

Original Paper

Restoration of karst paleogeomorphology and its natural gas geological implications: An example from the Ma5 member of the Ordovician Majiagou Formation in the central Ordos Basin, NW China

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ABSTRACT

Carbonate weathering crust reservoirs have consistently represented a pivotal area of research in hydrocarbon exploitation. Karst paleogeomorphology emerges from the intricate interplay of weathering, denudation, karstification, and diverse geological conditions. Various landforms significantly influence the distribution of karst reservoirs; thus, reconstructing paleogeomorphology establishes an essential foundation for subsequent investigations into carbonate reservoirs and gas reservoir distributions. A pertinent example is found in the Yan'an area of China, where the paleogeomorphology of the Ordovician Majiagou Formation remains inadequately understood. Based on the sedimentary background and reservoir characteristics, the impression method, residual thickness method and trend surface compensation method are adopted to collaboratively restore the Ordovician paleogeomorphology to elucidate how different landform units affect gas reservoir distribution. The findings indicate that the study area's paleogeomorphology consists of a karst highland in the west, a karst slope in the central, and a karst basin in the east. The paleotopography reveals a tectonic configuration characterized by a steep terrain in the west transitioning to gentler slopes in the east. Additionally, eight third-order paleogeomorphic units were delineated within these second-order units: upland, tableland, hillside, valley, gentle hill, terrace, monadnock, and depression, respectively. Due to various geological processes like denudation and leaching, the influences on physical properties vary markedly across geomorphic units. Notably favorable natural gas accumulation zones include gentle hills on the karst slope, as well as monadnocks within the karst basin alongside both sides of valleys exhibiting pronounced karstification with excellent reservoir qualities. This study may be applied to basins with similar sedimentary backgrounds, by analogy, to more systematically reconstruct the paleogeomorphology and predict the favorable areas for gas accumulation.

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1. Introduction

Paleogeomorphology represents the configuration of landforms that developed in response to specific paleoenvironmental forcing mechanisms (e.g., paleoclimate, tectonic activity, and base

level) during a particular geological period, which are distinct from contemporary geomorphic processes (Valero-Garcés et al., 2014; Yu et al., 2022). These ancient landforms fundamentally control the development and spatial distribution of post-depositional sedimentary facies in basins, while exerting a primary influence on reservoir-caprock configurations in subsequent gas accumulation systems (Rahimpour-Bonab et al., 2010; Jin et al., 2017; Hu et al., 2019). Consequently, reconstructing paleogeomorphic features and deciphering their genetic relationships with hydrocarbon reservoirs are critical for optimizing exploration strategies (Zabidi and De Freitas, 2011). The evolutionary history of

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paleogeomorphology directly impacts reservoir characteristics through multistage weathering-denudation cycles (Beckert et al., 2016). Particularly in carbonate sequences, which exhibit heightened susceptibility to dissolution processes (Lukoczki et al., 2019), these dynamics facilitate the development of karst reservoirs characterized by well-connected pore-fracture-cave systems (Immenhauser and Rameil, 2011; Yan et al., 2024). Given that carbonate reservoirs account for approximately 60% of global hydrocarbon production (Bourdet et al., 2010; Baniak et al., 2013; Anan and Wanas, 2015), they represent a priority target for resource development (Liang et al., 2025).

The restoration of paleogeomorphology and its hydrocarbon reservoir implications have become a focal point in petroleum geology (Arena et al., 2014; Dai et al., 2017). However, the preservation of paleogeomorphology is often compromised by poly-genetic controls, including paleoclimatic fluctuations, tectonic dynamics, and hydrodynamic regimes (Petrash et al., 2017; Rustichelli et al., 2017; Fu et al., 2020), particularly in tectonically uplifted and denudated terranes (Zhang et al., 2024). This inherent complexity has driven the development of diverse reconstruction methodologies (Ronchi et al., 2010). Geochemical proxy methods, such as speleothem $\delta^{13}\text{C}/\delta^{18}\text{O}$ stratigraphy, provide high-resolution records of paleoenvironmental conditions, ideal for identifying marine transgression-regression cycles and subaerial exposure surfaces (Surić et al., 2005). However, their application is generally limited to near-surface processes and they are less effective in deeply buried strata where direct sampling is challenging. Seismic-geophysical techniques, including 3D seismic inversion and residual thickness analysis, offer regional-scale coverage and are powerful for resolving large-scale structural features like karst valleys and basement topography (Geng et al., 2025). A key limitation of these methods is their relatively low vertical resolution (often >35 m), which can obscure finer-scale geomorphic details, and they can be costly to deploy extensively in onshore basins. In contrast, stratigraphy-driven approaches, such as quantifying grainstone accumulations within isochronous frameworks, deliver high accuracy in defining depositional topography and facies distribution (Wang et al., 2025). Their primary constraint is the necessity for dense well control to build reliable models, and they often struggle in terranes with significant post-depositional erosion where stratigraphic continuity is lost (Schmoker and Halley, 1982; Tavakoli, 2021). Numerical surface modeling, like trend surface analysis and machine-learning-enhanced paleotopography, provides efficient spatial interpolation and can identify subtle geomorphic features (Ma et al., 2022; Ye et al., 2023). The trade-off is a tendency to over-smooth high-relief areas, potentially masking critical details, and the models require careful calibration against physical data to avoid artifacts. Critical limitations persist in existing studies: (1) overreliance on single-method approaches without cross-validation using integrated techniques; (2) discrepancies exceeding 12%–15% between seismic-based and stratigraphy-derived reconstructions; (3) insufficient evaluation of paleogeomorphic controls on post-burial diagenesis and hydrocarbon migration pathways.

This study presents an integrated approach to karst paleogeomorphological reconstruction of the weathering crust in the Majiagou Formation (Ordovician) within the Yan'an Gas Field. Addressing the limitations of previous restoration efforts that showed a >15% discrepancy in elevation estimation between stratigraphic and seismic methods, we develop for the first time a multi-method constrained model combining: (1) high-resolution wireline log interpretation (GR/AC/DEN-RT crossover analysis), (2) a revised impression method for denudation surface calibration, and (3) a co-iterative deviation correction based on the least square method. The synthesized reconstruction achieves a <5 m

vertical resolution across 90% of the study area, and the karst geomorphology unit is divided into macro-scale second-order geomorphology and meso-scale third-order geomorphology. Crucially, the established gas reservoir distribution model demonstrates an 83% spatial correlation between paleotopography and proven gas reservoirs, revealing that interconnected fracture-cave systems within lateral valleys function as dominant hydrocarbon migration pathways.

2. Geological setting

Located in the western part of North China Plateau, the Ordos Basin spans an area of approximately $37 \times 10^4 \text{ km}^2$ and is the second largest inland basin in China. It is renowned for its abundant hydrocarbon resources and holds significant potential for exploration (Zou et al., 2013). The basin is characterized by the fastest-growing natural gas reserves and production in China (Zhu et al., 2020). It can be categorized into six tectonic units, including Yimeng Uplift, Western Fault-Folded Zone, Tianhuan Depression, Yishan Slope, Jinxi Folded Zone, and Weibei Uplift, according to the tectonic development characteristics (Zhu et al., 2013). Jingbian stands out as one of the principal gas fields within the Ordos Basin and currently represents China's largest gas field from the Lower Ordovician (Yang et al., 2012). The Yan'an Gas Field, located in the central paleo-uplift zone of the North China Massif, constitutes a significant southward extension of the Jingbian Gas Field (Fig. 1(a)).

During the Ordovician deposition, the entire stratigraphic sequence was uplifted by the Caledonian Orogeny (Zhao et al., 1996); consequently, Silurian, Devonian and Early Carboniferous deposits were absent before re-deposition occurred in the Late Carboniferous (Chen et al., 2018) (Fig. 1(b)). Since the Cretaceous, late tectonic activities such as the Himalayan Orogeny have uplifted the crust, creating the current tectonic pattern of the basin tilting westwards (Fig. 1(c)). In the Middle Ordovician, marine carbonate rocks interbedded with evaporites were deposited under conditions dictated by a regression system (Guo et al., 2012), these rocks are collectively referred to as the Ordovician Majiagou Formation. This formation can be subdivided into six members, designated Ma1 through Ma6, among which Ma5 serves as a primary gas-producing member (Zhang, 2004). Based on lithological characteristics, sedimentary cycles and phase sequence, the Ma5 Member can be further subdivided into ten sub-members, labeled Ma5₁ to Ma5₁₀ (Xie et al., 2020a). The target strata of this study are identified as Ma5₁₊₂ (Fig. 2(a)). The sedimentary environment of the Ma5 Member is a gently sloping evaporative tidal setting, where a variety of dolomite reservoirs have developed (Fig. 2(b)). Weathering and denudation lasted for 120–150 million years, with varying degrees of erosion across different regions (Niu et al., 2019), the tectonic uplift associated with the Caledonian Orogeny established the regional hydraulic gradient, driving focused groundwater flow through developing fracture networks. This process resulted in the formation of a paleokarst landform characterized by buried platforms, monadnocks and valleys distributed under the slope background, laying the foundation for the development of carbonate weathering crust reservoirs (Xiao et al., 2019).

3. Methodology

Based on the stratigraphic development characteristics of the Ordovician Majiagou Formation across different regions, stable sedimentation isochrones were identified within both the overlying and residual strata. Following decompaction correction, the original sediment thickness was restored. A comprehensive analysis was conducted using both impression method and residual

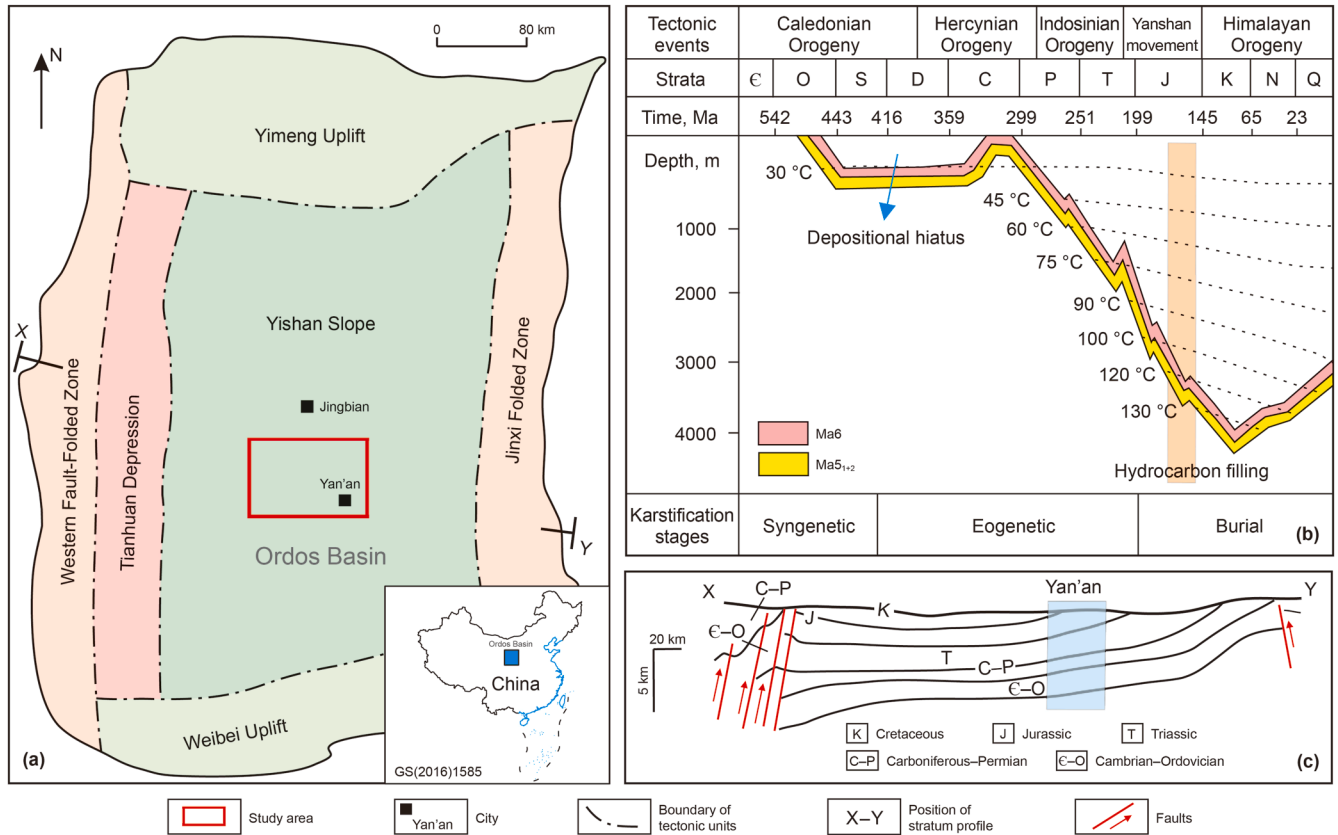


Fig. 1. Location and geological background of the study area. (a) Tectonic units of the Ordos Basin and the location of the Yan'an area; (b) burial history and thermal evolution history of strata; (c) stratigraphic structure along the line X-Y across the study area.

thickness method, supplemented by trend surface compensation to address discrepancies in the restoration processes. This approach aimed to enhance the accuracy of the reconstructed paleotopography of the weathering crust, bringing it closer to actual geological conditions (Fig. 3).

3.1. Impression method

The impression method entails identifying a set of stable and regionally correlated marker layers at the top of the denudation surface within the sedimentary environment, determining stratigraphic thickness from interface to weathering crust, and subsequently reflecting the paleotopographic elevation (Martin, 1966). During burial, tectonic stress exerted by overlying sediments causes clastic particles to become tightly arranged, thereby reducing porosity and leading to volume shrinkage and formation thickness reduction. Consequently, it is essential to decompact the formation below the base level and above the weathering crust interface. The formation volume consists of skeleton volume and pore volume. During mechanical compaction, skeleton volume remains essentially constant, while pore volume decreases with increasing burial depth (Fig. 4; Equations (1)–(3)).

According to the compaction principle, assuming that the porosity of the stratum at buried depth Z is $\varphi(Z)$, with original top and bottom depths Z_1 and Z_2 respectively, the skeleton thickness H can be expressed as:

$$H = \int_{Z_1}^{Z_2} [1 - \varphi(z)] dz \quad (1)$$

Since the volume of stratum skeleton is basically constant, the formula is:

$$\int_{Z_1}^{Z_2} [1 - \varphi(z)] dz = \int_{Z_3}^{Z_4} [1 - \varphi(z)] dz \quad (2)$$

During initial compaction process, porosity is inversely proportional to burial depth. Assuming an initial deposition thickness is h , then there is:

$$\int_{Z_1}^{Z_2} [1 - \varphi(z)] dz = \int_0^h [1 - \varphi(z)] dz \quad (3)$$

This study employs a lithology-specific porosity conversion model to reconstruct sedimentary thickness. Compaction-induced thickness reduction primarily results from progressive pore volume loss. Based on porosity–depth relationships in the central basin, the empirical formulas of various porosity changes with buried depth are shown in Fig. 5, and expressed as Equation (4).

$$\varphi(z) = ae^{cz} \quad (4)$$

where φ is the porosity of a certain depth, %; z is the burial depth, m; a and c are constants and have no dimension.

Based on the porosity conversion model, the restoration thickness h of different lithologies is calculated as:

$$h = \frac{(1 - \varphi) \cdot h_0}{1 - \varphi_0} \quad (5)$$

$$\lambda = \frac{h_0}{h} = \frac{1 - \varphi}{1 - \varphi_0} \quad (6)$$

φ_0 is the original porosity of sediment, and the parameter obtained by experimental simulation (Xu et al., 2018); λ is the

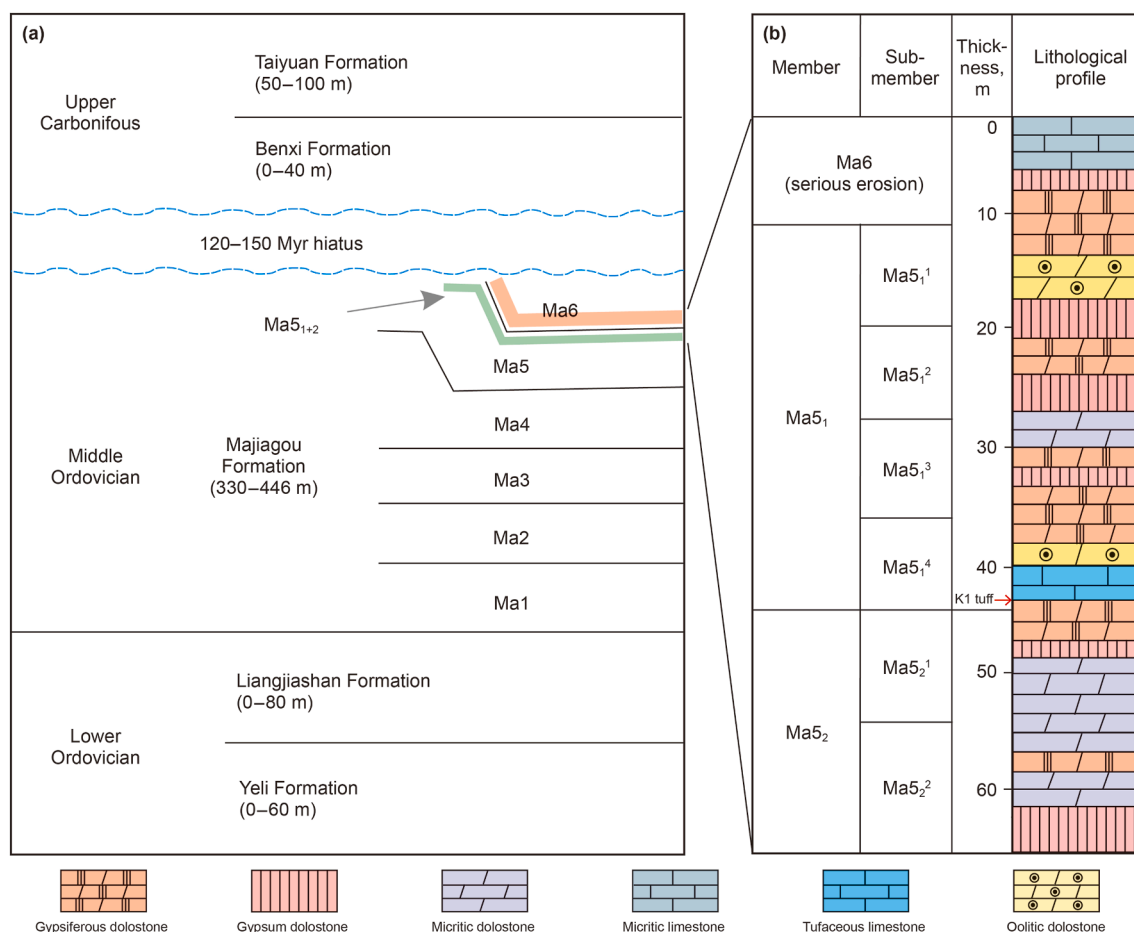


Fig. 2. Stratigraphic development in the study area. **(a)** the stratigraphic development framework of the Ordovician; **(b)** a generalized lithological column of the Ma5_{1+2} and Ma6 members.

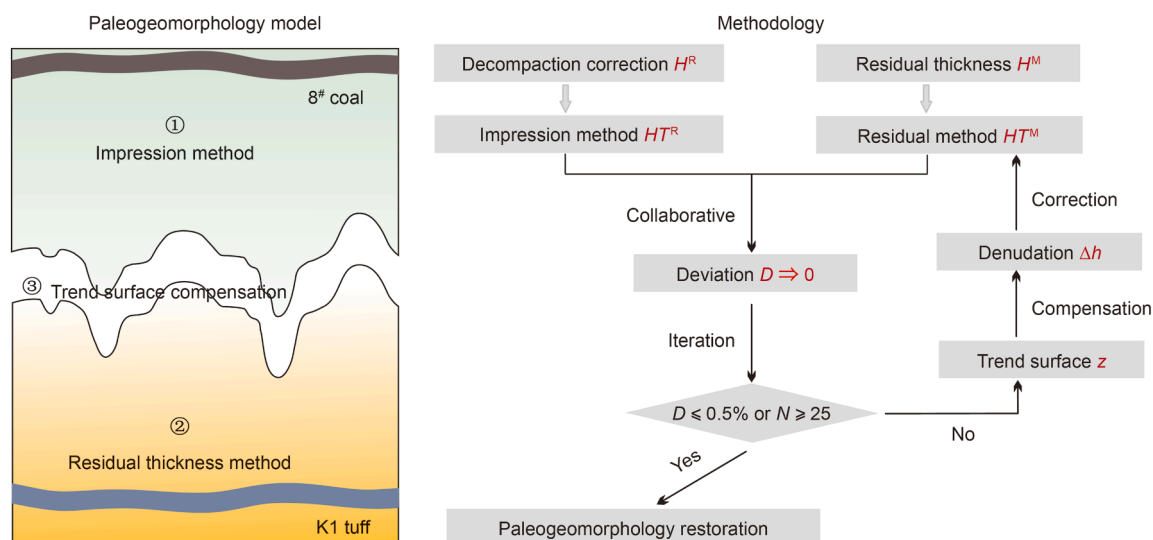


Fig. 3. Methods and processes of paleogeomorphology restoration. H^R represents the original thickness of overlying strata, H^M is the thickness of residual strata, HT^R is the paleogeomorphology elevation restored by impression method, HT^M is the paleogeomorphology elevation restored by residual method, D is the deviation value, Δh is the denudation thickness, and z is the trend surface.

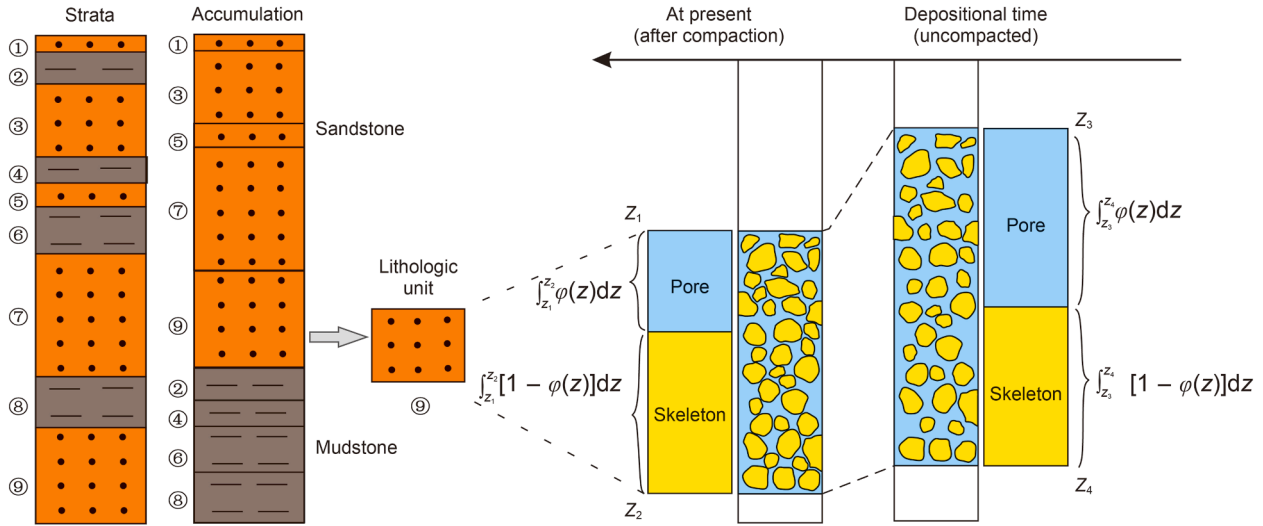


Fig. 4. Schematic diagram of decompaction correction principle.

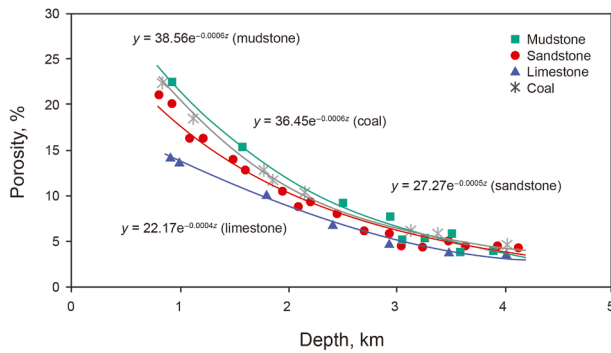


Fig. 5. Relationship between lithologic porosity and buried depth in the central Ordos Basin (Lin et al., 2020).

compaction coefficient and h_0 is the present thickness of a particular lithology.

$$h = \frac{(1 - ae^{cz}) \cdot h_0}{1 - \phi_0} \quad (7)$$

h is the monolayer restoration thickness of a certain lithology, and the whole formation restoration thickness H can be expressed as:

$$H = \sum_{i=1}^4 \sum_{j=1}^n h_{ij} \quad (8)$$

h_{ij} is the recovery thickness of a monolayer with a certain lithology, $i = 1, 2, 3, 4$ represents different lithology, $j = 1, 2, 3 \dots n$ represents the number of layers developed by the lithology. After accumulation, the restored thickness of the overlying strata can be obtained, and the paleogeomorphic features can be reflected by the impression method.

3.2. Residual thickness method

The residual thickness method is a technique based on sedimentological and geomorphological principles, designed to reconstruct paleolandforms by assessing the discrepancy between the original thickness of strata and the present-day thickness of sediments. Initially, the thickness of the present sedimentary layer

is obtained through high-resolution wireline logging, while the total thickness of the original sedimentary layer is retrieved by stratigraphic analysis. Subsequently, karst erosion is quantified by calculating the difference in thickness between the modern stratum and the original stratum. Based on the spatial distribution of erosion amount, the paleogeomorphology in geological history can be reconstructed. This methodology presupposes spatially uniform erosional intensity under equivalent paleoelevation gradients during discrete geological intervals, allowing inversion of paleotopographic relief variations through quantitative denudation analysis.

3.3. Trend surface compensation method

Trend surface analysis, in essence, utilizes the principles of regression analysis, employing the least squares method to fit a two-dimensional function. This approach aims to simulate spatial variation trends associated with geological features. Moreover, this methodology effectively describes characteristics of paleotopography within stratigraphic space (Ma et al., 2022). Trend surface analysis comprises two main components: the trend surface itself and its residuals. The trend surface encapsulates broad, large-scale variations across the region, whereas the residuals, defined as discrepancies between measured values and those predicted by the trend surface, emphasize the local, microscale variations (Fig. 6).

For the paleogeomorphic reconstruction model, this study considers control well coordinates (x_i, y_i) as independent variables and the karst denudation measurements $z_i(x_i, y_i)$ ($i = 1, 2, \dots, n$) as dependent variable. The geomorphic fitting value is represented as $z'_i(x_i, y_i)$, and ε_i is the residual. The essence to trend surface compensation method relies on deducting the erosion surface from the measured value and adopting regression analysis to minimize the residual sum of squares Q , which is expressed as:

$$z_i(x_i, y_i) = z'_i(x_i, y_i) + \varepsilon_i \quad (9)$$

$$Q = \sum_{i=0}^n \varepsilon_i^2 = \sum_{i=0}^n [z_i(x_i, y_i) - z'_i(x_i, y_i)]^2 \rightarrow \min \quad (10)$$

$z_i(x_i, y_i)$ is the measured value of denudation, m ; $z'_i(x_i, y_i)$ is the geomorphic trend fitting value, m ; x_i and y_i adopt control

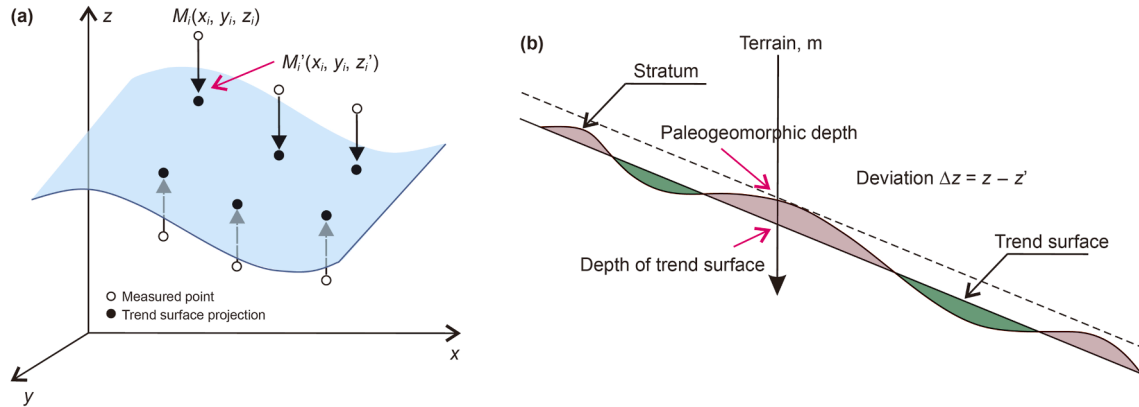


Fig. 6. (a) Principle of trend surface compensation method; (b) Calculation of karst denudation.

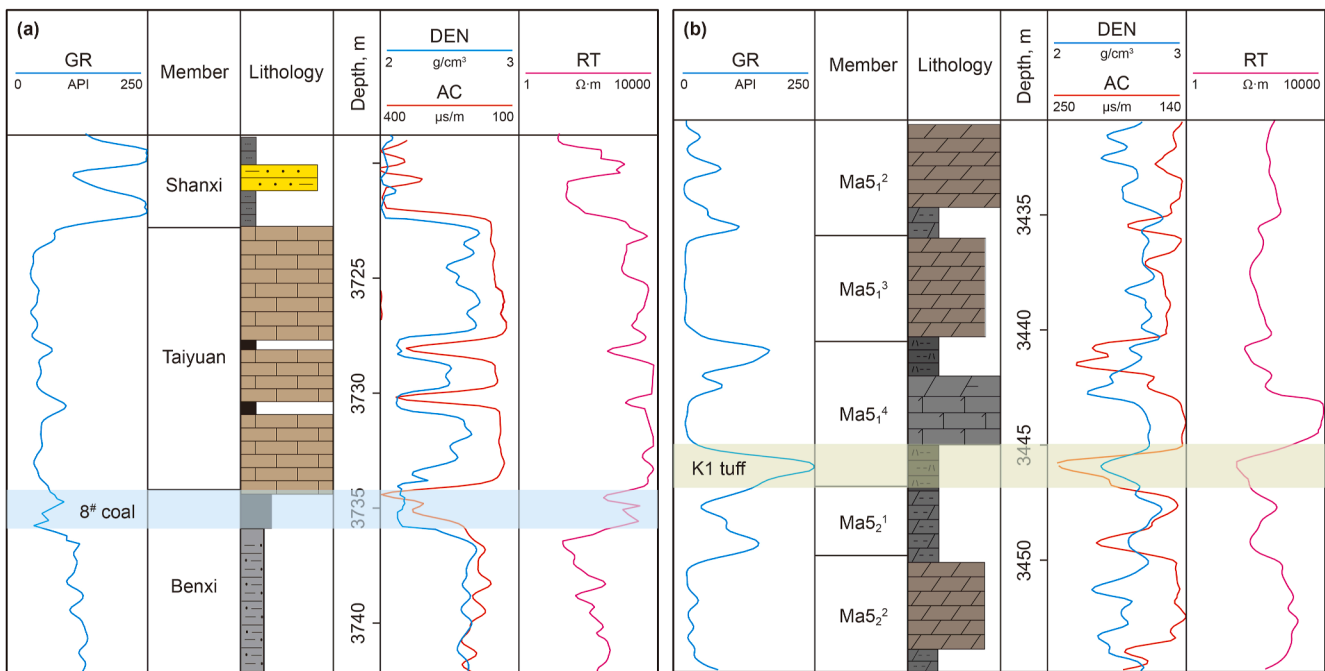


Fig. 7. Logging response characteristics of coal and tuff. (a) Benxi Formation 8[#] coal seam (Well Y23), (b) K1 tuff at the bottom of Ma5₁⁴ (Well Y33).

well coordinates; ε_i is a residual, m ; Q is the sum of squares of residuals, m^2 .

In the process of reconstructing paleotopography, multiple candidate models are typically established, and correlation tests are conducted using coefficients of fit. This process involves several aspects, including R^2 (coefficient of determination) testing, significance F -testing, and stepwise regression analysis. Ultimately, the formula with the highest correlation is selected as the trend surface model (Mongelli et al., 2016).

4. Results and discussion

4.1. Paleotopographic elevation

The overlying strata adjacent to the weathering crust comprise a set of coal-bearing clastic rocks from the Benxi Formation, characterized by transitional facies characteristics. These clastic rocks exhibit a complementary relationship with the pre-Carboniferous erosion surface, featuring stable deposition and

extensive lateral continuity. This suggests that the Ordovician karst unconformity was completely overlain by Carboniferous strata, resulting in the infilling of landforms during the late stage of Carboniferous deposition, consequently, low-lying areas typically exhibit thicker deposits while high terrain regions show thinner accumulations. In this study, the No. 8 coal seam (8[#] coal) at the top of Benxi Formation is selected as the base level, this set of coal seams demonstrates stable regional distribution and can be regarded as an isochronous interface. The logging electrical properties are characterized by low gamma (GR), high acoustic time difference (AC), low density (DEN), and high resistance (LLD) (Fig. 7(a) and 8). The stratigraphic interval spanning from the coal seam to the weathering crust can reflect the karst denudation intensity and paleotopographic elevation through decompaction-corrected original thickness restoration.

Utilizing the paleogeomorphic restoration by the impression method, this study systematically identified and quantified the thickness of diverse lithologies (sandstone, mudstone and limestone) ranging from the weathering crust to the 8[#] coal seam, and

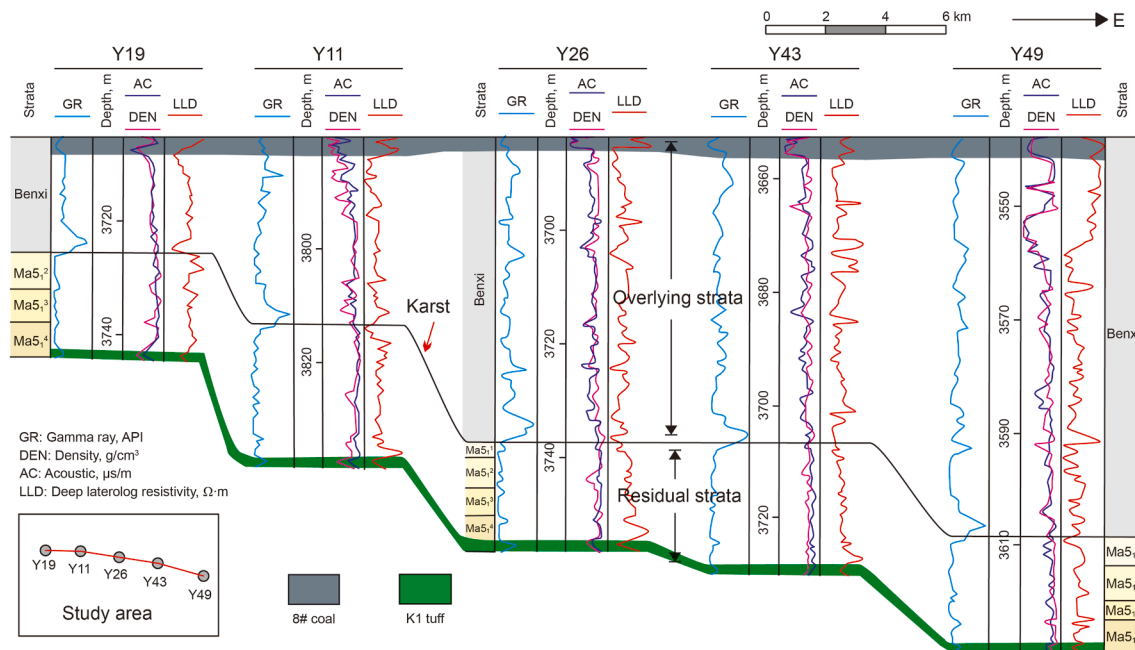


Fig. 8. The well connection section between the upper and the lower marker layer.

the original formation thickness of Benxi Formation was restored after decompaction correction (Table 1). The thickness of the overlying strata ranges from 0 to 120 m, with notably thinner deposits in western regions while significantly thicker deposits in eastern areas. The elevation of paleogeomorphy was restored by means of impression method (i.e., compensating reflect principle). Note that the result of restoration here is the paleogeomorphic elevation of the underlying Ordovician strata at the beginning of the Carboniferous deposition, rather than the residual thickness of the Majiagou Formation. Consequently, according to the classification standard of karst paleogeomorphology by impression method, with the overlying original strata thicknesses of 50 m and 90 m as the demarcation values, the paleogeomorphology is categorized into karst highland, karst slope and karst basin (Fig. 9).

4.2. Distribution of residual strata

The residual thickness method involves the selection of an isochronous, regionally comparable key bed within the underlying

strata of unconformity and flattening it (Xie et al., 2020b). The magnitude of the residual thickness between this key bed and the unconformity represents the morphology of paleogeomorphology. The bottom of the volcanic ash-fall type vitric dusty tuff (K1) at the bottom of Ma5₁, which contains crystal flakes and stone flakes, is utilized as the key bed for strata correlation to compile the karst paleogeomorphology map. Firstly, K1 tuff is isochronous, stable in thickness, and covers a large area of the Ordos Basin, making it traceable and comparable throughout the region. Electrically, it is distinguished by high gamma, high acoustic velocity, low density, and low resistivity (Morgan et al., 2019; Piper and Pe-Piper, 2020), forming a prominent “anomaly bed” on the logging curve (Fig. 7(b)). These features render it highly recognizable and suitable as an ideal key bed for map compilation.

According to the irreversibility of burial compaction and the duration of exposure to weathering, the thickness of Benxi Formation at the selected base level was less than the pre-uplift burial depth, so the distance from the weathering crust to the base level—the K1 tuff—was identified (Fig. 10). In the western

Table 1
Comparison of formation thickness before and after decompaction correction in Benxi Formation.

Area	Well	Sandstone thickness, m	Mudstone thickness, m	Limestone thickness, m	Coal thickness, m	Present thickness, m	Restoration thickness, m
Western high terrain region	Y15	3.1	8.7	2.3	2.9	17.0	27.5
	Y16	4.9	10.1	3.6	3.7	22.3	35.1
	Y18	8.6	9.7	2.9	3.8	25.0	39.4
	Y19	8.4	10.3	3.7	2.9	25.3	41.8
	Y21	11.6	7.6	8.2	5.3	32.7	47.2
Central gentle terrain region	Y20	9.1	12.8	5.3	5.3	32.5	52.7
	Y24	7.3	17.9	1.8	6.8	33.8	58.3
	Y32	9.7	19.2	7.7	6.6	43.2	68.6
	Y40	4.6	23.8	5.5	5.8	39.7	72.8
	Y44	12.7	26.2	6.2	6.2	51.3	83.1
Eastern lower topographic region	Y50	4.7	39.1	3.1	5.8	52.7	95.3
	Y51	12.2	33.5	6.5	4.9	51.7	92.5
	Y47	20.9	25.2	7.0	7.1	60.2	90.4
	Y48	4.8	41.7	3.1	6.7	56.3	98.8
	Y49	11.2	39.1	4.9	8.3	63.5	103.1

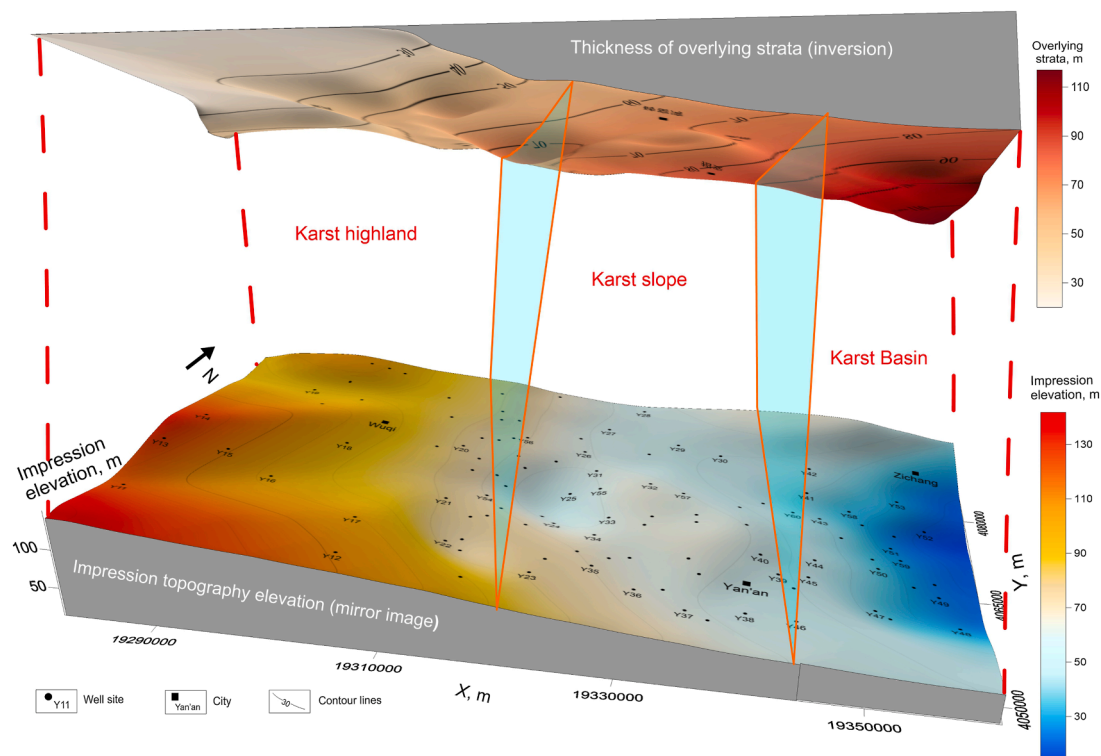


Fig. 9. Overlying strata thickness and its restored impression of topographic elevation.

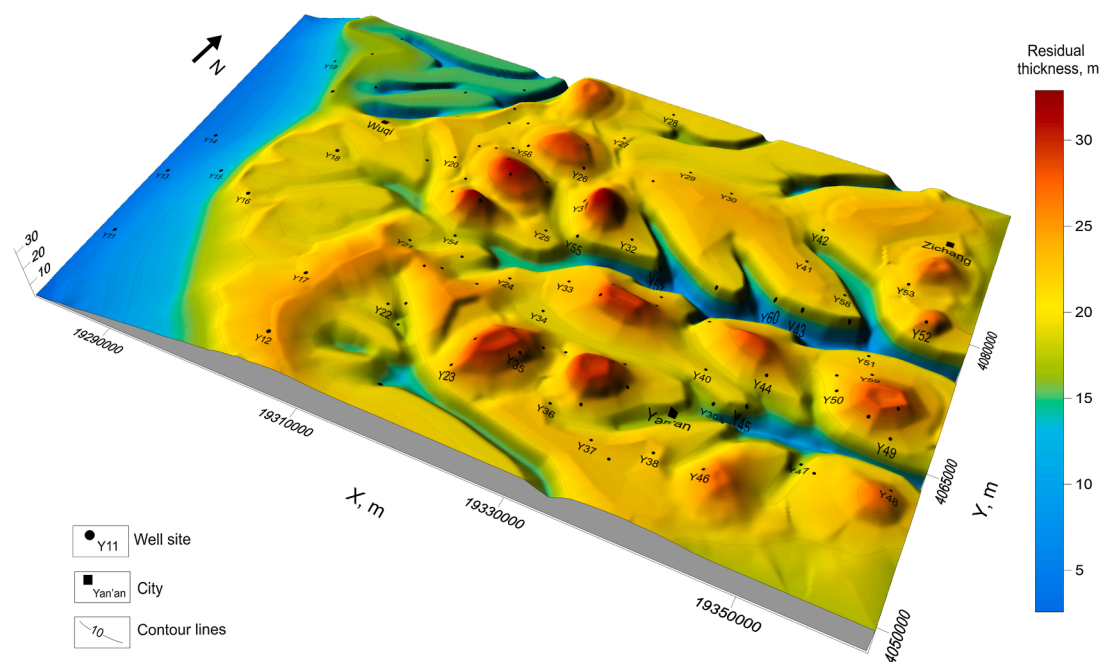


Fig. 10. 3D map of residual thickness (weathering crust to the tuff bed at the bottom of Ma5₁) in the study area.

part of the study area, the distribution of residual thickness was notably thin, ranging from 5 m to 15 m. Conversely, in the central region, it was thicker, with values between 25 m and 35 m, while in the eastern part, it measured between 10 m and 20 m. This resulted in a west-to-east trend characterized by a “thin-thick-thin” distribution pattern. The western area exhibits

significant denudation, indicative of high paleotopography, whereas the central region displays substantial residual thickness and better stratigraphic preservation, reflecting relatively flat terrain. In contrast, the eastern area demonstrates low paleotopography due to valley erosion, leading to thinner residual thicknesses.

4.3. Collaborative iteration of reconstruction accuracy

Theoretically, the paleogeomorphic elevation recovered via impression method and residual thickness method should maintain correspondence and compensate each other. The correlation coefficient approaching -1 , indicating a negative correlation between these two methodologies.

In this study, the least squares method was applied to fit the trend surface equation, and to derive the equations for the first-order linear trend surface z_{11} , the first-order bilinear trend surface z_{12} and the quadratic trend surface z_2 :

$$z_{11} = 31245 + (-9.37 \times 10^{-4})x + (1.18 \times 10^{-4})y \quad (11)$$

$$z_{12} = 0.837 - 7.65x + 1.24y + (3.17 \times 10^{-4})xy \quad (12)$$

$$z_2 = 3104 - 0.196x - 0.135y + 2.7 \times 10^{-8}x^2 + 1.3 \times 10^{-8}xy - 1.6 \times 10^{-8}y^2 \quad (13)$$

z_{11} , z_{12} and z_2 respectively represent the trend fitting values of the paleogeomorphic elevation model, m. After correlation test, the results of R^2 test and successive test of the quadratic trend surface z_2 show a better fit, and the results of the F -test for significance are significant.

$$\Delta z = z - z_i' \quad (14)$$

$$\Delta h = z_i' - d \quad (15)$$

where z is paleogeomorphic depth, m; z_i' is the trend surface depth, Δz is the calculated deviation value, d is the residual thickness of weathering crust, Δh is the amount of denudation.

Within the western karst highland where erosion is pronounced—exceeding 12.0 m—the overall denudation within central areas remains weak at under 8.0 m. Strong erosion exceeding this threshold also characterizes eastern regions, and it follows a banded distribution pattern instead. From west to east across these areas lies an observable “strong-weak-strong” trend regarding denudation amounts (Fig. 11).

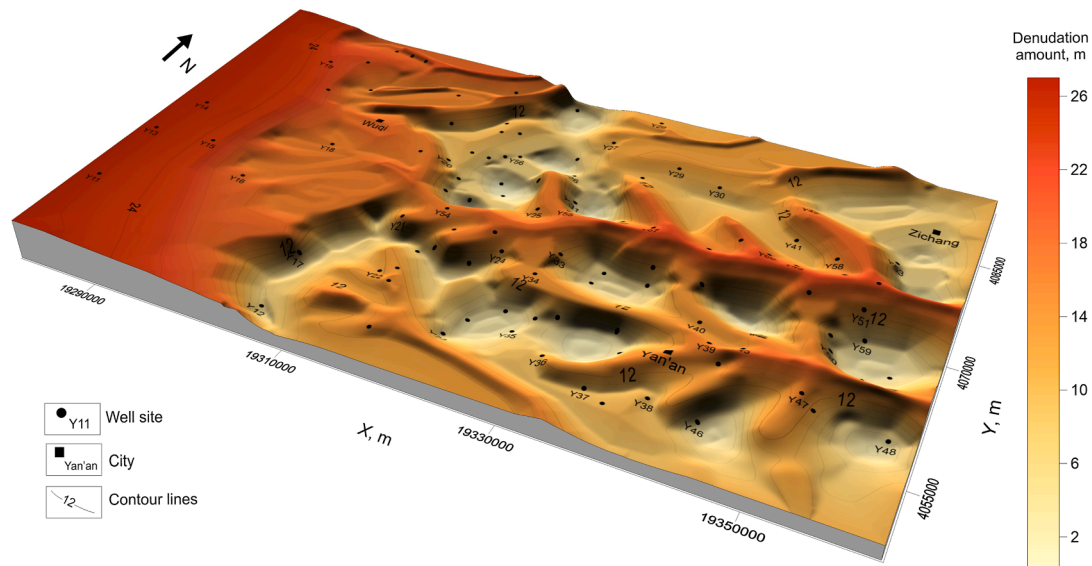


Fig. 11. Amount of karst denudation of the weathering crust in Majiagou Formation.

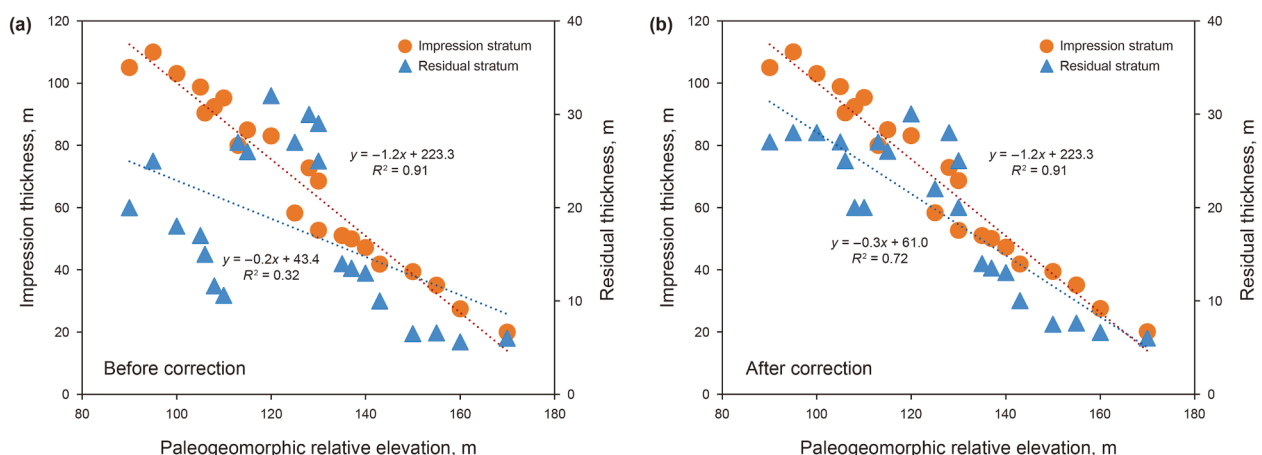


Fig. 12. Paleogeomorphic changes reflected before (a) and after (b) deviation correction.

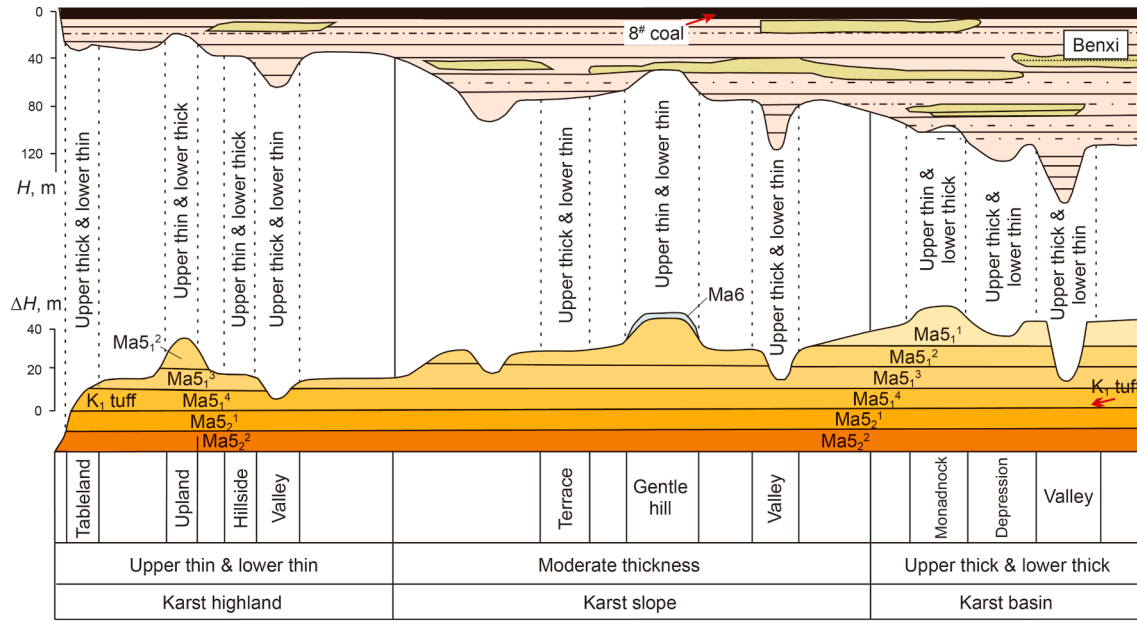


Fig. 13. Relationship map of residual thickness between the paleogeomorphic weathering crusts of the upper and lower key beds (modified from Yao et al., 2015).

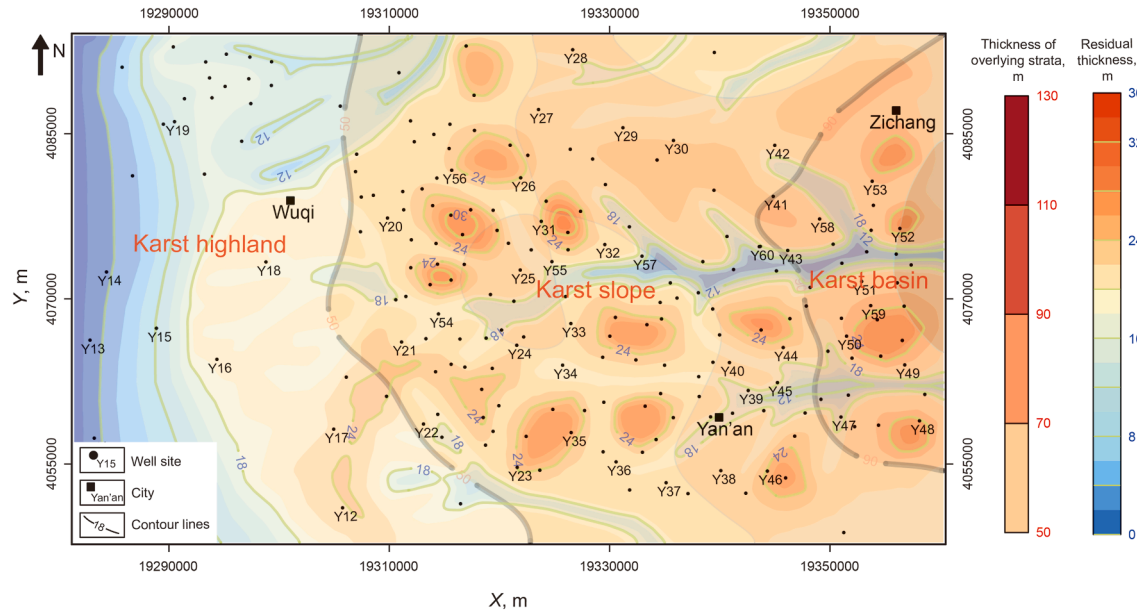


Fig. 14. Superposition map of the overlying and the residual stratigraphic thickness (black contour line is the thickness of the overlying strata, and green contour line is the thickness of the residual strata).

Suppose that there are N wells used for paleogeomorphology reconstruction, original and residual thickness of the i -th well are H_i^R and H_i^M , respectively. The paleogeomorphic magnitude restored by impression method is:

$$HT_i^R = \frac{H_i^R - \min_j H_j^R}{\max_j H_j^R - \min_j H_j^R} \quad (16)$$

The paleogeomorphic amplitude recovered by residual thickness method is as follows:

$$HT_i^M = \frac{H_i^M - \min_j H_j^M}{\max_j H_j^M - \min_j H_j^M} \quad (17)$$

The deviation D between the two is:

$$D = \sum_{i=1}^N (HT_i^R - HT_i^M)^2 \Rightarrow 0 \quad (18)$$

It should be emphasized that the selected isochronal marker bed is not completely isopachous, thus D rarely approaches zero

Table 2
Classification criteria for the second- and third-order paleogeomorphology units of the Ordovician weathering crust in the Yan'an area. *H*: thickness of the upper strata.

Second-order geomorphic units	Third-order geomorphic units	Strata thickness	Residual thickness ΔH , m	Amount of denudation Δh , m
Karst highland ($H < 50$ m) Upper thin & lower thin	Upland ($H < 20$ m)	Upper thin & lower thick	$\Delta H < 10$ m	$\Delta h > 16$ m
	Tableland ($H < 30$ m)	Upper thin & lower thick	$10 \text{ m} < \Delta H < 20$ m	$\Delta h > 12$ m
	Hillside ($H > 30$ m)	Upper thick & lower thin	$\Delta H > 20$ m	$\Delta h > 8$ m
Karst slope ($50 \text{ m} < H < 90$ m) Moderate thickness	Gentle hill ($H < 65$ m)	Upper thin & lower thick	$\Delta H > 25$ m	$\Delta h < 4$ m
	Terrace ($H > 70$ m)	Upper thick & lower thin	$10 \text{ m} < \Delta H < 25$ m	$\Delta h < 6$ m
	Valley ($H > 80$ m)	Upper thick & lower thin	$\Delta H < 15$ m	$\Delta h > 8$ m
Karst basin ($H > 90$ m) Upper thick & lower thin	Monadnock ($H < 95$ m)	Upper thin & lower thick	$\Delta H > 20$ m	$\Delta h < 6$ m
	Depression ($H > 100$ m)	Upper thick & lower thin	$15 \text{ m} < \Delta H < 25$ m	$\Delta h < 8$ m
	Valley ($H > 110$ m)	Upper thick & lower thin	$\Delta H < 20$ m	$\Delta h > 12$ m

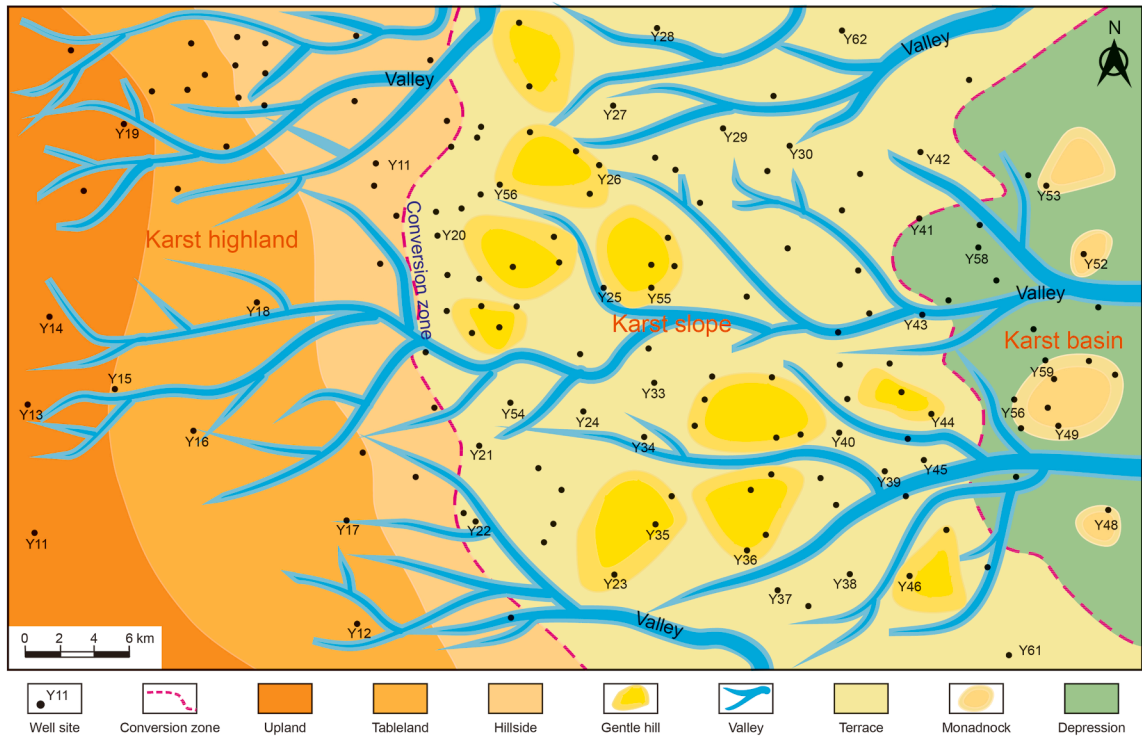


Fig. 15. 2D distribution characteristics of Ordovician karst paleogeomorphology in Yan'an area.

but rather converges towards a reasonable error (Wang et al., 2022). Consequently, adjustments can be made on residual thickness based on karst denudation amount, ensuring consistency between paleogeomorphology derived through the impression method and that utilizing the residual method.

The relationship between H_i^R , H_i^M and the denudation amount Δh can be expressed as:

$$H_i^R = B \times H_i^M + A \sum_{j=1}^N (HT_j^R + \Delta h) \tag{19}$$

where A is the isochronous reference plane deviation; B is the coefficient, approaching -1 .

Under identical constraints applied jointly, the impression thickness and residual thickness are applied to restore the paleogeomorphology, which minimizes discrepancies arising from epigenetic geomorphology, provides a compensation mechanism for the residual thickness method, and makes the results recovered by the two methods as consistent as possible. The comparison indicates a linear correlation between the two variables following

deviation correction. The methodology employed in this study effectively addresses the interphase discrepancies inherent in traditional paleogeomorphic restoration. Compared with a single method, the reconstruction accuracy, expressed as Equation (20), increases by 23.3% (Fig. 12).

$$\Delta R_N^2 = \frac{R_B^2 - R_A^2}{1 + R_B^2} \times 100\% \tag{20}$$

where ΔR_N^2 is the proportion of the normalized accuracy improvement; R_B^2 is the value after deviation correction, $R^2 = 0.72$; R_A^2 is the value before deviation correction, $R^2 = 0.32$.

4.4. Division of paleogeomorphology units

From the perspective of tectonic uplift and sedimentary evolution, the Ordovician paleogeomorphology exhibits a negative correlation with the degree of weathering crust infill, while demonstrating a positive correlation with denudation intensity.

Specifically, in regions where paleogeomorphology is relatively elevated, denudation is pronounced and infill strata are thin; conversely, in areas characterized by lower paleogeomorphology, denudation is minimal and infill strata are more substantial (Fig. 13).

The impression method effectively reflects the paleotopographic elevation of the underlying Majiagou Formation but does

not accurately delineate third-order microgeomorphic units. While residual thickness can indicate slight paleotopographic fluctuation, it fails to represent the general paleotopographic trend. In this study, both the impression method and the residual thickness method are employed synergistically to precisely characterize the distribution pattern of paleogeomorphology associated with weathering crusts based on a “thin-thick combination

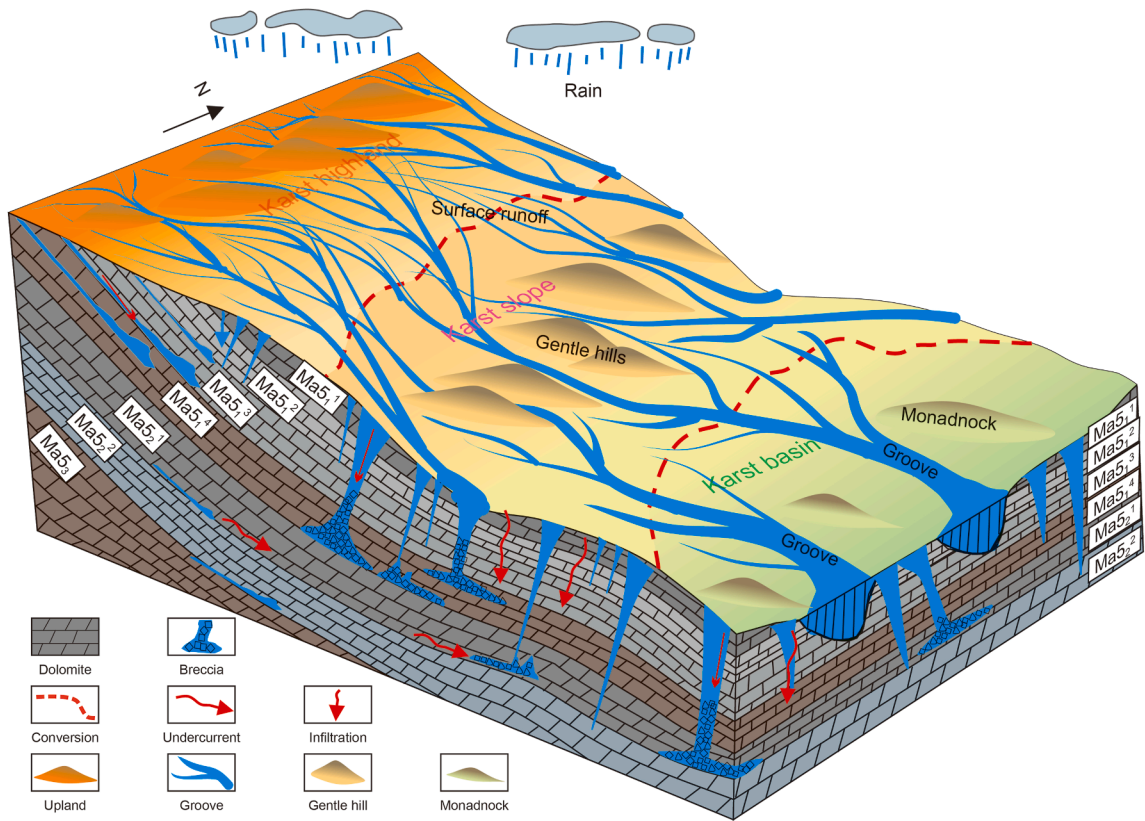


Fig. 16. 3D restoration map of Ordovician karst paleogeomorphology in Yan'an area.

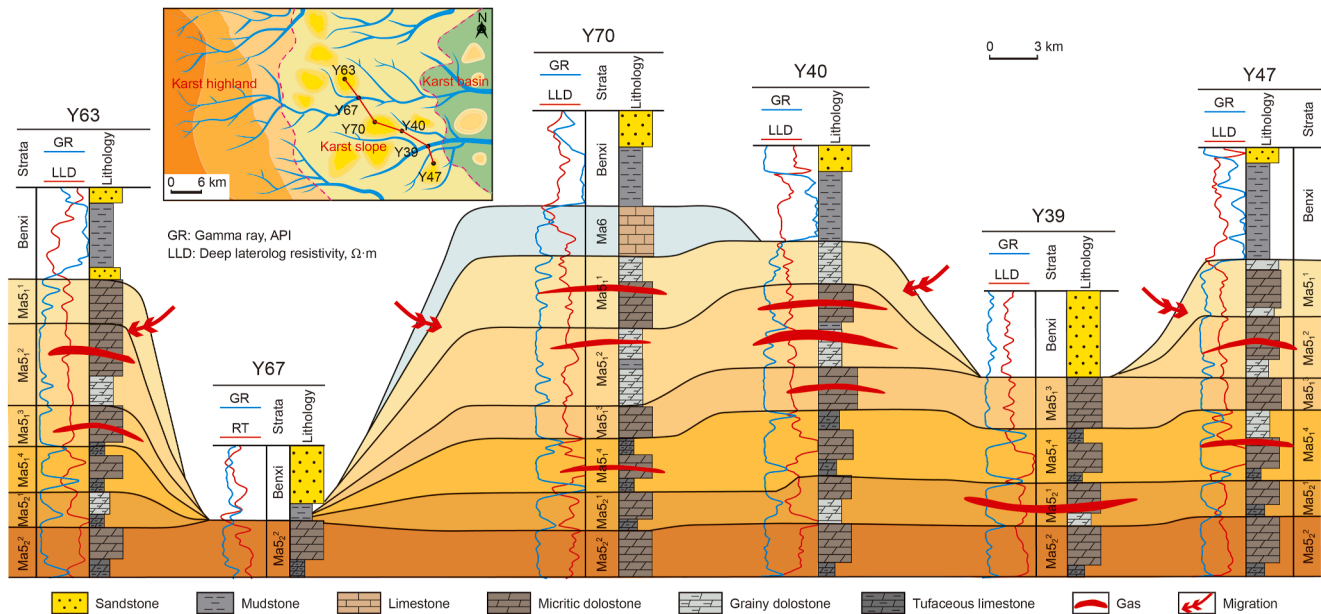


Fig. 17. Karst paleogeomorphic well-tie section map of wells Y63–Y47 (W–E direction).

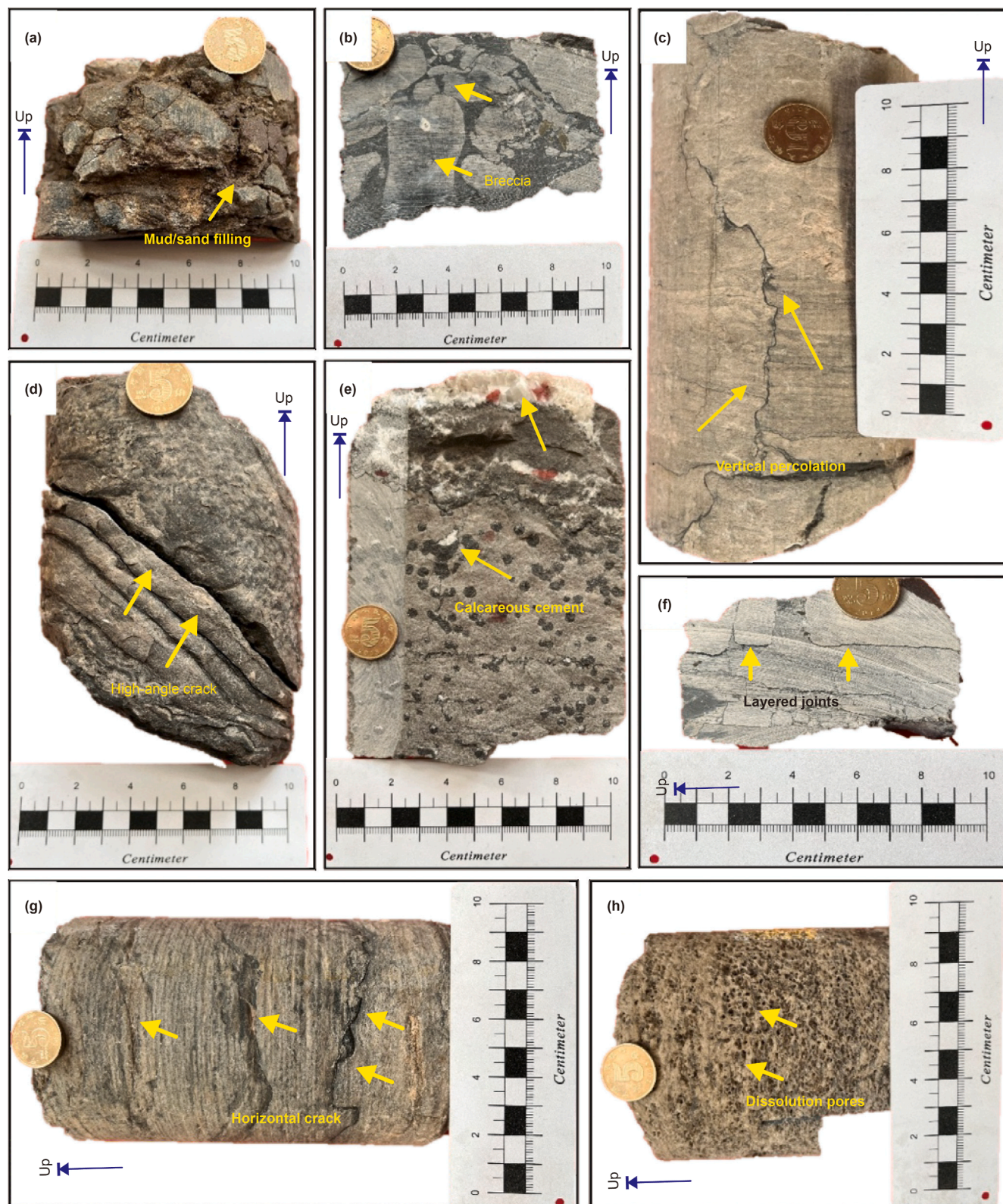


Fig. 18. Core characteristics of different paleogeomorphic units. (a) Mud/sand fills the cracks in a loose state, Well Y19, 3590.4 m, karst highlands; (b) karst breccia, with breccia diameters of approximately 1–3 cm, rapidly accumulated, Well Y11, 3688.2 m, karst highland; (c) vertical cracks gradually transition to high-angle cracks, and are cemented by the filling material, Well Y20, 3796.2 m, the transition zone between highland and slope; (d) stacked high-angle cracks, Well Y25, 3644.1 m, valley flanks; (e) the holes in the paste mold are filled with calcareous cements, which has poor physical properties, Well Y58, 3711.4 m, karst basin; (f) horizontal layered joints indicate that the water flow moves slowly, Well Y49, 3604.8 m, karst basin; (g) horizontal crack, Well Y41, 3643.3 m, the transitional zone between slope and basin; (h) dissolution pores, Well Y55, 3598.2 m, gentle hill.

pattern” between upper and lower strata. Subsequently, second- and third-order geomorphic units are divided (Fig. 14).

Utilizing quantitative indices derived from the overlying marker bed to weathering crust thickness—and referencing classification frameworks proposed by Xia et al. (1999); Bai et al. (2002); Su et al. (2010)—this study establishes criteria for dividing second-order geomorphic units within Yan'an Gas Field into karst highland, karst slope, and karst basin. Furthermore, by integrating data on residual strata thickness, paleogeological exposure terrain, and denudation rates after deviation correction, the classification of third-order geomorphic units such as gentle hills, depressions, terraces, monadnocks, and valleys is further refined, thereby proposing standardized criteria for categorizing paleogeomorphic units (Table 2).

4.5. Reconstructed paleogeomorphic framework

According to the distribution of overlying strata and residual strata, as well as their overlapping relationships, the amount of karst denudation, and the classification criteria of second- and third-order geomorphic units, the paleogeomorphic pattern of the weathering crust in the Ordovician Majiagou Formation is reconstructed (Fig. 15). Yan'an Gas Field exhibits karst highland in the west, karst slope in the middle and karst basin in the east, which is generally high in the west and low in the east. Karst highland can be further divided into upland, tableland, hillside, and valley, and the terrain gradually decreases from west to east. Karst slope can be further divided into gentle hills and terraces, and the topography shows a small slope. The karst basin can be further divided into depression and monadnock, presenting a low-lying hilly landform.

The Ordovician weathering crust features numerous W–E-oriented valleys. In the upper reaches, karst water flow is concentrated within these valleys at a large scale, while continuous

downstream erosion has resulted in the formation of drainage channels extending to the east. Typically, the filling stratum in the valley's developed position is thick, while the residual stratum is thin and distributed in a strip-like manner. Due to prolonged exposure to a water-rock leaching environment, noticeable differences in karst processes have led to superior physical properties on both sides of the valley and well-developed reservoir space, facilitating the formation of advantageous migration channels. Considering these factors, this study reconstructed a three-dimensional map of the karst paleogeomorphology in the Ordovician Majiagou Formation within Yan'an Gas Field (Fig. 16).

5. Geological significance of natural gas exploitation

Numerous studies have confirmed that paleogeomorphology exerts a significant influence on the physical properties of reservoirs to varying degrees, leading to natural gas enrichment at different scales (Kenward et al., 2012; Guo et al., 2014). The paleogeomorphology of the Ordovician Majiagou Formation controlled karstification and seepage patterns, creating reservoir spaces and fractures with different pore throat structures within the weathering crust. Consequently, the pathways for natural gas migration and accumulation exhibit significant variability (Gamaletsos et al., 2017). The paleotopography was intermittently exposed at the surface in response to cyclical fluctuations in sea level. Although mud/sand filling and calcareous cementation have compromised the connectivity among certain pores, prolonged weathering leaching has effectively facilitated the extensive development of reservoir fractures.

The profile of the wells Y63–Y47 traverses two valleys (Fig. 17). Wells Y63, Y70, Y40 and Y47 are situated on either side of these valleys, with daily production of 17,000 m³, 2,000 m³, 6,000 m³ and 10,000 m³ respectively, and corresponding gas saturations are recorded at 62.3%, 51.2%, 56.1% and 74.3%. Conversely, wells Y67

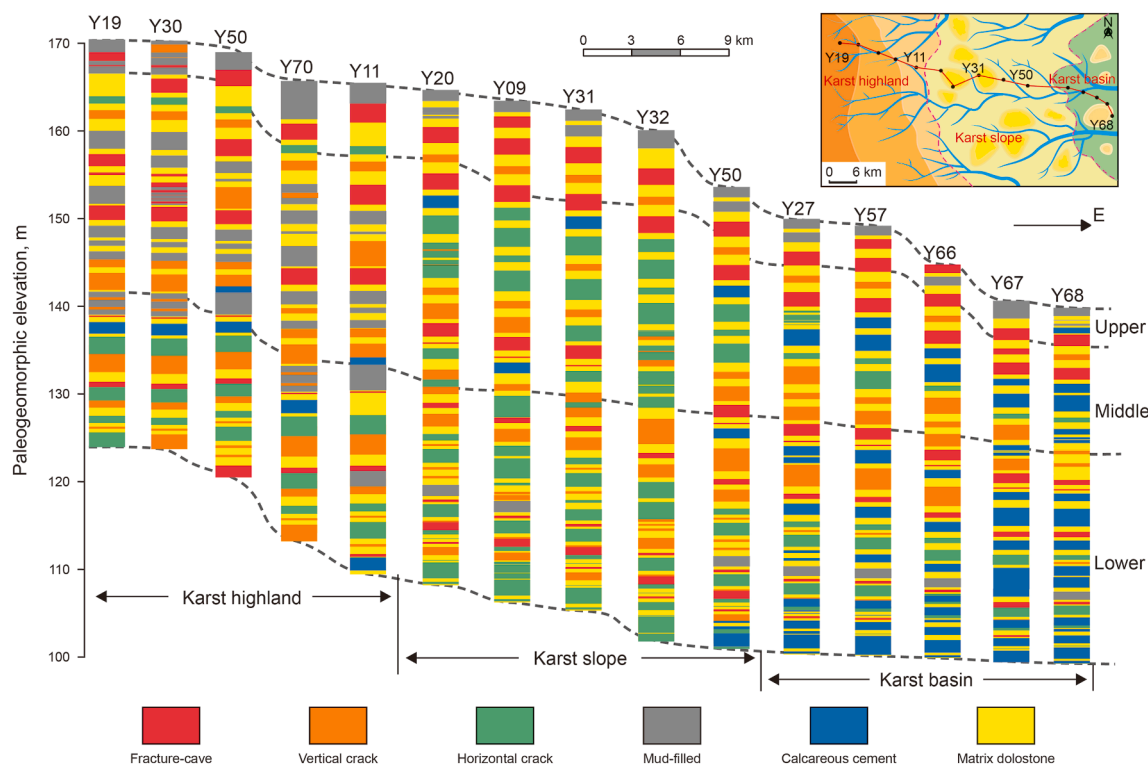


Fig. 19. The occurrence and development characteristics of fractures in different paleogeomorphic units (the data were statistically analyzed by drilling core sampling).

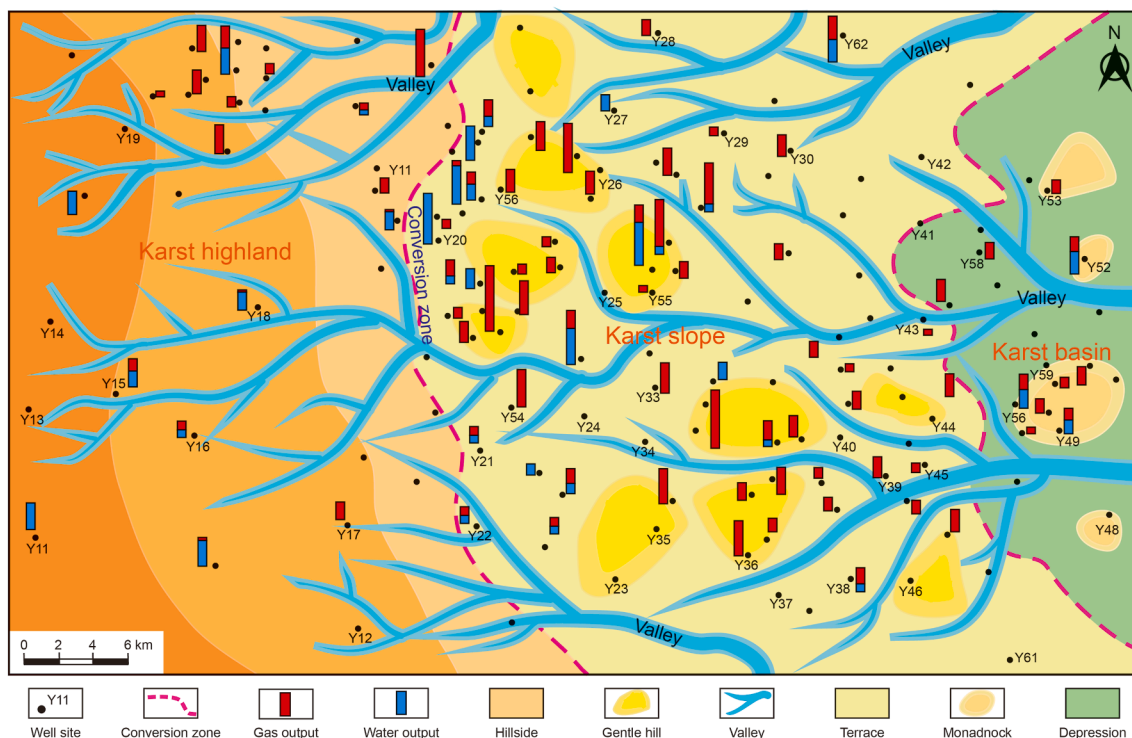


Fig. 20. The relationship between gas-water production and paleogeomorphology in the study area. In the figure, the height of gas/water column represents the level of production.

and Y39 located within the valleys, and rarely have gas accumulation due to the absence of strata.

The karst highlands, with an overall elevated terrain characterized by predominantly vertical percolation through developed fractures and dissolution pores, exhibit largely denuded strata, with residual layers primarily filled by muddy materials exhibiting poor physical properties that hinder effective gas reservoir formation (Fig. 18). The gentle hills on karst slopes exhibit the highest gas productivity primarily because their geomorphic stability—positioned at the long-term interface between vadose and phreatic zones—facilitated prolonged water-rock interaction. Here, infiltrating meteoric water enriched with CO₂ (derived from paleoatmosphere) sustained continuous dissolution of carbonate matrices without significant physical denudation; the gentle slope gradient reduced erosional shear stress while maintaining optimal water residence time for selective dissolution of unstable minerals, creating well-connected pore networks (Fig. 19).

Along the valley flanks, intensified karstification is attributed to convergent groundwater flow paths that enhanced lateral dissolution. During paleo-rainfall events, runoff concentrated along valleys created high-energy hydrodynamic zones, accelerating mechanical erosion and chemical dissolution simultaneously. The valley-side topography functioned as natural conduits for phreatic water circulation, where waters of different chemical saturation further amplified porosity development.

Integration of paleoclimatic proxies suggests that the Late Carboniferous humid phase (evidenced by high Gamma-ray values in coal-bearing strata) promoted acidic fluid generation, which optimized dissolution efficiency across gentle slopes and valley flanks. This climatic-hydrogeological coupling ultimately established the dual sweet spots: gentle hills for sustained matrix porosity and valley flanks for fracture-cave systems (Fig. 20).

The methodology presented in this study is most reliably applicable to sedimentary basins characterized by stable

depositional conditions, the absence of significant allochthonous material transport, and the presence of well-defined, regionally correlatable upper and lower marker beds. This includes, but is not limited to, intracratonic basins experiencing tectonic quiescence during the target geological period, such as the Ordos Basin itself. Consequently, the findings hold significant implications for predicting reservoir distribution in basins with analogous paleogeomorphic and sedimentary settings.

6. Conclusions

- (1) Marine carbonate rocks were developed in the Ordovician Majiagou Formation, and the Caledonian Orogeny raised the basin as a whole. During the sedimentary discontinuous period, the basin experienced multiple stages of weathering and leaching, forming a typical karst paleolandform. The study area exhibits a three-tiered geomorphic pattern: karst highland in the western part, karst slope in the central part, and karst basin in the eastern part. The overall pattern of ancient landforms is high and steep in the west and low in the east.
- (2) According to the impression method, residual thickness method and trend surface compensation method, the error accuracy of traditional paleogeomorphic reconstruction is significantly improved after collaborative iterative deviation correction. Based on the three second-order geomorphic units (highland, slope and basin), the quantitative evaluation criteria for third-order geomorphic units were established, and eight third-order geomorphic units (upland, tableland, hillside, valley, gentle hill, terrace, monadnock and depression) were identified.
- (3) Paleogeomorphology controls karstification and percolation patterns, forming reservoir spaces and fractures with different pore throat structures in the weathering crust.

Therefore, the routes of natural gas migration and accumulation show significant variability. The gentle hills, monadnocks and both sides of valleys experience strong karstification, which improves the reservoir physical properties during the process of erosion and leaching, making them favorable areas for natural gas accumulation and production.

CRedit authorship contribution statement

Zhen Yang: Writing – review & editing. **Jin Lin:** Supervision. **Wei-Bo Zhao:** Conceptualization. **Jin-Song Zhou:** Data curation. **Jun Cao:** Investigation. **Wei Cheng:** Methodology, Formal analysis. **Jia-Hao Chen:** Project administration, Investigation.

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.

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