RESEARCH ARTICLE

Reconstructing large-scale karst paleogeomorphology at the top of the Ordovician in the Ordos Basin, China: Control on natural gas accumulation and paleogeographic implications

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Funding information
CNPC Major Research Project, Grant/Award Number: 2016E-0502; China’s National Science & Technology Major Project, Grant/Award Number: 2016ZX05004006-001-001; PetroChina, Grant/Award Number: 2016ZX05004006-001-001, 50- and 2016E-0502

Abstract
Karstification in carbonate successions has an important influence on hydrocarbon accumulation. Taking the Ordos Basin, currently the largest petroliferous basin in China, as an example, this study examines the large-scale, long-term (~120 Myr) paleokarst at the top of the Ordovician. The objectives of the study are to characterize the karst paleogeomorphology of this area, to explain the inconsistency between existing understandings of karst paleogeomorphology and exploration in the eastern Ordos Basin, and to reveal the control of paleokarst on natural gas accumulation and its paleogeographic significance. A total of 860 exploration wells were used for detailed stratigraphic correlation and analysis, along with core observations, well-logging analyses, physical property characterization, and isotope analyses. Results of residual thickness and moldic thickness reconstruction reveal variation in karst paleogeomorphology between north and south in the eastern Ordos Basin, differing from the traditionally recognized E-W variation. Two geomorphic units are classified as follows: the karst highland and the karst slope from north to south, with the karst slope being subdivided into northern and southern slope areas. The karst highland area has negligible reservoir capacity and hydrocarbon accumulation owing to the enhanced denudation that occurred there. In contrast, the northern karst slope shows favorable reservoir properties and has abundant gas wells according to well-logging interpretations, whereas the southern karst slope is of poor reservoir quality and hosts mainly water wells. Differences in dissolution-filling effects controlled by the surface paleodrainage system are suggested to be the main contributor to differential reservoir space preservation, which, together with the variable width and depth of source rocks in the grooves (thereby variably exposing source rock), further promoted differential gas accumulation. The Ordos Basin and its periphery in the southwestern North China Craton (NCC) show inheritance of sedimentary-tectonic patterns from the Middle Ordovician to the Late Carboniferous. These results should provide a reference for hydrocarbon exploration in the Ordovician of other basins in the NCC in which karst occurs and karst basins worldwide, and deepens...
INTRODUCTION

Karstification of carbonate strata refers to dissolution of the contained carbonate and associated rocks in the same strata. The development of karstification has been demonstrated to significantly influence hydrocarbon accumulation. The various processes involving in karstification are complex and include dissolution, collapse, and filling, resulting in marked reservoir heterogeneity and presenting challenges to the accurate prediction of hydrocarbon occurrence. In this context, because karst paleogeomorphology controls differential dissolution and filling of strata, its detailed characterization helps to describe such heterogeneity. However, characterizing karst paleogeomorphology is subject to several constraints, such as poor seismic data quality, erroneous seismic interpretation, and insufficient well data for control. Consequently, the description of karst paleogeomorphology remains a challenging aspect of karst geology and also of petroleum geological assessments of carbonate rocks.

An extended and widespread hiatus lasting for up to 120 Myr during the Middle Ordovician to early Carboniferous in the North China Craton (NCC) corresponded to an important geological event, that is, Caledonian Movement, which led to a change from marine to transitional facies and eventually terrestrial facies. The Ordos Basin in the south-western NCC recorded this process and therefore provides an opportunity to investigate the regional differential uplift pattern at that time, during which the extensive paleokarst unconformity and its paleogeomorphology had profound influences on the paleogeography and diagenesis of the corresponding strata. On the one hand, extensive and long-term meteoric water karstification transformed the Ordovician Majiagou Formation carbonate rocks, contributing to the formation of the Jingbian gas field in the central part of the basin. On the other hand, the karst surface paleodrainage system, together with crustal uplift, resulted in the formation of a complex erosion groove geomorphic system within a continental basin setting. This regime had morphological similarity to a glacially etched trough or tensional taphrogenic basin, with trough-like features, both of which are known to favor the accumulation of source rocks and to control the distribution of source rock. In addition, the spatial configuration of the source-reservoir-cap assemblage in a paleokarst system should provide favorable conditions for hydrocarbon accumulation. Therefore, the Ordos Basin is regarded as a classic area for investigating karstification, hydrocarbon accumulation, and the relationship between the two.

Previous research conducted in the central Ordos Basin, which shows high Ordovician relief, led to the discovery of the Jingbian gas field. The terrain in the eastern part of the Jingbian gas field was speculated to be low according to the macrogeological background, which meant that exploration and exploitation were generally not directed to the eastern part of the Ordos Basin. However, some exploration wells in the eastern part of the basin, such as wells T1 and Zh1 (Figure 1, have since been shown to be highly productive. Moreover, further drillcore data and associated exploration have shown that the intensity of karst development in the eastern part of the basin is similar to that in the central part. All of these findings suggest that the current understanding of the karstic aspects of the Ordos Basin may not be fully accurate. Specifically, the influence of regional karstification was likely more extensive than realized, which means that the exploration area can potentially be expanded eastward from the center of the basin. Therefore, a more comprehensive description of the karst paleogeomorphology of the basin, and particularly of the eastern part, should be able to inform and guide future exploration. Moreover, such an investigation should lead to a better understanding of the evolution of paleosedimentary-tectonic patterns during the large-scale hiatus that occurred in the southwestern NCC.

Accordingly, this paper provides a detailed description of regional karst paleogeomorphology based on stratigraphic correlations between 860 densely distributed exploration wells covering the entire study area, using comprehensive core observations, well-logging analyses, physical property characterization, and isotope analyses. These methods allow the paleogeomorphic pattern of dissolution and filling in the context of North China Platform regional uplift to be defined, the occurrence and distribution of reservoir rocks underlying the unconformity and of source rocks overlying the unconformity to be investigated, and the spatial configuration of the source-reservoir-cap assemblage and corresponding hydrocarbon accumulation mechanisms in the paleokarst to be examined. In addition to informing exploration in the Ordos Basin, the results should provide guidance for exploration in other basins worldwide where hydrocarbon accumulations...
are related to erosion grooves caused by the surface paleodrainage system.

2 | GEOLOGICAL SETTING

The Ordos Basin is currently a quasi-rectangular-shaped tectonic basin located in the southwestern North China Platform and covers an area of about 2.5 × 10⁵ km² (Figure 1A). The study area, located in the eastern part of the basin, includes the Shenmu, Yulin, Mizhi, and Suide areas and is tectonically situated in the Yishan Slope Belt (Figure 1B). The Ordovician Majiagou Formation, the target layer of this study, can be divided into six members (Ma 1 to Ma 6) from bottom to top (Figure 1C). Moreover, the fifth member (Ma 5) can be further divided into ten submembers, with the first and second submembers (Ma 51+2) being the main targets for weathered-karst reservoir exploration. Six sublayers are further divided within Ma 51+2, respectively, referred to as Ma 51, Ma 52, Ma 53, Ma 54, Ma 55, and Ma 56 (Figure 1D). During deposition of the Ma 5 member, the basin was in a restricted-evaporative epicontinental sea carbonate-platform environment with high salinity, and the main reservoir was composed of gypsiferous moldic pore-bearing micritic dolomites. During deposition of the Ma 6 member, the sedimentary environment gradually transitioned to open, with micritic dolomitic limestones as the main lithology, and there were no evaporates formed as in Ma 5.

During the Late Ordovician to Early Carboniferous, the Caledonian Orogeny uplifted the North China Platform above sea level. The Ordos Basin and its periphery were characterized by a series of uplifts and depressions controlled mainly by the Yimeng Paleo-uplift in the north and the Central Paleo-uplift in the center (Figure 1B). The Majiagou Formation in the Ordos Basin underwent spatially variable rates of denudation, with the greatest amounts of denudation occurring in the paleo-uplifts. On the basin periphery, denudation removed rocks down to the level of the Ma 56 submember. In contrast, denudation intensities in the western and southeastern parts of the basin were relatively weak, with the residual Ma 56 retaining thicknesses of several tens to hundreds of meters. Within the study area (Figure 1A, B),

FIGURE 1 Location and geological setting of the study area. A, Locations of the Ordos Basin and the study area; B, locations of the Jingbian gas field and the study area in the Ordos Basin; C, stratigraphic framework of the Ordovician in the study area; D, generalized lithology of the Ordovician Majiagou, Carboniferous Benxi, and Carboniferous-Permian Taiyuan formations in the study area; E, distribution of cored wells with observations in the study area
the northern Yimeng Paleo-uplift underwent the most severe denudation, generally reaching Ma 5$_p$$_c$ whereas the denudation intensity gradually weakened southward, leaving residual Ma 6 deposits. Subsequently, the Majiagou Formation and the overlying unconformity surface underwent marked karstification over a period of 120 Myr and were then covered by the upper Carboniferous Benxi and Carboniferous-Permian Taiyuan formations.

3 | MATERIALS AND METHODS

Much of the Ordos Basin at present is covered by thick loess deposits, which has generally resulted in poor seismic data that fail to satisfy the requirements for hydrocarbon exploration. Consequently, most existing paleokarst research has been based on well data. In this study, logging and drilling data of 860 wells covering nearly the entire study area were obtained. A total of 45 representative wells (Figure 1E) were selected for detailed downhole core observations and descriptions, and more than 300 core samples were collected for preparation of thin sections and pore-casted sections. Petrographic and mineralogical analyses were conducted using a Nikon Eclipse E200 microscope and a Nikon microscope equipped with a CI8200-MKS cold cathode-luminescence system at the State Key Laboratory for Mineral Deposits Research, Nanjing University, China.

Isotope analyses were performed using a laser microsampling stable isotope analyzer (MAT252) at the Exploration and Development Research Institute of PetroChina Southwest Oil and Gas Field Branch, Chengdu, China. Samples were heated in an oven for 1 h prior to isotope analysis to remove organic matter and moisture, after which a He-Ne laser beam was used for micro-area localization, and a high-energy laser beam (with a krypton lamp current of 25 A and a pulse frequency of 1 kHz) was utilized to sample the selected area in a high-vacuum environment (<3 × 10$^{-2}$ Pa). The ablation gas was cooled and purified by vacuum liquid nitrogen to remove impurities such as CO, H$_2$O, and O$_2$ to obtain pure CO$_2$, which was finally introduced into a MAT mass spectrometer to measure C and O isotopic compositions of the gas. The analytical precision of δ$^{13}$C and δ$^{18}$O was better than 0.1‰, and results are reported relative to Peedee Belemnite. The reservoir capacity variables of porosity and permeability were measured using a JS100007 Helium Porosimeter and an A-10133 Gas Permeameter, respectively, at the PetroChina Changqing Oilfield Company with reference to China’s national industry standard methods.

Residual thickness and moldic thickness methods were combined to reconstruct karst paleogeomorphology based on the geological background of the study area, available data, and comparison with other basins with similar conditions. The prerequisite for application of the residual thickness method is that the original sedimentary thickness of the target strata should show low regional variation. Therefore, this method should be applicable to the upper Majiagou Formation, deposition of which was spatially uniform. Specifically, for the residual thickness method, a layer underlying the unconformity surface should be firstly selected as the isochronous reference surface, and then, the residual thickness between the reference surface and the unconformity surface should indirectly reflect paleogeomorphology. The moldic thickness method requires stable synsedimentary tectonics during the filling process over the denuded strata, which is applicable to the Carboniferous Benxi Formation. In this method, a layer overlying the unconformity surface should be firstly selected as the isochronous reference surface, and then, the thickness of the overlying strata should represent the paleogeomorphology given the mirror-image relationship between the overlying strata and the unconformity surface. Therefore, residual thickness (H) and moldic thickness (h) data as acquired from different exploration wells can be used to determine paleogeomorphology. Large values of H and h generally indicate good preservation of underlying strata and large filling thickness of overlying strata on top of the unconformity, suggesting a geomorphic low. In contrast, small values of H and h imply intensive erosion of the underlying strata and thin overlying strata owing to limited accommodation space, which suggests a geomorphic high. Small H and large h values are indicators of intensively eroded underlying strata and thick overlying strata, which are characteristics of erosion grooves, whereas large H and small h values suggest good preservation of the underlying strata and thin filling thickness of the overlying strata on top of the unconformity, which are features of denuded monadnocks.

4 | RESULTS

4.1 | Stratigraphic correlation and lateral variation

In practice, the coal seam at the top of the Benxi Formation was selected as the reference surface for the residual thickness method (Figures 1D and 2), whereas the mudstone at the bottom of sublayer Ma 5$_d$$_1$ was used as the reference surface for the moldic thickness method (Figures 1D and 2).

Stratigraphic correlation was conducted along two profiles, each intersecting several wells, one profile oriented ~W-E (Figure 2A) and the other oriented ~N-S (Figure 2B). The stratigraphy from W to E has a uniform distribution, and although some wells (eg, Wells Sh 55 and Sh 136) are different, the strata bounded by Ma 5$_d$$_1$ and the unconformity are relatively thin, whereas those of the Benxi Formation are relatively thick (Figure 2A). In contrast, the stratigraphy from N to S has an obvious differentiation. The strata in the north bounded by Ma 5$_d$$_1$ and the unconformity...
are very thin, with enhanced denudation at the top of the Majiagou Formation (Figure 2B). Moreover, these strata gradually thicken southward (generally reaching 80 m) and have better stratigraphic preservation (with preserved Ma 6). Similarly, the Benxi Formation also thickens from N to S. In addition, in Wells Shen 7 and Yu 130, the strata bounded by Ma 54 and the unconformity are relatively thin, and correspondingly, the Benxi Formation is relatively thick. In summary, the stratigraphy shows variation along the N-S direction but uniformity along the W-E direction.
4.2 | Stratigraphic plane distribution

Stratigraphic thickness data from 860 wells obtained using the residual thickness and moldic thickness methods were used to construct corresponding isopach maps (Figure 3), which show similar patterns of variation. Specifically, both maps show the thinnest strata in the north of the Shenmu-Wulate area, being 0-30 m for the residual isopach map (Figure 3A) and 10-30 m for the moldic isopach map (Figure 3B). Strata thicken southward in both maps, with the thickness reaching up to 70-80 m and 30-50 m in the Suide-Qingjian area for the residual and moldic isopach maps, respectively. The residual isopach map shows a ~N-S stratigraphic thinning belt (Figure 3A), whereas the moldic isopach map displays a ~ N-S stratigraphic thickening belt (Figure 3B). These two isopach maps show a good inverse relationship, and the thickness difference between the two sets of isopachs is generally within 30-40 m. These maps support the dominant N-S variation identified in the stratigraphic distribution of sedimentary layers in the study area.

5 | DISCUSSION

5.1 | Reconstruction of karst paleogeomorphology

Karst paleogeomorphology at the top of the Ordovician in the study area was reconstructed based on an understanding of the sedimentary and tectonic settings of the Ordos Basin. This paleogeomorphology shows N-S variation rather than the previously considered W-E variation. Previous studies were generally constrained by available well data, and the
The thickness of the Benxi Formation in some wells reaches 60 m, much thicker than that in the basin center. Accordingly, the top of the Ordovician in the basin was argued by Wang et al.\textsuperscript{28,29} to be high in the west and low in the east for the central and eastern parts of the Ordos Basin, and the study area in the eastern part of the basin was suggested to lie within a karst basin. However, strata thicker than 60 m are found within the N-S stratigraphic thickening belt according to results from 860 wells in the present study, and the strata on both sides of the thickening belt are generally thinner than 40 m, consistent with the thicknesses of strata in the basin center. Moreover, as shown in Figures 2 and 3, there is clear N-S stratal thickness variation but not W-E. Intensive karstification observed in many cores further rejects the possibility that the study area is situated in a karst basin. In addition, the sedimentary filling characteristics of the entire Ordos Basin indicate overall poor preservation of Majiagou Formation member Ma 6 underlying the unconformity, although preservation is better in the southeastern part of the study area and southeastern Ordos Basin, with thicknesses ranging from 25 to >50 m.\textsuperscript{37} Furthermore, the Benxi and Taiyuan formations overlying the unconformity are also very thick in the southeastern part of the basin, locally reaching 150 m.\textsuperscript{43} In summary, the region spanning from the study area to the southeastern Ordos Basin shows overall features of a large-scale, southward-inclining slope.

Strata in the north of the study area are generally thin although variable, indicating high topography and steep slopes, whereas those in the south are characterized by low topography and gentle slopes (Table 1, Figure 4). Accordingly, two geomorphic units can be identified in the study area, which are the karst highland in the north and the karst slope (subdivided into northern and southern slopes) in the south. Furthermore, secondary geomorphic units can be classified, including denuded monadnock, groove, and groove edge, according to the relationship between the residual and moldic thicknesses of different geomorphic units. Specifically, grooves, as a characteristic type of landform, are extensively distributed throughout the study area. According to the residual stratigraphic distribution of the Ma 5\textsubscript{1+2} and Ma 5\textsubscript{2} sublayers (Figure 5), grooves are generally wider (and deeper) in the northern karst slope region (closer to the karst highland), where they commonly penetrate Ma 5\textsubscript{1+2}, compared with the generally narrower (and shallower) grooves in the southern karst slope region (closer to the karst basin in the southeastern Ordos Basin), where they only partially penetrate Ma 5\textsubscript{1+2}. Therefore, a N-S variation is observed in the characteristics of grooves.

On the basis of the degree of preservation of Ma 6 and other data (Table 1), the karst slope was further divided into the northern karst slope and the southern karst slope (Table 1, Figure 4). This distinction likely reflects two aspects. First, Ma 5\textsubscript{1+2} was more directly exposed subaerially in the northern karst slope, whereas Ma 6 (ca. 20 m thick) partially covered Ma 5\textsubscript{1+2} in the southern karst slope. Ma 5\textsubscript{1+2} in the northern karst slope underwent more intensive erosion within grooves, with grooves becoming deeper as well as wider, being eroded closer to the unconformity surface at the top of the Ordovician. Second, lithological difference played a role. Specifically, Ma 5\textsubscript{1+2} and Ma 6 are composed of gypsiferous dolomites and tight micritic dolomitic limestones, respectively, and the former are more susceptible to dissolution than the latter.\textsuperscript{44} Therefore, the northern karst slope experienced stronger dissolution and hosted wider and deeper grooves, whereas grooves in the southern karst slope were rarely widened despite the gradual convergence of the surface drainage network from north to south.

To conclude, the study area was controlled mainly by the northern Yimeng Paleo-uplift, and the geomorphology at the top of the Ordovician was characterized by high topography in the north and low topography in the south.

| Geomorphic unit | Secondary geomorphic unit | Moldic thickness method | Residual thickness method | Preservation condition of the Majiagou Formation |
|-----------------|--------------------------|-------------------------|--------------------------|-----------------------------------------------|
| Karst highland  | Monadnock                | H < 20 m                | H < 20 m                 | Complete denudation of Ma 5\textsubscript{1+2}|
|                 | Groove edge              | 20 m ≤ H < 40 m        | 50 m ≤ h < 70 m          | Complete denudation of Ma 6                   |
|                 | Groove                   | 40 m ≤ H, strip-shaped  | 20 m ≤ h < 40 m, strip-shaped | Partially preserved Ma 6 with maximum thickness reaching 25 m |
| Karst slope     | Northern karst slope     | Monadnock              | 20 m < H < 40 m         | 70 m ≤ h                                       |
|                 | Groove edge              | 40 m ≤ H < 60 m        | 50 m ≤ h < 70 m          | Partially preserved Ma 6 with maximum thickness reaching 25 m |
|                 | Groove                   | 60 m ≤ H, strip-shaped  | 20 m ≤ h < 40 m, strip-shaped | |
|                 | Southern karst slope     | Monadnock              | 20 m < H < 40 m         | 70 m ≤ h                                       |
|                 | Groove edge              | 40 m ≤ H < 60 m        | 50 m ≤ h < 70 m          | |
|                 | Groove                   | 60 m ≤ H, strip-shaped  | h < 50 m, strip-shaped   | |

Note: H stands for moldic thickness, and h stands for residual thickness.
with intertwined grooves and monadnocks aligned N-S (Figure 4). Generally, within the central and eastern parts of the Ordos Basin, the karst paleogeomorphology at the top of the Ordovician reflects control by the western Central Paleo-uplift and the northern Yimeng Paleo-uplift, with the top surface being inclined toward the southeastern part of the basin and grooves converging southeastward from the W-NW in addition to the dominant N-S-trending grooves.

5.2 | Differences in reservoir rocks due to karst paleogeomorphology

Target submembers Ma 5_1+2 were almost entirely denuded in the karst highland, and thus, only those in the northern karst slope and the southern karst slope were compared and analyzed (Table 2).

5.2.1 | Petrological characteristics

According to core and thin-section observations, gypsiferous moldic pore-bearing micritic dolomite is the most favorable reservoir rock type in Ma 5_1+2. Moldic pores constitute the main reservoir space, and their degree of filling is much lower in the northern karst slope than in the southern. In addition, the filling material assemblage differs, whereby moldic pores in the northern karst slope are partly filled with seepage silt and ankerite (Figure 6A), whereas those in the southern karst slope are fully filled
with predominant fine crystalline calcite and seepage silt as the subordinate material (Figure 6C). Ankerite does not show luminescence, seepage silt has weaker luminescence compared with the micritic matrix (Figure 6B), and fine crystalline calcite displays alternating bands of dark and bright luminescence (Figure 6D).

5.2.2 Reservoir physical properties

The physical properties of the Ma 51+2 reservoirs in the northern and southern karst slopes were analyzed (Figure 7). For the northern karst slope, the mean porosity is 3.42%, and the mean permeability is 0.66 mD. There is a generally positive correlation between porosity and permeability, which is consistent with the known characteristics of pore-type reservoirs (Figure 7A). Mean porosity and permeability in the southern karst slope are 2.32% and 0.30 mD, respectively, with most data falling in the region with porosity lower than 6% and permeability <1 mD, indicating overall tighter reservoir rocks than those in the northern karst slope (Figure 7A, 7). Physical properties of secondary geomorphic units in the northern and southern karst slopes were also characterized. Given that the Ma 51+2 submembers generally severely eroded or lacking in grooves, physical properties of Ma 51+2 for groove edges and monadnocks were examined (Figure 7C-F). In general, physical property values of Ma 51+2 in groove edges (mean porosity 3.33%, mean permeability 0.67 mD) of the northern karst slope are slightly lower than those in monadnocks (mean porosity 3.50%, mean permeability 0.79 mD). In contrast, the Ma 51+2 submembers in groove edges of the southern karst slope have a lower mean porosity (2.00%) than that of monadnocks (2.59%) but a higher mean
permeability (0.42 mD vs 0.19 mD). Overall, there are no substantial differences between secondary geomorphic units in terms of their porosity and permeability within both the southern and northern karst slopes. However, porosity and permeability of Ma 51+2 in the northern karst slope are higher than those in the southern karst slope.

Results for the aforementioned measures of reservoir capacity (porosity and permeability) are supported by computed tomography (CT) scanning results of two representative core samples obtained from Well Sh 148 in the northern karst slope and Well Yu 116 in the southern karst slope. The Well Sh 148 core shows partially filled pores and high connectivity. In Figure 8A, the red areas of the image represent the parts with the largest space and the highest connectivity in the pore-fracture system, followed by the blue and green areas. However, as shown in Figure 8B, the Well Yu 116 core shows highly filled pores and low connectivity, as indicated by only sporadic green and rare red and blue areas in the CT image.

5.2.3 | Variation in reservoir capacity indicated by C and O isotopes

C and O isotope analyses were performed on the main filling minerals in moldic pores to investigate reasons for the observed variation in reservoir capacity in the study area. The analyses provide information on the origin of diagenetic cements and on dissolution and filling in reservoirs. Extensively distributed seepage silt and differentially developed ankerite and fine crystalline calcite in the whole karst slope were examined using isotope analysis of micritic dolomite matrix.

Three domains were classified according to C and O data distribution on a δ13C-δ18O diagram, namely, domains 1, 2, and 3 (Figure 9, Table 3). Domain 1 contains ankerite, whose O isotopes show obvious negative anomalies compared with those of micritic dolomite. Domain 2 contains mainly fine crystalline calcite, which has clear negative C isotope

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**TABLE 2** Comparison of reservoir and hydrocarbon accumulation characteristics of the Ma 51+2 submembers between the northern and southern karst slopes

| Geomorphic units       | Reservoir                            | Hydrocarbon accumulation                                      |
|------------------------|--------------------------------------|---------------------------------------------------------------|
|                        | Pore preservation              | Physical properties | Gas testing results            | Interpretation of reservoir gas content |
| The northern karst slope| Moldic pores semifilled with ankerite | Mean porosity of 3.416% and mean permeability of 0.656 mD | High percentages of high-productivity wells in both monadnock and groove edge | Dominant gas wells and gas-bearing wells, with a few water wells in the monadnock |
| The southern karst slope| Moldic pores fully filled with calcite | Mean porosity of 2.322% and mean permeability of 0.296 mD | Only one industrial well with high-productivity, and the other low-productivity wells are almost all in the groove edge | Dominant gas-water wells and water wells, with a few gas-bearing wells in the groove edge |

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**FIGURE 6** Main pore-filling characteristics of micritic dolomites in the eastern Ordos Basin. A, Moldic pore-bearing micritic dolomite filled with ankerite and seepage silt, geopetal structure, blue color indicating residual pores, Well M 35, 2570.07 m, Ma 513, blue casting; B, cathodoluminescence image of Figure 6A; C, moldic pore-bearing micritic dolomite filled with calcite and seepage silt, geopetal structure, Well Yu102, 2556.25 m, Ma 512, plane-polarized light; D, cathodoluminescence image of Figure 6C
anomalies compared with those of micritic dolomite. Domain 3 contains mainly seepage silt, which has an isotopic signature similar to that of micritic dolomite but a slight negative C anomaly.

5.2.4 | Interpretation of differences in reservoir properties

The higher reservoir capacity (as shown by porosity and permeability measurements) in the northern karst slope than in the southern karst slope could be due to the differential dissolution-filling effects of groundwater under the control of karst paleogeomorphology.\textsuperscript{3,15,45} Previous studies have highlighted the formation of moldic pores by selective fabric dissolution resulting from syngenetic karst during the deposition of Ma 5\textsubscript{1+2} and argued that this process was the key to reservoir formation in karstic materials.\textsuperscript{20,35} However, there was no significant regional difference across the study area in terms of karstification during the deposition of Ma 5\textsubscript{1+2}.\textsuperscript{46} Alternatively, the regional differences in reservoir capacity could be explained by variation in Caledonian karstification, which was controlled largely by karst paleogeomorphology. Specifically, the northern karst slope was close to the meteoric water recharge area of the karst highland, and the grooves were formed by the surface paleodrainage system as it cut through Ma 5\textsubscript{1+2}. Therefore, Ma 5\textsubscript{1+2} is likely to have been at a depth close to the water table or in the overlying vadose zone (Figure 10A). During the Caledonian, karst water was generally unsaturated. This, together with the significant gravity gradient in the northern karst slope, promoted the migration of chemical dissolution and mechanical fragmentation products during groundwater runoff.\textsuperscript{32} These conditions were conducive to pore preservation. In contrast, the southern karst slope was distant from the meteoric water recharge area but close to the karst water discharge area. Moreover, grooves in this southern area eroded down only as far as Ma 5\textsuperscript{1+2}. This meant that the main reservoir layers (ie, Ma 5\textsubscript{1}, Ma 5\textsubscript{1+4}, and Ma 5\textsubscript{2}) were likely situated in the deep-saturation or slow-flow zone under the water table for an extended duration (Figure 10B). In this setting, the karst water underwent deteriorating hydrodynamic conditions, being subjected to supersaturation of CaCO\textsubscript{3} and thus intense chemical precipitation.\textsuperscript{11} This resulted in filling and densifying of the reservoir rocks.

The above interpretations are supported by petrological and geochemical characteristics of different minerals in the moldic pores. Seepage silts have been argued to be products of syngenetic karstification.\textsuperscript{20,35} The very low contents of Mn and Fe under near-surface oxidation conditions explain the observed weak luminescence of seepage silts under
Moreover, despite the widespread distribution of seepage silts, karstification in the vertical dimension was controlled by high-frequency sedimentary cycles, which contributed to low degrees and short durations of individual karstification episodes. Therefore, discrete seepage silts present similar geochemical characteristics to those of matrix rocks owing to the buffering effects of these rocks.

In contrast, ankerites partially filling pores in the northern karst slope material lack luminescence owing to their higher Fe contents. Entry of Fe$^{2+}$ from fluid into the crystal lattice occurs mainly under reducing conditions. Furthermore, negative O isotope anomalies in the ankerite reflect the effect of high temperature. Therefore, it is inferred that the ankerites represent the products of fillings during the burial stage and that they are indicators of good porosity preservation before reservoir space was partially filled in the northern karst slope. Fine crystalline calcites fully filling pores of rocks in the southern karst slope are characterized by negative C isotope anomalies, although the amplitude is not large, disfavoring the possibility that their origin could be related to organic components. The slight negative O isotope anomalies, compared with those of the matrix, suggest relatively low temperature. Therefore, these calcites are speculated to be precipitation products following meteoric water saturation. Moreover, alternating bright and dark bands of luminescence imply multiple episodes of complex redox reactions during groundwater precipitation. In addition, the gypsum-bearing dolomite reservoir might have been affected by thermochemical sulfate reduction (TSR), as reported in the Cambrian of the Tarim Basin and the Triassic of the Sichuan Basin. Such TSR calcites are commonly characterized by large negative C and O isotope anomalies compared with matrix dolomite (Figure 9). However, the C and O isotope values of the Ma 51+2 calcites in the study area are clearly different from those of typical TSR calcites. Thus, TSR is unlikely to have occurred in the study area, possibly because most of the gypsum was dissolved during shallow burial. As such, the material basis for the occurrence of TSR was lacking.

To conclude, the northern karst slope was dominated by dissolution and pore preservation during the Caledonian, and the pores were partially cemented and filled under reducing conditions during the medium-deep-burial stage. In contrast, the southern karst slope was characterized by full cementation...
**FIGURE 9** C and O isotope distributions of main pore fillings and matrix (data from Table 3). The blue dashed rectangle shows the ranges of C and O isotopic values of calcites precipitated from Middle Ordovician seawater. The red dotted and solid rectangles indicate the C-O isotopic ranges of dolomite matrix and TSR calcites in the Triassic of the Sichuan Basin, China, respectively. The purple dotted and solid rectangles indicate the C-O isotopic ranges of dolomite matrix and TSR calcites in the Cambrian of the Tarim Basin, China, respectively.

**TABLE 3** C and O isotope values of main pore fillings and matrix

| Well | Depth (m) | Analyzed mineral | \(\delta^{13}C\) (‰) | \(\delta^{18}O\) (‰) | Well | Depth (m) | Analyzed mineral | \(\delta^{13}C\) (‰) | \(\delta^{18}O\) (‰) |
|------|-----------|------------------|----------------------|----------------------|------|-----------|------------------|----------------------|----------------------|
| M 35 | 2578.74   | Ankerite         | −0.55                | −10.09               | S h138 | 2486.62 | Micritic matrix dolomite | 0.03                | −7.52               |
| M 35 | 2579.07   | Ankerite         | −1.04                | −10.90               | Sh 141 | 2573.87 | Micritic matrix dolomite | 0.14                | −7.90               |
| M 35 | 2579.07   | Ankerite         | −1.11                | −10.94               | Sh 141 | 2577.71 | Micritic matrix dolomite | 0.23                | −6.31               |
| M 37 | 2844.03   | Ankerite         | −2.85                | −11.25               | Yu 57 | 2584.8  | Fine crystalline calcite | −5.28                | −9.37               |
| M 37 | 2837.62   | Ankerite         | −1.49                | −11.86               | Yu 57 | 2584.8  | Fine crystalline calcite | −3.02                | −7.99               |
| M 37 | 2844.03   | Ankerite         | −1.32                | −10.23               | Yu 57 | 2584.8  | Fine crystalline calcite | −5.30                | −9.81               |
| M 37 | 2844.03   | Micritic matrix dolomite | −0.69               | −8.81               | Yu 57 | 2584.8  | Fine crystalline calcite | −4.96                | −7.27               |
| S 118 | 2991.75  | Ankerite         | −0.30                | −9.83                | Yu 57 | 2584.8  | Fine crystalline calcite | −3.22                | −7.94               |
| S 118 | 2991.75  | Ankerite         | −0.45                | −10.37               | Yu 102 | 2555.79 | Fine crystalline calcite | −5.94                | −8.64               |
| M 39  | 2852.95   | Micritic matrix dolomite | 0.60                 | −8.25                | Yu 102 | 2555.79 | Fine crystalline calcite | −6.57                | −8.92               |
| M 39  | 2852.95   | Micritic matrix dolomite | 0.61                 | −7.93                | Yu 102 | 2555.79 | Fine crystalline calcite | −2.61                | −7.87               |
| Yu 57 | 2584.8    | Micritic matrix dolomite | 1.06                 | −8.00                | Yu 102 | 2560.07 | Fine crystalline calcite | −4.12                | −8.65               |
| Yu 89 | 2669.09   | Micritic matrix dolomite | −0.72                | −8.45                | Shen 52 | 2367.93 | Seepage silts               | −1.13                | −8.79               |
| M 35  | 2579.07   | Micritic matrix dolomite | 0.03                 | −7.52                | Shen 52 | 2367.93 | Seepage silts               | −2.11                | −8.88               |
| Sh 118 | 2555.4   | Micritic matrix dolomite | −1.09                | −5.40                | M 35  | 2580    | Seepage silts               | −1.98                | −7.10               |
| Sh 118 | 2553.33  | Micritic matrix dolomite | 0.48                 | −6.61                | M 45  | 2248.69 | Seepage silts               | −2.65                | −8.55               |
| Sh 133 | 2720.78  | Micritic matrix dolomite | 1.89                 | −6.77                | Sh 138 | 2486.62 | Seepage silts               | −2.87                | −8.69               |
and filling during exposure and the shallow-burial stage, resulting in an inferior reservoir compared with that of the northern karst slope. These findings indicate the control of different geomorphic units on dissolution-filling and support the accuracy and reliability of the reconstruction of karst paleogeomorphic units in the study area (Section 5.1).

5.3 | Hydrocarbon accumulation differences due to karst paleogeomorphology

5.3.1 | Gas testing results

As mentioned above, given the high level of denudation in the karst highland, Ma 5_{1+2} was investigated in the karst slope. Gas testing results show that almost all of the high-productivity wells are located in the northern karst slope, including Wells Sh 79 (21.34 × 10^4 m³/d), M 35 (6.25 × 10^4 m³/d), and Qi 20 (7.86 × 10^4 m³/d; Figure 4). Most of the natural gases are accumulated in Ma 5_{1}^1, Ma 5_{1}^3, Ma 5_{1}^4, and Ma 5_{2}^2, with the highest gas contents being found in Ma 5_{1}^3. In contrast, wells in the southern karst slope are almost all of low gas content. The wells with relatively good testing results in the southern slope, such as Wells Zh 1 (3.48 × 10^4 m³/d), Yu 94 (1.4 × 10^3 m³/d), and Yu 97 (1.27 × 10^4 m³/d), still have lower productivity than those in the northern karst slope. These fairly high-productivity wells in the southern slope are located mainly along groove edges, with the main production being found in the Ma 5_{1}^3 of the top part of Ma 5_{1+2}. In general, therefore, gas accumulation volumes are much larger in the northern karst slope than in the southern karst slope.

5.3.2 | Well-logging-based gas-bearing results

Similar to the gas testing results, well-logging-based gas content results also indicate higher numbers of high/low gas-bearing wells in the northern karst slope and of gas-containing water wells and water wells in the southern karst slope, revealing an obvious difference in gas content between north and south (Figure 4). For the secondary geomorphic units (Figure 11), gas-bearing wells are roughly equal in number in the monadnocks and groove edges in the northern karst slope, with water wells being found mainly in monadnocks. In contrast, in the southern karst slope, gas-bearing wells are located predominantly in groove edges, with water wells being equally distributed between groove edges and monadnocks.

In addition to the strongly denuded Ma 5_{1}^1 and Ma 5_{1}^2 layers, all of the other layers in the northern karst slope show gas content, whereas gas-containing water and water layers are found only locally in Ma 5_{2}^2. In contrast, all of the layers of the Ma 5_{1+2} submembers are well preserved in the southern karst slope. Furthermore, except that Ma 5_{1}^2 and Ma 5_{1}^3 of local areas host gas layers and gas-containing water layers, all of the other layers are dominated by water.

5.3.3 | Interpretation of differences in gas accumulation

Gas production in the northern karst slope is significantly higher than that in the southern karst slope as described above, which in theory should be related to source rocks and reservoir rocks. Previous studies have suggested that the overlying upper Carboniferous was the main source rock for natural gas in Ma 5_{1+2}. However, the effective thickness of such source rocks in the northern karst slope is lower than in the southern slope, in contrast to the gas accumulation distribution. Therefore, the main reason for the difference in gas accumulation between the northern and southern slopes is not the effective thickness of source rocks.

Interestingly, the N-S karst slope gas accumulation difference is likely related to the superior reservoir properties in the northern slope, as identified above (Section 5.2). Moreover, high-gas-accumulation wells in the northern karst slope are equally developed in groove edges and monadnocks, whereas water wells tend to be developed along monadnocks. In contrast, water wells in the southern karst slope are equally developed in groove edges and monadnocks, and gas wells are distributed mainly in the vicinity of grooves, suggesting a relationship between gas accumulation and groove distribution. Specifically, grooves cutting into Ma 5_{1+2} in the northern karst slope are wide and deep, contributing to exposure of wide and thick source rocks. In contrast, those in the southern karst slope are narrow and shallow, only locally reaching Ma 5_{1}^2. Therefore, although effective source rocks in the northern karst slope are thinner than those in the southern karst slope, the lateral and vertical extents of source rocks in the grooves of the northern karst slope are greater than in the southern karst slope.
The study area

Discharge zone

Recharge zone

Karst highland (the reservoir was denuded)

Northern karst slope (the reservoir was mainly preserved)

Southern karst slope (the reservoir was mainly filled)

Vadose zone

Phreatic zone

Water table

Micritic dolomitic limestone of Ma6

Gypsum-mold-bearing dolomite of Ma51+2

Dolomite underlying Ma51+2

Source rock of Benxi Formation

Surface karst flow

Gas charging and migration

Formation water

Benxi Formation

Ma6

Ma51+2

strata below Ma51+2

A

A'

B

B'

(A)

(B)

(C)

(D)
grooves of the southern karst slope. This resulted in the formation of a much larger hydrocarbon-charging area in direct contact with the Ma 51+2 reservoir in the northern karst slope compared with the southern slope (Figure 10C,D).

In addition, Ma 6 at the top of the Majiagou Formation is generally preserved in the southern karst slope but is widely absent in the northern slope. The Ma 6 member comprises tight micritic dolomitic limestone, meaning that it acted as a baffle between the overlying Benxi Formation source rocks and the underlying Ma 51+2 reservoir rocks in the southern karst slope (Figure 10D). In contrast, in the northern karst slope the direct contact between overlying source rocks and underlying Ma 51+2 reservoir rocks favored large-scale hydrocarbon charging under the influence of local anomalously high pressure (Figure 10C). Moreover, the relatively high-quality reservoir in the northern karst slope was more conducive to charging and migration of natural gas, which might account for the similar amounts of natural gas accumulation in the grooves and monadnocks as well as the different volumes of gas shown in different layers (Figure 10C). In contrast, the low efficiency of source rocks and low capacity of reservoir rocks in the southern karst slope determined the predominant accumulation of natural gas near grooves, mainly within the upper part of Ma 51+2 (Figure 10D).

To conclude, the spatial configuration of grooves controlled the lateral pattern of hydrocarbon charging, assisted by their width and depth together with the baffling effect of Ma 6 on the hydrocarbon supply from source rocks. These factors determined the intensity of hydrocarbon charging. Reservoir capacity also influenced gas charging and migration, as discussed above (Section 5.2.4). These factors jointly contributed to the spatial variations in gas accumulation throughout the study area. Differences between the northern and southern karst slopes in the development and configuration/dimensions of grooves, and in the degree and extent of stratigraphic preservation, were the key factors that influenced the efficiency of hydrocarbon charging from source rocks and resultant gas accumulation distributions.

5.4 | Significance and implications

5.4.1 | Exploration significance

Karst paleogeomorphology at the top of the Ordovician in the study area in the eastern Ordos Basin shows obvious N-S differentiation, and two main geomorphic units are identified, namely, karst highland and karst slope, but an absence of a previously considered karst basin, which lies to the southeast of the study area. The northern karst slope shares a similar karst geomorphology with the Jingbian gas field in the central Ordos Basin (Figure 12), which suggests possible favorable regions for natural gas accumulation in the northern karst slope. Sweet spots in groove edges and monadnocks should be specified as targets in future exploration. However, some important differences are found between the study area and the Jingbian gas field. The Majiagou Formation in the central and eastern parts of the basin is characterized by an E-high-W-low monoclinic structure, whereas source rocks in the grooves of the central part of the basin are distributed in an E-W direction, the combination of which promoted large-scale lateral natural gas migration and charging in the central part of the basin. In contrast, source rocks in the grooves of the eastern part of the basin are distributed in a N-S direction, and they also acted as baffles for lateral natural gas migration, resulting in high local productivity. Specifically, natural gas in the eastern Ordos Basin was bounded by grooves and became concentrated in certain areas, leading to a strongly uneven distribution of natural gas, which could explain why a giant gas field, such as the Jingbian gas field, has not been formed/found in the study area.

Given the above discussion, potentially favorable exploration areas at the top of the Ordovician in the Ordos Basin are expected to lie farther to the east, that is, the study area. Grooves formed by the surface paleodrainage system are speculated to have had a far-reaching influence on reservoir capacity and hydrocarbon accumulation in the study area. Therefore, detailed characterization of such groove-type paleogeomorphology would significantly deepen the
understanding of reservoir formation as well as of hydrocarbon accumulation and occurrence within a karst geological setting. Groove-type geomorphology as reported in this study was extensive and common in the karst area resulting from erosion by the surface paleodrainage system and has been widely reported in previous research on Quaternary and ancient cases. Therefore, the results and findings of the present study are expected to have universal and wider significance.

5.4.2 Implications for regional sedimentary-tectonic patterns

The marine sedimentary pattern during the Middle Ordovician and the continental sedimentary pattern during the late Carboniferous in the NCC has been well studied. However, there has been little investigation of and no consensus regarding the paleogeomorphology that developed during the 120 Myr hiatus from the end of the Ordovician. Using the example of the Ordos Basin, the present study proposes an inherited evolution of sedimentary patterns from the Middle Ordovician to late Carboniferous, based on comparative research (Figures 12, 13). During the Middle Ordovician, an epicontinental sea was the dominant environment across the North China Platform. At that time, the Ordos Basin in the southwestern North China Platform was constrained by the northern Yimeng Paleo-uplift, the Central Paleo-uplift, and the eastern Lishi Paleo-uplift, resulting in the development of a large-scale evaporative-restricted-platform sedimentary environment centered on the Mizhi area (Figure 13A). Subsequently, the closure of the Qilian and Qinling marine

**FIGURE 12** Karst paleogeomorphology at the top of the Majiagou Formation (top of Ordovician) in the Ordos Basin and its relationship to favorable exploration areas.
basins during the late Carboniferous promoted the formation of a continuous uplift belt in the northern, southern, and western periphery of the basin. The Lüliang Paleo-uplift was connected to the ancient continent of Inner Mongolia, leaving only one opening in the southeastern part of the basin, where transitional facies deposits became dominant (Figure 13B). Therefore, during the 120 Myr sedimentary hiatus, the Ordos Basin was first confined by paleo-uplifts in the north, west, and east and then confined by connected ancient continents in the northeast and southwest, with an opening left in the southeast. Under this configuration, the surface paleodrainage system in the northeastern part of the basin could not flow from west to east, according to the inherited evolution of the uplift belt in the eastern part of the basin. The paleogeomorphology was overall inclined downwards toward the southeastern corner of the basin, accompanied by lower topography in that direction.

6 | CONCLUSIONS

1. This study established the pattern of karst paleogeomorphology at the top of the Ordovician in the eastern Ordos Basin. The topography is generally high in the north and low in the south, and two geomorphic units were correspondingly classified, namely, karst highland and karst slope, with the latter being divided into the northern karst slope and the southern karst slope. The unconformity surface is cut by a number of grooves, thus presenting karst paleogeomorphic patterns with intertwined grooves and monadnocks being aligned N-S. In contrast to traditional views, the study area does not contain a karst basin, and nor does it show an E-W differentiated karst framework.

2. Majiagou Formation submembers Ma 5 1+2 are almost completely denuded in the karst highland, and thus, the highland is of no exploration significance. Both the reservoir capacity and gas accumulation of Ma 51+2 in the northern karst slope are higher than in the southern karst slope. Moreover, high-gas-bearing wells in the northern karst slope are almost equally distributed in groove edges and monadnocks, but those in the southern karst slope are limited to the vicinity of grooves.

3. Differential dissolution-filling effects in different geomorphic units resulted in pores being better preserved in the northern karst slope than in the southern. Moreover, differences in the preservation of Ma 6 and in groove development further controlled gas accumulation, leading to higher gas-bearing properties in the northern karst slope. Therefore, groove edges and monadnocks in the northern karst slope are identified as favorable exploration sweet spots in the eastern Ordos Basin. Source rocks in the N-S-oriented grooves in the study area acted as baffles for lateral gas migration, which may explain the observed gas accumulation heterogeneity. No giant gas field like the Jingbian gas field in the central Ordos Basin has been discovered in the study area.

4. The Ordos Basin and its periphery in the southwestern part of the NCC inherited the sedimentary-tectonic patterns of
the Middle Ordovician to late Carboniferous. During the 120 Myr hiatus following the end of the Ordovician, the entire Ordos Basin was characterized by an inclining and lowering from the periphery of the basin to the southeast corner. The Bohai Bay Basin in the northern-central NCC shares similar gas accumulation conditions and potential with the Ordos Basin, suggesting that the former should possess favorable exploration areas in large karst reservoirs in Ordovician carbonate rocks.

ACKNOWLEDGMENTS

We thank the editor and anonymous reviewers for insightful comments that helped to improve the manuscript. We thank PetroChina Changqing Oilfield Company for providing basic data and permission to publish this work. This study was supported by China's National Science & Technology Major Project (Grant No. 2016ZX05004006-001-001) and CNPC Major Research Project (Research and Application on Key Technologies for Sustainable and High-efficiency Production of 50-Millions tons of Oil & Gas in the Changqing Oilfield, Grant No. 2016E-0502).

CONFLICT OF INTEREST

None declared.

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**How to cite this article:** Xiao D, Tan X, Fan L, et al. Reconstructing large-scale karst paleogeomorphology at the top of the Ordovician in the Ordos Basin, China: Control on natural gas accumulation and paleogeographic implications. *Energy Sci Eng*. 2019;7:3234–3254. [https://doi.org/10.1002/ese.3.494](https://doi.org/10.1002/ese.3.494)