



Karstification of Ordovician carbonate reservoirs in Huanghua depression and its control factors

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Abstract

With extensive ancient karsts and abundant oil and gas resources, the Ordovician carbonate reservoirs in the Huanghua depression have broad prospects of exploration and development. The types, characteristics, distribution and controlling factors of karsts were investigated by means of the analysis of cores, thin slices, logging, seismic, and geochemical data in this study. The study reveals that the Ordovician carbonate reservoirs in the Huanghua depression falls into three main categories, pore type, pore-vug-fracture type and fracture type, of which, pore-vug-fracture reservoirs account for 62%. The epigenetic uniform karst mainly developed in the Late Ordovician to Early Carboniferous, while the differential karst developed in the Mesozoic. The uniform karstification mainly include chemical dissolution of the original carbonate rock, while the differential karstification not only include chemical dissolution but also hydraulic erosion and biochemical dissolution by organic acid. The burial karstification mainly involved the dissolution of the Ordovician reservoir by large amount of acidic fluids generated by the overlying Upper Paleozoic coal measure source rock while generating hydrocarbon. The dissolution caused by upwelling magmatic-tectonic hydrothermal fluids along faults also contributed to the formation of burial karst reservoirs. The sedimentation-diagenesis and paleogeomorphology-tectonic movement have certain control effects on the karstification of the Ordovician reservoirs in the Huanghua depression, determining the reservoir quality.

Keywords Ordovician · Karstification · Surface karst · Burial karst · Carbonate rock · Huanghua depression

Introduction

Studies on karst and reservoirs started in the 1960s abroad (Roehl 1967; Ford and Ewers 1978; Esteban and Klappa 1983; James and Choquette 1984). With the rise of the oil and gas industry, study on karst reservoir has also advanced and gradually become a systematic discipline, karstology. Chinese karstology study started back in the 1970s (Tang 1978). To the 1990s, with the rise of China's oil and gas industry, the study on karst and oil and gas reservoirs in

China basically went shoulder and shoulder with those abroad. Some achievements on karstology study and oil discoveries were made in the Ordos Basin, Sichuan Basin and Tarim Basin (Su et al. 2015; Zhang et al. 2017; Fu et al. 2017; Xu et al. 2017; Li et al. 2017; Han et al. 2017).

The oil and gas exploration targeting Ordovician karst reservoir of Huanghua depression in the central of the Bohai Bay Basin started early in the 1970s but failed to make major discoveries due to the lack of basic geological understanding. Since the discovery of the high production Ordovician reservoirs inside Qianmiqiao Buried hill and Kongxi buried hill in the late 1990s, basic geological research on Ordovician has received due attention (Yu et al. 1999; Jiang 2000; Wang et al. 2000). Subsequently, industrial oil and gas flows were tapped in several Ordovician carbonate karst reservoirs in Gangbei buried hill, Wumaying–Wanguantun buried hill, Chenghai buried hill, Zhaodong buried hill and Nandagang buried hill (Fu et al. 2002, 2010, 2013; Zhang et al. 2019a). Therefore, to study karstification of the Ordovician carbonate rocks in the Huanghua depression, we examined the petrologic features and classified the karst reservoirs

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through core observation, thin section identification, well logging analysis and core CT scanning, sorted out controlling factors of karstification through analysis of carbon and oxygen isotope, strontium isotope and fluid inclusions and defined the lateral and vertical distribution of karstification using 3D seismic and 2D seismic data. The study will enrich and improve the basic geological information of the Ordovician reservoir in the buried hill, and provide the geological basis for the fine exploration of buried hill.

Geological background

The Huanghua depression is located in the central part of the Bohai Bay Basin in eastern China, and geologically between the Cangxian uplift and Chengning uplift, ending at Yanshan tectonic belt in the north. The depression, with an area of $1.8 \times 10^4 \text{ km}^2$, is a first-order negative structure of Bohai Bay Basin in eastern China (Fig. 1). The Huanghua depression has all strata from Proterozoic to Neogene,

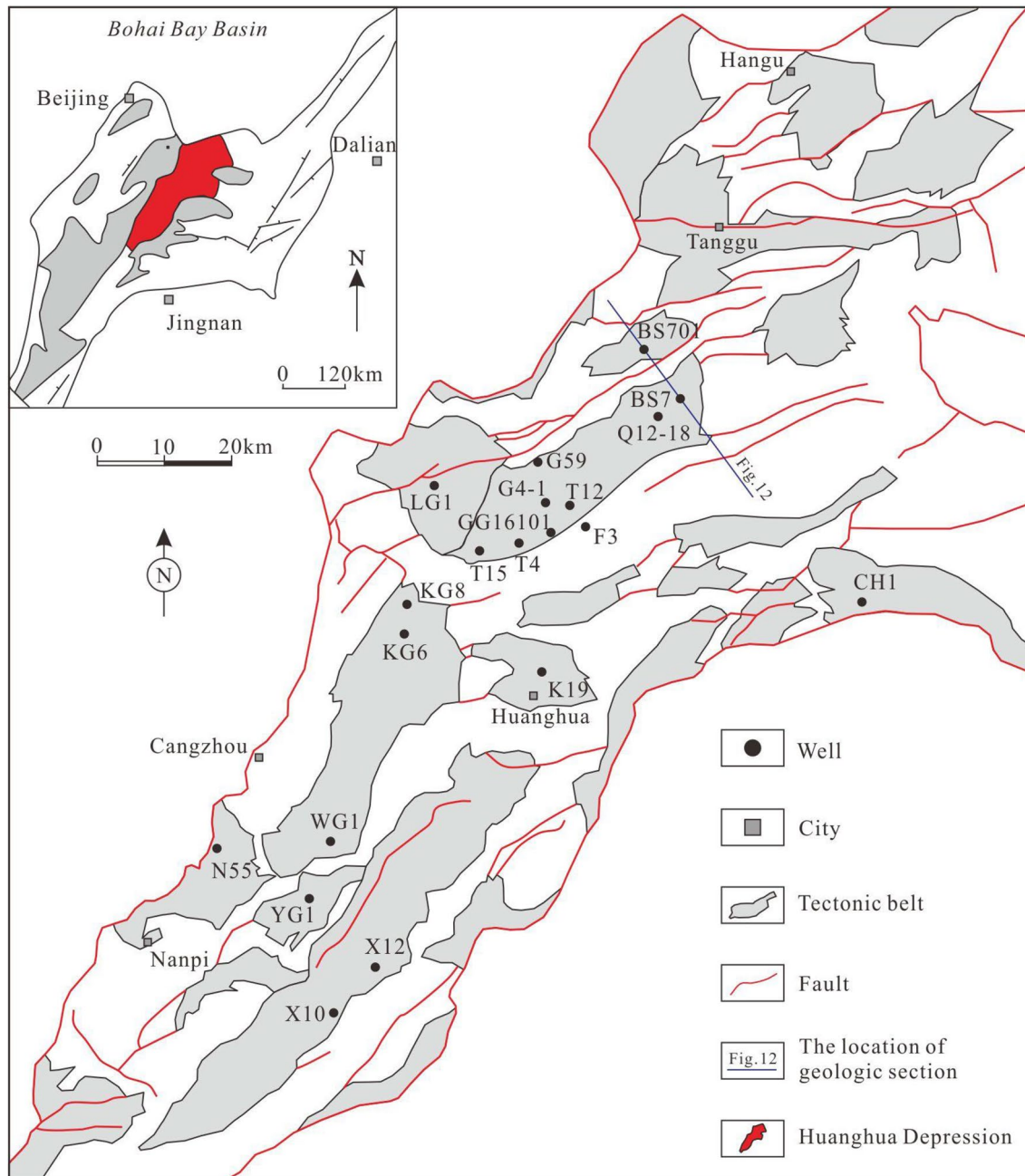


Fig. 1 Location map of the study area. The information of the map sources from the internal data of Dagang Oilfield Company

which correspond to six major tectonic cycles, Jixian, Caledonian, Hercynian, Indosinian, Yanshanian and Himalayan (Meng et al. 2014). The Upper Proterozoic to Lower Paleozoic Cambrian and Ordovician in the Huanghua depression are marine deposits of epicontinental sea facies on stable craton dominated by marine carbonate strata, with minor coastal clastic strata between the Lower Cambrian and the Lower Proterozoic (Zhang et al. 1999; Zhao et al. 2017). Caledonian tectonic movement happened in North China during middle-late Ordovician; from Silurian to early Carboniferous, North China experienced regional uplift and a depositional hiatus of 120 Ma, consequently, Silurian and Devonian strata are absent (Zhai 2010). From Carboniferous of Late Paleozoic, the North China craton entered the evolution period of large scale depression of in-land basin, and coal measures strata of alternative marine-continental facies deposited during late Carboniferous, and continental clastic strata deposited during Permian along with large scale marine regression. During Mesozoic, Huanghua depression experienced the Indosinian and Yanshan movements, Jurassic to Cretaceous and locally residual Triassic deposited, which represent products during the breakup of Huabei craton and are dominated by clastic strata in intracontinental faulted depression (Zhou et al. 2012). The lower Jurassic strata are mainly thick pebbly sandstone interbedded with coal measures, and the upper strata are composed of volcanic rock interbedded with graywacke. The Cretaceous is composed of purple mudstone and volcanic rock with sandstone interbeds. Affected by rifting activities of NNE fault belts like Tanlu fault belt (Wang 2006; Zhu et al. 2010), during Cenozoic, Huanghua depression evolved from the initial rift in Eocene to extensional rift in Oligocene, going through several stages of rifting (Zhang et al. 2019b), Kongdian Formation, Shahejie Formation, Dongying Formation, Guantao Formation, Minhuazheng Formation and Pingyuan Formation deposited and from bottom to top, and subsidence center shifted several times, which can be divided into six stages of evolution (Fig. 2). Affected by multi-phases of tectonic movements, more than ten oil-bearing buried hill structures including, Qianmiqiao, Gangbei, Nandagang, Wangguantun and Wumaying are formed in Huanghua depression. With a large quantity of oil and gas resources, the Ordovician in the Huanghua depression is the major target of buried hill reservoir exploration and has broad prospects of exploration and development.

Data and study methods

The cores this study were all taken from Ordovician carbonate intervals in 50 exploration wells of the Huanghua depression. The wells are at Heilongcun uplift, Kongdian uplift, Qinan sub-depression, Gangxi uplift, Qibei sub-depression

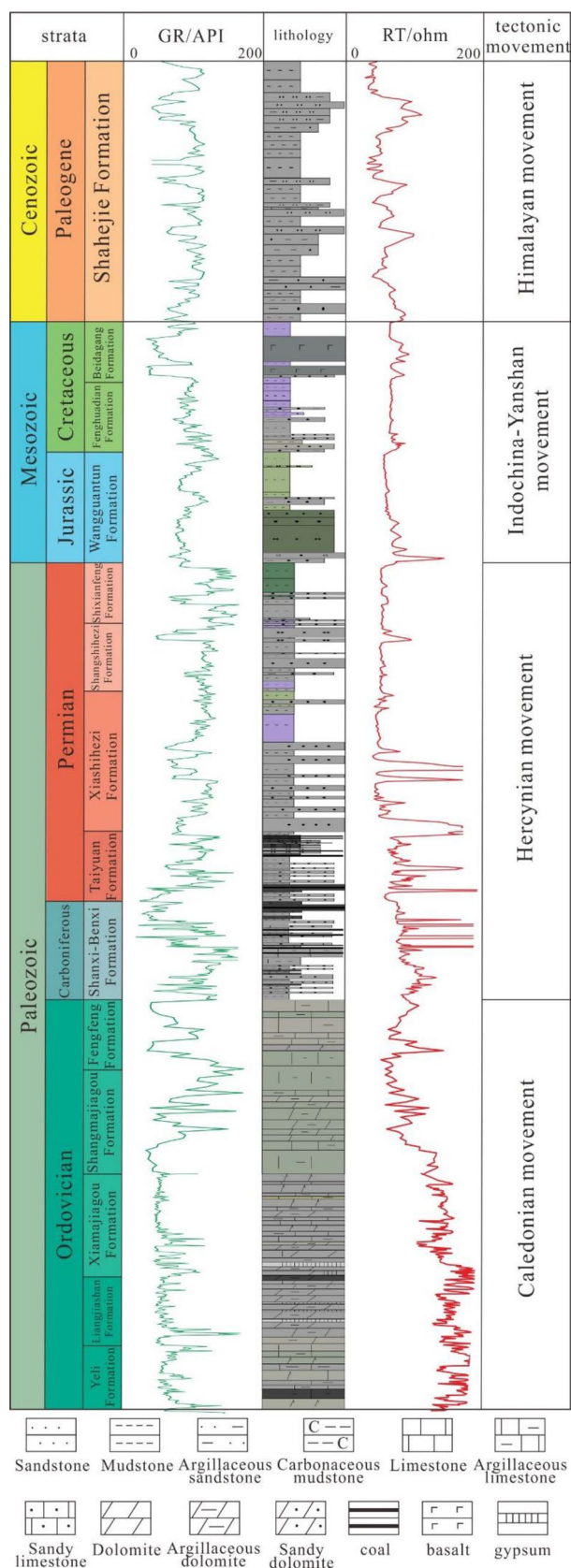


Fig. 2 The strata frame of the Huanghua depression. The information of the map sources from the internal data of Dagang Oilfield Company

and Chengbei uplift and the core recovery rates of all the coring intervals are nearly 100%. Over 100 samples in total were collected from cores of these 50 wells, and thin sections were observed with a Leica DMLP polarizing microscope.

Cores from Well GG16101 were scanned with a 16-bit X-ray CT scanner with high resolution and micro focus in the State Key Laboratory of Coal Resources and Safe Mining of China University of Mining and Technology.

Fluid inclusions in eight of the over 100 core samples were tested in the Beijing Research Institute of Uranium Geology with a THMSG-600 hot and cold table system produced by British Linkam Company at the temperature range of $-196\text{ }^{\circ}\text{C}$ to $600\text{ }^{\circ}\text{C}$, homogenization temperature reproduction error of less than $2\text{ }^{\circ}\text{C}$ and freezing point temperature reproduction error of less than $0.2\text{ }^{\circ}\text{C}$.

Fifty-five samples were ground and tested for carbon and oxygen isotopes at the Experimental Center of Earth Sciences and Technology Institute of Southwest Petroleum

University with MAT-252EM gas stable isotope ratio mass spectrometer manufactured by Finnigan, USA.

The 3D seismic data and logging data used this study are provided by Dagang Oilfield Company of PetroChina. The seismic data has a trace spacing of $25\text{ m} \times 25\text{ m}$ and an area of 7654 m^2 .

Characteristics of Ordovician reservoir

According to the core observation and thin slice identification of 50 wells such as Well GG16101, T12 and BS7, the pore space of Ordovician reservoir in Huanghua depression is mainly composed of primary pores, dissolved pores, vugs and fractures. In this paper, the reservoirs are classified into pore type, pore-vug-fracture type and fracture type (Fig. 3).

The first type, the pore type reservoir mainly contains dolomite and limestone primary pores, and most dolomite

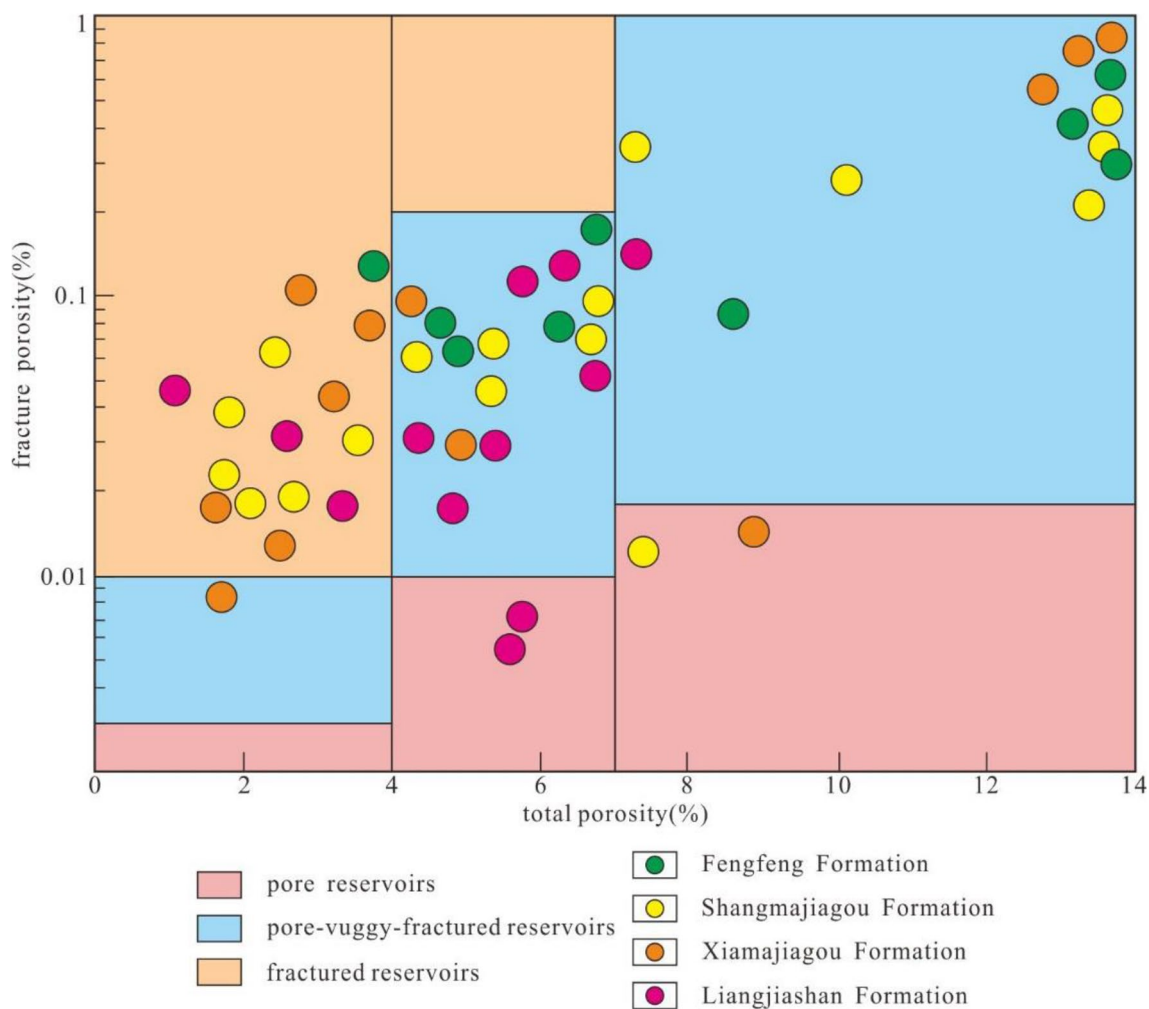


Fig. 3 Classification of the Ordovician karst reservoirs in the Huanghua depression

primary pores are filled by late cement. According to sample statistics, this kind of reservoir accounts for 8% of the total.

The second type, the pore-vug-fracture type reservoir, is controlled by karstification and tectonic fractures jointly. Karstification is the key factor affecting the quality of the reservoir. Most of the buried hill reservoirs in Huanghua depression are pore-vug-fracture ones, accounting for 62% of the total. Especially, the reservoirs in the area of Beidagang to Qianmiqiao have large numbers of fractures, dissolved pores and vugs in the cores (Fig. 4). The fractures and dissolved pores in the cores are not completely filled with cement, so the effective pores can serve as favorable reservoir space, and the reservoir is high in quality and the focus of oil and gas exploration in the Huanghua depression.

The third type, the fracture-type reservoir, which is characterized by low matrix porosity but higher permeability, has mainly fracture-vugs controlled by tectonic

fractures as main storage space. This type of reservoir is widely distributed in Huanghua depression, accounting for 30% of the total samples. The carbonate reservoir within tectonic fracture or broken belt of fault is dissolved or cemented, and some unfilled fractures become favorable storage space of oil and gas (Fig. 5).

Analysis of reservoir karstification

There are three types of Ordovician carbonate reservoirs in the Huanghua depression, among which, the pore-vug-fracture type shows features of intense karstification. The available data reveals the karstification includes two types, epigenetic karstification and burial karst. Due to the different mechanisms, they have differences in petrological characteristics.

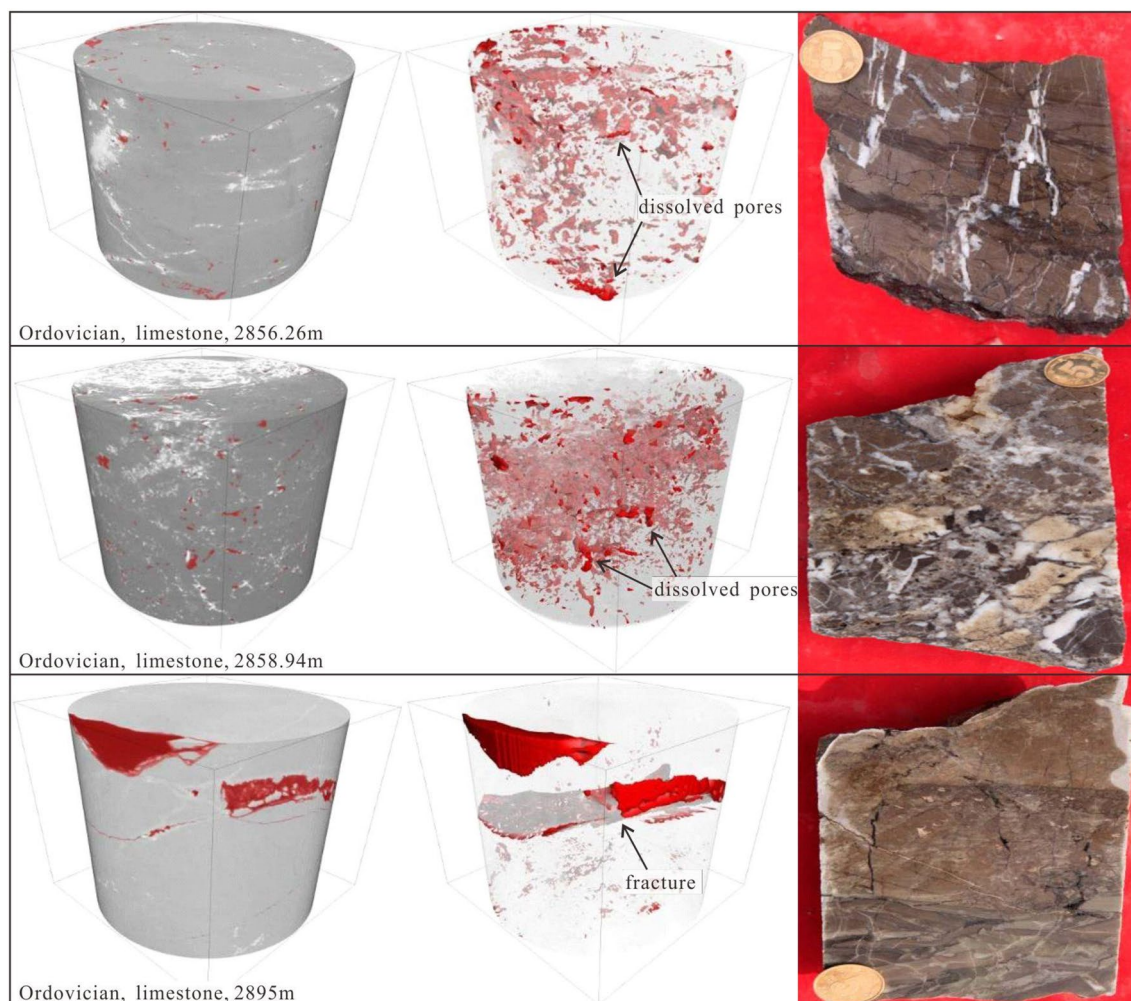


Fig. 4 CT scan images of cores from the Ordovician karst reservoir in Well GG16101. Fractures and secondary dissolution pores are abundant

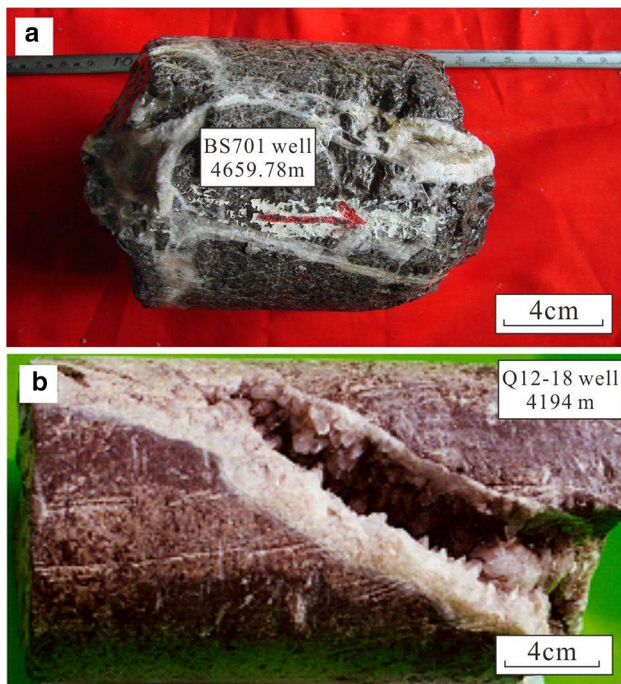


Fig. 5 Core characteristics of fractured reservoirs in the Huanghua depression. **a** Core from Well BS701, 4659.78 m, Fengfeng Formation, with high angle fractures filled by calcite; **b** Core from Well Q12-18, 4194 m, Fengfeng Formation of Ordovician, with large fractures partially filled by calcite

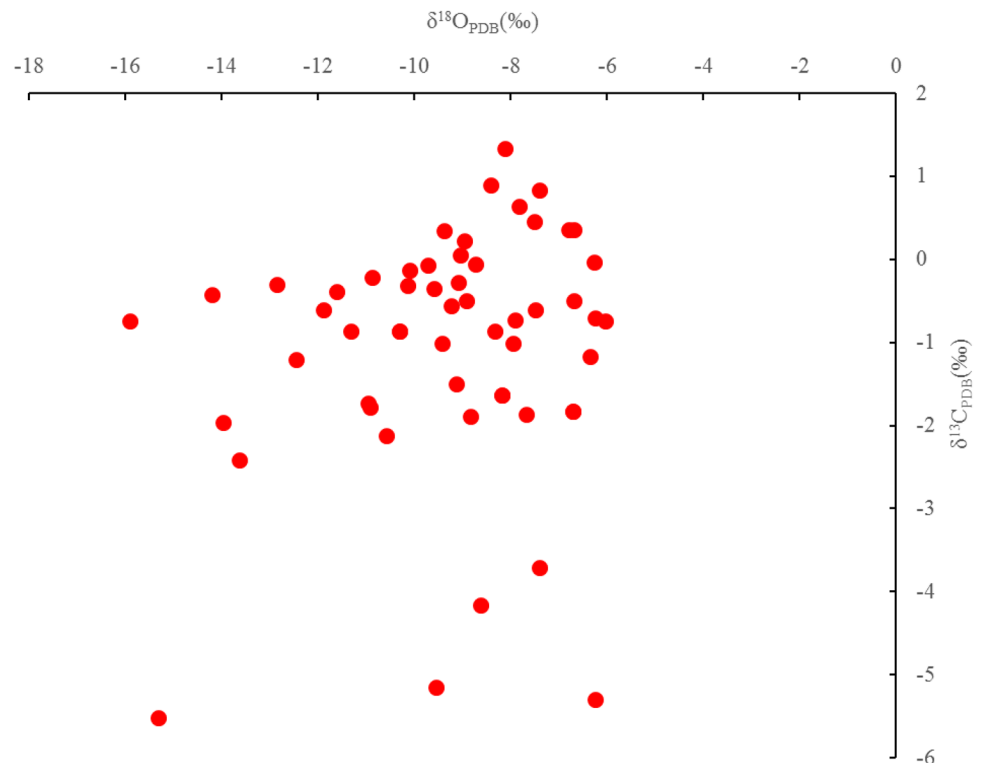
Epigenetic karst reservoir

Geochemical characteristics

The dolomite and calcite minerals fillings of the samples were tested for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, and the results show that dolomite and calcite minerals produced by karstification have small ranges of $\delta^{13}\text{C}$ (PDB) and $\delta^{18}\text{O}$ (PDB) (Fig. 6), with $\delta^{13}\text{C}$ (PDB) values ranging from -5.52 to -1.33 , -1.07 ‰ on average; and $\delta^{18}\text{O}$ (PDB) values ranging from -15.9 to -6.03 , -9.37 ‰ on average. The obvious negative value of $\delta^{18}\text{O}$ indicates that the fillings of dissolved pore-vug-fracture was affected by meteoric freshwater, reflecting the epigenetic weathered crust environment of the karstification. A few samples have highly negative $\delta^{18}\text{O}$ (PDB) values, which may be related to burial karstification.

The Sr/Ba ratio can reflect whether the carbonate rock is of seawater origin or freshwater origin (Loucks 1999; Mcmechan et al. 2002; Breesch et al. 2009). Generally, Sr/Ba of freshwater facies sediment is less than 1, while that of marine sediment is greater than 1. As Ba^{2+} can replace Ca^{2+} in sulfate and carbonate, the Sr/Ba value of micritic dolomite containing anhydrite is more than 1; while the Sr/Ba value of dolomite and limestone not containing anhydrite or gypsum pseudocrystals is less than 1, suggesting they may be related to karstification of meteoric freshwater. Most samples from Ordovician reservoir in Huanghua depression have Sr/Ba

Fig. 6 Cross plot of carbon and oxygen isotopes of Ordovician carbonate rock samples from Huanghua depression



of less than 1, ranging between 0.109 and 0.952 (Table 1), indicating freshwater weathering and leaching background.

Macroscopic and microscopic signs of epigenetic karstification reservoirs

In epigenetic karstification, as the formation is exposed directly to the surface to suffer leaching by meteoric freshwater, while forming karst rock, the pores, vugs and fractures of karst would be filled with terrigenous materials (such as mud, silt sand and silt mud), neogenic minerals (such as bauxite, iron oxide, clay minerals, tuffaceous matter, and freshwater calcite), and insoluble residues in carbonate rocks (Fig. 7a, b). The dissolved pores and vugs filled with purple sparry calcite and bauxite layer over weathered crust are commonly seen. For instance, in Well X12, X10 and T4, purple sparry calcite is seen along vugs, fractures and between grains (Fig. 7c). In Well T4, the bauxite layer in weathered crust is nearly 3 m thick, and in Well K19, the bauxite layer over weathered crust is even over 11 m thick. Gypsum/anhydrite pseudocrystals formed by surface dissolution-filling are observed in thin sections of some wells.

Burial karstification reservoir

In burial condition, as the diagenetic fluid contained acidic materials like CO₂, H₂S, organic acids and even hydrothermal fluids after the magma period, it would cause dissolution the surrounding rock, especially carbonate rock, giving rise to dissolved pores, vugs, and fractures and some new minerals. The homogenization temperature of fluid inclusion in a mineral is a good indicator of the ambient temperature and burial conditions at which the mineral is formed (Jiang et al. 2016). The mineral species associated with burial environment or hydrothermal activities can be seen on cores and thin sections, which include deformed dolomite, sphalerite,

fluorite, pyrite, quartz, ankerite and ferroan calcite in some occurrences etc.

Fluid inclusion characteristics

The temperatures of the fluid inclusions in calcite filling in dissolved pores and vugs of the Ordovician reservoir were tested. It is found the fluid inclusions in the samples are mainly hydrocarbon-bearing brine inclusions formed after calcite filling in the limestone pores, most inclusions are in linear or in belt distribution along micro-cracks of calcite veins. The liquid hydrocarbon in the inclusions is light yellow or yellow, and sends out green and yellow-green fluorescence. The hydrocarbon gas in the inclusions is gray, with no fluorescence. Among these inclusions, oil inclusions account for 15%, oil and gas inclusions account for 60%, and gas inclusions account for 25%. The temperature measurement results show that inclusions of the 106 samples have a homogenization temperature range from 96 to 168 °C, and an average of 135 °C (Fig. 8), which is much higher than the normal formation temperature. The inclusions have a salinity range from 0.18 to 22.31, and 7.65% on average, which is much higher than the normal seawater salinity. The test results show that the reservoir has experienced reformation by high-temperature brine fluid.

Some gas inclusions in the samples contain methane, methane content of some inclusions reaches 100%. Some gas inclusions also contain acidic gas such as CO₂ and H₂S. Some liquid inclusions contain a small amount of CO₂, H₂S and methane. Twenty-six samples contain methane, accounting for approximately 52% (Table 2). Nine samples contain H₂S, accounting for approximately 18%. The acidic fluid from the evolution of hydrocarbons was mixed into the burial karst fluid, causing organic acid dissolution to the Ordovician reservoir.

Table 1 Sr/Ba analysis data of Ordovician reservoirs in Huanghua depression

Well name	Well depth (m)	Horizon	Lithological description	Sr (%)	Ba (%)	Sr/Ba
K19	2173.55	O _{2f}	Granular micrite with several calcite veins	0.02542	0.23258	0.109
GG4-1	2185.73	O _{2f}	Micrite, with dissolved fractures filled by calcite	0.03575	0.18746	0.191
K19	2172.4	O _{2f}	Granular micrite with calcite veins	0.02142	0.10315	0.208
G2035	3074.39	O _{1y}	Dolomitic micrite, with dissolution pores filled by calcite	0.05147	0.13589	0.379
BS701	4621.98	O _{1y}	Micrite with network calcite veins	0.03033	0.05846	0.519
KG8	3014.1	O _{2f}	Micrite, with dissolution fractures filled by calcite	0.01888	0.03364	0.562
LG1	3901.3	O _{2s}	Micritic dolomite, with dissolution cave filled by calcite	0.01556	0.02087	0.746
BS701	4656.76	O _{1y}	Dolomitic karst breccia	0.01338	0.01774	0.754
N55	1973.44	O _{2f}	Micritic dolomite with calcite veins	0.00612	0.00782	0.783
G2035	3072.03	O _{1y}	Micrite limestone with calcite veins	0.03851	0.04338	0.888
CH1	2350.75	O _{2s}	Powdered crystal dolomite with calcite veins and ferrous calcite veins	0.01292	0.01357	0.952

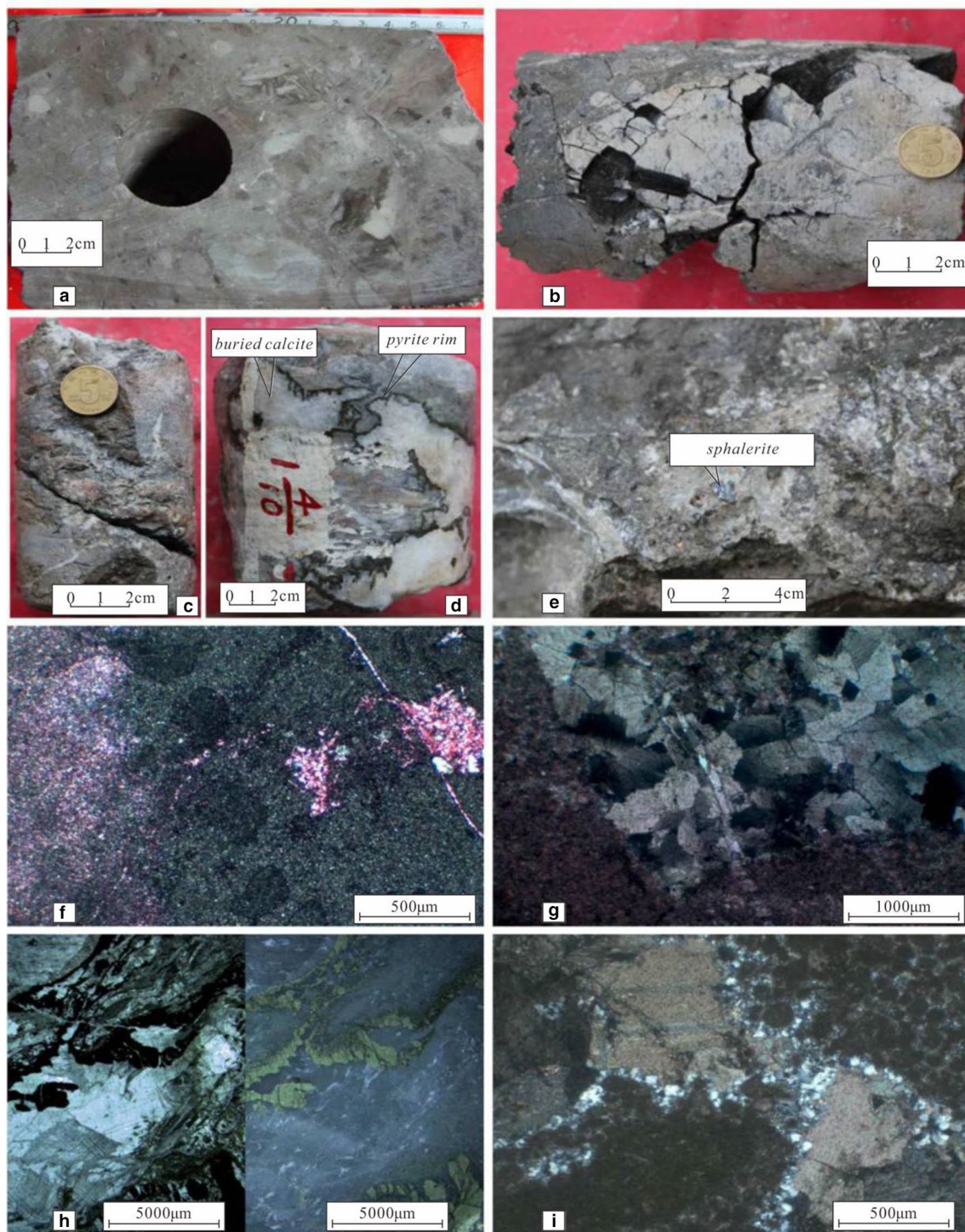
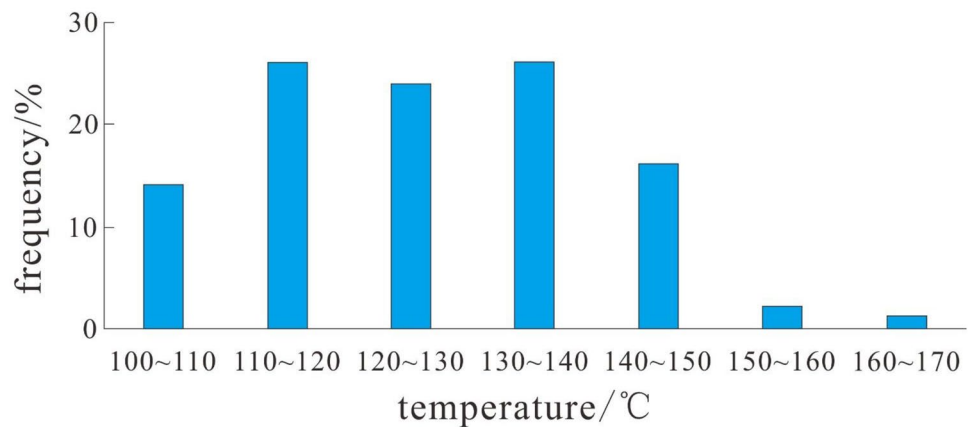


Fig. 7 Macroscopic and microscopic signs of reservoir karstification **a** Well Q12-18, 4192 m, Fengfeng Formation of Ordovician, dissolution caves filled with breccia; **b** Well LG1, 3690.21 m, Fengfeng Formation of Ordovician, caves filled with black limestone- argillaceous; **c** Well X12, 1464 m, Fengfeng Formation of Ordovician, greenish gray karst breccia, the purple breccia is coarse crystalline calcite; **d** Well T4, 2066.25 m, the Lower Majiagou Formation of the Ordovician, grey micrite with calcite vein, caves and pyrite ring along cave wall; **e** Well KG6, 2721 m, Upper Majiagou Formation of Ordovi-

cian, with spherulite developed; **f** Well KG6, 2721.28 m, the Upper Majiagou Formation of Ordovician, fractures filled with purple-red spherulite crystals (+), **g** Well CH1, 2227.39 m, Lower Majiagou Formation of Ordovician, fractures and dissolved pores filled with coarse deformed dolomite (+), **h** Well BS701, 4459.78 m, Fengfeng Formation of Ordovician, fluorite in micritic dolomite(+); **i** Well T4, 2067 m, Fengfeng Formation of Ordovician, dissolved pores filled with pyrite ring (+)

Fig. 8 Homogenization temperature of hydrocarbon bearing brine inclusions of Well WG1**Table 2** Data of inclusion components

Well name	Well depth (m)	Liquid inclusions (%)				Gaseous inclusions (%)						
		CO ₂	H ₂ S	CH ₄	H ₂ O	CO ₂	H ₂ S	CH ₄	N ₂	H ₂	C ₂ H ₄	C ₆ H ₆
BS701	4623.92	0.9		0.2	98.9		4.1	95.9				
BS701	4648.78	1.2		0.2	98.6			57.7		42.3		
BS701	4628.63		0.3	0.4	99.2		10.7	84		5.3		
K19	2378.07		0.4		99.6			46	54			
G2035	3070.39			0.9	99.1			80.6		6	13.4	
LG1	3901.3			0.6	99.4			88.4		4.8		6.8
T9	2995		0.3	0.3	99.4			69.7		30.3		
T12	1968.5				100			72.9		27.1		
T15	2620.23			1.7	98.3			100				
YG1	1577.26				100	68.7	21.8			9.5		

Macroscopic and microscopic signs of the burial karst reservoir

Burial karstification mainly produces microscopic dissolved pores and specific diagenetic minerals. For example, dissolution pores filled with pyrite ring at pore wall and then coarse sparry calcite were seen at 30 m from the formation top in Well T4 (Fig. 7d). Sphalerite was found at the top of the upper Majiagou Formation in Well KG6 (Fig. 7e, f). Powdered micrite and dissolution pores and fractures filled with coarse crystalline anomalous dolomite were observed at lower Majiagou Formation in Well CH1 (Fig. 7g). Fluorite emitting blue light under cathodoluminescence was found in the micritic dolomite at 4659.78 m of Well BS701 (Fig. 7h). The appearance of this low-temperature hydrothermal mineral proves thermal fluid karstification and metasomatism happened during burial of the formation. Not only pyrite rings, but also giant crystal calcite and interlaced pyrite were also found in the dissolved pores and vugs at 30 m from the formation top in Well T4 (Fig. 7i).

Development and control factors of karstification

Epigenetic karstification

The regional tectonic movement caused the rise or fall of the sedimentary basin. The epigenetic karstification took place when the formation outcropped. Therefore, tectonic movement controls the development of epigenetic karstification. The Ordovician in the Huanghua depression experienced two stages of weathering and leaching (Zhang et al. 2019b). The first stage is the Late Ordovician to Early Carboniferous, during which the Huanghua depression experienced overall uplifting, and the whole Ordovician outcropped above the ground, so the karstification of this first stage is uniform karstification (Fu et al. 2016). The second stage is from Late Triassic to Late Jurassic, during which the northern part of the Ordovician in the Huanghua depression outcropped, while the southern part didn't crop out of the surface, so the karstification of this stage is differential karstification.

Development characteristics of uniform karstification

The background of uniform karstification in the Huanghua depression was the vertical uplifting of vast area of carbonate platform with similar lithology and initial flat geomorphology but no faults and fractures (Fig. 9). In the process of dissolution of the dense carbonate rock of similar lithology by meteoric freshwater, there weren't enough fractures and geomorphic difference to guide meteoric freshwater to move and erode along specific vertical direction, resulting in similar karstification strength laterally and no obvious vertical karst geomorphology difference.

The development of uniform karstification needs three basic conditions: flat initial landform, no vertical faults and fractures, and dense and uniform lithology. For Huanghua depression, what we can tell from these three basic conditions is: ① The initial topography in the interior of the Huanghua depression was flat; ② the uplifting from late Ordovician to Early Carboniferous was overall uplifting, so there was no fault or fracture developed at early stage of the depression, and there were only folds and fractures developed at the edge of the depression; ③ Huanghua depression then was offshore carbonate platform where a large set of soluble but dense carbonate deposits with uniform lithology laterally developed.

Normally, karstification includes chemical dissolution and hydraulic erosion, but from Late Ordovician to Early

Carboniferous, the Ordovician carbonate in Huanghua depression only had chemical dissolution but no hydraulic erosion. The atmospheric precipitation with high CO_2 content should have been very conducive to the dissolution of carbonate rock, but due to the flat original geomorphology and the lack of geological structures such as faults and fractures, when the atmospheric precipitation with high CO_2 content fell on the ground, it flew on the ground surface and quickly flew away, and couldn't stay long to react with surface carbonate or get down deep, so the karstification wasn't high in intensity and failed to form karst landform differences. Since the Huangqi depression was flat during this period and there was not high enough slope, therefore, the hydraulic erosion then was weak, especially in the Late Ordovician. Only after the early Carboniferous when obvious topography or landform difference occurred, was the contribution of hydraulic erosion increased somewhat.

In the Huanghua depression, the uniform karstification produced small scale of dissolved pores, dissolved fractures and dissolved vugs, and karst caves in gypsum-salt layers across the area. The reservoir after this reformation turns better in storage capacity in general. Uniform karstification mainly took place on the surface, but the atmospheric freshwater rich in CO_2 could also flow along the microscopic cracks generated by physical weathering and seep down vertically, and stay longer in the fractures, thus enhancing karstification intensity and producing

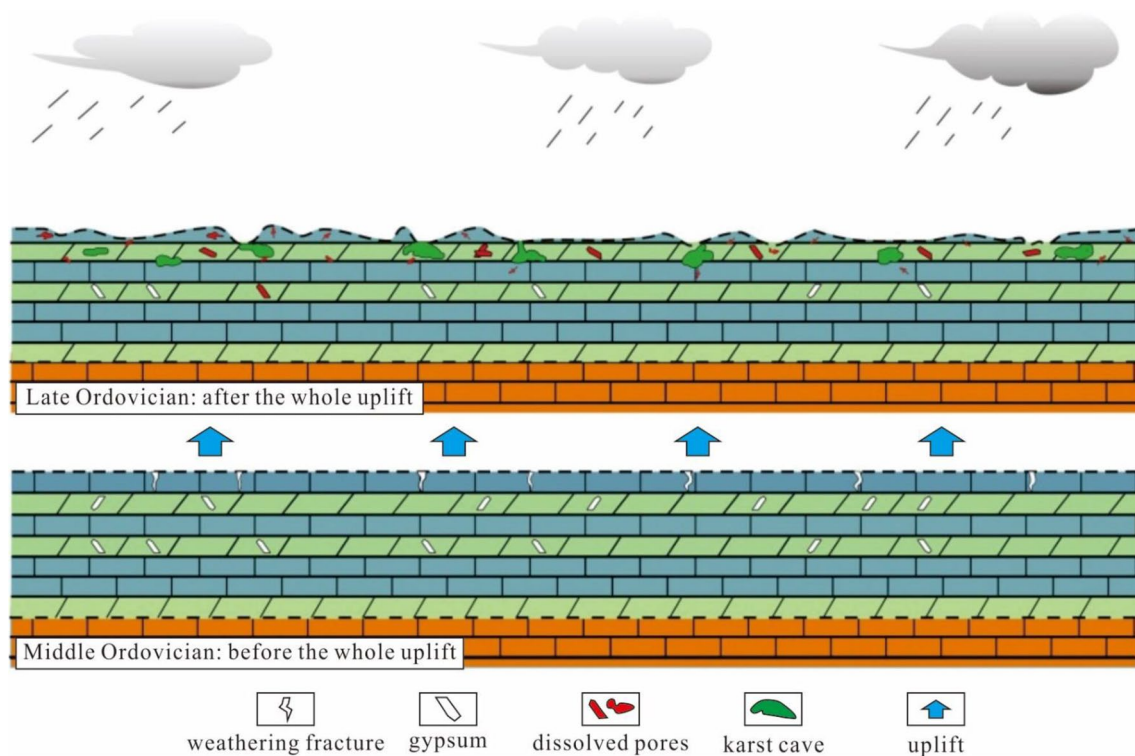


Fig. 9 Model of the uniform karstification of the Ordovician buried hill

dissolved pores, dissolved vugs and fractures. The topography/landform difference would get bigger with time, the soluble evaporative salt minerals such as anhydrite would be dissolved in large scale, even forming karst caves. The topographic features in early uniform karstification were similar to those of the karst highland, while the later karst has both vadose dissolution and phreatic lateral dissolution, so it has features of both karst highlands and karst slope.

Mechanism and occurrence of differential karstification

Differential karstification happened in the Huanghua depression in the Mesozoic with intense dissolution, producing a large number of karst caves. The differential karstification came about, as differential uplifting of the basement and tectonic movements gave rise to faults, fractures and folds, and long-term uniform dissolution in the late stage of uniform karstification resulted in big difference in landform and widely distributed gullies in the outcrop area (Fig. 10). Based on the difference in topographic and tectonic setting, the differential karstification in Huanghua depression is

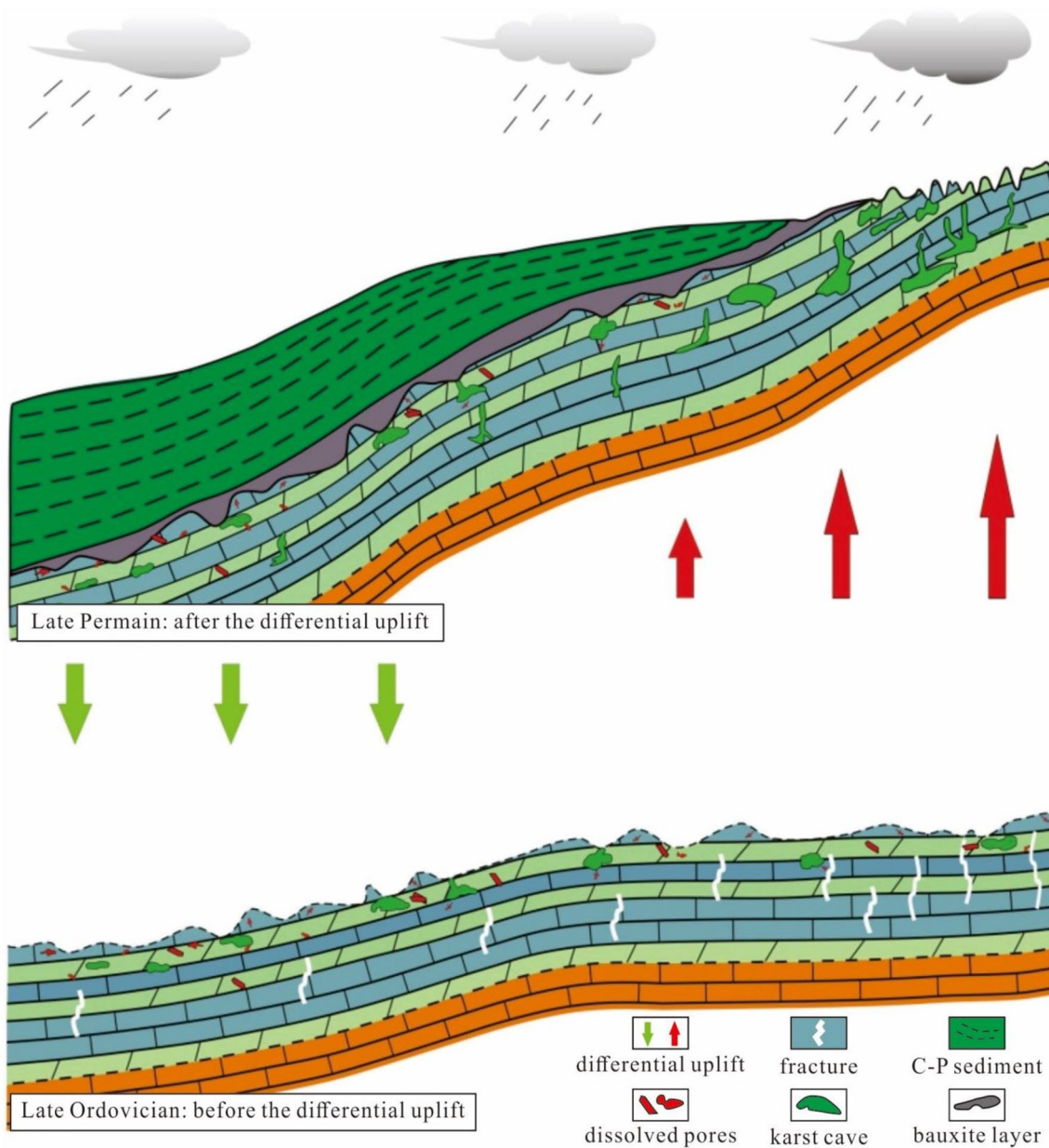


Fig. 10 Model of differential karstification of the Ordovician buried hill

further divided into topographic differential karstification and tectonic differential karstification.

Under constraints of seismic data, the karst paleo-geomorphology was restored according to the contact relationship between the Ordovician and its overlying strata, the results show that differential karstification in the Huanghua depression mainly occurred in the northern part (Fig. 11).

The topographical differential karstification is essentially the aggravation of topographic difference caused by differences in dissolution duration and intensity resulted from original topographic difference, and the karst topographic difference would accordingly enlarge during exposure period. Different from uniform karstification, topographic differential karstification includes both chemical dissolution and hydraulic

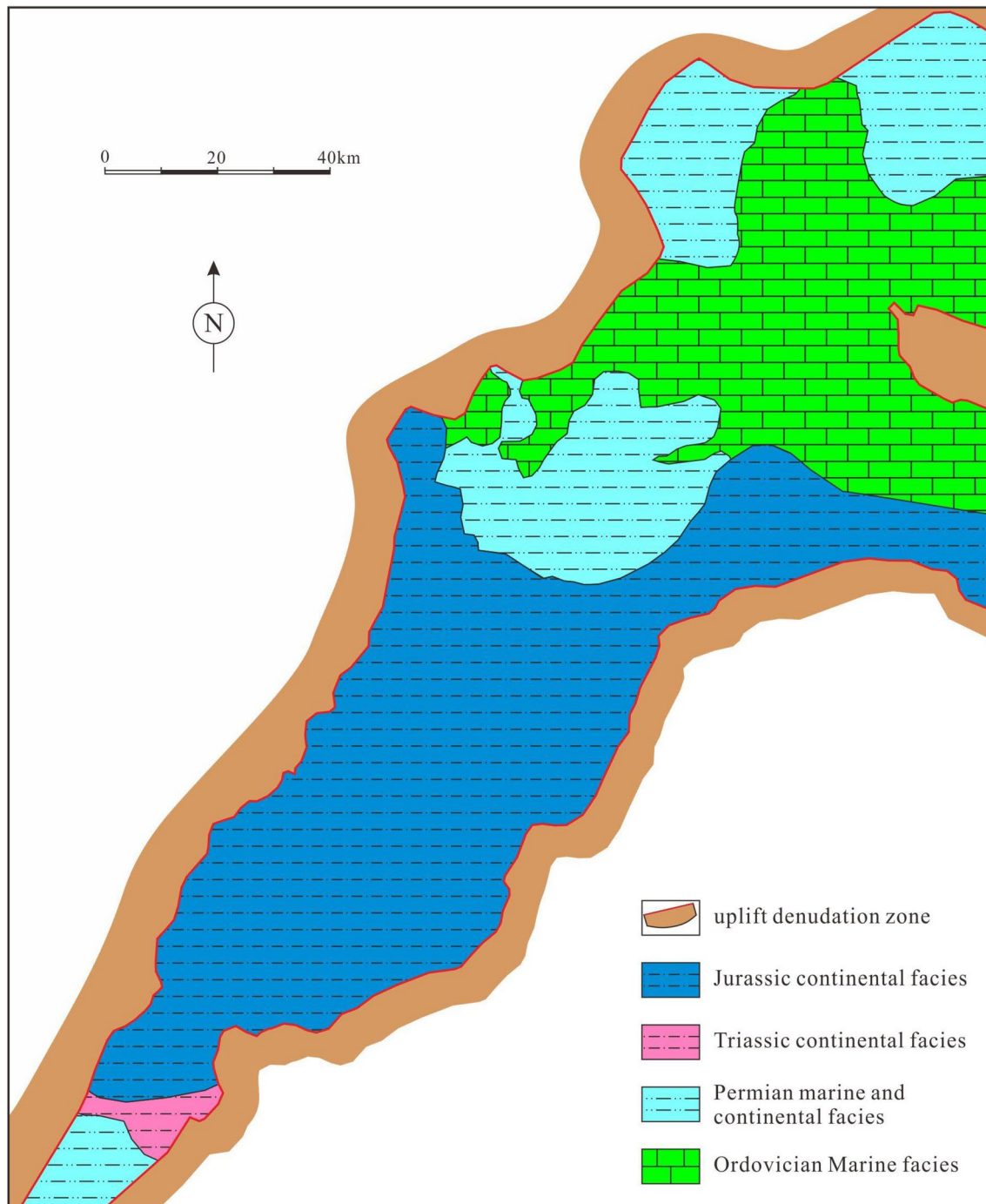


Fig. 11 Distribution of Ordovician epigenetic karstification in Mesozoic, the Huanghua depression

erosion. As the topographic difference increases, the potential energy of the surface meteoric water, and therefore its erosion force when converted into kinetic energy will increase, accelerating karstification.

The tectonic differential karstification refers to vertical and lateral dissolution of meteoric freshwater to the primary carbonate rock along the faults and fractures etc. when meteoric water seeping along the faults and fractures, which could enhance the topographic difference, karst pore-vug-fracture difference and even form karst caves. Huanghua depression has several discordogenic faults and a large number of structural fractures associated with the faults. Instead of running off and evaporating quickly as on the flat surface, the atmospheric precipitation rich in CO_2 would enter the faults and fractures and be entrapped there longer, giving it sufficient time to react with the primary carbonate rock, to dissolve the primary rock and improve physical properties of the reservoir.

In general, the topographical differential karstification and tectonic differential karstification in the Huanghua depression are significantly different from the uniform karstification in the period, mode and intensity of karstification: ① The karstification period is different, the uniform karstification happened mainly from the Late Ordovician to Early Carboniferous, while differential karstification took place in the Mesozoic; ② uniform karstification merely include chemical dissolution of carbonate rock, while differential karstification not only include chemical dissolution, but also hydraulic erosion and biochemical dissolution of organic acids, so it is a combined effect of multiple kinds of dissolutions; ③ as the differential karstification is a combined effect of multiple dissolution processes, therefore it is higher in intensity, giving rise to more dissolved pores, vugs and caves, and better reservoirs.

Burial karstification

The burial karstification in the Huanghua depression occurred in the zone affected by the acidic fluid formed during the hydrocarbon generation of the Upper Paleozoic coal-measure source rock, and the magmatic-structural hydrothermal dissolution also contributed to the burial karst reservoir.

Dissolution of organic acid generated during the maturation of upper Paleozoic coal-measure source rock

The coal-measure source rock of Upper Paleozoic in the Huanghua depression is characterized by hydrocarbon generation in multiple stages (Zhang et al. 2008, 2019c). During hydrocarbon generation, the source rock would produce a large amount of acidic fluids such as CO_2 , to dissolve the adjacent Ordovician carbonate reservoir. Due to the high intensity of Mesozoic-Cenozoic tectonic movement in the Huanghua depression, a large number of tectonic fractures developed in the Ordovician, which on the one hand provided infiltration paths for the meteoric water rich in CO_2 , and on the other hand also acted as paths for organic acid entering the reservoir during the burial stage together with faults. The mixing of the two types of fluids provided conditions for burial karstification (Fig. 12), thereby improving reservoir quality.

Dissolution of magma-structural hydrothermal fluid

After Indosinian movement, the Huanghua depression experienced multiple stages of volcanic hydrothermal activities, among which the magma activity of Cenozoic was most

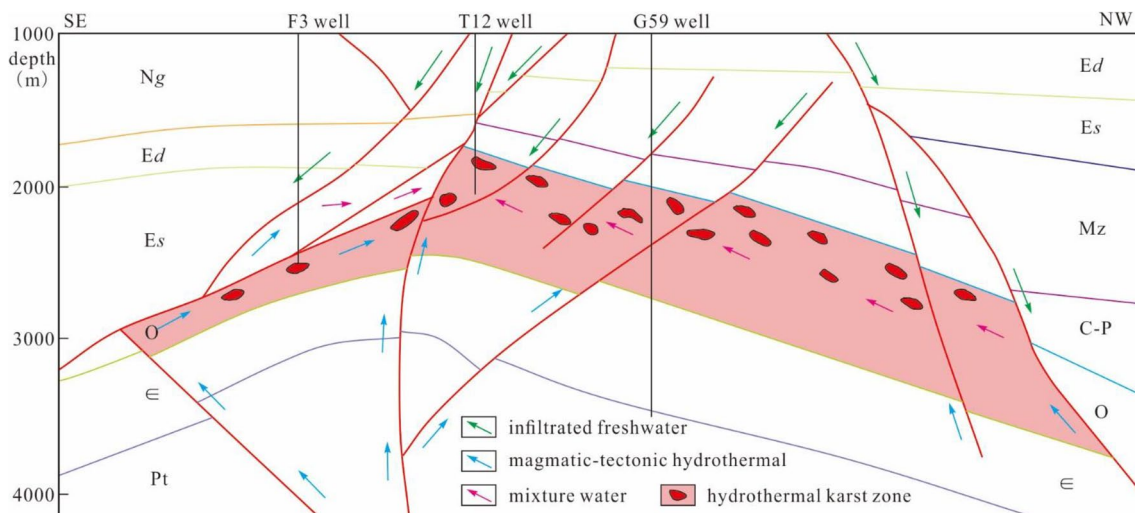


Fig. 12 Schematic diagram of magma-tectonic hydrothermal fluid karstification

extensive (Yang et al. 2014; Zhang et al. 2014). The direct impacts of magmatic activity on the Ordovician carbonate rock in this area include dissolution and filling. In addition to silicates, metal minerals and radioactive elements, magma also contains some volatile components such as H_2O , CO_2 , H_2S , F, Cl and so on. Water is the main component in the gas phase and liquid phase of the magma. When the hydrothermal fluid rich in CO_2 and H_2S mixed with the heated atmospheric freshwater, and entered carbonate formation along faults and fractures, it would erode the carbonate rock. At this time, the dissolution basically happened along faults and fractures, and the reticular fractures are especially favorable for magma-structural hydrothermal karstification.

Dominant factors controlling the development of karst reservoirs

Control of sedimentation and diagenesis on the development of karst reservoirs

Sedimentation controls the distribution of soluble minerals such as anhydrite-rock salt. The Ordovician in the Huanghua depression generally consists of limestone, dolomite and gypsum dolomite-anhydrite. Due to the low energy constraint-evaporation environment during the Ordovician period, the sediment developed was characterized by fine structure carbonate with evaporite interbeds. The lower parts of lower Majiagou Formation, Upper Majiagou Formation and Fengfeng Formation of the Middle Ordovician contain anhydrite or anhydrite dolomite of different amount. These anhydrite dolomite and anhydrite would be dissolved easily when contact with meteoric freshwater, first forming dissolution pores and fractures, then caves and cave breccia when collapsed (Fig. 13). The dissolution pore and vug layers in Huanghua depression show some regularity in distribution

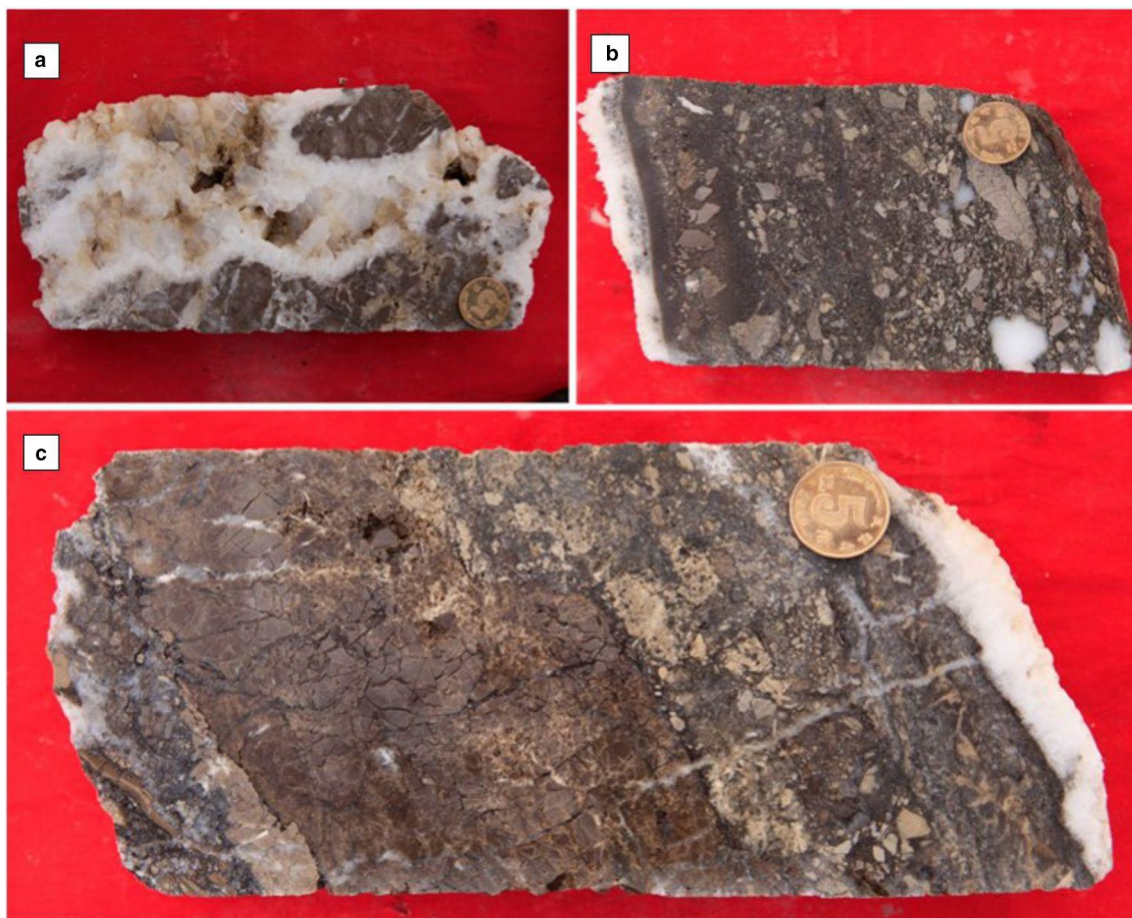


Fig. 13 Ordovician cave breccia in Well GG16101. 2857.28 m, calcite filling dissolved caves with oil trace; **b** 2861.83 m, breccia mixite, dissolved cave filled with breccia; **c** 2861.63 m, pebbly calcarenite, with normally graded bedding, dissolved pores, and caves

and are mostly within about 100 m from weathering crust top.

The Upper Paleozoic coal measure source rock in the Huanghua depression overlies on the Ordovician, and the large amount of acidic fluid produced during hydrocarbon generation of the source rock would dissolve the underlying Ordovician reservoir. Therefore, the distribution scope of the coal measure strata controls the range of organic acid dissolution of Ordovician. The Upper Paleozoic coal measure strata are mainly distributed in the middle and south areas of the Huanghua depression, and are eroded out in the northern part due to uplifting during Mesozoic.

Control of paleogeomorphology and tectonic movement on the development of karst reservoirs

The control of tectonic movement on karstification in Huanghua depression is reflected in 3 aspects: ① The tectonic movement controlled karst paleo-geomorphology and karstification of the outcropping zone of soluble rock, and affected the path of karstification water. ② The tectonic movement controlled the formation and development of faults and fractures, and the intersected and intercrossed fracture system improved the permeability of the rock, altered the circulation system of karst water, and increased the dissolution area of the soluble rock. ③ The magmatic-structural hydrothermal fluid upwelling created a hydrothermal karst zone in the Ordovician reservoir adjacent to the large basement fault and volcanic channels, which together with other types of karstification enhanced reservoir property.

Conclusions

- (1) The Ordovician carbonate reservoirs of the Huanghua depression have primary pores, dissolution pores and vugs, and fractures as main storage space, and can be divided into three main categories, pore type, pore-vug-fracture type and fracture type. The pore-vug-fracture reservoirs accounting for 62% are the key targets of oil and gas exploration in Huanghua depression.
- (2) The epigenetic uniform karstification of the Ordovician reservoir mainly took place in the Late Ordovician to Early Carboniferous, while the epigenetic differential karstification reservoir happened in the Mesozoic. The uniform karstification involves chemical dissolution of the carbonate primary rock, while the differential karstification not only includes chemical dissolution but also hydraulic erosion and biochemical organic acid dissolution. With several types of karstification working together, the karstification intensity of Ordovician reservoirs is high, and thus a large number of pores,

fractures and caves were produced, forming dominant reservoirs.

- (3) The burial karstification in the Huanghua depression mainly involves the dissolution of acidic fluid generated during the hydrocarbon generation of the Upper Paleozoic coal measure source rock to the underlying Ordovician reservoir, and the upgoing magmatic-structural hydrothermal fluid along fault also made a contribution to burial karst reservoir.
- (4) Sedimentation-diagenesis and palaeogeomorphology tectonic movement have certain effects on the karstification of the Ordovician reservoir in the Huanghua depression, determining the reservoir quality.

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