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RESEARCH PAPER

Paleokarst features and reservoir distribution in the Huanglong Formation of eastern Sichuan

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Abstract: The identification markers of paleokarst have been described in detail and include a combination of surface geology, drilling data and the isotopic characteristics of carbon, oxygen and strontium. The relationships between the vertical zoning, plane distribution and karstification degree of paleokarst and the reservoir development were further analyzed. The study shows that karstic breccias are the most direct sign of paleokarst features. Karsts of different genetic types and the intensity of dissolution have different stable isotopic characteristics from the surrounding cements, and their formation and evolution are significantly influenced by fluid sources, fluid nature and isotopic fractionation. The identification markers of small scale pinholes are quite different from that of large scale holes. The development and evolution of palaeokarsts are mainly controlled by structure, palaeoclimate and lithology. The best lithology for the development of reservoirs is dolomite in the C_2hl_2 formation. The best zones for the development of the reservoir is located in the upper and lower dissolution intervals of the C_2hl_2 formation and the best position for the development of reservoir is located in the karst highlands, remnant hills and sloping fields in the karst slope.

Key words: eastern Sichuan; Huanglong Formation; palaeokarst reservoir; geochemistry; karst topography; karst cycle

Eastern Sichuan is one of China's main natural gas producing areas. Natural gas primarily occurs in the widely developed Huanglong paleokarst reservoirs. In recent years, predecessors have provided insightful research on karst features of the Huanglong Formation in eastern Sichuan, and accumulated extensive research achievements[1−7]. However, they have been restricted by research methods, incomplete data sets and therefore their understanding. These predecessors rarely carried out special studies on well logging information, trace element and stable isotope information[6−8] for paleokarstification in the Huanglong Formation as well as reservoir distribution characterisation. Based on existing research results, combining surface geology, drilling data and stable isotope geochemistry characteristics, a comprehensive research effort was made to describe the identification signs of paleokarst in detail. The relationship between paleokarst vertical zonation and plane division, karst intensity and reservoir development have all been analyzed, providing more information for reservoir evaluation and prediction.

1 Geological overview

At the latter stages of the late Carboniferous, the eastern Sichuan region was uplifted by the Yunnan movement. Due to strong weathering and erosion, preservation of the Huanglong Formation was incomplete. The Huanglong Formation is located on a palaeo-high and was denuded partially or completely in some areas, forming a paleokarst geomorphology on top of the Huanglong Formation and resulting in a paleokarst system within the layers. Up until the early Permian, the geology was such that it received offshore lacustrine facies coal deposits of the Liangshan Formation[9].

The study area starts from Zhangjiachang, Xuanhan in the north, to Xiangguo Temple, Chongqing in the south, west to Guang′an City, and east to Wu gorge and Jianshi county of Hubei province, covering an area of approximately 10.2×10^4 km^2 (Fig. 1). In the study area, the Upper Carboniferous Huanglong Formation is an evaporite-carbonate, with middle Silurian shale at its base. In the middle and late Carboniferous, the Huanglong experienced the Yunnan tectonic movement. After short-term burial and diagenetic transformation, the Huanglong Formation suffered up to 15−20 Ma of weathering and erosion and resultant karst transformation[9], which involved the eastern Sichuan and adjacent areas, with losses of 3.5−86.0 m of residual thickness in places. The top of the

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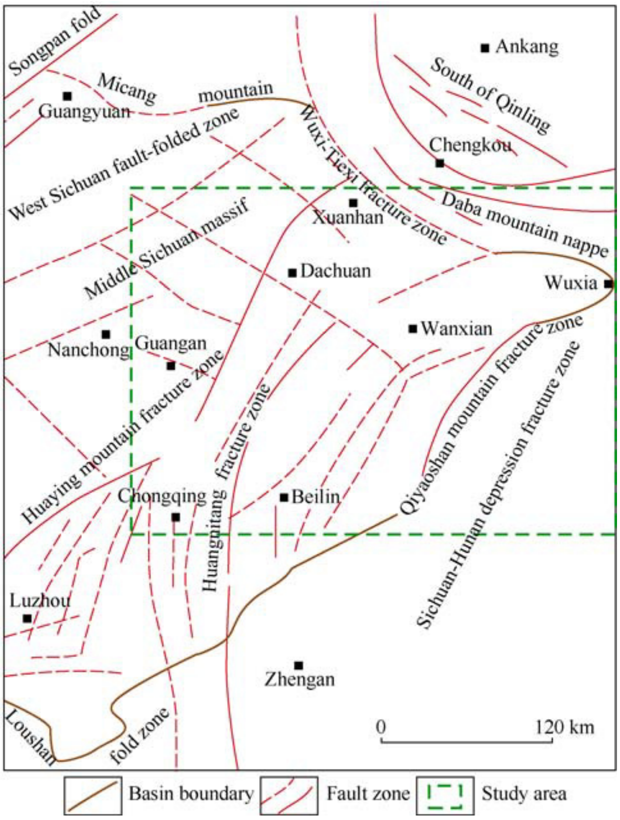


Fig. 1 Tectonic overview of study area

Huanglong developed a karstic weathered crust, and is covered by the lower Permian Liangshan Formation coal series where carbonaceous shale is the main lithology (Fig. 2).

The Huanglong study area is divided into three lithologic units[9] from bottom up: the first (C_2hl_1) is a Sabkha deposit. The lithology is a dark gray–grayish brown secondary limestone with loss of gypsum and presence of dolomite intercalated with a grayish brown secondary limy karst breccia, with 1.0–5.0 m residual thickness. The second (C_2hl_2) is a restricted - half restricted estuarine deposit, where the lithology is a light grayish-brown dolomite and dark gray powder-aplitic dolomite interbedded with microlitic dolomite, frequently intercalated with a grayish brown dolomite karst breccia, with 12–50 m residual thickness. The third (C_2hl_3) is an open estuarine deposit, where the lithology is the interbedded combination of light-gray micritic or sparry grain limestone and grain micrite and dark gray micrite, with 0–20 m residual thickness, and intercalated with grayish brown limy karst breccia. The Huanglong reservoir is mainly controlled by shallow facies grain dolomite, crystal grain dolomite and dolomitic karst breccia deposited in a partially restricted gulf similar to the second lithologic unit (C_2hl_2). Reservoirs are not only related to the burial dolomitization[10], but also subject to paleo-karstification[4–8]. Whether it is the grain dolomite, crystal grain dolomite or dolomitic karst breccia, the dissolution pores, vugs and fissures are well developed, with good porosity and permeability.

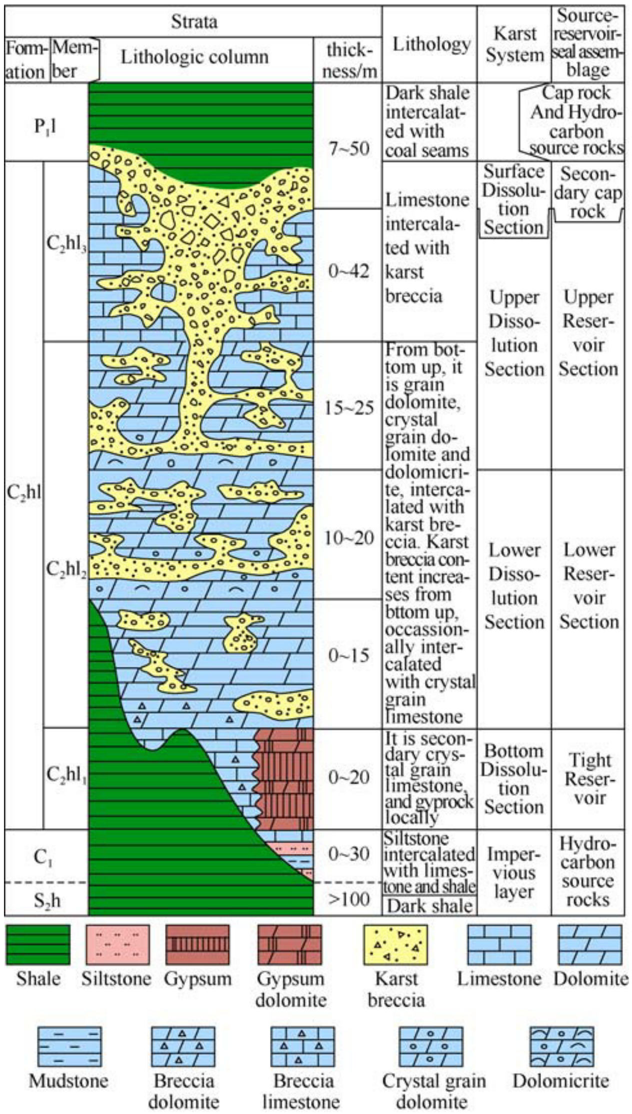


Fig. 2 Integrated histogram of the paleokarst system in the eastern Sichuan Huanglong Formation

2 Identification characteristics of the Huanglong paleokarst

2.1 The main characteristics

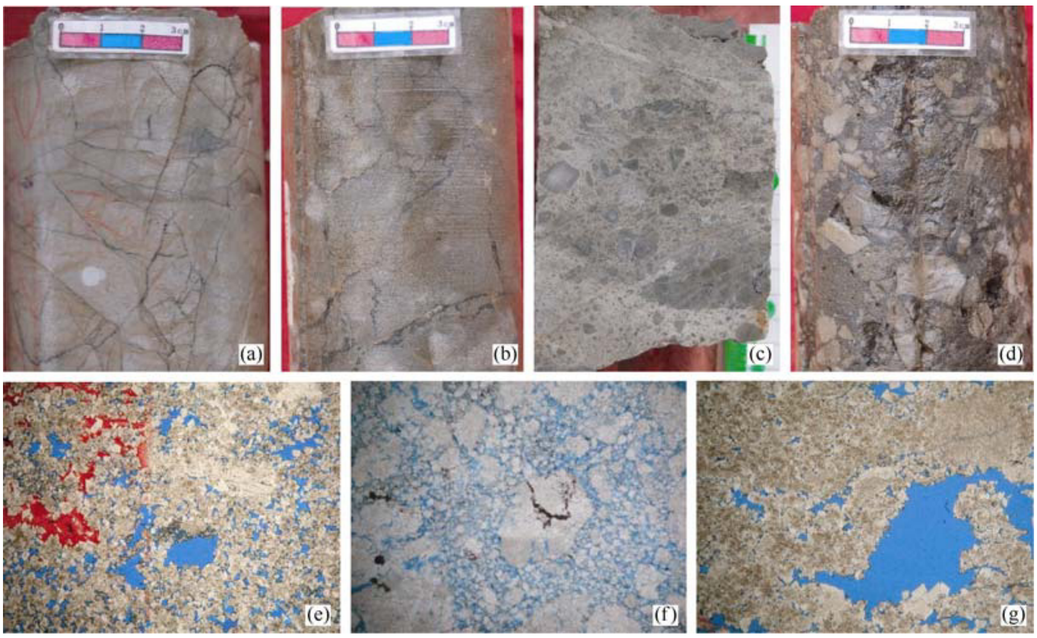
According to observations, the Huanglong karst rocks contain a large number of erosion cuttings, crystal debris, insoluble residues and a large number of clays, carbonaceous material or coal and plant fossils from the Liangshan Formation. Occasionally siliceous debris with agate structures consistent with silicified patch features in base rock is seen. In the karst cavities of each of the lithologic units, erosion breccias, debris and residues (mud, sand or organic matter) from the layers are generally deposited, however karst breccias, debris or residues from the overlying strata are still seen. Under cathode ray luminescence, the non-karst origin breccias and matrix materials radiate a uniform dark red light, while the karst origin breccias, matrix, dissolution pores and dissolution seam edges have very bright orange light bands. The limnic dolomite, calcite cement and secondary calcite with loss of gypsum and dolomitic origin have light and dark alternate zones shown by cathodoluminescence, and belong typically to flow-underflow sediment structures[11].

2.2 Karst breccia features

Karst breccia is the most obvious identification mark of karstification, and it is also the most effective and direct basis for judging ancient hydrological conditions and palaeogeomorphology in the karstification process[12]. Therefore a reasonable classification and analysis of karst breccia is most important for karstification study. In this study, according to the structure-composition features[4], we have classified the Huanglong karst breccias (Table 1). The structure reflects the breccias origins, accumulation manner and hydrological conditions, while the composition reflects the karst development layers and material source. The various karst breccias identified from the Huanglong Formation (Fig. 3) confirmed the conclusion that "Eastern Sichuan Huanglong karst reservoir is the product of regional karstification"[5,13].

Table 1 The structure-composition classification of eastern Sichuan Huanglong karst breccias

Breccias structure	Breccias composition			Origin type
	Limestone (developmental horizon C_2hl_3)	Dolomite (developmental horizon C_2hl_2)	Secondary grain limestone (developmental horizon C_2hl_1)	
Net–fissure mosaic shape	Net-fissure mosaic limy karst breccias	Net-fissure mosaic dolomitic karst breccias	Net-fissure mosaic secondary limy karst breccias	In-situ dissolution breccia along fissures, breccia has no obvious displacement
Breccias support, matrix filling	Breccias support limy karst breccias	Breccias support dolomitic karst breccias	Breccias support secondary limy karst breccias	Disorderly accumulated debris due to cave top erosion and collapse, lack of underground turbulent transformation
Breccias support, sparry cementation	Breccias support sparry cement limy karst breccias	Breccias support sparry cement dolomite and karst breccias	Breccias support sparry cement secondary limy karst breccias	Disorderly accumulated debris due to cave top erosion and collapse, have underground turbulent transformation
Matrix support	Matrix support limy karst breccias	Matrix support dolomitic karst breccias	Matrix support secondary limy karst breccias	Surface residuals and cave fillings transported by underground water, some are accumulated debris due to cave top erosion and collapse



(a) Tiandong 14 well, Sample 3-125, C_2hl_2, net-fissure mosaic dolomitic karst breccias; (b) Tiandong 14 well, Sample 3-125, C_2hl_2, net-fissure mosaic dolomitic karst breccias, showing lots of suture lines, filling with carbonate shale; (c) Ban 2 well, Sample 3-74, C_2hl_2, Matrix support dolomitic karst breccias; (d) Tiandong 14 well, Sample 2-72, C_2hl_2, Breccias support dolomitic karst breccias, showing lots of dissolution pores and vugs; (e) Bandong 1 well, Sample 3-82, C_2hl_3, net-fissure mosaic limy karst breccias, dolomite intercrystal pores and intercrystal dissolution pores developed (blue stain), some dissolution pores were filled by calcite (dye red), dyeing cast thin section(—), 10×4; (f) Ban 2 well, 3 222.86 m, C_2hl_2, Breccias support dolomitic karst breccias, fillings are mainly dolomicrite, cast thin section(—), 10×10; (g) Wu 1 well, 2 863.16 m, C_2hl_3, Breccias support limy karst breccias, dolomite intercrystal pores and intercrystal large dissolution pores developed (blue cast), cast thin section(—), 10×2

Fig. 3 Major types of karst breccia in the eastern Sichuan Huanglong Formation

2.3 Carbon, oxygen and strontium isotope geochemistry indicators

Carbon, oxygen and strontium isotope geochemistry characteristics of palaeokarst are significant to understanding the distribution of carbonate rocks, such as the sedimentary depositional environment, diagenesis and the origin and formation conditions of cementation and fillings[7,8]. In the study area, carbonate rocks and carbonate cements with different origins and dissolution strengths have different distribution ranges and different average values of carbon, oxygen and strontium (Table 2). With an increase in dissolution intensity, the average value of $\delta^{13}C$ and $\delta^{18}O$ decreases, which is the most prominent feature of the isotopic data (Table 2, Fig. 4a). The average value of $\delta^{13}C$ and $\delta^{18}O$ of the penecontemporaneous dolomicrite is the highest, while the average value of $\delta^{13}C$ and $\delta^{18}O$ of limnic calcite cements filling dissolution pores, cavities and fissures is lowest. It shows that the stronger the dissolution by atmospheric water, the higher the carbon and oxygen isotope fractionation strength of the carbonate. The strontium isotope analysis showed that the $^{87}Sr/^{86}Sr$ values have a different evolution trend which is offset to the direction of $\delta^{18}O$ and $\delta^{13}C$ trend (Table 2, Fig. 4b, Fig. 4c). This further demonstrates that dissolution has occurred in atmospheric fluids with atmospheric sourced CO_3^{2-} rich in ^{12}C and ^{16}O and weathering crust sourced ^{87}Sr whose abundance increases gradually[7,8,14].

In the vertical profile, from top to bottom, there are at least two cycles of $\delta^{13}C$ and $\delta^{18}O$ composition changes from depleted to enriched, then to depleted, then to enriched. Taking the Macao well 1-1 (Fig. 5) as an example, the karst residual zones on the surface and the deep karst cavity development zones correspond with strong negative offsets of the $\delta^{13}C$ and $\delta^{18}O$ composition. It indicates that the Huanglong Formation not only experienced atmospheric percolation dissolution, but also experienced a more intensive surface and ground water horizontal undercurrent dissolution.

2.4 Logging identification characteristics of paleokarst

Carbonate rocks in the eastern Sichuan Huanglong Formation experienced long-term weathering, denudation and dissolution transformation. Small pinholes and large cavities and fractures are well developed, and most of the reservoirs have dual medium characteristics. Therefore, the log response characteristics and combination types (Fig. 6) of both pinhole reservoirs and cavity-fracture reservoirs become one of the most important indicators to identify the karstification of the reservoir[15].

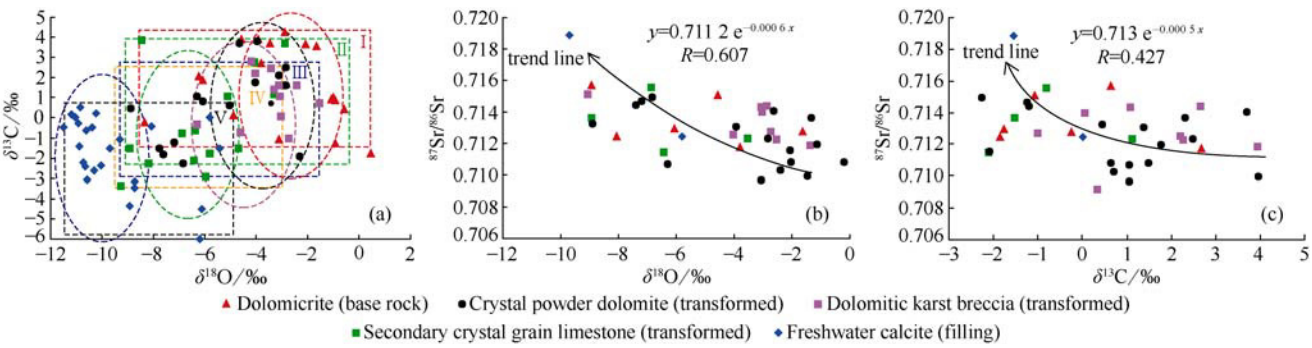
2.4.1 The identification characteristics of a pinhole reservoir

Small pinhole reservoirs are one of the most important res-

Table 2 Carbon and oxygen isotopes of various carbonate, karst and cements

Karst intensity	Rock type	Sample number	zonation	$\delta^{13}C$/‰ Range	$\delta^{13}C$/‰ Average value	$\delta^{18}O$/‰ Range	$\delta^{18}O$/‰ Average value	$^{87}Sr/^{86}Sr$ Range	$^{87}Sr/^{86}Sr$ Average value
No dissolution	Penecontemporaneous dolomicrite	18	I	−1.77–4.24	1.585	−8.33–0.47	−3.050	0.707 473–0.715 714	0.712 007
Weak dissolution	Grain-powder crystal dolomite	24	II	−2.27–3.96	0.971	−8.89– −0.20	−3.650	0.707 525–0.716 997	0.712 371
Strong dissolution	Dolomitic karst breccia	13	III	−3.00–2.79	0.934	−9.02– −1.50	−3.920	0.709 540–0.718 976	0.713 206
Strong dissolution metasomatism	Secondary grain limestone	14	IV	−3.37–2.73	−0.313	−9.26– −2.90	−6.169	0.709 640–0.716 584	0.713 312
Cements	Freshwater clacite	24	V	−5.98–0.52	−1.714	−11.5– −5.40	−9.453	0.710 717–0.718 865	0.715 165

Note: C, O isotope analysis equipment is MAT252 gas isotope mass spectrometer, detection basis SY/T 6039-94, working standard TTB-2, completed by Geology Laboratory of Exploration and Development Research Institute of PetroChina Southwest Oil and Gas Field Company; Sr isotope analysis equipment is MAT252 gas isotope mass spectrometer, experimental temperature 22°C, humidity 50%, the testing standard is ANSI standard sample NBS987, completed by professor Yinguan from Isotope Laboratory of Chengdu University of Technology.



Zoning: I - not dissolution; II - weak dissolution; III - strong dissolution; IV - strong dissolution metasomatism; V - cements

Fig. 4 The relationship between ä13C, ä18O and 87Sr/86Sr in the carbonates and cements

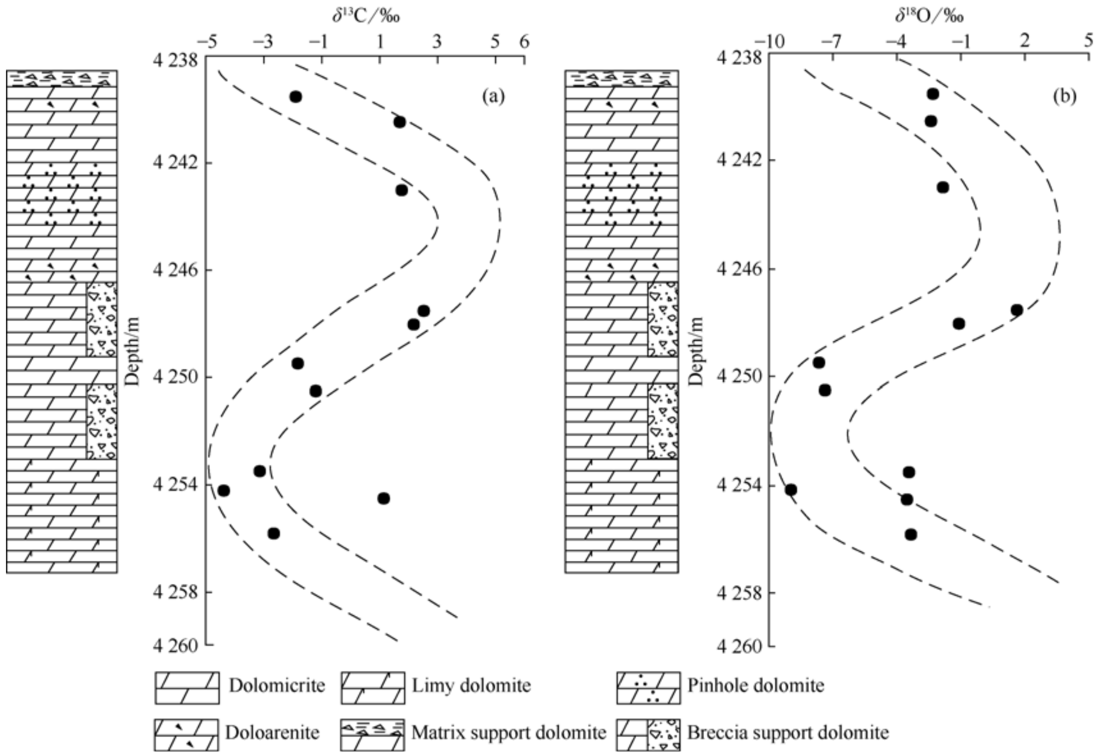


Fig. 5 The relationship between depth and ä^{13}C, ä^{18}O of Macao well 1-1

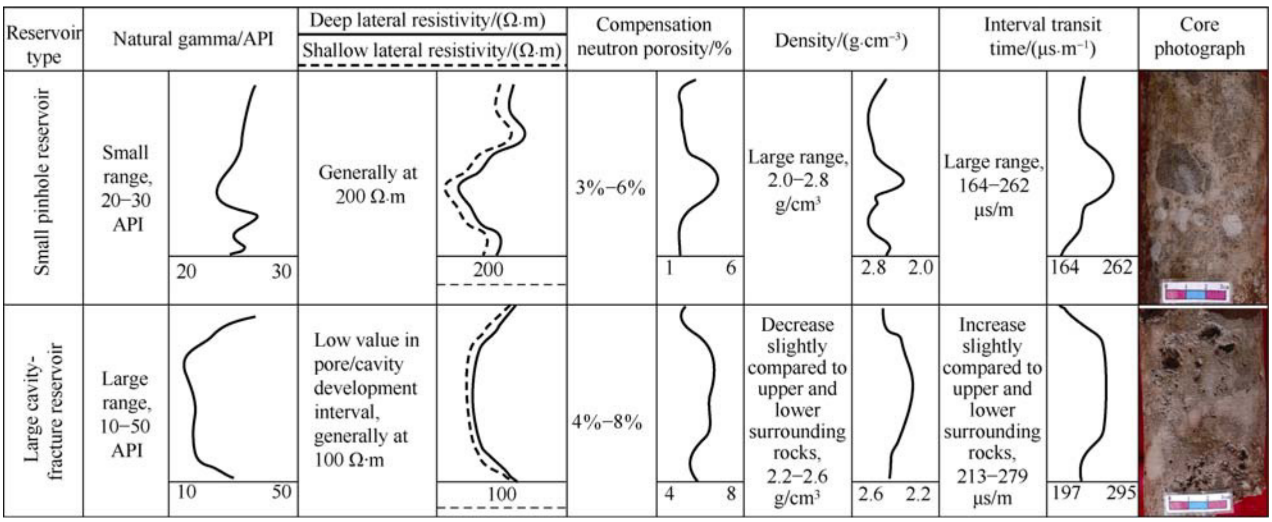


Fig. 6 Logging response mode of different karst reservoirs in the eastern Sichuan Huanglong Formation

ervoir types, and are mainly found in grain dolomites and crystal grain dolomites. The logging response characteristics of pinhole reservoirs include: relatively high natural gamma value, within a small range, generally 20–30 API; relatively high resistivity, generally around 200 Ω·m, the curve is "left convex"; the porosity logging curve has a relatively high density value, lower neutron porosity and interval transit time. Therefore, pinhole reservoir development intervals can be interpreted as a base rock dissolved pore development interval.

2.4.2 The identification characteristics of cavity-fracture reservoirs

A cavity-fracture reservoir mainly exists in karst breccias. They have good reservoir properties, and are one of the most important reservoir types. The logging response characteristics of cavity-fracture reservoirs include: natural gamma value is low, with a large range (10–50 API); low resistivity, (about 100 Ω·m); the double lateral resistivity curves generally show acertain range in "bow" form; in porosity logging curves, the neutron porosity values are relatively higher than in the surrounding rocks, and the density curve values decrease while the acoustic time values increase, and there are large holes and cracks. Therefore, a cavity-fracture reservoir development interval can be explained as cave development interval.

3 Division of paleokarst cycle and dissolution interval

3.1 The division of paleokarst cycle

The dissolution process caused by the dramatic drop of atmospheric water at the phreatic surface is a karst cycle. From top to bottom, it is composed of the surface dissolution interval, the upper percolation dissolution interval, the lower active undercurrent dissolution interval and the bottom static undercurrent dissolution-filling zone. Under the undercurrent zone, is a ground water saturated zone or impervious layer[5,12,13]. The multi-stage decrease of erosion datum caused by corresponding regional tectonic pulsed uplift has led to repeated ground water level decline and corresponding multi-stage karst cycle superposition development. Since the dissolution zones have specific development position and karst phase combinations during every karst cycle, when a karst cycle at a different stage has migrated to a deeper stratum, the same karst phase can appear many times at different depths. For this reason, during a relatively stable period of tectonic activity, the horizontal cavities resulting from expanded erosion of active undercurrent zone and the static undercurrent cementation zone may act as an important symbol of karst cycle division and can be regionally correlatable. Regional tectonic pulsed uplifts and intermittent apparent decreases of the erosion datum, can correspond to a pattern with an with a vertical profile that goes from new to old, in four stages of the karst cycle (Stage IV to I), and can be determined from the paleokarst system of the Huanglong Formation (Fig. 7, Fig. 8). Every karst cycle has the following evolution characteristics, where the top strata become thin due to erosion. The old karst record may disappear and the vadose zone expanded while the undercurrent zone moves to deeper stratum gradually[5]. In different karst geomorphic units, the strata can be subjected to erosion to different degrees, so the preserved karst cycle stages and geochemical characteristics are different[16]. For example, in a micro geomorphic unit such as slope or residual hill in the karst slope zone, the karst cycle is preserved relatively well, and mostly includes the four stages. The karst valley and shallow depressions generally have 3~4 stages while the micro geomorphic units such as at the margin, the inside-slope karst highlands and karst fractures are less well preserved, and generally include only 2~3 stages. Some local units only include one stage or have disappeared completely after denudation.

3.2 The division of the dissolution interval

As time goes by, the karst cycle at different stages has the characteristic of cross-layer and cross-stage superposition development, as a karst cycle at a late stage may run through one or more older karst cycles. Therefore, it is difficult to correlate paleokarst systems regionally on the basis of the cycles alone, and it is also difficult to establish the corresponding karst phase mode. The Huanglong Formation paleokarst profile has been divided into four dissolution intervals based on geological records at different stratum depths using the concept of dissolution intervals, which mainly describes the karst cycle superposition stages, dissolution types and dissolution intensity[5] from old to new when each karst cycle migrated to deeper stratum intervals (Fig. 7, Fig. 8). From top to bottom, it is the surface dissolution interval, the upper dissolution interval, the lower dissolution interval and the base dissolution interval. Among them, the upper and lower dissolution intervals are the main development intervals of paleokarst reservoirs, corresponding to the upper and lower reservoir development intervals in production practice. The lithologic-facies and log facies of the four dissolution intervals have large differences (Table 3), so they can act as an indicator for the division of stratigraphic units in the dissolution interval and for regional correlation (Fig. 8). This allows the basis of establishing a stratigraphic framework and paleokarst reservoir development model for dissolution intervals (Fig. 9).

4 Karstification and reservoir distribution

4.1 Main control factors of karstification

The ancient climate, lithology, lithofacies and structures have controlled the paleokarstification of the Huanglong Formation in Eastern Sichuan.

4.1.1 Ancient climate

Ancient climate is one of the important environmental factors for karst development. A warm climate is more favorable to the development of paleokarst than dry or cold climate. The data show that in the eastern Sichuan karst system, fillings from the surface and the overlying Liangshan Formation are rich in carbonaceous, coal and continental fossil plant materials. This shows that, in the exposure period of the Huanglong Formation, hot and humid climate conditions were available. Prosperous plant growth and abundant rainfall were favorable for karst development.

4.1.2 Lithology and lithofacies

The original carbonate permeability is the main factor influencing karstification pathways and reservoir development characteristics[17–25]. It can be divided into two cases: (1) pipe flow dissolution is dominant for poorly permeable limy base rock. Fractures and bedding surfaces are the main migration channels and create dissolution space for pipe flow. Large cavities often form along the fractures or bedding planes, and the cavities are strongly filled with dissolution debris, breccia and sediments from the surface. The low-permeability base rocks experience weak karstificaition due to limited infiltration by underground water. So the base rock often maintains its characteristics of low permeability and low porosity, and reservoirs mainly develop in cavities filled by dissolution debris and breccias, and the base rocks containing large dissolution cavities and fractures, result in the reservoir having strong heterogeneity; (2) scattered flow uniform karstification is dominant for dolomitic base rock with better permeability. Intergranular and intercrystalline pores are the main migration channels and dissolution space for scattered flow. All kinds of small or numerous dissolution pores, cavities and fractures are well developed, often associated with numerous small or large cavities. Thus, reservoirs are not only widely

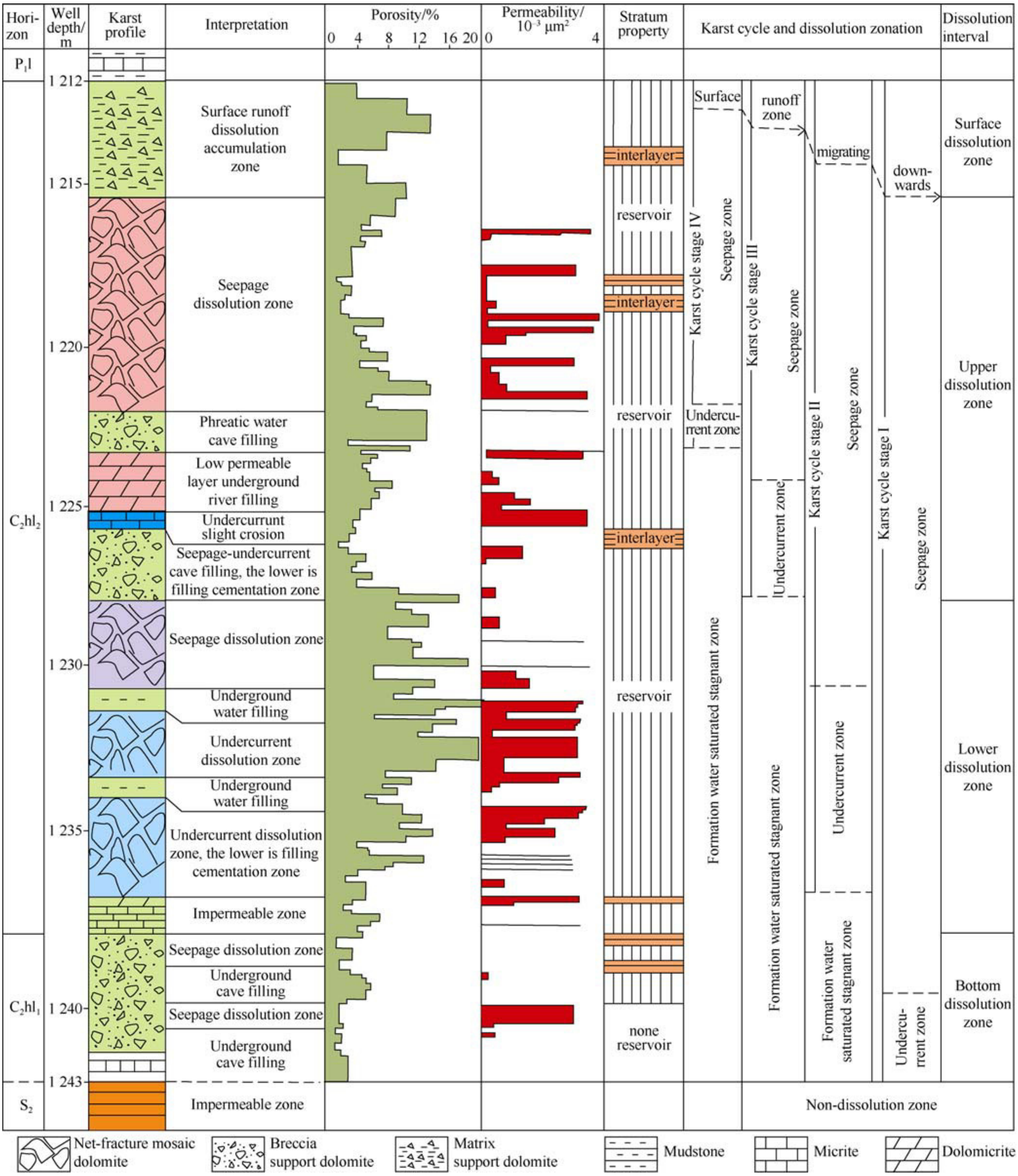


Fig. 7 Division of karst cycle and dissolution intervals for well Tiandong 2

developed with cavities filled by dissolution debris and breccia, but also developed in the dissolved base rocks. These reservoirs have relatively weak heterogeneity. Obviously, in the same dissolution conditions, generally porous beach facies grains or crystal grain dolomite are more easily dissolved and transformed to form reservoirs with high permeability and porosity than dense shelf or lagoon facies limestone or dolomicrite. This shows the lithology and lithofacies control conditions.

4.1.3 Structure

Tectonic movement has a strong control on the karstification of the eastern Sichuan Huanglong Formation[3–5]. For example, due to the Yunnan tectonic uplift movement, the area was uplifted and entered a karst environment and so suffered weathering and denudation. At the same time, lots of fractures formed, which provide favorable space for late karst development. It is reflected in the following four aspects: (1) The

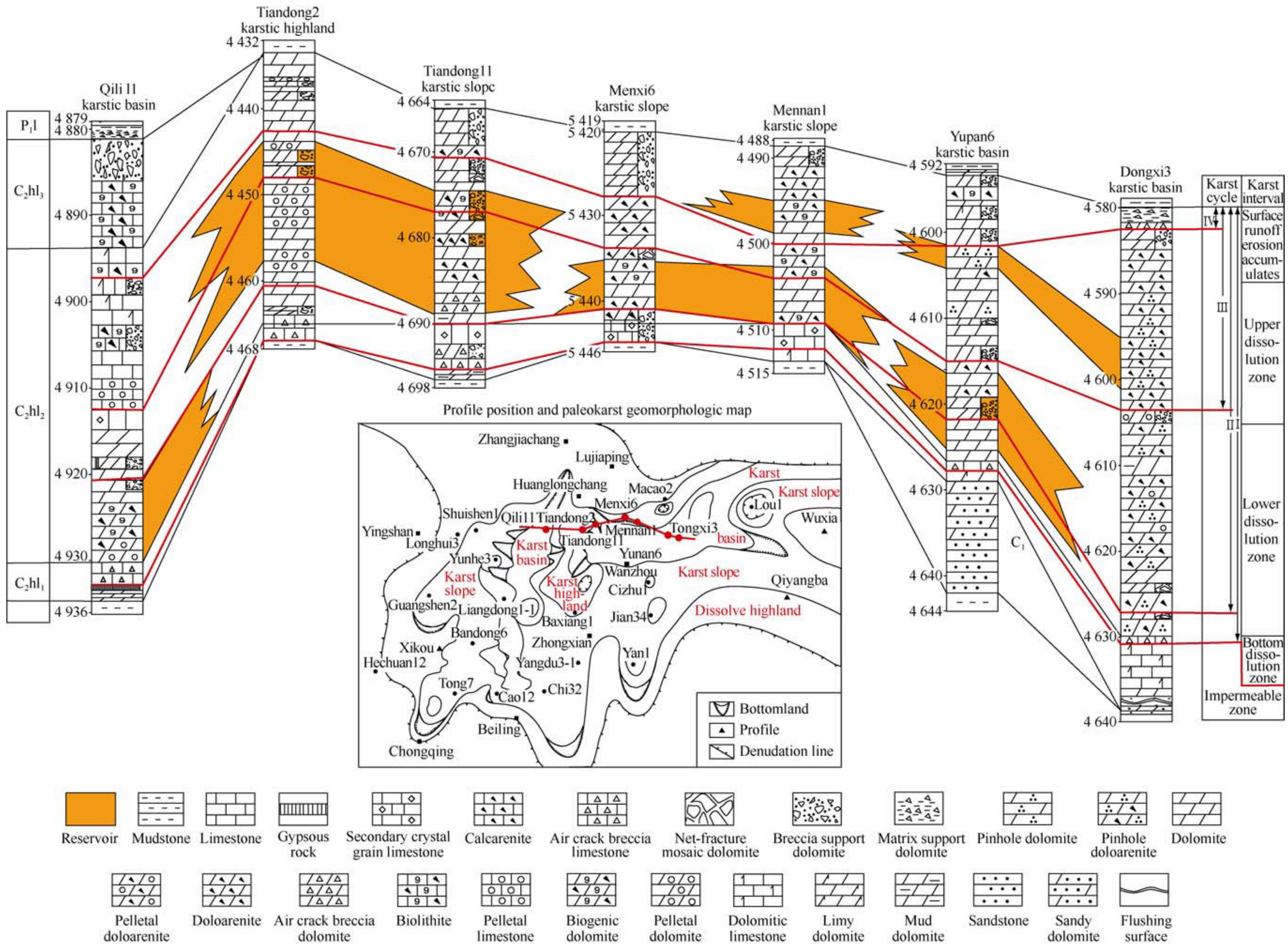


Fig. 8 Distribution and correlation of a dissolution interval framework and reservoir model for the eastern Sichuan Huanglong Formation paleokarst system

Table 3 Vertical zones and features of the east Sichuan Huanglong karst

Division of Dissolution interval	Karst Depth	Logging curve response			Karst cycle superposition development features	Development position	Karst fillings	Reservoir development
		Natural gamma	Interval transit time	Resistivity curve				
Surface dissolution interval	Exposed erosion surface	High value, serration	Low value, no significant variation	Low value, obvious serration	Composed of IVcycle undercurrent zone an III, II, I cycle vadose zone superimposition	Generally developed in each geomorphic unit	Surface dissolution residual deposit	undeveloped
Upper dissolution interval	Under erosion surface 0–30 m	Micro serration, close to density limestone	Great variation, high value for reservoir interval	Low dual lateral resistivity, positive anomaly	Composed of III cycle undercurrent zone and II, I cycle vadose zone superimposition	Mainly developed at karst slope	Exotic carbon shale, autochthonous collapse deposits, fresh-water cementation	Well developed (upper reservoir development interval)
Lower dissolution interval	Under erosion surface 10–50 m	It is low value when no mud filling, and high value after mud filling	Great variation, high value for reservoir interval	Breccia show obvious serration, positive anomaly	Composed of II cycle undercurrent zone and I cycle vadose zone superimposition	Mainly developed at karst slope	Exotic carbon shale, autochthonous collapse deposits, fresh- water cementation	Strong developed (lower reservoir development interval)
Bottom dissolution interval	Under erosion surface 30–70 m	Generally low value, some show box shape	Low value, close to skeleton value	Low resistivity, some show box shape	Composed of I cycle undercurrent zone	Generally developed in each geomorphic unit	Exotic carbon shale, fresh-water cementation	Mainly develop fractured reservoirs

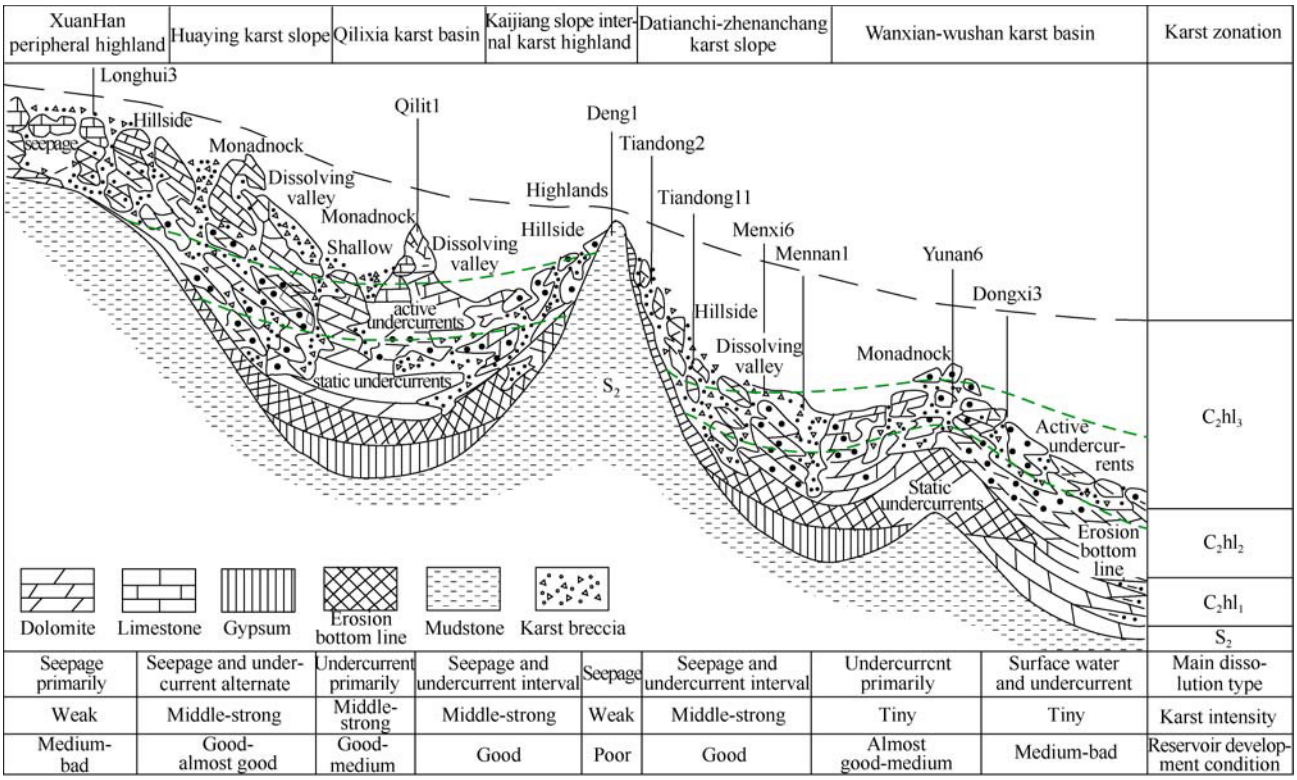


Fig. 9 Development mode of karst system and reservoir in the eastern Sichuan Huanglong Formation

uplift and depression structure directly controls karst geomorphology zonation such as karst highland, karst slope and karst basin, the micro landform assemblage, distribution and karst hydrological conditions in each karst geomorphic zone; (2) Structural fractures provided seepage and circulation channels for atmospheric water; (3) Structural fractures increase the dissolution range of surface water and underground water, improve and strengthen the hydrologic environment and hydropower circulation conditions of seepage and undercurrents, and a fresh water dissolution system can form in the rocks providing space for large-scale karstification; (4) Structural fractures increase the specific surface area for water-rock reactions during karstification and accelerate the dissolution rates, forming various reservoirs related to karst fractures.

4.2 The control of paleokarstification on reservior distribution

Because of different karst geomorphology, karst reservoirs have obvious differences in their regional distribution[19–25]. At present, many large natural gas reservoirs within the Huanglong Formation paleokarst system that act as the major pay zone have been discovered in eastern Sichuan. However, due to different paleokarst geomorphology and karstification stages (in terms of the form and characteristics of karst geomorphology, these plays can be divided into three major units, i.e. peripheral karst highlands, karst slope and karst basin), atmospheric water movement and dissolution stages controlled by different paleokarst geomorphic units can be different, and have different controls on the development and distribution of paleokarst reservoirs (Fig. 8 and Fig. 9).

4.2.1 The control of karst highlands on reservoir distribution

The dissolution base of the karst highlands is far higher than the regional dissolution datum, suggesting mainly seepage dissolution (Fig. 9). Reservoir development can occur in two ways: (1) In karst highlands, horizontal cavities develop along the phreatic surface of the palaeocurrent transporting layer, while the preserved stratum thickness is very thin, and generally unfavorable for the development of paleokarst reservoirs, such as in well Deng 1 at the top of the inner-slope karst highland in Kaijiang; (2) In peripheral karst highlands, there is a larger surface area to accomodate precipitation, and there is flat terrain and relatively large water seepage capacity so that the seepage dissolution is more intense. Examples can be seen in the Huanglong Member-2 dolomite, where there are locations in which the preserved thickness is large and grain dolomite or crystal grain dolomite are developed, or locations where fractures are dense and are favorable for reservoir development, such as in well Longhui 3 in the peripheral karst highlands.

4.2.2 The control of karst slope on reservoir distribution

According to the geographical position, karst slopes can be divided into upper and lower slopes which have different combined features of micro geomorphic units (Fig. 9) and have different controls on reservoir development: (1) In the upper slope, the slope field is the main land form, which is very steep, with base unconformity surfaces as the erosion base boundary, which is still higher than the phreatic surface. Surface waters in peripheral or inner-slope karst highlands infiltrate rapidly and fluids migrate laterally. Features include strong dissolution and weak filling. Thick vadose zones and thin active undercurrent zones are developed, and static undercurrent zones seldom appear. The phreatic surface between karst cycles have small intermittent declines. The superposition dissolution of each karst cycle is the most intense and the upper and lower dissolution intervals may overlap and develop at the same location, thus the karst slope is the best position for reservoir development in each karst geomorphic unit, such as at Tiandong well 2 and Tiandong well 11. (2) The lower slope has more complex landforms than the upper slope, including dissolution valleys, shallow depressions and residual hills within shallow depressions. The dissolution valley is steep. The active undercurrent zone developed near the valley mouth is thick, and it is favorable for the development of paleokarst reservoirs, such as at well Menxi 6 and well Mennan 1. Shallow depressions, from top to bottom of the slope transitions from steep to gentle, with a flat base. Its groundwater recharge capacity and gathering capacity are higher than other geomorphic units. However, the migration rate is slow and the phreatic surface is stable, while dissolution is relatively weak and the cemented filling is strong. This micro geomorphic unit is not favorable for reservoir development. Residual hills with shallow depressions are small scale, with a peak protuberant shape, but the underground hydropower field zoning is obvious. The phreatic surface between cycles has large intervals, and clearly controlled by the regional erosion datum which declines intermittently. Therefore, the upper section and lower section of residual hills within shallow depressions have relatively independent reservoir development positions. Overall, the paleokarst reservoir is the most developed in karst slope regions, especially in slope fields, where the upper and lower erosion sections are developed and overlap, and the reservoir's lateral distribution is extensive.

4.2.3 The control of karst basins on reservoir distribution

Karst basins are composed of two micro geomorphic units, i.e. karst fractures and residual hills in basins (Fig. 9). In the two micro geomorphic units, reservoir development status is very different for each: (1) Karst fractures have flat terrain, and the surface is flooded by water all year along, so the vadose zone is not developed and underground water flows slowly. Horizontal cavities resulting from undercurrent dissolution are not developed, but only appear at the edge of depressions at the karst valley mouth or around the residual hills and funnel edges. Due to dissolution of laterally flowing undercurrents, a horizontal dissolution zone with a limited range is formed, which is favorable for reservoir development, such as at Well Dongxi 3. (2) Residual hills in basins, in terms of geomorphic characteristics, are similar to the residual hills in shallow depressions in the karst slope. But they have a much larger scale and the main body of the residual hills in basins is located in the overlapping position of the upper thick vadose zone and the lower active – static undercurrent zone. It is favorable for reservoir development, such as at well Qili 11 and well Yun'an 6.

4.2.4 The relationship between dissolution interval and reservoir development

The vertical correlation of dissolution intervals and reservoir development in the Huanglong Formation in well Qili 11—well Tiandong 2—well Tiandong 11—well Menxi

6—well Mennan 1—well Yun'an 1—well Dongxi 3 (Fig. 8) shows that, the Huanglong Formation reservoirs are controlled by multi-stage karstification. Paleokarst reservoirs are mainly distributed in the middle and bottom of the upper dissolution interval and the middle and top of the lower dissolution interval, which have experienced multi-stage karstification, often with superposition dissolution of seepage and undercurrents. The reservoirs are mainly fracture-pore reservoirs and partly large fracture and large cavity reservoirs. At the base dissolution interval, pore reservoirs are generally undeveloped and only a few fractured reservoirs are developed. It indicates that the multi-stage paleokarstification, dissolution zonation and its superposition dissolution directly control the development scale vertically and horizontally and the distribution patterns seen in the karst development.

5 Conclusions

The widely developed karst breccia in the eastern Sichuan Huanglong Formation is the most direct means to identify palaeokarstification. Three main kinds of lithologies with different origins are identified, i.e. net-fracture mosaic karst breccia, breccia support karst breccia and base rock support karst breccia.

All kinds of karst rock and cements have different carbon, oxygen, strontium stable isotope geochemistry characteristics, controlled by atmospheric water ancient hydrological conditions and isotope fractionation during karstification. The basic characteristics include: (1) With the increase in dissolution intensity, the averages of $\delta^{13}C$ and $\delta^{18}O$ decrease vertically corresponding to the interlayer horizontal undercurrent dissolution zone, the values of $\delta^{13}C$ and $\delta^{18}O$ have more intensive negative corelations, reflecting that, the stronger the atmospheric water dissolution is, the higher the carbon and oxygen isotope fractionation intensity of carbonate rock is; (2) The trend of the $^{87}Sr/^{86}Sr$ value has evolve and offsets the $\delta^{18}O$ and $\delta^{13}C$ negative increase direction, proving that dissolution occurred in an enriched ^{12}C and ^{16}O atmosphere source CO_3^{2-} as the atmospheric fluids with ^{87}Sr abundance increase gradually, which is the source of the weathering crust.

In the study area, we made comprehensive comparisons between logging curves in many wells, and concluded that small pinhole paleokarst reservoirs have significantly different logging facies features compared to large cavity-fractured paleokarst reservoirs.

The development and regional distribution rule of paleokarst reservoirs are influenced by the combination of ancient climate, lithology and lithofacies, structure, ancient hydrological conditions and different karst landforms. The paleokarst reservoirs are mainly distributed in the middle and bottom of the upper dissolution interval and the top and middle of the lower dissolution interval, which experienced multi-stage karstification. Reservoirs are mostly crystal grain dolomite, grain dolomite and dolomitic karst breccia with dissolution pores, cavities and fractures well developed.

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