenic reef and multiple grain shoals on an intraplatform-shelf background.

Vertically, the succession passes upward from an FA4 calcareous–argillaceous shelf into an FA3 limestone background and then contains three FA2 grain-shoal units. The 5471.000–5478.000 m FA3 interval, 5449.000–5471.000 m FA1 interval, and 5423.000–5449.000 m FA2 interval form a complete reef-base–reef-core–reef-cap/grain-shoal succession. Together with two lower isolated grain shoals, this succession records repeated shallowing and sustained inheritance of a local buildup center at PS10.

Within this reef–shoal stacking framework, PS10 can be divided into two third-order sequences, Sq1 and Sq2, and four fourth-order cycles (Fig. 3). Sq1 records an overall shallowing trend from an FA4 fine-grained shelf to an FA2 grain shoal. Sq2 evolves upward from repeated FA3–FA2 stacking into an FA3–FA1–FA2 reef–shoal complex. Sequence boundaries correspond to long-term GR changes and stages of high-energy carbonate buildup. Reef–shoal development at PS10 was therefore strongly episodic.

MF1 grainstone and MF4 micritic limestone dominate PS2 and account for 41.73% and 29.54%, respectively. FA2 grain shoals and FA4 intershoal–tidal-flat fine-grained deposits occur in similar proportions of 41.73% and 39.10%. No reliable MF3 or FA1 was identified. The succession is therefore not dominated by a continuous reef core. Instead, it represents a platform-margin system with repeated stacking of grain-shoal and fine-grained intershoal deposits.

Vertically, three FA4–FA2 shallowing-upward cycles occur between 6030.000 and 6183.218 m. They record periodic grain-shoal expansion and intervening fine-grained intershoal deposition. The 5970.000–6030.000 m interval passes upward into an FA3 open-platform background containing a local

intraplatform bioclastic shoal. Only a thin FA5 siliceous calcareous association occurs near the top. Overall, PS2 records an upward transition from platform-margin shoal–intershoal cycles to a more intraplatform depositional setting.

## 4.2 Hierarchical structure and vertical variation of GR cycles

Within the revised facies-association framework, the GR logs of both wells show distinct vertical rhythms. Most of the PS10 carbonate succession maintains a low-GR background. Broad fluctuations extend across three FA2 grain shoals, the FA1 reef core, and intervening FA3 limestone intervals. Smaller-amplitude short-period variations are superimposed on this background. In the MTM spectrum, 31.185 m is the most prominent low-frequency component. Peaks at 9.625 and 7.315 m form a subordinate group, whereas 3.157 m lies at higher frequency. The 0.025–0.04375 cycles m<sup>-1</sup> low-frequency energy band is vertically persistent in the eFFT plot. Medium- to high-frequency energy increases locally within grain shoals, the reef core, and facies-transition intervals. The PS10 GR record therefore comprises successive reef–shoal pulses superimposed on long-period background variability (Fig. 4b).

PS2 displays more closely spaced GR variations. Baseline values and amplitudes change systematically with repeated alternations between FA2 grain shoals and FA4 intershoal–tidal-flat fine-grained deposits. The upper FA3 open-platform interval and local intraplatform bioclastic shoal produce a separate response. A 45.36-m spectral peak defines the long-period background. The 14.00- and 10.64-m bands are prominent in the MTM spectrum, and a 4.592-m high-frequency component is superimposed on them. The eFFT results show persistent 0.08125–0.10625 cycles m<sup>-1</sup> energy and adjacent high-frequency energy across three FA4–FA2 shallowing-upward cycles. Medium- to short-period variations are more vertically persistent and more responsive to facies boundaries in PS2 than in PS10 (Fig. 4a).

The 31.185-, 9.625-, 7.315-, and 3.157-m cycles in PS10 were selected for subsequent sedimentation-rate matching. The corresponding cycles selected in PS2 were 45.36, 14.00, 10.64, and 4.592 m.

After conversion from depth to relative time, EHA and wavelet analyses show a persistent 405-kyr background in both wells. Short-eccentricity, obliquity, and precession energy bands are superimposed on this background (Fig. 5). In PS10, 405-kyr energy extends through the basal FA4 background, three FA2 grain shoals, the FA1 reef core, and intervening FA3 intervals. Energy at 125/95 kyr and 41–23.7 kyr strengthens in bundles within grain-shoal and reef-core intervals. These patterns reveal distinct high-frequency production pulses within successive reef–shoal aggradational units. The 405-kyr background is also continuous in PS2. However, energy at 125/95, 41, and 23.7 kyr repeatedly strengthens across the three FA4–FA2 boundaries. The upper FA3–FA2 association contains another concentration of high-frequency energy. Both wells therefore preserve the same orbital hierarchy. Facies position integrated the high-frequency signal into repeated intraplatform reef–shoal aggradation at PS10 but amplified it into grain-shoal–intershoal/tidal-flat cycles at PS2.

## 4.3 Sedimentation-rate constraints, amplitude modulation, and floating astronomical timescales

Whole-interval COCO searches indicate equivalent mean sedimentation rates of  $7.7 \text{ cm kyr}^{-1}$  for PS10 and  $11.2 \text{ cm kyr}^{-1}$  for PS2. The highest correlation is 0.7195 at  $7.7 \text{ cm kyr}^{-1}$  for PS10 and 0.7575 at  $11.2 \text{ cm kyr}^{-1}$  for PS2. At these rates, the principal depth-domain cycles project simultaneously onto long eccentricity, short eccentricity, obliquity, and precession. These rates therefore provide the primary depth–time conversion for both wells (Fig. 6).

The eCOCO analysis further resolves local sedimentation-rate reorganization within each mean temporal framework. Median local Best SR values are  $4.1 \text{ cm kyr}^{-1}$  for PS10 and  $3.0 \text{ cm kyr}^{-1}$  for PS2. Maximum correlation coefficients reach 0.9702 and 0.7726, respectively, and median null-hypothesis probabilities are below  $1 \times 10^{-4}$  for both wells. The PS10 Best SR changes stepwise across FA4–FA3–FA2 transitions, boundaries of two isolated grain shoals, and the upper FA3–FA1–FA2 reef–shoal complex. High-correlation bands in PS2 shift repeatedly across the three FA4–FA2 shallowing-upward cycles. Whole-interval COCO characterizes the cumulative mean sedimentation rate of the complete succession. In contrast, eCOCO resolves local changes associated with grain-shoal expansion, reef-core growth, intershoal fine-grained accumulation, and facies migration. Together, they constrain total duration and local depositional dynamics at two scales.

At these mean rates, the 31.185-m cycle in PS10 and the 45.36-m cycle in PS2 correspond to 405-kyr long eccentricity. The 9.625- and 7.315-m cycles in PS10 and 14.00- and 10.64-m cycles in PS2 correspond to the 125/95-kyr short-eccentricity band. The 3.157- and 4.592-m cycles approximate the 41-kyr obliquity band. Persistent higher-frequency energy in the time–frequency plots corresponds to approximately 23.7-kyr precession. Both wells therefore record a complete 405-kyr–125/95-kyr–41-kyr–23.7-kyr orbital hierarchy.

Precession-band amplitude modulation provides an independent test of these cycle assignments (Fig. 7). The precession amplitude-envelope spectrum of PS10 contains clustered peaks near 104, 109, and 120 kyr. PS2 contains primary peaks near 111 and 127 kyr. All peaks fall within the short-eccentricity band. Coherence between the envelope and short-eccentricity curves is high near 110 kyr in PS10 and 109 kyr in PS2. Phase varies systematically across the high-coherence intervals. These results establish modulation of 23.7-kyr precession amplitude by 125/95-kyr short eccentricity. High-frequency GR pulses were therefore bundled depositional rhythms organized by short eccentricity rather than isolated fluctuations.

Gaussian band-pass filtering identifies five complete 405-kyr cycle bundles, E4051–E4055, in each well (Fig. 8). Each long-eccentricity cycle contains several 125/95-kyr short-eccentricity cycles and higher-frequency 41-kyr variations. Approximately 18 short-eccentricity cycles can be traced in PS10 and 16 in PS2. These counts correspond to relative durations of approximately 2.2 and 2.0 Myr, respectively. Short-eccentricity amplitudes in PS10 change systematically across the basal FA4–FA3 transition, boundaries

of three FA2 grain shoals, and the upper and lower boundaries of the FA1 reef core. In PS2, short-eccentricity and obliquity components strengthen in bundles within three FA4–FA2 shallowing-upward cycles. The filtered records directly link the orbital hierarchy to successive intraplatform reef–shoal pulses at PS10 and platform-margin shoal–intershoal cycles at PS2.

Multiple analyses establish independent depth–time conversions of 7.7 cm kyr<sup>−1</sup> for PS10 and 11.2 cm kyr<sup>−1</sup> for PS2. These analyses comprise whole-interval COCO, local eCOCO, time–frequency energy, amplitude modulation, and filtered-cycle counts. Both wells preserve five 405-kyr cycle bundles with internal short-eccentricity, obliquity, and precession hierarchies. Segmented changes in local Best SR record repeated grain-shoal and reef-core development in PS10 and grain-shoal–intershoal fine-grained transitions in PS2. The floating astronomical timescales constrain relative durations and directly link orbital phase, facies transitions, and reef–shoal growth stages.

## 5. Discussion

### 5.1 Multistage reef–shoal development on the intraplatform shelf

Changxing reef–shoal deposits are commonly interpreted within platform-margin high-energy belts. Regional hydrodynamic gradients, grain supply, and facies migration shaped these complexes (Read 1985; Burchette and Wright 1992; Schlager 2003, 2005; Pomar and Hallock 2008). The revised microfacies–facies-association framework shows that PS10 is neither a uniform thick open-platform limestone succession nor a single continuously prograding isolated reef. Instead, it contains three major grain shoals and one local reef core on an intraplatform-shelf background. This association accords with regional interpretations of Changxing intraplatform grain shoals and local buildups. Supporting studies include Wu et al. (2012), Tan et al. (2020), Wang et al. (2023), and Deng et al. (2023). FA2 accounts for 44.06%, considerably more than the 12.75% represented by FA1. Grain shoals therefore dominated high-energy carbonate development at PS10. FA3 and FA4 together account for 43.19% and record persistent intraplatform limestone and calcareous–argillaceous backgrounds between successive reef–shoal units. PS10 thus represents a composite development pathway comprising an intraplatform-shelf background, a local biogenic reef, and multiple grain shoals.

The vertical facies succession at PS10 contains three clearly differentiated buildup units. Above a basal FA4-to-FA3 transition, the 5515.000–5541.000 m grain shoal forms the first shallowing-upward unit. A second isolated grain shoal at 5478.000–5502.000 m overlies FA3 at 5502.000–5515.000 m. This succession records renewed expansion of the intraplatform carbonate factory after background limestone deposition. The upper 5471.000–5478.000 m FA3, 5449.000–5471.000 m FA1, and 5423.000–5449.000 m FA2 intervals form a comparatively complete reef-base–reef-core–reef-cap/grain-shoal complex. The transition from isolated grain shoals to a local reef-core–reef-cap association records progressive development from episodic shoal aggradation to skeletal stabilization and grain expansion across the buildup top.

This multistage architecture illustrates a mechanism for reef–shoal growth on the intraplatform shelf. A local paleotopographic high would have limited fine-grained sediment retention and maintained water exchange, allowing grain shoals to re-establish above FA3 limestone backgrounds. Continued carbonate aggradation enhanced relief and provided stable substrates for skeletal colonization and reef-core growth. Reef-core development subsequently promoted grain trapping and shallow-water hydrodynamic energy, favoring expansion of the overlying grain shoal. These interactions represent positive feedback among the carbonate factory, benthic constructors, and accommodation (Wilson 1975; Schlager 2003; Pomar and Hallock 2008; Flügel 2010). PS10 did not develop through a single episode of continuous aggradation. Instead, it progressively stabilized the carbonate-production center through repeated background limestone–grain shoal–background recovery–grain shoal–reef-core/reef-cap stages. In contrast to repeated replacement of platform-margin grain shoals at PS2, the local high at PS10 promoted vertical stacking of high-energy units in approximately the same area. This stacking produced an inherited intraplatform reef–shoal complex.

## **5.2 Temporal control of carbonate-buildup windows by orbital pacing**

PS10 preserves a multistage reef–shoal complex on an intraplatform-shelf background. Carbonate deposition advanced through three grain shoals and one reef-core–reef-cap association. Broad GR fluctuations and medium- to short-period variations recur across FA4, FA3, FA2, and FA1. The floating astronomical timescale organizes these transitions into 405-kyr, 125/95-kyr, 41-kyr, and 23.7-kyr cycles. Individual grain-shoal units and the upper reef–shoal complex span several short-eccentricity cycles. Orbital pacing therefore regulated the timing of carbonate-factory initiation, expansion, decline, and recovery rather than the isolated occurrence of a single microfacies.

Changes in accommodation, fine-grained sediment input, and shallow-water hydrodynamics organized reef–shoal development. Where carbonate aggradation kept pace with accommodation, argillaceous input declined, and water exchange strengthened, the FA3 background shifted rapidly into an MF1-dominated FA2 grain shoal. Greater topographic relief and substrate stability then permitted skeletal organisms to establish an FA1 reef core, followed upward by a reef-cap grain shoal. When conditions became less favorable, grain production and transport declined, and deposition returned to an FA3 limestone background or FA4 calcareous–argillaceous fine-grained association. FA3 intervals between the three PS10 grain shoals and the basal FA4 background were therefore recovery stages after periodic contraction of the carbonate factory. Together, these intervals record the opening, closure, and re-establishment of high-energy buildup windows.

Amplitude-modulation results further reveal hierarchical transmission of this temporal control. The strongly coherent modulation band near 109–110 kyr indicates that short eccentricity did not simply occur as an independent cycle. Instead, it regulated the amplitudes and bundling of precession-scale climate–hydrologic fluctuations. This modulation is consistent with eccentricity–precession coupling in astronomical solutions (Laskar et al. 2004, 2011). Long eccentricity defined the long-term state of

carbonate-factory maintenance or decline. Short eccentricity modulated the amplitudes of precession-scale pulses within that state. Obliquity and precession were expressed through high-frequency changes in shallow-water energy, fine-grained sediment input, and water exchange. Changxing reef–shoal development thus records hierarchical transmission from long-period environmental states to high-frequency production pulses.

Each orbital hierarchy played a distinct but connected role in reef growth. The 405-kyr long-eccentricity cycle formed the long-term environmental state and controlled whether favorable buildup windows persisted across several facies associations. The 125/95-kyr short-eccentricity cycles modulated precession amplitude and organized repeated strengthening, weakening, and recovery of carbonate production. The 41-kyr obliquity and 23.7-kyr precession cycles were expressed through high-frequency variations in water depth, hydrodynamic energy, and fine-grained sediment input (Hinnov 2000, 2013; Strasser et al. 2006). Under a favorable long-term state, high-frequency perturbations produced pulses in sedimentation rate and GR amplitude while the principal buildup remained active. When the long-term state deteriorated, similar perturbations were expressed as argillaceous input, shoal contraction, and interrupted buildup growth. Five long-eccentricity bundles and their internal short-eccentricity–precession modulation therefore define the temporal framework of Changxing reef–shoal development.

PS2 preserves the same orbital hierarchy but lacks a reliable FA1 reef core. Instead, FA2 intraplatform-to-platform-margin grain shoals alternate in near-equal thickness with FA4 intershoal–tidal-flat fine-grained deposits. Three FA4–FA2 shallowing-upward cycles show that each strengthening of the platform-margin carbonate factory produced upward grain-shoal expansion. Factory decline was rapidly expressed as fine-grained intershoal accumulation. A local intraplatform bioclastic shoal in the upper FA3 background records further landward migration of the facies belt. The difference between the wells does not reflect different orbital forcing. Identical temporal rhythms produced multistage vertical reef–shoal inheritance at PS10 and repeated grain-shoal–intershoal/tidal-flat replacement at PS2.

## **5.3 Facies filtering and differentiated depositional expression of orbital signals**

Long-period energy at PS10 extends through the basal intraplatform fine-grained background, three grain shoals, and the upper reef-core–reef-cap association. Medium- to short-period variability strengthens in bundles across FA3–FA2 and FA3–FA1–FA2 transitions. At PS2, FA2 grain shoals repeatedly alternate with FA4 intershoal–tidal-flat fine-grained deposits. Medium- to short-period components at 14.00, 10.64, and 4.592 m are more clearly expressed within three shallowing-upward cycles. Similar orbital hierarchies thus produced distinct stratigraphic architectures. PS10 integrated orbital pulses into multistage vertical inheritance of reef–shoal units within the same area. PS2 recorded stronger facies migration through grain-shoal expansion, intershoal infill, and an upward shift toward intraplatform conditions.

These differences primarily reflect depositional-space architecture. The fault-controlled local-high component shown in Fig. 9 follows regional evidence from the Sichuan Basin, where Changxing

Formation reef–shoal complexes developed preferentially along faulted highs and strike-slip faults influenced their distribution by shaping pre-depositional paleotopography (Liu et al. 2024). A local intraplatform high fixed the carbonate-production center at PS10. Orbital-scale changes were therefore expressed as repeated grain-shoal establishment, local reef-core growth, and reef-cap shoal expansion. Three FA2 units and one FA1 unit consequently accumulated vertically within approximately the same area. The Jiange–Langzhong platform margin had stronger lateral hydrodynamic and sediment-supply gradients. At PS2, changes in water depth and fine-grained sediment input produced FA2 grain-shoal expansion and retreat, with intervening FA4 intershoal–tidal-flat deposition. This contrast accords with established patterns of platform-margin facies migration and carbonate-factory differentiation (Burchette and Wright 1992; Pomar and Hallock 2008). It also resembles the depositional architecture of Changxing platform-margin reef–shoal systems in South China (Chen et al. 2012, 2018, 2024). The same orbital phase was converted into different sedimentary trajectories. PS10 mainly records vertical inheritance of high-energy units and stabilization of a local reef core. PS2 mainly records lateral migration and lithologic replacement within a grain-shoal–intershoal system.

Figure 9 summarizes this facies-filtering mechanism. When the carbonate factory strengthened, the local high at PS10 first supported grain shoals and then developed a skeletal reef core and reef-cap shoal. At PS2, platform-margin bioclastic shoals thickened along the high-energy belt and expanded into adjacent depositional areas. When the factory weakened, PS10 returned to FA3 or FA4 background deposition. These intervals separated successive episodes of grain-shoal re-establishment. PS2 shifted rapidly to FA4 intershoal–tidal-flat fine-grained accumulation. Orbital forcing determined the periodic state of the carbonate factory. Facies position determined whether that state entered the stratigraphic record as multistage reef–shoal stacking, shoal migration, or fine-grained deposition.

Sedimentation rates further amplified facies filtering. The whole-interval equivalent mean rate at PS2 is  $11.2 \text{ cm kyr}^{-1}$ , higher than the  $7.7 \text{ cm kyr}^{-1}$  at PS10. However, the median local Best SR at PS2 is only  $3.0 \text{ cm kyr}^{-1}$ . Platform-margin stratigraphic thickness therefore accumulated through both rapid grain-shoal expansion and thick intershoal–tidal-flat fine-grained deposition. The median local Best SR at PS10 is  $4.1 \text{ cm kyr}^{-1}$ . Stepwise changes occur across FA4–FA3–FA2 transitions, boundaries of two isolated grain shoals, and the upper FA3–FA1–FA2 reef–shoal complex. Local rate shifts coincide with facies boundaries and record carbonate-factory initiation, reef–shoal expansion, fine-grained infill, and facies migration. Facies position jointly controlled sedimentation rates, depositional continuity, and signal preservation. This control shaped differences in spectral energy, cycle thickness, and lithologic rhythm between the wells.

## 5.4 Local reef–shoal responses to the global Late Permian environmental transition

The Changhsingian represents an interval of accelerated greenhouse development after the waning Late Paleozoic Ice Age. Global climate, sea level, the carbon cycle, and marine redox conditions jointly reorganized the environmental boundaries of carbonate platforms. Glacial records from eastern

Australia and Paleozoic sea-level curves indicate that long-term ice-volume decline and multiscale sea-level change continued into the Late Permian. These changes affected accommodation and terrigenous sediment supply (Fielding et al. 2008; Rygel et al. 2008; Haq and Schutter 2008). Changxing reef–shoal systems were therefore not isolated bodies on a static platform. They were carbonate-production centers that adjusted during global warming and marine environmental change.

Global records further define the direction of this long-term environmental transition (Fig. 10). Changhsingian paleotemperature increased from approximately 21°C to nearly 28°C. Values of  $\delta^{13}\text{C}_{\text{carb}}$  remained near 3–4‰ through much of the stage, then declined. A sharp negative shift occurred near the end of the Permian (Wang et al. 2020; Gliwa et al. 2020; Korte and Kozur 2010; Shen et al. 2013). This trend forms part of rapid Late Permian warming within the Phanerozoic temperature record (Scotese et al. 2021). Marine redox proxies changed markedly near 252.8 Ma and then indicate sustained deoxygenation (Zhang et al. 2024). Warming intensified water-column stratification and metabolic stress, while carbon-cycle disruption reduced carbonate-factory stability. Ocean deoxygenation further contracted ecological space available to benthic reef builders. Temperature and ecophysiological evidence indicates that these coupled changes reorganized Late Permian shallow-marine ecosystems and carbonate production (Joachimski et al. 2012; Penn et al. 2018; Jurikova et al. 2020).

The local Best SR trajectory at PS10 records stepwise changes in the intraplatform carbonate factory during this global transition. Between approximately 253.7 and 252.4 Ma, sedimentation rates shifted rapidly from early high values to a low-rate plateau. Several subsequent steps culminated in sustained higher accumulation near 252.9–252.8 Ma (Fig. 10E). This reorganization coincided with continued warming, declining carbon-isotope values, and the onset of ocean deoxygenation. Its timing is constrained by the high-precision end-Permian chronology from South China (Shen et al. 2011; Burgess et al. 2014; Yuan et al. 2014). After the environmental boundary crossed a threshold, local accommodation, production efficiency, and sediment preservation changed systematically. PS10 did not passively replicate the global curves. Instead, reef–shoal aggradation and facies transitions converted global environmental change into a recognizable local stratigraphic response.

The stable 405-kyr rhythm in the Lopingian of South China provides an internal temporal structure for this long-term transition (Wu et al. 2013; Hinnov 2013). Global warming, declining carbon-isotope values, and deoxygenation defined the long-term state of the carbonate factory. Long eccentricity organized the persistence and contraction of favorable reef–shoal windows. Short eccentricity controlled production pulses within those windows through modulation of precession amplitude. Local facies belts then converted these pulses into contrasting records. PS10 preserves vertical inheritance among repeated intraplatform grain shoals and a local reef core. PS2 records migration between platform-margin grain shoals and intershoal–tidal-flat deposits. The Changxing Formation therefore records a hierarchical response chain. Global environmental boundaries modified platform production potential, orbital rhythms set the pace, and facies position determined depositional expression. Sedimentation rate and preservation finally shaped the stratigraphic record. This mechanism interprets local reef–shoal

evolution as a spatially differentiated response within a carbonate platform undergoing the global Late Permian environmental transition.

## 6. Conclusions

(1) PS10 and PS2 record an intraplatform-shelf reef–shoal complex and a platform-margin grain-shoal–intershoal/tidal-flat system, respectively. MF1 and FA2 dominate PS10. Three major grain shoals and an FA3–FA1–FA2 reef-base–reef-core–reef-cap/grain-shoal complex developed above an intraplatform calcareous–argillaceous background. PS2 contains near-equal alternations between FA2 grain shoals and FA4 fine-grained deposits. It forms three FA4–FA2 shallowing-upward cycles without a reliable reef core. The two wells therefore record contrasting development pathways: multistage vertical inheritance within the platform interior and dynamic shoal–intershoal migration at the platform margin.

(2) MTM, eFFT, EHA, wavelet, and COCO/eCOCO analyses constrain whole-interval equivalent mean sedimentation rates for both wells. The rates are 7.7 cm kyr<sup>−1</sup> for PS10 and 11.2 cm kyr<sup>−1</sup> for PS2. They establish an orbital hierarchy comprising 405-kyr long eccentricity, 125/95-kyr short eccentricity, approximately 41-kyr obliquity, and 23.7-kyr precession. Both wells preserve five 405-kyr cycle bundles. Approximately 18 short-eccentricity cycles occur in PS10 and 16 in PS2, corresponding to durations of about 2.2 and 2.0 Myr. The precession amplitude envelopes contain a strongly coherent modulation band near 109–110 kyr. This relationship supports organization of high-frequency depositional rhythms by short eccentricity.

(3) Orbital pacing controlled reef–shoal growth windows through hierarchical transmission. Long eccentricity defined the long-term state of the carbonate factory. Short eccentricity modulated precession amplitude and organized production pulses. Obliquity and precession were expressed through high-frequency changes in hydrodynamic energy, fine-grained sediment input, and sedimentation rate. Facies filtering converted these rhythms into repeated grain-shoal establishment, local reef-core growth, and reef-cap expansion at PS10. At PS2, the same rhythms were amplified through grain-shoal migration and intershoal–tidal-flat fine-grained accumulation.

(4) Global warming, declining  $\delta^{13}\text{C}_{\text{carb}}$ , and ocean deoxygenation formed the long-term environmental boundary for Changxing reef–shoal development. Stepwise changes in local Best SR at PS10 record repeated grain-shoal–reef-core development and reorganization of depositional space within this context. The proposed global environmental boundary–orbital modulation–facies filtering–sedimentary preservation model unifies the contrasting growth histories, cyclic expressions, and preservation styles of multistage intraplatform reef–shoal complexes and platform-margin grain-shoal–intershoal/tidal-flat systems.

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## Competing interests

The authors have no relevant financial or non-financial interests to disclose.

## Author Contribution

Weijie Tong led the conceptualization and implementation of the study, including data curation, formal analysis, cyclostratigraphic interpretation, visualization, and preparation of the original manuscript. Quansheng Cai and Zhonggui Hu contributed to the study design, methodological guidance, supervision, interpretation of the results, and critical revision of the manuscript. Saijun Wu, Wuren Xie, Liang Xu, Rong Li, and Chunyan Deng contributed to data acquisition and organization, geological and sedimentological interpretation, validation of the results, and manuscript review. All authors discussed the findings, contributed to the revision of the manuscript, and read and approved the final version.

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## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## References

1. Asquith G, Krygowski D (2004) Basic well log analysis, 2nd edn. AAPG Methods in Exploration Series 16, American Association of Petroleum Geologists, Tulsa. <https://doi.org/10.1306/MTH16823>
2. Burchette TP, Wright VP (1992) Carbonate ramp depositional systems. *Sedimentary Geology* 79:3–57. [https://doi.org/10.1016/0037-0738\(92\)90003-A](https://doi.org/10.1016/0037-0738(92)90003-A)
3. Burgess SD, Bowring SA, Shen S-Z (2014) High-precision timeline for Earth’s most severe extinction. *Proceedings of the National Academy of Sciences of the United States of America* 111:3316–3321. <https://doi.org/10.1073/pnas.1317692111>

4. Chen B, Xie X, Al-Aasm IS, Wu F, Zhou M (2018) Depositional architecture and facies of a complete reef complex succession: a case study of the Permian Jiantianba reefs, western Hubei, South China. *Minerals* 8:533. <https://doi.org/10.3390/min8110533>
5. Chen B, Wu F, Xie X, Gao Y, Xiao W, Tang Z (2024) Sequence stratigraphic analysis of the Late Permian Changhsingian platform marginal reef, western Hubei, South China. *Frontiers in Marine Science* 11:1470867. <https://doi.org/10.3389/fmars.2024.1470867>
6. Chen L, Lu Y, Guo T, Xing F, Jiao Y (2012) Seismic sedimentology study in the high-resolution sequence framework—a case study of platform margin reef-beach system of Changxing Formation, Upper Permian, Yuanba Area, Northeast Sichuan Basin, China. *Journal of Earth Science* 23:612–626. <https://doi.org/10.1007/s12583-012-0278-x>
7. Deng M, Zhao G, Lin X, Chen C, Li L, Liang Q (2023) Sedimentary facies, paleogeography, and depositional models of the Middle–Late Permian in the Sichuan Basin, Southwest China. *Minerals* 13:1406. <https://doi.org/10.3390/min13111406>
8. Dunham RJ (1962) Classification of carbonate rocks according to depositional texture. In: Ham WE (ed) *Classification of carbonate rocks*. AAPG Memoir 1, American Association of Petroleum Geologists, Tulsa, pp 108–121.
9. Ellis DV, Singer JM (2007) *Well logging for Earth scientists*, 2nd edn. Springer, Dordrecht. <https://doi.org/10.1007/978-1-4020-4602-5>
10. Embry AF, Klovan JE (1971) A Late Devonian reef tract on northeastern Banks Island, N.W.T. *Bulletin of Canadian Petroleum Geology* 19:730–781.
11. Fielding CR, Frank TD, Birgenheier LP, Rygel MC, Jones AT, Roberts J (2008) Stratigraphic imprint of the Late Palaeozoic Ice Age in eastern Australia: a record of alternating glacial and nonglacial climate regime. *Journal of the Geological Society* 165:129–140. <https://doi.org/10.1144/0016-76492007-036>
12. Flügel E (2010) *Microfacies of carbonate rocks: analysis, interpretation and application*, 2nd edn. Springer, Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-03796-2>
13. Gliwa J, Ghaderi A, Leda L, Schobben M, Tomás S, Foster WJ, Forel M-B, Ghanizadeh Tabrizi N, Grasby SE, Struck U, Ashouri AR, Korn D (2020) Aras Valley (northwest Iran): high-resolution stratigraphy of a continuous central Tethyan Permian–Triassic boundary section. *Fossil Record* 23:33–69. <https://doi.org/10.5194/fr-23-33-2020>
14. Haq BU, Schutter SR (2008) A chronology of Paleozoic sea-level changes. *Science* 322:64–68. <https://doi.org/10.1126/science.1161648>
15. Hinnov LA (2000) New perspectives on orbitally forced stratigraphy. *Annual Review of Earth and Planetary Sciences* 28:419–475. <https://doi.org/10.1146/annurev.earth.28.1.419>
16. Hinnov LA (2013) Cyclostratigraphy and its revolutionizing applications in the earth and planetary sciences. *Geological Society of America Bulletin* 125:1703–1734. <https://doi.org/10.1130/B30934.1>
17. Joachimski MM, Lai X, Shen S-Z, Jiang H, Luo G, Chen B, Chen J, Sun Y (2012) Climate warming in the latest Permian and the Permian–Triassic mass extinction. *Geology* 40:195–198.

<https://doi.org/10.1130/G32707.1>

18. Jurikova H, Gutjahr M, Wallmann K, Flögel S, Liebetrau V, Posenato R, Angiolini L, Garbelli C, Brand U, Wiedenbeck M, Eisenhauer A (2020) Permian–Triassic mass extinction pulses driven by major marine carbon cycle perturbations. *Nature Geoscience* 13:745–750.  
<https://doi.org/10.1038/s41561-020-00646-4>
19. Kodama KP, Hinnov LA (2015) *Rock magnetic cyclostratigraphy*. Wiley-Blackwell, Chichester.  
<https://doi.org/10.1002/9781118561294>
20. Korte C, Kozur HW (2010) Carbon-isotope stratigraphy across the Permian–Triassic boundary: a review. *Journal of Asian Earth Sciences* 39:215–235. <https://doi.org/10.1016/j.jseaes.2010.01.005>
21. Laskar J, Robutel P, Joutel F, Gastineau M, Correia ACM, Levrard B (2004) A long-term numerical solution for the insolation quantities of the Earth. *Astronomy & Astrophysics* 428:261–285.  
<https://doi.org/10.1051/0004-6361:20041335>
22. Laskar J, Fienga A, Gastineau M, Manche H (2011) La2010: a new orbital solution for the long-term motion of the Earth. *Astronomy & Astrophysics* 532:A89. <https://doi.org/10.1051/0004-6361/201116836>
23. Li M, Kump LR, Hinnov LA, Mann ME (2018) Tracking variable sedimentation rates and astronomical forcing in Phanerozoic paleoclimate proxy series with evolutionary correlation coefficients and hypothesis testing. *Earth and Planetary Science Letters* 501:165–179.  
<https://doi.org/10.1016/j.epsl.2018.08.041>
24. Li M, Hinnov L, Kump L (2019) Acycle: time-series analysis software for paleoclimate research and education. *Computers & Geosciences* 127:12–22. <https://doi.org/10.1016/j.cageo.2019.02.011>
25. Liu J, Wu G, Tang Q, Wu Y, Zhang W, Zhao Z (2024) Effects of intracratonic strike-slip fault on the differentiation of carbonate microfacies: a case study of a Permian platform margin in the Sichuan Basin (SW China). *Acta Geologica Sinica (English Edition)* 98:936–954.  
<https://doi.org/10.1111/1755-6724.15203>
26. Mann ME, Lees JM (1996) Robust estimation of background noise and signal detection in climatic time series. *Climatic Change* 33:409–445. <https://doi.org/10.1007/BF00142586>
27. Meyers SR (2012) Seeing red in cyclic stratigraphy: spectral noise estimation for astrochronology. *Paleoceanography* 27:PA3228. <https://doi.org/10.1029/2012PA002307>
28. Meyers SR, Sageman BB (2007) Quantification of deep-time orbital forcing by average spectral misfit. *American Journal of Science* 307:773–792. <https://doi.org/10.2475/05.2007.01>
29. Penn JL, Deutsch C, Payne JL, Sperling EA (2018) Temperature-dependent hypoxia explains biogeography and severity of end-Permian marine mass extinction. *Science* 362:eaat1327.  
<https://doi.org/10.1126/science.aat1327>
30. Pomar L, Hallock P (2008) Carbonate factories: a conundrum in sedimentary geology. *Earth-Science Reviews* 87:134–169. <https://doi.org/10.1016/j.earscirev.2007.12.002>
31. Read JF (1985) Carbonate platform facies models. *AAPG Bulletin* 69:1–21.  
<https://doi.org/10.1306/AD461B79-16F7-11D7-8645000102C1865D>

32. Rider M, Kennedy M (2011) The geological interpretation of well logs, 3rd edn. Rider-French Consulting, Sutherland.
33. Rygel MC, Fielding CR, Frank TD, Birgenheier LP (2008) The magnitude of Late Paleozoic glacioeustatic fluctuations: a synthesis. *Journal of Sedimentary Research* 78:500–511. <https://doi.org/10.2110/jsr.2008.058>
34. Schlager W (2003) Benthic carbonate factories of the Phanerozoic. *International Journal of Earth Sciences* 92:445–464. <https://doi.org/10.1007/s00531-003-0327-x>
35. Schlager W (2005) Carbonate sedimentology and sequence stratigraphy. *SEPM Concepts in Sedimentology and Paleontology* 8, Society for Sedimentary Geology, Tulsa. <https://doi.org/10.2110/csp.05.08>
36. Scotese CR (2014) Atlas of Permo-Triassic paleogeographic maps (Mollweide projection), maps 43–52, volume 3: The Late Paleozoic. PALEOMAP Atlas for ArcGIS, PALEOMAP Project, Evanston, Illinois.
37. Scotese CR, Song H, Mills BJW, van der Meer DG (2021) Phanerozoic paleotemperatures: the Earth's changing climate during the last 540 million years. *Earth-Science Reviews* 215:103503. <https://doi.org/10.1016/j.earscirev.2021.103503>
38. Shen S-Z, Crowley JL, Wang Y, Bowring SA, Erwin DH, Sadler PM, Cao C-Q, Rothman DH, Henderson CM, Ramezani J, Zhang H, Shen Y, Wang X-D, Wang W, Mu L, Li W-Z, Tang Y-G, Liu X-L, Liu L-J, Zeng Y, Jiang Y-F, Jin Y-G (2011) Calibrating the end-Permian mass extinction. *Science* 334:1367–1372. <https://doi.org/10.1126/science.1213454>
39. Shen S-Z, Cao C-Q, Henderson CM, Wang X-D, Shi GR, Wang Y, Wang W (2013) High-resolution  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphy from latest Guadalupian through earliest Triassic in South China and Iran. *Earth and Planetary Science Letters* 375:156–165. <https://doi.org/10.1016/j.epsl.2013.05.020>
40. Strasser A, Hilgen FJ, Heckel PH (2006) Cyclostratigraphy—concepts, definitions, and applications. *Newsletters on Stratigraphy* 42:75–114. <https://doi.org/10.1127/0078-0421/2006/0042-0075>
41. Tan L, Liu H, Tang Y, Luo B, Zhang Y, Yang Y, Liao Y, Du W, Yang X (2020) Characteristics and mechanism of Upper Permian reef reservoirs in the eastern Longgang area, northeastern Sichuan Basin, China. *Petroleum* 6:130–137. <https://doi.org/10.1016/j.petlm.2019.06.008>
42. Thomson DJ (1982) Spectrum estimation and harmonic analysis. *Proceedings of the IEEE* 70:1055–1096. <https://doi.org/10.1109/PROC.1982.12433>
43. Torrence C, Compo GP (1998) A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society* 79:61–78. [https://doi.org/10.1175/1520-0477\(1998\)079<0061:APGTWA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2)
44. Tucker ME, Wright VP (1990) Carbonate sedimentology. Blackwell Scientific Publications, Oxford. <https://doi.org/10.1002/9781444314175>
45. Wang D, Liu H, Tang S, Bai J, Zhou G, Li Z, Liang F, Tan X, Geng C, Yang Y (2023) Sedimentary architecture and distribution of intra-platform shoal in sequence framework of Permian Changxing

- Formation in central Sichuan Basin, SW China. *Petroleum Exploration and Development* 50:388–403. [https://doi.org/10.1016/S1876-3804\(23\)60395-7](https://doi.org/10.1016/S1876-3804(23)60395-7)
46. Wang WQ, Garbelli C, Zhang FF, Zheng QF, Zhang YC, Yuan DX, Shi YK, Chen B, Shen SZ (2020) A high-resolution Middle to Late Permian paleotemperature curve reconstructed using oxygen isotopes of well-preserved brachiopod shells. *Earth and Planetary Science Letters* 540:116245. <https://doi.org/10.1016/j.epsl.2020.116245>
47. Weedon GP (2003) *Time-series analysis and cyclostratigraphy: examining stratigraphic records of environmental cycles*. Cambridge University Press, Cambridge. <https://doi.org/10.1017/CBO9780511535482>
48. Wilson JL (1975) *Carbonate facies in geologic history*. Springer, New York. <https://doi.org/10.1007/978-1-4612-6383-8>
49. Wu H, Zhang S, Hinnov LA, Jiang G, Feng Q, Li H, Yang T (2013) Time-calibrated Milankovitch cycles for the late Permian. *Nature Communications* 4:2452. <https://doi.org/10.1038/ncomms3452>
50. Wu L, Jiao Y, Rong H, Wang R, Li R (2012) Reef types and sedimentation characteristics of Changxing Formation in Manyue–Honghua Section of Kaixian, northeastern Sichuan Basin. *Journal of Earth Science* 23:490–505. <https://doi.org/10.1007/s12583-012-0270-5>
51. Yuan DX, Shen SZ, Henderson CM, Chen J, Zhang H, Feng HZ (2014) Revised conodont-based integrated high-resolution timescale for the Changhsingian Stage and end-Permian extinction interval at the Meishan sections, South China. *Lithos* 204:220–245. <https://doi.org/10.1016/j.lithos.2014.03.026>
52. Zhang M, Qin H, Hou Y, He K, Deng C, Shen S-Z, Pan Y-X (2024) Shifts in magnetic mineral assemblages support ocean deoxygenation before the end-Permian mass extinction. *Communications Earth & Environment* 5:218. <https://doi.org/10.1038/s43247-024-01394-8>

## Figures

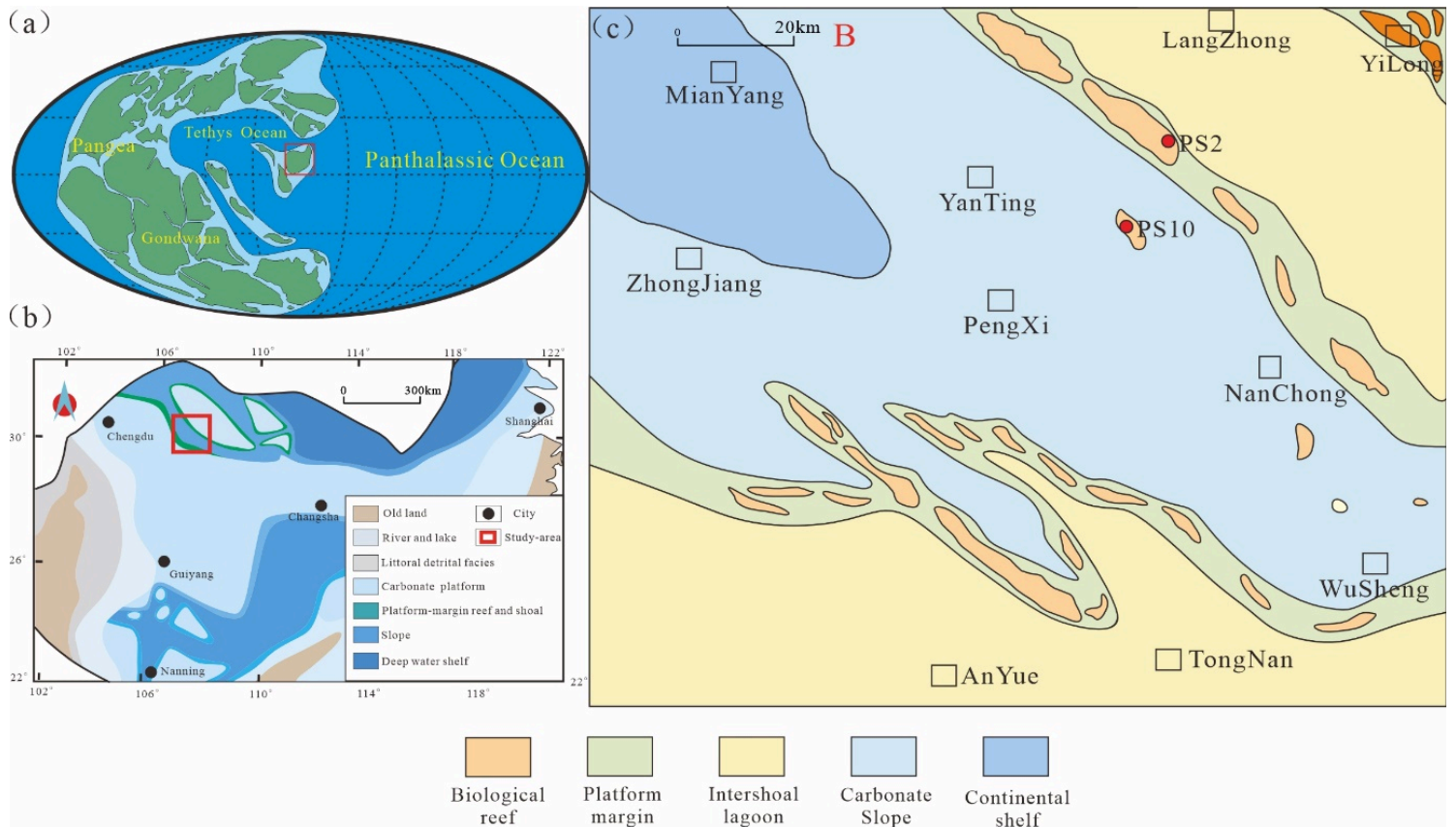


**Figure 1**

Paleogeographic location and depositional-facies distribution of the study area in South China and the Sichuan Basin during the Late Permian Changhsingian. (a) Global paleogeographic position; (b) Changhsingian lithofacies paleogeography of South China and location of the study area; (c) depositional-facies distribution in the Sichuan Basin and locations of wells PS10 and PS2. Paleogeographic framework synthesized from Scotese (2014), Wu et al. (2012), Chen et al. (2012), Wang et al. (2023), and Deng et al. (2023)

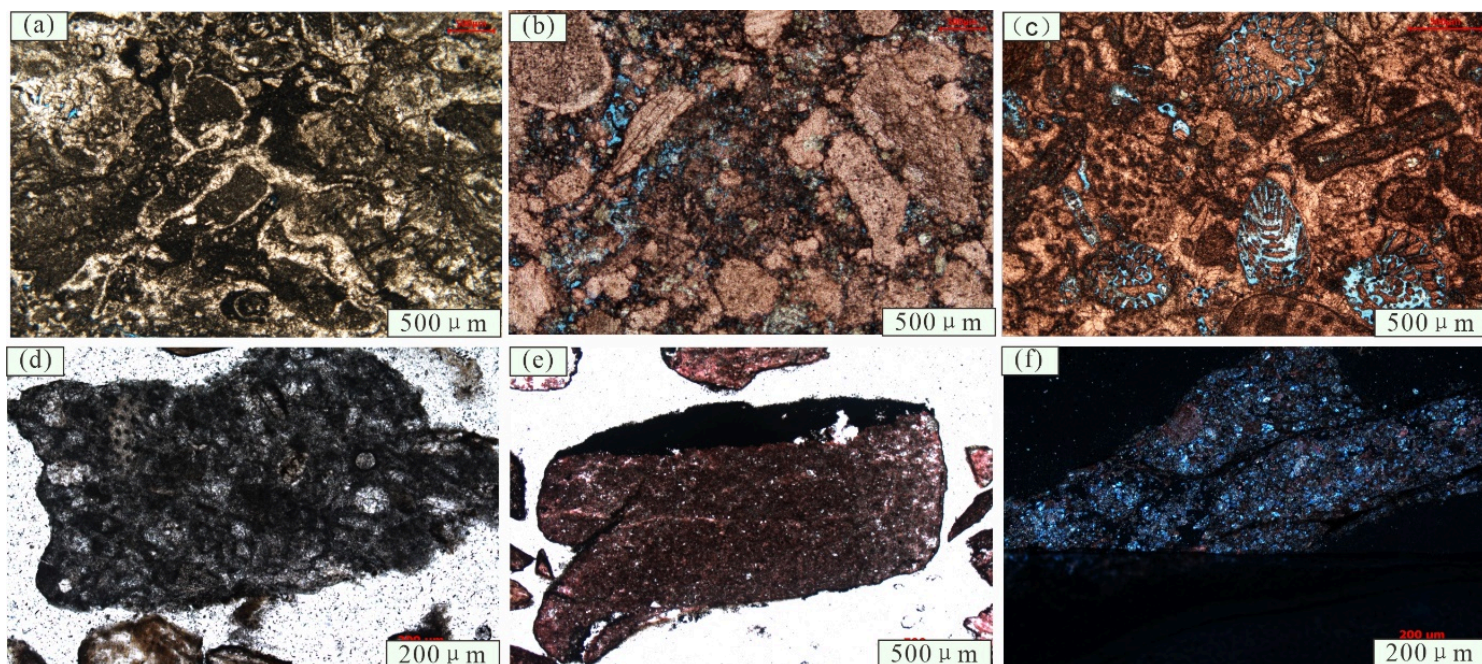


**Figure 2**

Representative thin-section characteristics of the Changxing Formation in wells PS10 and PS2. a PS10, 5465.92 m, micritic sponge-framework limestone with a clear sponge framework, MF3. b PS10, 5472.54 m, micritic bioclastic limestone with bioclasts dispersed in a micritic matrix and local interparticle and interparticle dissolution pores, MF2. c PS10, 5439.31 m, sparry bioclastic limestone containing *Colaniella* and palaeofusulinid fragments, with intraparticle dissolution and moldic pores, MF1. d PS2, 5986.00 m, micritic bioclastic limestone with bioclasts dispersed in a micritic matrix, MF2. e PS2, 6006.00 m, micritic limestone dominated by a homogeneous micritic fabric and containing few grains, MF4. f PS2, 6036.00 m, micritic bioclastic siliceous limestone with an evident siliceous component, MF7

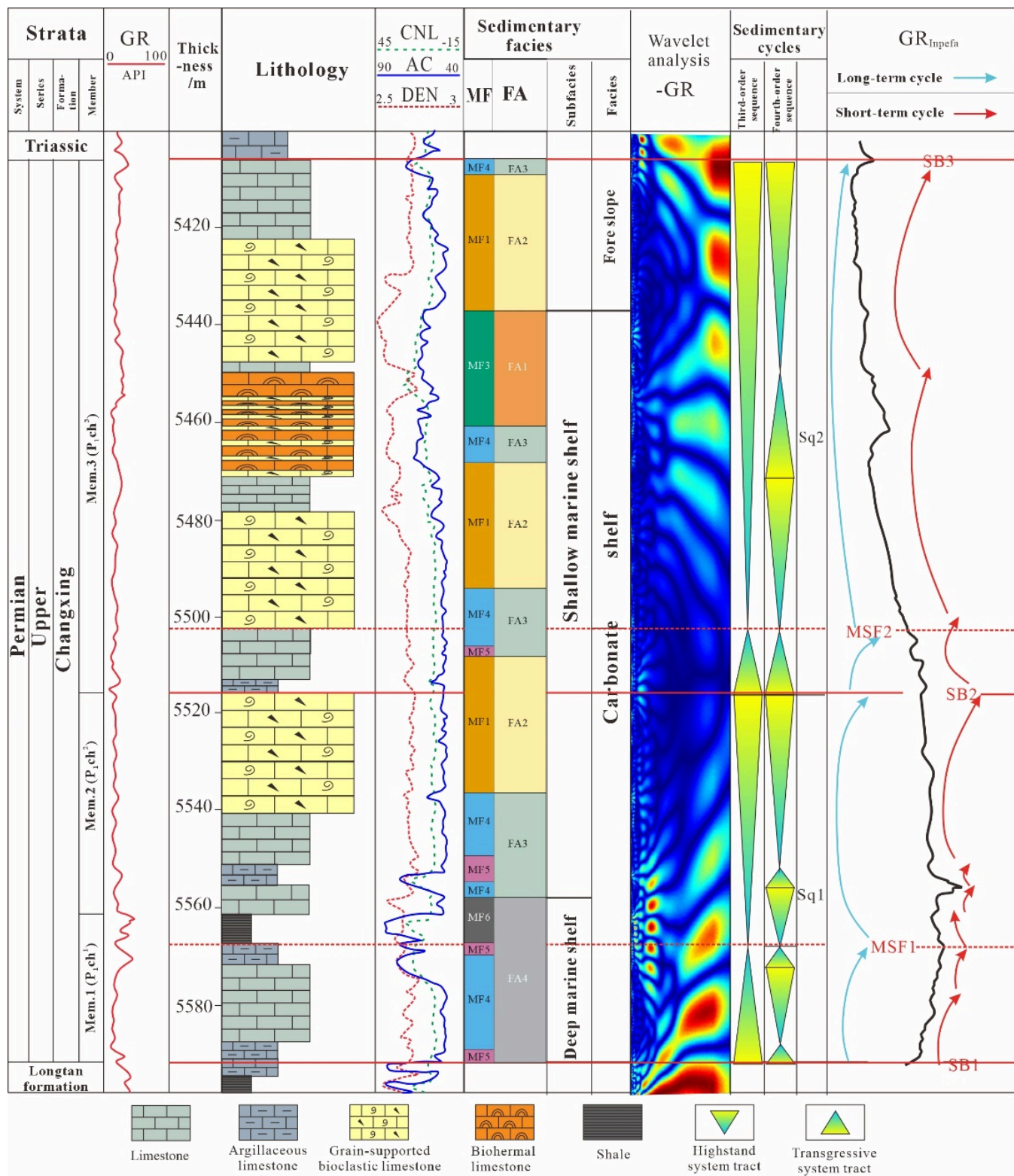


**Figure 3**

Composite stratigraphic column of the Changxing Formation in PS10. From left to right, the column shows stratigraphy, GR, lithology, compensated neutron (CNL), acoustic (AC), and density (DEN) logs, microfacies, facies associations, and depositional environments. It also shows GR wavelet energy, third- to fourth-order sequences, and long- and short-term GR envelopes. MF and FA denote microfacies and

facies associations, respectively. SB1–SB3 denote sequence boundaries, MSF1–MSF2 denote maximum flooding surfaces, and Sq1–Sq2 denote third-order sequences

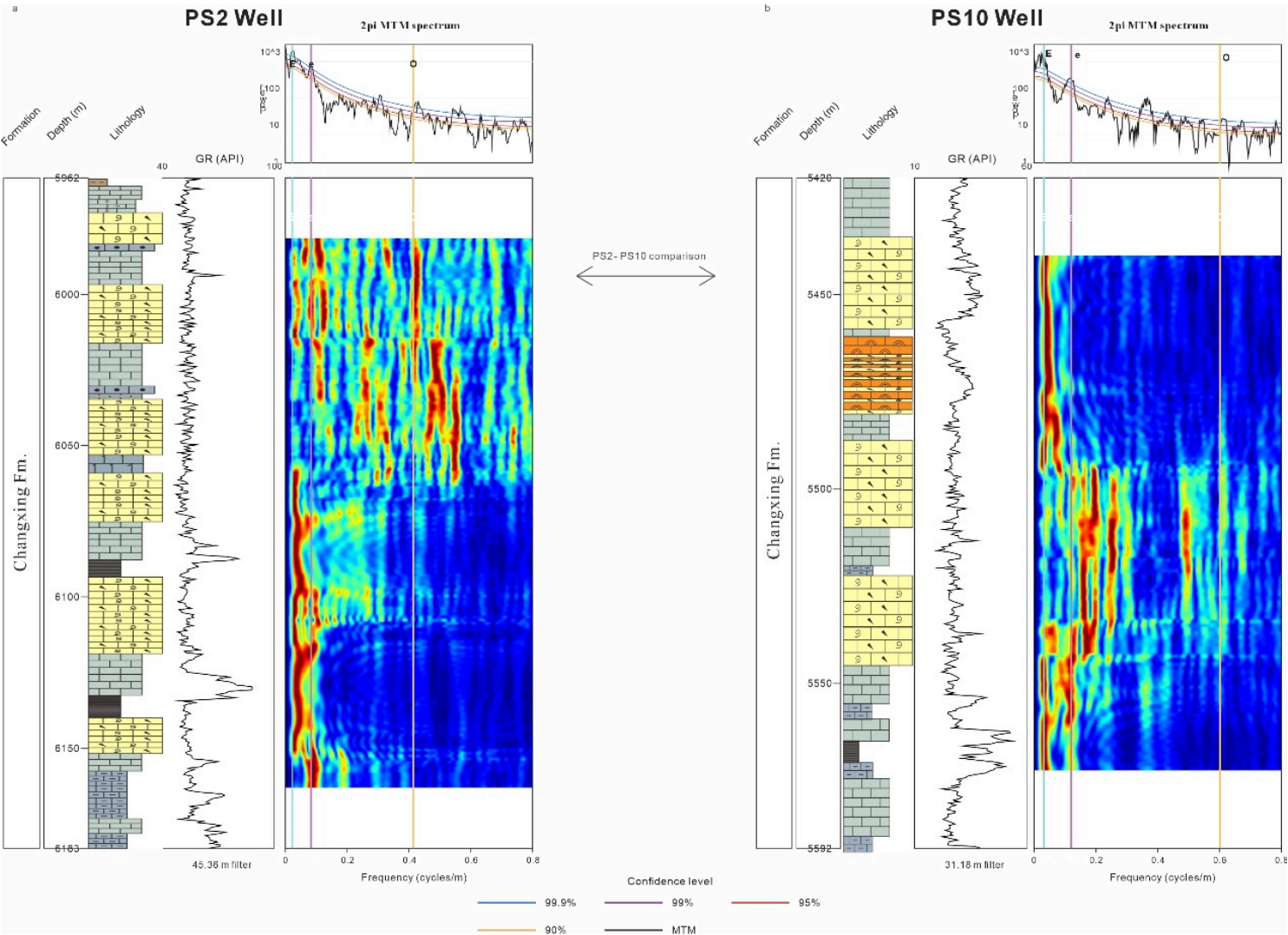


**Figure 4**

Depth-domain spectral and time–frequency expressions of GR cycles in PS2 (a) and PS10 (b). Each panel shows the lithologic column, raw GR log,  $2\pi$  MTM spectrum, and eFFT energy distribution. Vertical lines indicate the principal candidate orbital bands, and the basal curves show long-period filtered components

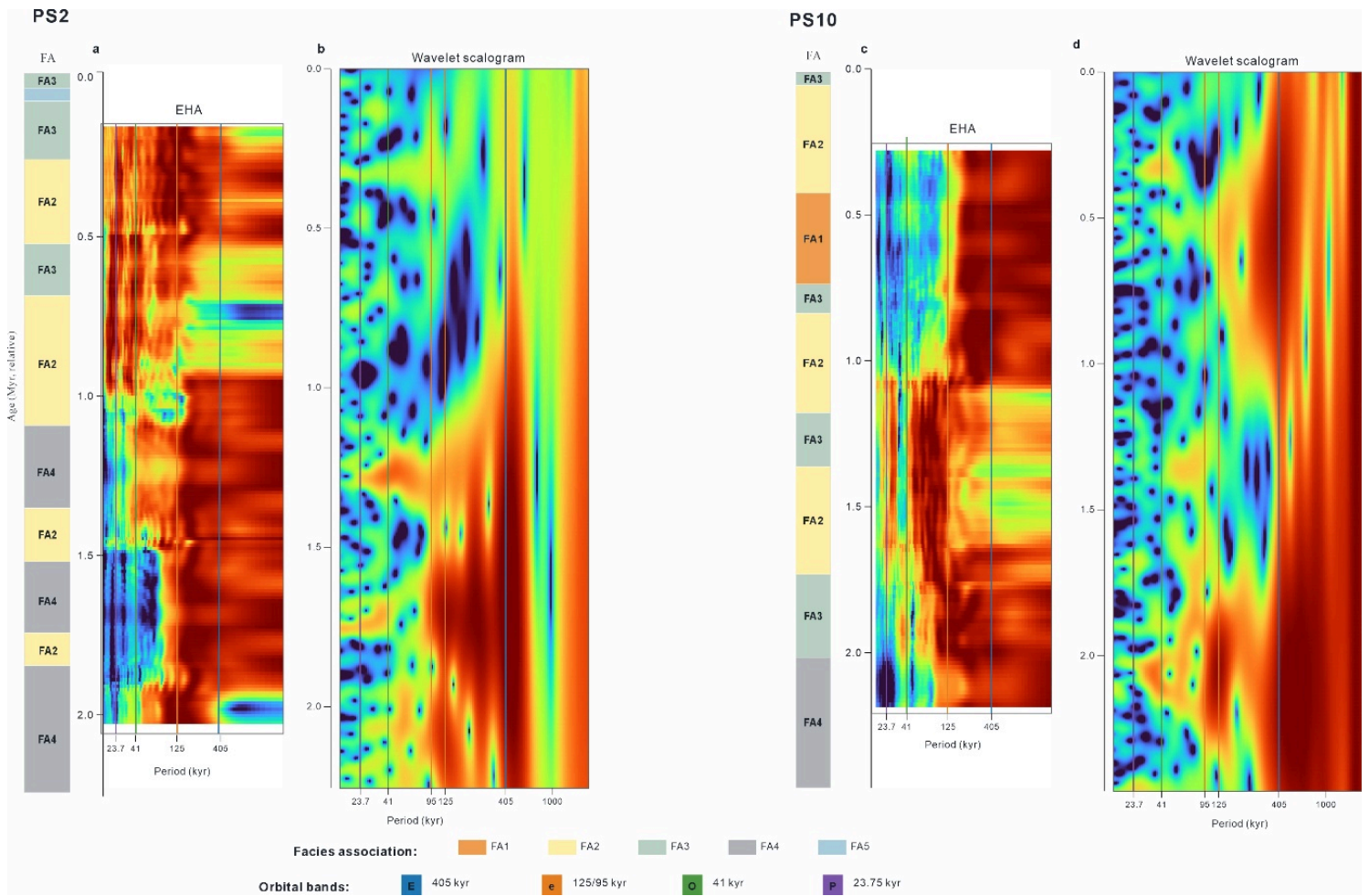


**Figure 5**

Age-domain EHA and wavelet scalograms for PS2 (a, b) and PS10 (c, d). Facies-association successions are shown on the left. Vertical lines indicate the 405-kyr long-eccentricity, 125/95-kyr short-eccentricity, 41-kyr obliquity, and 23.7-kyr precession bands

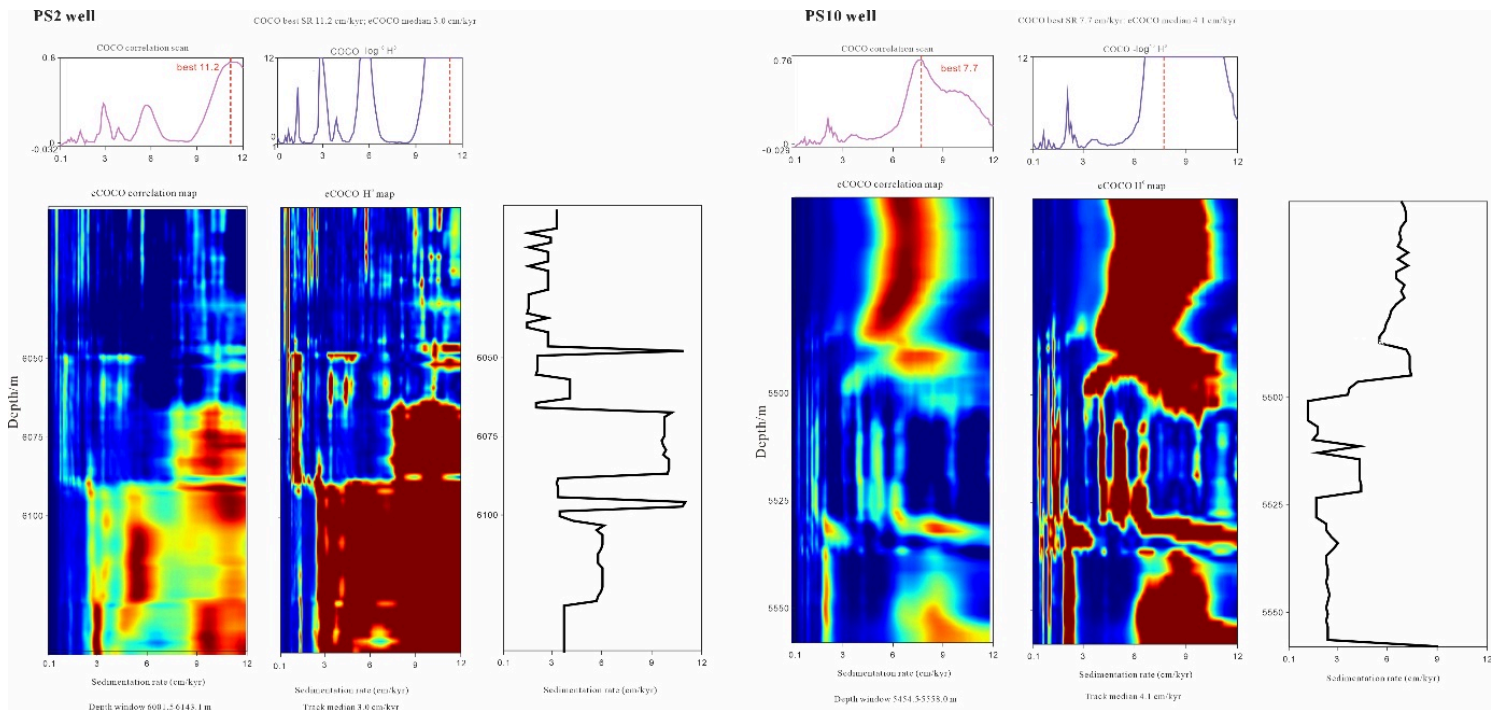


**Figure 6**

COCO/eCOCO sedimentation-rate constraints for PS2 (left) and PS10 (right). The upper panels show whole-interval COCO correlation coefficients and null-hypothesis tests. The lower panels show eCOCO correlation, null-hypothesis probability, and local Best SR trajectories. Optimal COCO rates are 11.2 cm kyr<sup>-1</sup> for PS2 and 7.7 cm kyr<sup>-1</sup> for PS10. Median eCOCO Best SR values are 3.0 and 4.1 cm kyr<sup>-1</sup>, respectively

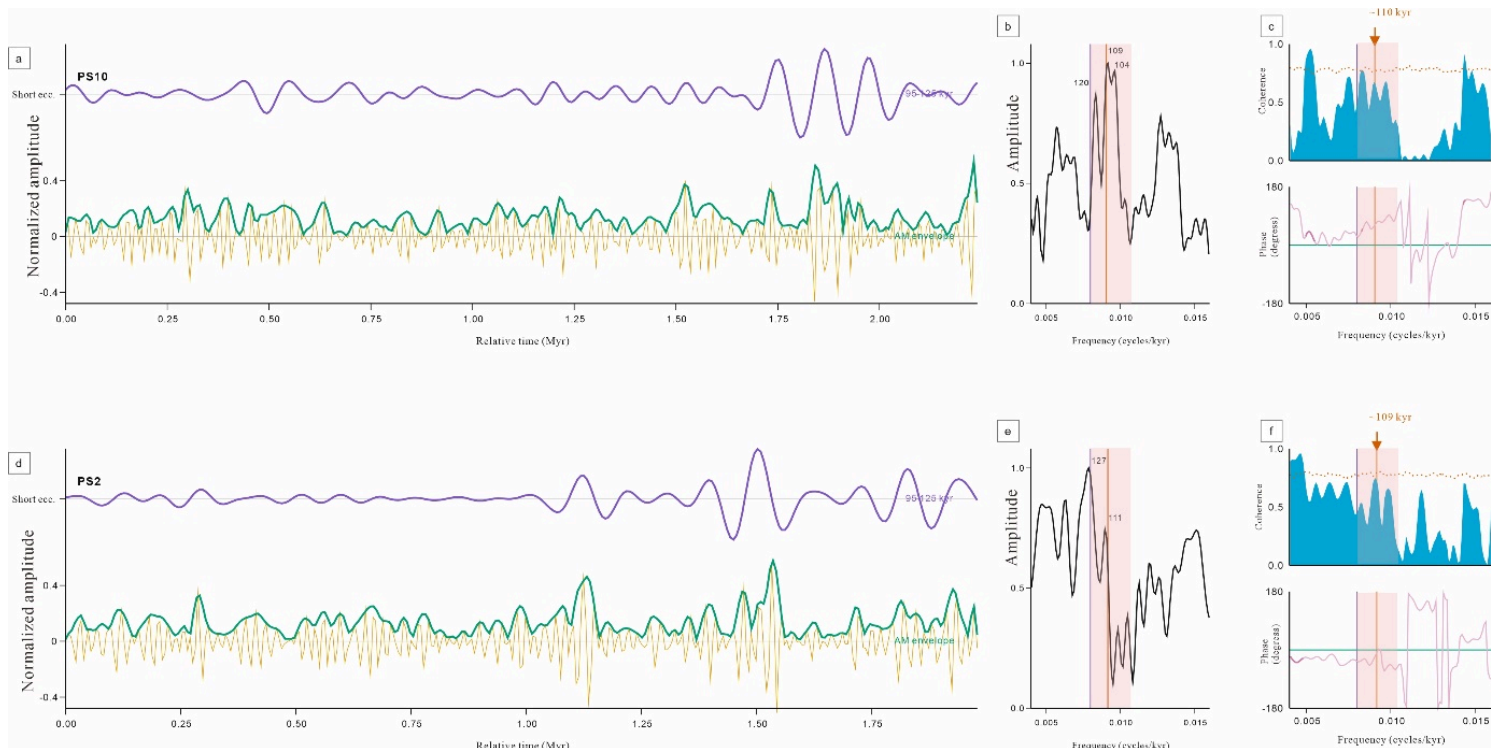


**Figure 7**

Precession amplitude-modulation analysis for PS10 (a–c) and PS2 (d–f). Panels a and d show the 125/95-kyr short-eccentricity and 23.7-kyr precession filters and Hilbert amplitude envelopes. Panels b and e show envelope spectra. Panels c and f show coherence and phase relationships between the envelopes and short-eccentricity components. Shading indicates the principal modulation band near 109–110 kyr

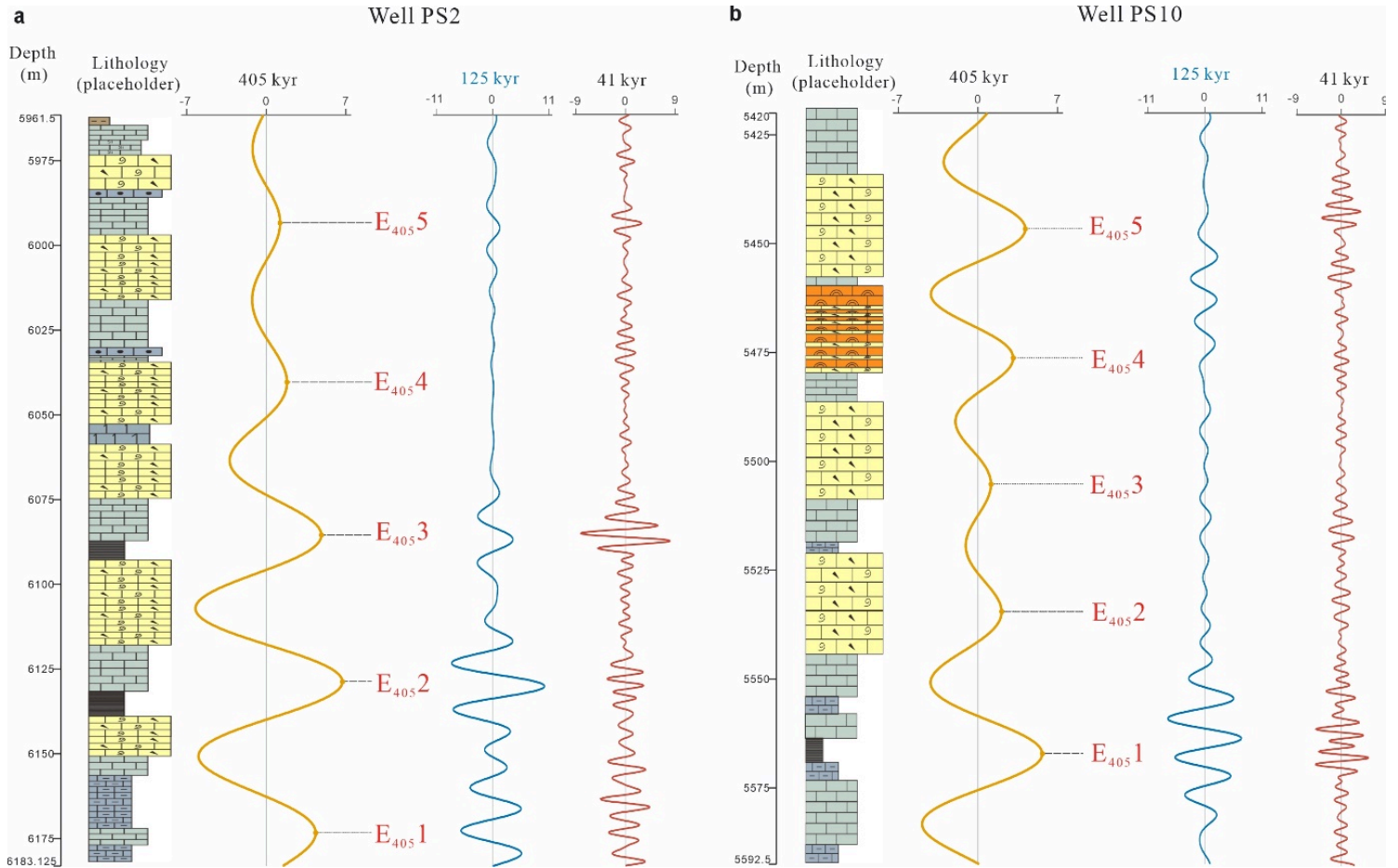


**Figure 8**

Orbital filters and cycle subdivision for the Changxing Formation in PS2 (a) and PS10 (b). From left to right, each panel shows the depth–lithology column and 405-kyr long-eccentricity, 125-kyr short-eccentricity, and 41-kyr obliquity components. E<sub>405</sub>1–E<sub>405</sub>5 denote five long-eccentricity cycle bundles

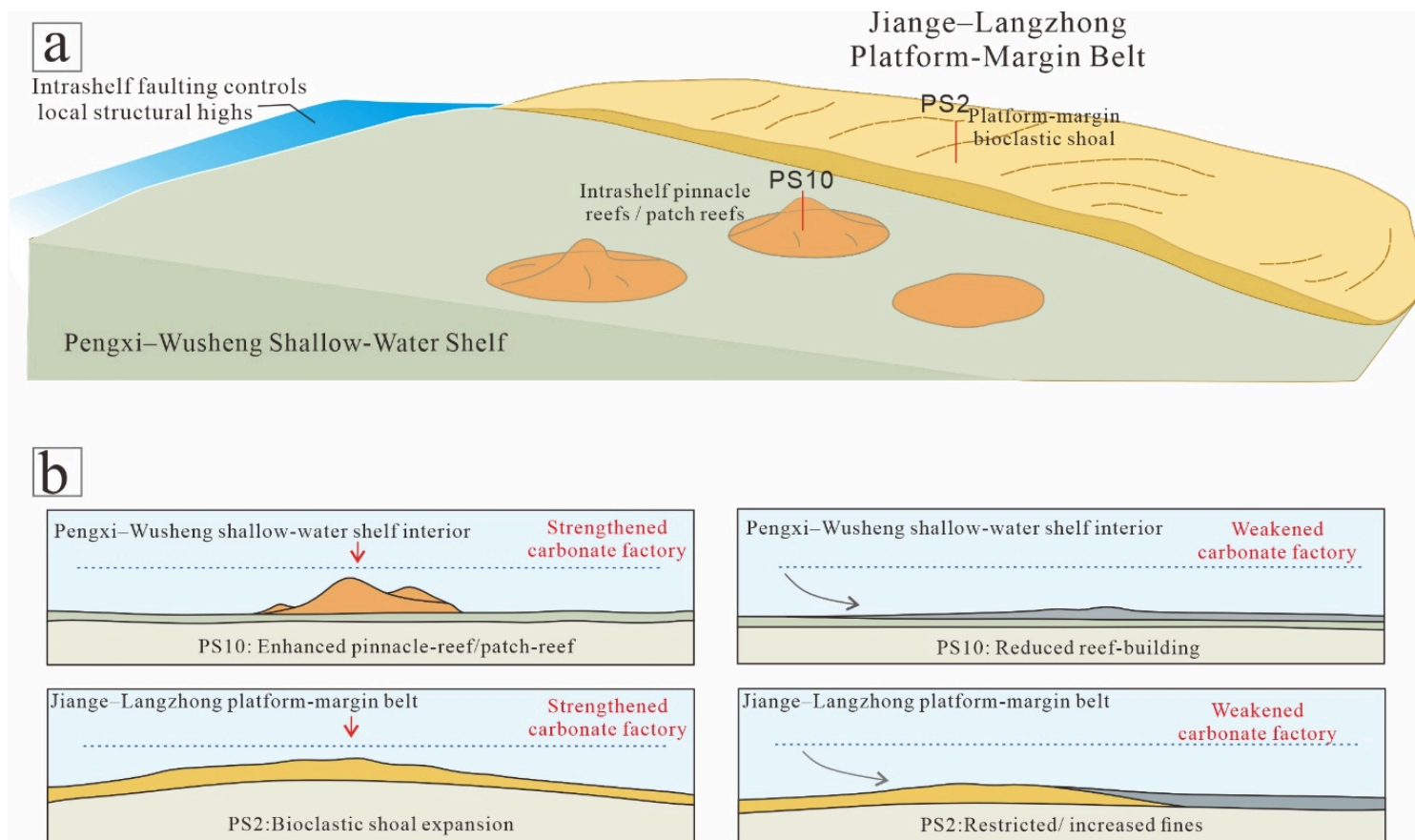


**Figure 9**

Facies-filtering model for the orbital response of Changxing reef-shoal systems. a Paleogeographic configuration of the Pengxi-Wusheng intraplateform high with the multistage grain-shoal-local-reef complex at PS10, and the Jiange-Langzhong platform-margin grain-shoal-intershooal/tidal-flat system at PS2. The fault-controlled local-high element follows regional evidence from the Changxing Formation in the Sichuan Basin (Liu et al. 2024). b Contrasting responses of both facies belts during strengthening and weakening of the carbonate factory

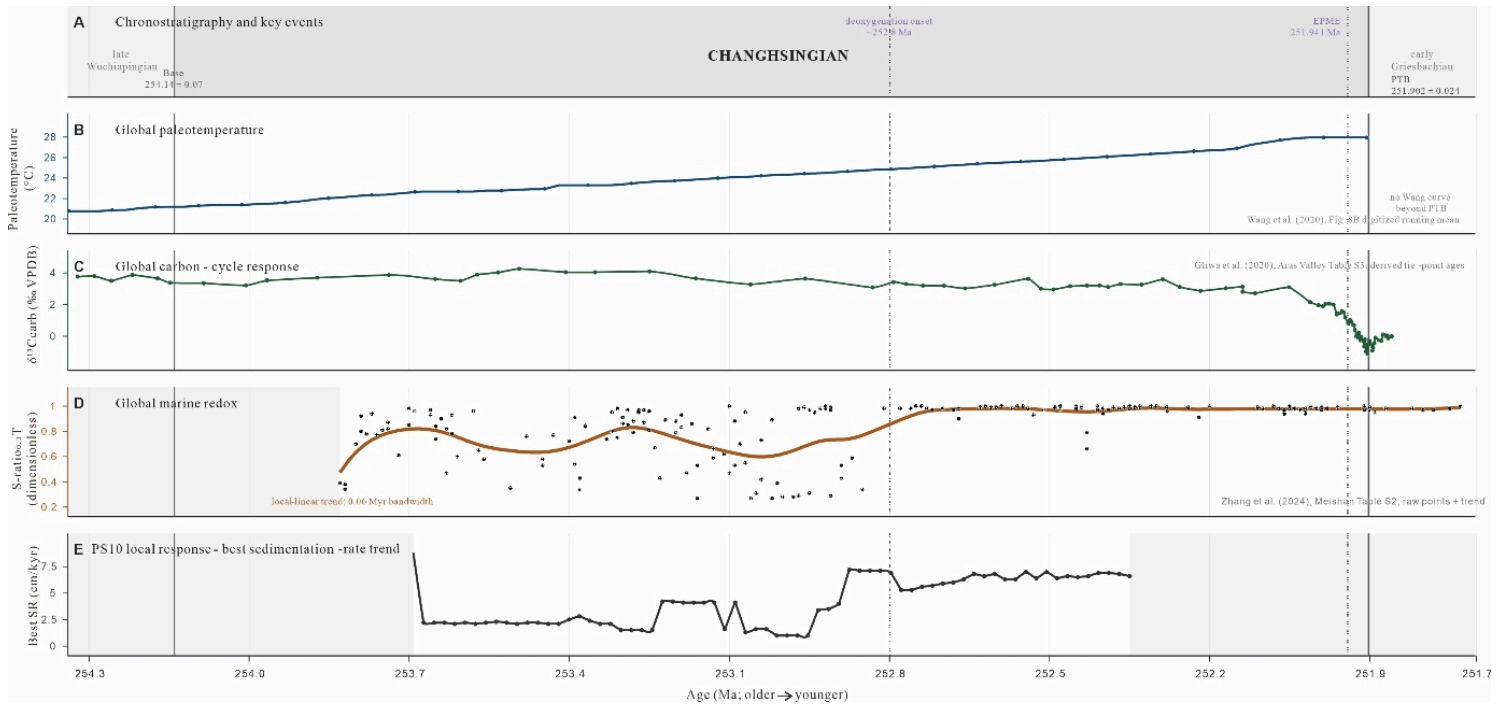


**Figure 10**

Comparison between global environmental transition and the local depositional response of PS10 during the Changhsingian. (A) Chronostratigraphy and key events; (B) global paleotemperature trend (Wang et al. 2020); (C) global  $\delta^{13}\text{C}_{\text{carb}}$  record (Gliwa et al. 2020); (D) global marine redox proxy and trend (Zhang et al. 2024); (E) age-domain eCOCO Best SR trajectory of PS10. Numerical age calibration follows Shen et al. (2011), Burgess et al. (2014), and Yuan et al. (2014). The dashed line marks the onset of marine deoxygenation at ca. 252.8 Ma; dotted and solid lines mark the end-Permian mass extinction and the Permian–Triassic boundary, respectively