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Magmatic activity and hydrocarbon potential revealed by Paleozoic collapse structures in the Hangjinqi area, northern Ordos Basin, China

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Abstract: Collapsed reflections of lower Ordovician carbonates and upper Carboniferous-lower Permian coal-bearing strata occur below the middle Permian lower Shihezi Formation in the Hangjinqi area, northern Ordos Basin. This study takes advantage of three-dimensional seismic data, logging data, core data and well-testing data to investigate the genesis of the collapsed reflections and their implications for hydrocarbon potential. These collapse structures have a subcircular appearance in map view. The columnar reflections in the basement and the volcanic tuff in the lower Shihezi Formation around collapse structures indicate that the formation of these structures are related to magmatic activity. Most of the collapse structures terminate upward in the H₁ member of the lower Shihezi Formation, which explains its greater thickness and supports the hypothesis that magmatic activity occurred during the depositional stage of the lower Shihezi Formation in the early middle Permian. The collapse structures can increase the thickness and

space of the reservoirs, and the collapse of magma conduit can also increase the thickness of the regional sedimentary cap rock above the collapse structures and improve the sealing capacity of the cap rock. These results provide insights into the magmatic activity and hydrocarbon potential of Paleozoic rocks in the Ordos Basin.

Key words: collapse structures; coal-bearing strata; carbonates; magmatic activity; cratonic basin

1. Introduction

Collapse structures are negative relief features, and their development can be related to karstification, magmatism, gravity and erosion (McDonnell et al., 2007). The scale of collapse structures varies considerably. For example, lithospheric-scale collapses are caused by orogenic collapse (Wang et al., 2014a), collapse structures develop within sedimentary basins, and crater and hydrothermal vent collapses, which are more widely recognized, are induced by magmatism (Zhang et al., 2016a; Senger et al., 2017; Reynolds et al., 2018).

Karst collapse pillars are the most common collapse structures in the Ordos Basin, and the bottom strata of these structures are composed of Ordovician carbonate rocks and Carboniferous-lower Permian coal-bearing strata (He et al., 2009; Gui et al., 2017). The formation of these pillars was ascribed to the collapse of previously developed caves and cracks in the carbonate sequence induced by the gravitational load of the overlying strata and tectonic stress (Gui et al., 2017). The development of karst collapse pillars disrupts the continuity of the coal seams (He et al., 2009; Zuo et al., 2009; Gui et al., 2017), and their identification can be important in assessing petroleum potential. For example, collapse craters are generally filled with permeable beds that form a reservoir (Zhang et al., 2016a), and the collapse of carbonate platforms caused by hydrothermal activity has been proven to significantly improve the quality of carbonate reservoirs (Yang et al., 2017). However, research into the origin of collapse structures of carbonate rocks and coal-bearing strata as well as their geological relevance is limited. In addition, collapse structures are caused by various processes, and it is unclear whether the collapse structures characterized by disrupted lower Ordovician carbonate strata and upper Carboniferous-lower Permian coal-bearing strata in the Ordos Basin can be classified as karst collapse pillars.

Geologists regard features such as “pushed down”, interrupted, bifurcated and merged patterns evident in seismic reflection studies as the main basis for identifying karst collapse pillars (Zhang and Lin, 2008; Zuo et al., 2009). In map view, the distributions of these features appear approximately circular. In this study, a seismic analysis of the collapse structures in the Ordos Basin was conducted. Moreover, the basement structures related to the collapse of Paleozoic strata and the time of their collapse have been considered to reveal the formation mechanism and petroleum-related geological implications of the collapse structures. This research addresses these issues by (1) providing a map showing variations in the thickness of the collapsed and deformed strata (coal-bearing measures and the lower Shihezi Formation) overlying the carbonate formation; (2) describing the seismic expression and map-view distribution and identifying the basement structures related to the collapse structures; (3) identifying reasonable geological processes that correspond to the core photographs and the anomalous compositions of formation water and gas in the strata overlying the carbonate layer; (4) determining whether magmatic activity was the primary factor in generating Paleozoic collapse structures by deducing its timing relative to collapse and the geological factors that affected magma emplacement; and (5) analyzing the impact of magmatic activity and collapse structures on gas exploration.

This paper provides a case study of the seismic reflections suspected to be related to karst collapse pillars. Meanwhile, the early middle Permian magmatism in the Ordos Basin is reported for the first time based on seismic data. This work provides new insights into the magmatism in the Ordos Basin and will benefit interpretations of the collapse of carbonate rocks elsewhere.

2. Geological setting

The Ordos Basin is a large cratonic basin located in central China, and it has a surface area $3.7 \times 10^5 \text{ km}^2$ (Figure 1a). The Ordos Basin can be divided into six first-order tectonic units: the Yimeng uplift, Weibei uplift, Western thrust belt, Jinxi flexural fold belt, Tianhuan depression, and Yishan slope (Xiao et al., 2005; Yang et al., 2005). The Hangjinqi area is located in the northern part of the Ordos Basin, and in terms of regional structures, it occurs in the northern part of the Yimeng uplift, Yishan slope and Tianhuan depression (Figure 1a). The study area is located on the Yishan slope in the southern part of the Hangjinqi area (Figure 1b and 1c).

The metamorphic basement of the Ordos Basin formed during the Archean and early Proterozoic (Liu et al., 2006). In the middle Proterozoic, the region evolved into a platform syncline, with aulacogens developed in its peripheral areas. However, a few local aulacogens extended into the syncline and filled with marine clastic sediments (Xu et al., 2018). Due to regional uplift, lower Paleozoic strata are absent but Ordovician carbonate deposits occur on the Yishan slope (Xu et al., 2009). The upper Carboniferous Taiyuan Formation is composed of coal-bearing strata deposited in a marine-continental transitional environment. The distribution of this formation is controlled by the Porjianghaizi fault, Sanyanjing fault and Wulanjilinmiao fault, and the formation is exposed mainly to the south of these faults in areas that include the Yishan slope and Tianhuan depression (Yang et al., 2015).

With the uplift of the northern cratonic areas and marine regression in the Permian, the strata in the Hangjinqi area are characterized by deltaic and braided fluvial deposits (Wang et al., 2014b). The thicknesses of the early Permian Shanxi Formation and the middle Permian Lower Shihezi Formation increase southward. After the early Permian, the initial pericratonic basin evolved into an intracratonic basin (Figure 2) (Xu et al., 2018).

Exploration drilling and previous studies have demonstrated that the Paleozoic sedimentary successions in the Hangjinqi area transitioned from marine to fluvial to lacustrine, and consisted of coal-bearing, fluvial and lacustrine deposits, forming the upper Paleozoic gas-bearing system in the Ordos Basin (Zhang et al., 2016b). The coals and dark mudstones of the upper Carboniferous Taiyuan Formation and lower Permian Shanxi Formation are the primary hydrocarbon source rocks (Wang et al., 2011). The fluvial sandstones and mudstones of the Shanxi and lower Shihezi formations act as hydrocarbon reservoirs and direct-seal rocks. The widespread and thick (up to 325m) lacustrine mudstones of the Upper Shihezi and Shiqianfeng Formation are regional seals (Qi, 2016).

3. Data and methods

The study area is located on the Yishan slope at elevations ranging from 1300 to 1600 m (Figure 1a and 1c). The data used in this study include three-dimensional seismic data, logging data, gas-testing data, and core data. A 3D seismic survey covering 830 km² was acquired and

processed according to Society of Exploration Geophysicists (SEG) standard polarity, with red representing troughs and black representing peaks. The sampling interval was 1 ms, and the bin size was 25 m inline $\times$ 25 m crossline. In the study area, the dominant frequency of the study is no more than 22 Hz. The survey contains 17 exploration wells and 5 horizontal wells (Figure 1c), but only 6 exploratory wells (J106, J104, J94, J121, J122, and J6) penetrated the Ordovician carbonate rocks. In addition, core, formation water and gas composition data obtained from the exploratory wells were used in this study.

The analysis of the hydrocarbon implications of the collapse structures was performed as follows. (1) High amplitude reflectors in the synthetic seismograms were interpreted to calibrate the sequence boundaries of the carbonates, the coal-bearing measures, and the lower and upper Shihezi Formation. A thickness map of the collapse deformation layers (coal-bearing measures and the Lower Shihezi Formation) overlying the Ordovician carbonates was constructed to reflect the structural variation tendency associated with basin evolution; and (2) extraction of the coherence attributes in order to delineate the distribution collapse structures, and throw attributes to determine the relative magnitude of the collapse depth. The seismic features of the collapse structures were described, and the basement structures below the collapse structures were analyzed. Because both a tuff bed and a calcite vein are present in the H₁ member of the Lower Shihezi Formation, the difference between the salinity and metamorphism coefficient in the formation water was analyzed to determine the relative temporal relationships between the calcite precipitates and the H₁ member deposits. The combined interpretation of basement structures, similarity attributes, core analysis, thickness variation trends and the regional geological background was conducted to verify the presence of magmatic activity. Collapse structures identified in this study were compared with the published carbonate collapse structures in other studies to confirm that the collapse structures in the study area were caused by magmatic diapirism. The timing of magmatic activity and collapse structures were determined according to the offset layers and thickness variations formed by the collapse. The regional tectonic evolution effect on the emplacement of magma was evaluated, and the distribution patterns of the collapse structures were established. The effects of magmatic activity on gas exploration were investigated based on the spatial and temporal distribution of magmatism, and the hydrocarbon potential of the

collapse structures was evaluated according to the features.

4. Results

4.1 Horizon calibration and formation thickness

In this 3D seismic survey, six key horizons with relatively high amplitudes were recognized through synthetic seismograms (Figure 3): the bottom interface of the Shiqianfeng Formation (T9g), the Upper Shihezi Formation (T9f), the H₂ member of the Lower Shihezi Formation (T9e), the Lower Shihezi Formation (T9d), the coal seam of the Shanxi Formation (T9c), the Taiyuan Formation (T9b) and the Ordovician carbonates (T10). According to previous studies (Gui et al., 2017), the strata most closely related to the karst collapse pillars are the coal-bearing strata and the carbonate strata. The coal seams in the study area are mainly located between the T9b peak and the T9d peak, and the carbonate rocks are located between the T9b peak and the T10 trough. The reflection with two peaks and two troughs transitions into a peak-over-trough reflection as the carbonate thickness decreases from south to north (Figure 3).

Based on the east-west well section that crosses the southern part of the seismic survey, the carbonate strata are marked by low gamma values, low acoustic values and high densities. The coal seam is characterized by low gamma values, low density values and high acoustic values. The thickness of the Ordovician carbonate is 127-170 m, and the accumulated thickness of the coal-bearing measures is greater than 90 m. The lower Shihezi Formation has a thickness greater than 100 m (Figure 4a). An opposite trend between the thickness of the coal-bearing strata and that of the lower Shihezi Formation was observed in the well section. The thickness of the coal-bearing strata appeared to be thicker in the east of the lower Shihezi Formation than that in the west; however, the thickness of the lower Shihezi Formation is thicker in the west than the east (Figure 4a). The deposition of the Taiyuan and Shanxi formations was associated with the terrain formed by the erosion of the Ordovician carbonates as evidenced by the north-south-trending belts in the isopach map of the coal-bearing strata. In the study area, the coal-bearing measure thickness varies from 90-135 m (Figure 4b). The lower Shihezi Formation has a thickness range of approximately 95-168 m (Figure 4c). Based on the thickness distribution of the lower Shihezi Formation, the depositional center of the coal-bearing measures with the maximum thicknesses

formed bulges during the deposition of the lower Shihezi Formation (Figure 4b and 4c).

4.2 Distribution of collapse structures and reflection patterns in the basement

The presence of collapse structures produces offsets or concavities in the seismic reflection from T9d; thus the coherence attribute computed over a ± 10 ms window around the T9d reflection was used to reveal the distribution of the collapse structures (Figure 5a). Furthermore, the throw attribute over the ± 10 ms window around the T9d reflection was calculated to indicate the relative magnitude of the collapse depth (Figure 5b). Collapse structures manifest as subcircular shapes in plan view. These structures are mostly distributed in three subdomains: the region around well J56 in the southwestern survey, which covers an area of approximately 85 km²; the region confined by wells J120, J121, J51 and J122, which covers an area of 15 km²; and the region near a curved trending fault, which covers an area of 12 km². The throw attribute in the time window of the T9d reflection within ± 10 ms exhibits a drop of 1-6 ms among these collapse structures. The largest collapse-related drop lies to the south of well J77P1HDY (Figure 5a), whereas the two smaller areas identified in the coherence attribute map exhibit smaller drops ranging from 2 to 4 ms (Figure 5b). The curved faults in these two attributes were initially produced under Mesozoic compressional stress (Xu et al., 2018).

The crystalline basement exhibits two distinct layer reflections at greater reflection times as illustrated in Figure 6a, and this information is consistent with Teng et al., (2008) who indicated that a double-layer structure exists in the upper crust in the Hangjinqi area. The weakly chaotic reflections in the basement may correspond to low- to moderate-grade metamorphic sediments, and the underlying strongly chaotic reflections likely correspond to Archean to early Proterozoic basement rocks. Note that some columnar reflections with widths of approximately 20 km penetrate the overlying weakly chaotic reflections, and they terminate slightly below the lower interface of the carbonate rocks. The collapses of coal-bearing measures above the columnar reflections are bounded by normal faults, and some events of coal-bearing strata show concave features. The reflection intensity of the coal-bearing strata, which is either broken by faults or concave, is consistent with that of the surrounding events. The occurrence of faults did not cause the footwall thickness to increase, although the lower Shihezi Formation was flexed and thickened

due to the influence of peripheral faults caused by the collapse structure (Figure 6b).

Four basement reflection patterns below collapse structures are illustrated in Figure 7. Several neighboring columnar reflections on the northern side of Figure 7a can be observed under the wider collapse structures. The columnar reflection on the southern side of Figure 7a exhibits a push-down reflection at its top position. Additionally, the en echelon reflections in Figure 7b are interpreted as blind faults because offset is observed in the basement but not in the overlying strata. The horizontal width of the en echelon reflections is equal to the half wavelength of the overlying anticline. Furthermore, a local Proterozoic rift is present in the basement (Figure 7c), and concave reflections lie directly above the rift center. Certain columnar reflections are difficult to interpret because their widths are close to the spatial resolution, small lateral widths cause the formation of slight concave reflections. However, the seismic reflection of coal-bearing strata exhibits dislocation when the columnar reflections have greater widths (Figure 7d).

4.3 Special cores and gas and formation water composition data

Well J77 is located on the northeastern side of the collapse structures and contains two notable lithologies. A calcite vein and a tuff are found in the H₁ member of the lower Shihezi Formation, and they may be related to deep fluid and magmatic activities (Figure 8a and 8b). The calcite vein is located above the tuff deposits, suggesting that it formed later than the tuff and precipitated within the dark gray mudstone of the H₁ member (2682.32-2682.66 m). The vein has a length of 0.51 m and a maximum width of approximately 0.07 m (Figure 8a). The tuff (2683.37-2683.44 m) is thin at approximately 0.07 m (Figure 8b). The highest and lowest salinity of the water of the H₁ member of the lower Shihezi Formation are 6.13×10^7 mg/l (well J20) and 0.45×10^7 mg/l (well J77), respectively. Well J77 has the highest metamorphism coefficient of 69.54, while well J75 has the lowest metamorphism coefficient of 21. Variations in salinity seem to be unrelated to the distance between the well location and collapse structures. Nevertheless, the metamorphic coefficients of the formation water in these exploratory wells (wells J77, J56 and J51) around the collapse structures have higher values than in other wells (Figures 5a, 5b and 8d). The gas composition in the Shanxi Formation includes hydrocarbons (accounting for more than 50%), nitrogen (2.2-7.1%) and carbon dioxide (0.2-1.3%) (Figure 8e). Furthermore, the amount of

carbon dioxide in the wells near the collapse structures (wells J77, J51, J104, and J56) is slightly higher than that in well J76, and these wells are also accompanied by higher gas production (greater than 3000 m³).

5. Discussion

5.1 Evidence for magmatic activity

This study argues that the formation of the collapse structures identified by the seismic survey was closely related to deep geological processes. The magmatic activity was determined based on the following interpretations. An obvious inheritance relationship does not occur among the lower Shihezi Formation, the underlying coal-bearing deposits, and their paleostructural highland lows as the thickness maps are quite distinct (Figure 4b and 4c). Nevertheless, large synsedimentary growth faults in the study area did not exist during the late Carboniferous – middle Permian. Therefore, the transformation of the structural appearance was not related to faulting activity. The increase of the thickness of the lower Shihezi Formation is caused by the collapse structures located vertically above the basement structures. From the perspective of the sedimentary evolution of the Hangjinqi area, the Ordovician carbonate rocks, upper Carboniferous Taiyuan Formation, and lower Permian Shanxi Formation were deposited in a marine-continental transitional depositional environment and the middle Permian Lower Shihezi Formation was deposited in a completely terrestrial depositional environment (Wang et al., 2011; Xu et al., 2009; Yang et al., 2015). Synchronously, the Hangjinqi area evolved from a pericratonic basin into an intracratonic basin and the climate changed from tropical and humid to arid (Wang et al., 2014b). Furthermore, the columnar reflections rooted in the deep basement show abnormally low values in the similarity attribute sections (Figures 9a, 9b, 10a, 10b), suggesting the upwelling of deep material. The combined features of collapse reflections and basement reflections are highly similar to the characteristics of igneous diapirism-related collapse reported in previous studies (Hansen et al., 2008; Hsu et al., 2017; Magee et al., 2016).

As noted above, magmatic activity might be an important deep geological process that led to basin property adjustments, climate change and paleostructural changes. The tuff deposited in the H₁ member of the lower Shihezi Formation further indicates the presence of regional magmatism.

The petrographic and geochemical analyses of the tuff suggest that the volcanic activity is related to the progressive closure of the paleo-Asian ocean located to the north of the study area (Zhang et al., 2014), and the intrusive bodies in the study area solidified at depths of less than 300 meters.

The formation of calcite veins is commonly associated with hydrothermal activity (Li et al., 2006), although the calcite vein observed in this study is not considered to be related to magmatic hydrothermal fluid. Indeed, the calcite vein is located in the H₁ member of well J77, and the formation water of this interval features the lowest salinity and the highest metamorphism coefficient among the tested wells (Figure 8c and 8d). The salinity of the porewater is barely reduced in such units with high porosity and permeability because the water circulation and diffusion are sufficient to balance the salinity. The development of the collapse structures increased the thickness of the H₁ member; thus, the Lower Shihezi Formation formed during the sedimentary stage when the collapse structures were produced. Accordingly, the calcite vein formed after the deposition of the lower Shihezi Formation and most likely precipitated under conditions in which the porewater flow was very restricted. In fact, the formation water of the H₁ member is the CaCl₂ type (Li et al., 2017) and the formation of a calcite vein would reduce the salinity in a closed system.

5.2 Comparison of collapse structures in this study with those of other carbonate collapses

Carbonate collapse, as documented in previous studies, commonly produces long collapsed columns in seismic sections (McDonnell et al., 2007; Chen et al., 2015; Yang et al., 2017). Although the carbonates have experienced dissolution from shallow to deep burial processes, the long collapsed columns indicate that the gravitational load was vital to the collapse process. For example, dissolution-collapse columns identified in the Worth Basin, the Pearl River Mouth Basin and the Sichuan Basin have lengths of 800, 1000 and 4000-4500 m, respectively (McDonnell et al., 2007; Chen et al., 2015; Yang et al., 2017). However, the deformed strata generated by the collapse structures in the present study are far thinner, i.e., 400 m (Figure 4), suggesting that the collapse structures experienced a weaker gravitational load than the carbonate collapse structures noted above. The most noteworthy feature of the collapse structures in this study is that the carbonate rocks, which experienced long exposure and fresh water flushing and are overlain by

thin swamp sediments, developed carbonate collapse structures due to igneous diapirism and the cooling of magma chambers. Consequently, some collapsed carbonate layers are surrounded by basement rocks (Figure 11a).

The collapse strata include the Ordovician carbonate rocks and the upper Carboniferous-lower Permian coal-bearing strata, which are also the key for the study of karst collapse pillars in China (Zhang and Lin, 2008). However, magmatic activity is not included in current theories regarding the formation of the karst collapse pillars. Karst collapse pillars usually appear after a coal seam is formed. When the karst collapse pillars are formed, the coal-bearing strata overlying the collapse pillars breaks, which leads to discontinuity and subsequently produces push-downs in the coal-bearing seismic reflections and generates weak reflections (Zhang and Lin, 2008; He et al., 2009; Zuo et al., 2009; Gui et al., 2017). In contrast, the coal-bearing seismic reflections in the research area are still characterized by high amplitudes and are not weakened by the presence of collapse structures. Therefore, the collapse formed just after the accumulation of the peat, and the high-amplitude reflections are generated due to the later coalification after the generation of the collapse structures. Consequently, as the collapse structures in this study were generated before coal formation, they are not karst collapse pillars which form after coal formation.

5.3 Occurrence time of collapse structure formation and magmatic activity

From the seismic reflection perspective, the age of intrusive activity could be determined by the analysis of the overlying unconformity reflections generated by magmatism (Hansen et al., 2005; Magee et al., 2016). The intrusion time of magma is usually earlier than the collapse. The formation time of collapse structures can be confirmed by examining the thickness variations in the overlying strata, and then age of the magmatic activity can be determined. When the results of the early collapse and the late collapse of magma conduit caused by magmatism are superimposed, a larger collapse structure will occur. Such structures increased the thickness of the lower Shihezi Formation above the collapse structure, as well as the thickness of the upper Shihezi Formation (Figure 11a,b). This finding implies that the collapse structure formed before the deposition of upper Shihezi Formation, which indicates that magmatic activity terminated before

the deposition of upper Shihezi Formation. The faults related to collapse structures cut the H_1 member of the Lower Shihezi Formation upward and the coal-bearing measures and carbonates downward (Figure 11c); however, these faults do not lead to any thickness variations in the coal-bearing measures or carbonates. The magmatic activity probably occurred during the deposition of the Lower Shihezi Formation and after the deposition of the early Permian Shanxi Formation. The faults cut the H_1 member and increase its thickness, and the H_2 and H_3 members are marked by flexural thickening. Accordingly, the timing of magmatic activity interpreted from seismic sections corresponds to the depositional interval of the H_1 member. Coincidentally, the appearance of the tuff in the H_1 member of well J77 indicates that there was volcanic activity near the study area during the deposition of this member, which supports the magmatic activity time suggested by the seismic data.

5.4 Factors affecting magma emplacement

Several large-scale basement-penetrating faults in the Hangjinqi area, including the Sanyanjing fault, Porjianghaizi fault and Wulanjilinmiao fault, formed in the early Paleozoic Caledonian period before magmatic activity in the study area (Yang et al., 2015; Xu et al., 2018). However, the Lijiaqu fault in the 3D seismic survey was generated after magmatic activity during the Mesozoic (Xu et al., 2018). The study area is located more than 30 km south of the Porjianghaizi fault (Figure 1b); thus, the magma emplacements in this paper are not related to the large regional faults.

Nevertheless, igneous rocks distributed along faults have been reported in many basins (Hansen et al., 2005; Magee et al., 2016). The Ordos Basin is a cratonic basin that was primarily formed by tectonic flexure in response to north-south compression in the Paleozoic (Liu et al., 2000). Notably, cratonic basins may be affected by several subsidence mechanisms throughout their history (Allen and Armitage, 2012). Continuous subduction to the north of the Ordos Basin, could have contributed to magma generation, implying magmatism may have been a secondary mechanism modifying the subsidence mechanism in the Hangjinqi area. Moreover, mantle upwelling is supported by petrologic studies (Zhang et al., 2014), and the Hangjinqi region is characterized by a tectonic framework that is high in the west and low in the east. Accordingly,

the magmatic activity in the eastern part of the Hangjinqi region might be a result of subsidence. During the sedimentary stage of the H₁ member in the middle Permian, the magma in the study area upwelled in zones of structural weakness, such as blind faults and Mesoproterozoic rifts in the basement (Figure 12), and collapse structures subsequently formed in response to the igneous diapirism.

5.5 Exploration implications of magmatic activity and collapse structures

Magmatic intrusions can affect the thermal evolution of source rocks and deform host rocks into folds, which then serve as seals and reservoirs (Hansen et al., 2005; Delpino and Bermúdez, 2009; Gudmundsson and Løtveit, 2014; Peace et al., 2017). The temporal and spatial distribution of magmatic activity is important for estimating the exploration potential (Delpino and Bermúdez, 2009). The upper Carboniferous-lower Permian coal seams are the major source rocks in the Hangjinqi area, and the burial depths of the Shanxi and Taiyuan Formations were less than 200 m when the magmatic activity occurred during the early middle Permian. At that time, the source rocks were immature and magmatism could have enhanced the thermal evolution of the source rocks. However, magma rising along conduits intruded the basement below the source rocks and carbonate layers only and the isolated distribution of magmatic conduits differed from that of regional sill emplacement. Therefore, the magmatic activity had minor impacts on the thermal evolution of the source rocks. In addition, thermal anomalies are not present in the thermal history simulation of the source rocks (Zhao, 2016). Furthermore, the collapse structures increased the burial depth of the source rocks, and the gas analysis of the Shanxi Formation indicates that the wells near collapse structures have greater gas production and higher CO₂ levels than those in other wells. The amount of CO₂ in the gas in the Hangjinqi area is 0-0.45% (Peng et al., 2017), whereas the content of CO₂ in the gas in the Shanxi Formation in the study area ranges from 0.2-1.3%, which may be associated with organic and inorganic degassing. In addition, the occurrence of collapse structures increases the accommodation of both reservoirs and cap rocks.

The hydrocarbons in the Hangjinqi region migrated relatively short distances vertically from the source rocks and then became trapped, while faults acted as effective migration paths (Zhang et al., 2016b). Consequently, explorations of the lower Shihezi Formation have concentrated on

identifying faults that connect source rocks and reservoirs. However, certain normal faults were formed by magmatic diapirism in the southwestern portion of the 3D seismic survey, and these faults are considered open and could have transported gas (Xu et al., 2018). Accordingly, high-yield gas wells are located around the fault-bounded collapse structures (Xu et al., 2018). Meanwhile, the metamorphism coefficient of the formation water in the H₁ member increases abruptly in proximity to these collapse structures, which is likely due to the mixing of the H₁ member water with the deeper water with a high metamorphism coefficient. Therefore, the search for favorable exploration targets should concentrate around collapse structures.

6. Conclusions

The genesis and exploration implications of suspected reflections of karst collapse pillars have been investigated based on a combination of 3-D seismic data, gas-testing data, logging data and cores. The main conclusions of this paper are as follows.

Columnar reflections in the basement occur below collapse structures, suggesting that the generation of the collapse structures was associated with magmatic activity. This hypothesis is supported by the tuff deposited in the overlying strata around the collapse structures. The formation of a calcite vein in the Lower Shihezi Formation reduced the salinity of the formation water, and the vein was formed after the deposition of the Lower Shihezi Formation.

The major collapse strata in this study are similar to the strata of the karst collapse pillars in northern China. However, the collapse structures in this study formed before coalification. Thus, the coal-bearing strata are characterized by high-amplitude reflections that are quite different from the pattern associated with karst collapse pillars. Meanwhile, the collapse structures caused relatively little deformation in the overlying layers (less than 400 m), revealing that the gravitational load was much lower than that associated with other documented carbonate collapse structures.

The collapse structures in this study were formed by primary collapse caused by magmatic activity and secondary collapse generated by the collapse of magmatic conduits. The primary collapse increased the thickness of the lower Shihezi Formation, and the secondary collapse

increased the thickness of the upper Shihezi Formation. The synsedimentary faults generated by igneous diapirism cut the H₁ member of the Lower Shihezi Formation, implying the magmatic activity occurred during the depositional stage of the Lower Shihezi Formation in the early middle Permian.

The magmatic activity identified in this study might have been responsible for a slight modification of the subsidence mechanism in this cratonic basin. The magmatism was located in the eastern part of the Hangjinqi area, and the basin basement in this region exhibits a relatively greater burial depth than that of the western part of the Hangjinqi area. The pre-existing blind faults and rifts in the basement represented weak zones exploited by upwelling magma. The magma mainly intruded into the basement, and the emplacement exhibited an isolated distribution; thus, the thermal impacts on the source rocks were minor. The collapse structures increased the burial depths of the source rocks and the thicknesses of the regional cap rocks. Some collapse structures are bounded by obvious faults, and these faults are meaningful in terms of gas migration.

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References

- Allen, P.A., and Armitage, J.J. 2012. Cratonic basins. John Wiley & Sons, Ltd.
- Chen, D., Wu, S., Völker, D., Dong, D., Shi, H., Zhao, S., and Zhu, L. 2015. Tectonically induced, deep-burial paleo-collapses in the Zhujiang Miocene carbonate platform in the northern South China Sea. *Marine Geology*, **364**: 43-52.
- Delpino, D.H., and Bermúdez, A.M. 2009. Petroleum systems including unconventional reservoirs in intrusive igneous rocks (sills and laccoliths). *The Leading Edge*, **28**: 804-811.

- 417 Gudmundsson, A., and Løtveit, I.F. 2014. Sills as fractured hydrocarbon reservoirs: examples and
418 models. Geological Society, London, Special Publications, **374**: 251-271.
- 419 Gui, H., Xu, J., and Zhang, D. 2017. Relationship between hydraulic conductivity of karst collapse
420 column and its surrounding lithology. Environmental Earth Sciences, **76**: 215.
- 421 Hansen, D.M., Redfern, J., Federici, F., Di Biase, D., and Bertozzi, G. 2008. Miocene igneous
422 activity in the Northern Subbasin, offshore Senegal, NW Africa. Marine and Petroleum
423 Geology, **25**: 1-15.
- 424 Hansen, J.P.V., Cartwright, J.A., Huuse, M., and Clausen, O.R. 2005. 3D seismic expression of
425 fluid migration and mud remobilization on the Gjallar Ridge, offshore mid-Norway. Basin
426 Research, **17**: 123-139.
- 427 He, K., Yu, G., and Lu, Y. 2009. Palaeo-karst collapse pillars in northern China and their damage
428 to the geological environments. Environmental Geology, **58**: 1029-1040.
- 429 Hsu, H.-H., Liu, C.-S., Chang, Y.-T., Chang, J.-H., Ko, C.-C., Chiu, S.-D., and Chen, S.-C. 2017.
430 Diapiric activities and intraslope basin development offshore of SW Taiwan: A case study of
431 the Lower Fangliao Basin gas hydrate prospect. Journal of Asian Earth Sciences, **149**:
432 145-159.
- 433 Li, B., Xie, Z., and Chen, C. 2006. Analysis on origin of calcite vein in Early Palaeozoic of Jiyang
434 Depression. Petroleum Geology & Recovery Efficiency, **13**: 22-24.
- 435 Li, G., Chen, Y., Jia, H., Zhao, Y., Xie, R., Liu, S., and Li, L. 2017. Occurrence and distribution
436 characteristics of fluids in tight sandstone reservoirs in the Shilijiahan zone, northern Ordos
437 Basin. Natural Gas Industry B, **4**: 174-181.
- 438 Liu, C.Y., Zhao, H.G., Gui, X.J., Yue, L.R., Zhao, J.F., and Wang, J.Q. 2006. Space—time
439 coordinate of the evolution and reformation and mineralization response in Ordos Basin. Acta
440 Geologica Sinica, **80**: 617-638.
- 441 Liu, H., Wang, Z., Xiong, B., Li, Y., Liu, L., and Zhang, J. 2000. Coupling analysis of

- 442 Mesozoic-Cenozoic foreland basin and mountain system in central and western China. *Earth*
443 *Science Frontiers*, **7**: 55-72.
- 444 Magee, C., Duffy, O.B., Purnell, K., Bell, R.E., Jackson, C.A.L., and Reeve, M.T. 2016.
445 Fault-controlled fluid flow inferred from hydrothermal vents imaged in 3D seismic reflection
446 data, offshore NW Australia. *Basin Research*, **28**: 299-318.
- 447 McDonnell, A., Loucks, R.G., and Dooley, T. 2007. Quantifying the origin and geometry of
448 circular sag structures in northern Fort Worth Basin, Texas: Paleo cave collapse, pull-apart
449 fault systems, or hydrothermal alteration? *AAPG Bulletin*, **91**: 1295-1318.
- 450 Peace, A., McCaffrey, K., Imber, J., Hobbs, R., van Hunen, J., and Gerdes, K. 2017. Quantifying
451 the influence of sill intrusion on the thermal evolution of organic-rich sedimentary rocks in
452 nonvolcanic passive margins: an example from ODP 210-1276, offshore Newfoundland,
453 Canada. *Basin Research*, **29**: 249-265.
- 454 Peng, W., Hu, G., and Huang, S. 2017. Natural gas geochemical characteristics and genetic
455 analysis: A case study of the Dongsheng gas field in the Ordos basin of China. *Journal of*
456 *China University of Mining & Technology*, **46**: 74-84.
- 457 Qi, R. 2016. Gas reservoir types in Shiguhao area of the Yimeng Uplift, Ordos Basin. *Oil & Gas*
458 *Geology*, **37**: 218-223.
- 459 Reynolds, P., Schofield, N., Brown, R.J., and Holford, S.P. 2018. The architecture of submarine
460 monogenetic volcanoes – insights from 3D seismic data. *Basin Research*, **30**: 437-451.
- 461 Senger, K., Millett, J.M., Planke, S., Ogata, K., Eide, C.H., Festøy, M., Galland, O., and Jerram,
462 D.A. 2017. Effects of igneous intrusions on the petroleum system: a review. *First Break*, **35**:
463 47-56.
- 464 Wang, M., He, D., Bao, H., Liu, R., and Gui, B. 2011. Upper Palaeozoic gas accumulations of the
465 Yimeng Uplift, Ordos Basin. *Petroleum Exploration and Development*, **38**: 30-39.
- 466 Wang, M., Song, S., Niu, Y., and Su, L. 2014a. Post-collisional magmatism: Consequences of

- 467 UHPMterrane exhumation and orogen collapse, N. Qaidam UHPM belt, NW China. *Lithos*,
468 **210**: 181-198.
- 469 Wang, T., Hou, M., Chen, H., Hou, Z., Chen, A., and Su, Z. 2014b. Coupling relationship between
470 Yinshan episodic orogenic movement of Hercynian tectonic cycle and filling cycle of the
471 North Ordos Basin in China *Journal of Chengdu University of Technology*, **41**: 310-317.
- 472 Xiao, X.M., Zhao, B.Q., Thu, Z.L., Song, Z.G., and Wilkins, R.W.T. 2005. Upper Paleozoic
473 petroleum system, Ordos Basin, China. *Marine and Petroleum Geology*, **22**: 945-963.
- 474 Xu, B., Nie, H., and Wang, M. 2009. A study of hydrocarbon-generating potential of Hangjinqi
475 prospect area in Ordos Basin. *Petroleum Geology & Recovery Efficiency*, **16**: 38-40.
- 476 Xu, Q., Shi, W., Xie, X., Busbey, A.B., Xu, L., Wu, R., Liu, K., 2018. Inversion and propagation
477 of the Late Paleozoic Porjianghaizi fault (North Ordos Basin, China): Controls on
478 sedimentation and gas accumulations. *Marine and Petroleum Geology*, **91**:706-722.
- 479 Yang, M., Li, L., Zhou, J., Jia, H., Sun, X., Qu, X., Zhou, D., Gong, T., and Ding, C. 2015.
480 Mesozoic structural evolution of the Hangjinqi area in the northern Ordos Basin, North China.
481 *Marine and Petroleum Geology*, **66**: 695-710.
- 482 Yang, P., Ding, B., Fan, C., Zhu, X., Wang, Y., and Yang, P. 2017. Distribution pattern and origin
483 of the columnar pull-down anomalies in Gaoshiti Block of Central Sichuan Basin, SW China.
484 *Petroleum Exploration and Development*, **44**: 399-408.
- 485 Yang, Y., Li, W., and Ma, L. 2005. Tectonic and stratigraphic controls of hydrocarbon systems in
486 the Ordos basin: A multicycle cratonic basin in Central China. *AAPG Bulletin*, **89**: 255-269.
- 487 Zhang, C., Liu, S., Luo, S., and Wang, M. 2016a. Structure and Geological Significance of Pishan
488 Caldera in Tarim Basin. *Xinjiang Petroleum Geology*, **37**: 281-285.
- 489 Zhang, S.-h., and Lin, C.-r. 2008. Study on the genesis of karstic collapse column and
490 characteristics of high resolution seismic data in one coal field. *Journal of Coal Science and*
491 *Engineering (China)*, **14**: 648-650.

Zhang, W., Li, L., and Jia, H. 2016b. Reservoir-forming dynamics and gas-water distribution characteristics of lithologic traps in the 1st Member of Xiashihezi Formation in the Shilijiahan zone, Hangjinqi area, Ordos Basin. *Oil & Gas Geology*, **37**: 189-196.

Zhang, Z., Zhang, H., Shao, J.a., Ying, J., Yang, Y., and Santosh, M. 2014. Mantle upwelling during Permian to Triassic in the northern margin of the North China Craton: Constraints from southern Inner Mongolia. *Journal of Asian Earth Sciences*, **79**: 112-129.

Zhao, G. 2016. Thermal evolution modeling of Neopaleozoic source rocks in Hangjinqi region, Ordos Basin. *Petroleum Geology & Experiment*, **38**: 641-646.

Zuo, J.-P., Peng, S.-P., Li, Y.-J., Chen, Z.-H., and Xie, H.-P. 2009. Investigation of karst collapse based on 3-D seismic technique and DDA method at Xieqiao coal mine, China. *International Journal of Coal Geology*, **78**: 276-287.

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Figure 2. Schematic Paleozoic stratigraphic column of the Hangjinqi area. The logging curves are from well J94.

Figure 3. Horizon calibration of the Paleozoic strata in the study area. The Ordovician carbonate has been drilled by wells J94, J121 and J104.

Figure 4. (a) The west-east well section crossing the southern part of the study area. (b) Isopach map of the coal-bearing measures thickness based on well control. (c) Isopach map of the Lower Shihezi Formation based on well control. The map was created by 3D seismic data using OpenSpectra.

Figure 5. Attribute map of coherence (a) and throw (b) in the southern part of the 3D seismic survey. The map was created by 3D seismic data using OpenSpectra.

Figure 6. (a) The deep reflection time profile in northeast orientation; black box indicates the location Figure 6(b). (b) The enlarged section of collapse structures.

Figure 7. The basement structures associated with collapse structure, including the wider columnar reflections (a), the blind faults (b), the preexisting basement rifts (c) and the smaller columnar reflections in the basement (d).

Figure 8. Core photographs of the calcite vein (a) and the tuff (b) in the H₁ member of well J77. The histograms of salinity (c) and metamorphism coefficient (d) of the formation water of the H₁ member. (e) The gas composition histogram labeled with gas production in Shanxi Formation.

Figure 9. The west-east seismic profile (a) and waveform similarity profile (b) crossing collapsed structures. The seismic profile, together with the waveform similarity profile seems to reveal magmatic conduits.

Figure 10. The south-north seismic profile (a) and waveform similarity profile (b) crossing collapsed structures. The pull-up reflection and thinning carbonate strata can be seen from seismic section.

Figure 11. (a) The seismic profile of the largest collapse of the T9d. The thickness between the T9d and the T9g has increased due to the collapse structures. (b) The seismic profile of T9g horizon is flattened (c) The north-south seismic profile crossing collapse structures. Pull-up reflection existing in the internal magmatic conduit reflection, with the T9b and T9d reflections offset.

Figure 12. Distribution pattern of collapse structures in the three-dimensional seismic surveys.