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Diagenetic facies of carbonate rocks in Yijianfang Formation, Shunbei area, Tarim Basin

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Abstract: The diagenetic facies of the Ordovician Yijianfang Formation in the Shunbei area of the Tarim Basin are analyzed with core description, thin section analysis, as well as logging trace and seismic data. There are five diagenetic facies types: dissolution, dolomitization, fracture-dissolution, cementation and hydrothermal facies, which are further divided into eight subfacies: atmospheric freshwater dissolution, burial dissolution, fracture-dissolution, penecontemporaneous dolomitization, burial dolomitization, subsea cementation, freshwater cementation, and burial cementation. Five composite diagenetic facies are identified: cementation-hydrothermal, fracture-dissolution, fracture-cementation, fracture-hydrothermal, and dolomitization-cementation-hydrothermal facies. The subsea cementation subfacies are developed in the low system tract, while the tectonic-hydrothermal and cementation subfacies are developed in the high system tract. In intra-platform beach sediments, atmospheric freshwater dissolution and atmospheric freshwater cementation subfacies, and a small amount of tectonic-hydrothermal subfacies develop. In interstitial marine sediments, there develop burial dolomitization, dissolution and cementation subfacies. In intra-platform reef sediments, atmospheric freshwater dissolution and atmospheric freshwater cementation subfacies appear. The diagenetic facies evolution is controlled by tectonics, sedimentary facies and sequence and constrained by points, single-well profiles, diagenetic facies connected wells and root mean square amplitude. The distribution of favorable diagenetic facies in the Shunbei area gradually transits from the southwest to the northeast.

Keywords: diagenetic facies; carbonate; Yijianfang Formation; Ordovician; Shunbei area; Tarim Basin

The concept of diagenetic facies was proposed by the American scholar Railsback [1] in 1984, and it is considered to be the rock itself defined by the characteristic diagenetic texture; then scholars have carried out related research on it and made some progress [2–13]. In 1994, Chen et al. [14] introduced the concept of diagenetic facies to China and defined it as the material manifestation of the diagenetic environments, which means the general diagenetic environment integrating petrological, geochemical, and petrophysical characteristics. They also emphasized that the diagenetic facies is the integration of diagenetic environments and diagenetic products. For the definition of diagenetic facies, different scholars have proposed their own ideas. Although there is no unified conclusion, most scholars define it as a comprehensive reflection of diagenetic environments, rock particles, fabrics, cements and reservoir spaces [14–23].

In recent years, most of the China's oil fields have entered the exploration stage of lithologic-stratigraphic reservoirs, especially in the basins with proved source rocks and structural conditions. The diagenetic facies-based prediction of favorable reservoir zones can open a new way for oil and gas exploration [24], but most of these studies mainly focus on clastic rocks [15–16,22,25–26]. This paper applies this method to the marine carbonate rocks of the Ordovician Jianfang Formation in the Shunbei area, Tarim Basin. Previous studies revealed that good oil and gas displays have been observed during the drilling along the fault zone of this area, but the oil and gas displays are not favorable in the areas slightly far from the fault zone. It indicates that the physical properties of the reservoir are directly related to faulting. The sparry calcarenite reservoirs containing silica and dolomitic components present good physical properties, and the porosities of sparry calcarenite and micritic calcarenite that experienced dolomitization have been improved by 102.7% and 117.9%, respectively. The porosity of bioclastic limestone is higher than that of the algal limestone. Therefore, the distribution laws of reservoirs are related not only to the fault, but to the diagenesis process. This paper focuses on the analysis of

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diagenetic facies, explores its relationship with logging facies, and determines the distribution of diagenetic facies under the control of sequence and sedimentary facies. It will provide a new reference for the prediction of carbonate reservoirs in this area.

1 Regional geological setting

The Shunbei area is located in the Shuntuoguole low uplift in the central uplift zone of the Tarim Basin, and it is adjacent to the Awati Depression in the west and the Manjiaer Depression in the east. It is located in the transition zone between Katake uplift and Shaya uplift in the N-S direction, showing a saddle-shaped distribution and presenting the characteristics of "depression-in-uplift and uplift-in-depression." The strata in this area are relatively gentle as a whole, mainly appearing as low-amplitude anticline traps and stratigraphic lithologic traps. Affected by the multi-stage tectonic movements of this basin, the Cambrian–Early Ordovician strata are located inside the platform and far from the subsidence center, with the complete sedimentary sequence. Regional uplift occurred in the late Middle Ordovician, and the Middle Ordovician Yijianfang Formation in the Shunbei area was subjected to exposure and erosion. In the late Ordovician, due to the ocean basin reduction and the plate collision at the southern and northern plate margins, the tilting structures at the north and south ends of Shuntuoguole were developed, and the platform limestone was deposited in the Lianglitage Formation. The Ordovician strata are completely developed in the Shunbei area, and they can be divided into Lower Penglaiba Formation, Middle-Lower Yingshan Formation, Middle Yijianfang Formation, Upper Qiaerbake Formation, Lianglitage Formation, and Sangtamu Formation [27] (Fig. 1). Yijianfang Formation has a set of open platform facies sediments, and it mainly develops intraplatform beach and interstitial marine subfacies. On the basis of the characteristics of rock electricity and previous research results, Yijianfang Formation can be divided into one standard third-order sequence and four fourth-order sequences [28–29] (Fig. 1).

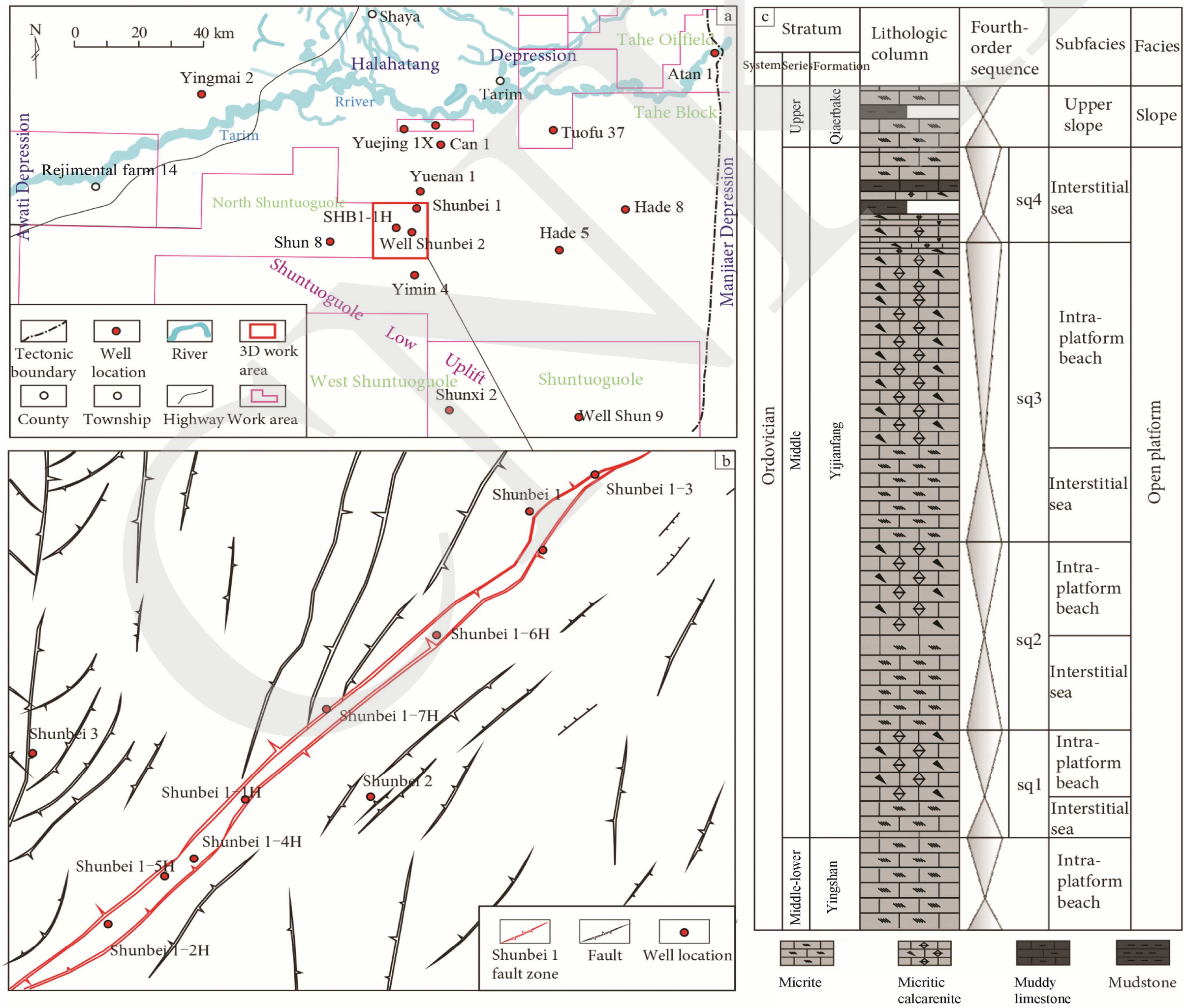

Fig. 1 Location and tectonic units of Shunbei area, Tarim Basin

The study area is located in the east of the Shunbei block, where the No. I fault zone is developed (Fig. 1). This area is covered by a 3D seismic work area, and many wells have continuous coring data and complete logging data, with a solid data basis. The top interface of Yijianfang Formation is located below the stable red limestone layer in the Qiaerbake Formation [30], which can be characterized by a large set of light gray limestone. The rock types of limestone are mainly micrite and (containing) grainstone, as well as their transitional rock. The particles are mainly bioclast and sand debris, ultra-fine sand debris, and coarse dust debris; additionally, the biolithite is also common in this area, mainly the algae-bonded limestone; traces of dolomitic limestone and siliceous limestone can be observed. The biological combination of Yijianfang Formation is mainly characterized by echinoderms, brachiopods and Girvanella; a small number of ostracodas, trilobites and bryozoans are also found.

2 Division of diagenetic facies

This paper follows the classification [28] and terminology system [31] of Mou and Benner (1982). The cores and thin sections from Wells Shunbei 2, Shunbei 1 and Yuejin 1X and the thin sections of cuttings from Well Shunbei 1-3 are analyzed. Then considering the development characteristics of fault system, the study area is divided into dissolution, dolomitization, fracture, cementation and hydrothermal facies. According to different forming environments of each diagenetic facies, eight diagenetic subfacies are further divided, namely atmospheric freshwater dissolution, burial dissolution, fracture-dissolution, penecontemporaneous dolomitization, burial dolomitization, subsea cementation, freshwater cementation and burial cementation. Generally, diagenesis will not work alone, and instead, it will exert a joint effort with two or more diageneses under certain environmental conditions. Therefore, five types of composite diagenetic facies can be divided in this study area, including cementation-hydrothermal facies, fracture-dissolution facies, fracture-cementation facies, fracture-hydrothermal facies, dolomitization-cementation facies.

2.1 Dissolution facies

(1) Atmospheric freshwater dissolution subfacies: The study area is characterized by intergranular dissolution pores and moldic pores, but the scale is small, and there are a small number of dissolution fractures in the area. Because most of these fractures are filled with freshwater calcite, the residual effective reservoir space is very limited, with strong heterogeneity and poor reservoir connectivity (Fig. 2a).

(2) Burial dissolution subfacies: It is mostly developed in bioclastic micrite or micritic bioclastic limestone. The dissolution fractures usually appear as suture lines, and the dissolution pores mostly appear along the edges of the suture lines. Most dissolution pores are filled with asphaltene, with sparsely distributed dolomite grains (Fig. 2b).

(3) Fracture-dissolution subfacies: Dissolution fractures are mostly distributed along edges of fractures that are not filled with calcite, and asphaltenes, argillaceous, and quartz are commonly observed. It indicates that the charging of thermal fluid and oil/gas along the fractures in the late stage. Generally, it is associated with the burial dolomitization (Fig. 2c).

2.2 Dolomitization facies

(1) Penecontemporaneous dolomitization subfacies: The grain size belongs to the micrite-powder crystal level, and the grains exist in idiomorphic form or semi-idiomorphic form. Many bird-eye structures can be observed in the core, basically free of biological fossils (Fig. 2d).

(2) Burial dolomitization subfacies: The grain is relatively small, with straight surface and in idiomorphic form or semi-idiomorphic form. These grains distribute in intergranular point-to-surface contact and intergranular surface-to-surface contact. This subfacies is mainly developed under metasomatic genesis in the shallow-medium burial period, with argillaceous cladding. It is mostly distributed along suture lines and pressolution fissures (Fig. 2c).

2.3 Fracture facies

The core observation results suggest that the fractures in Yijianfang Formation are mainly high-angle and near-vertical fractures; their overall sizes are relatively small, with the length mainly in the range of 5–15 cm, and their fracture openings vary greatly, generally greater than 0.2 cm. The fractures are developed in multiple stages, and most of them are filled with calcite, silicon, pyrite and asphaltene. Only small part of fine fractures are left unfilled, mostly accompanied with fracture-dissolution subfacies (Fig. 2e).

2.4 Cementation facies

(1) Subsea cementation subfacies: Thin section analysis results suggest that the calcite cements in this period are mostly fibroblastic or ctenoid texture; they grow perpendicularly to the particles (calcite rim), and some particles have incomplete rims around them due to dissolution (Fig. 2f).

(2) Atmospheric freshwater cementation subfacies: The atmospheric freshwater cements in this study area mostly appear as crystal stock calcite, which grows around the rim of fibrous cement. The cleavage is visible under the microscope; wave-shaped extinction and crystal edge mosaic contact are observed. This type of cement further destroys the residual intergranular pores and the effective pores generated by freshwater solution (Fig. 2g).

(3) Burial cementation subfacies: It is mainly coarse-grained calcite, and the cement is in the crystalline form, mostly incising suture lines or filling in the residual intergranular pores or dissolution pores formed after atmospheric freshwater cementation. It greatly reduces the primary porosity of rocks (Fig. 2h).

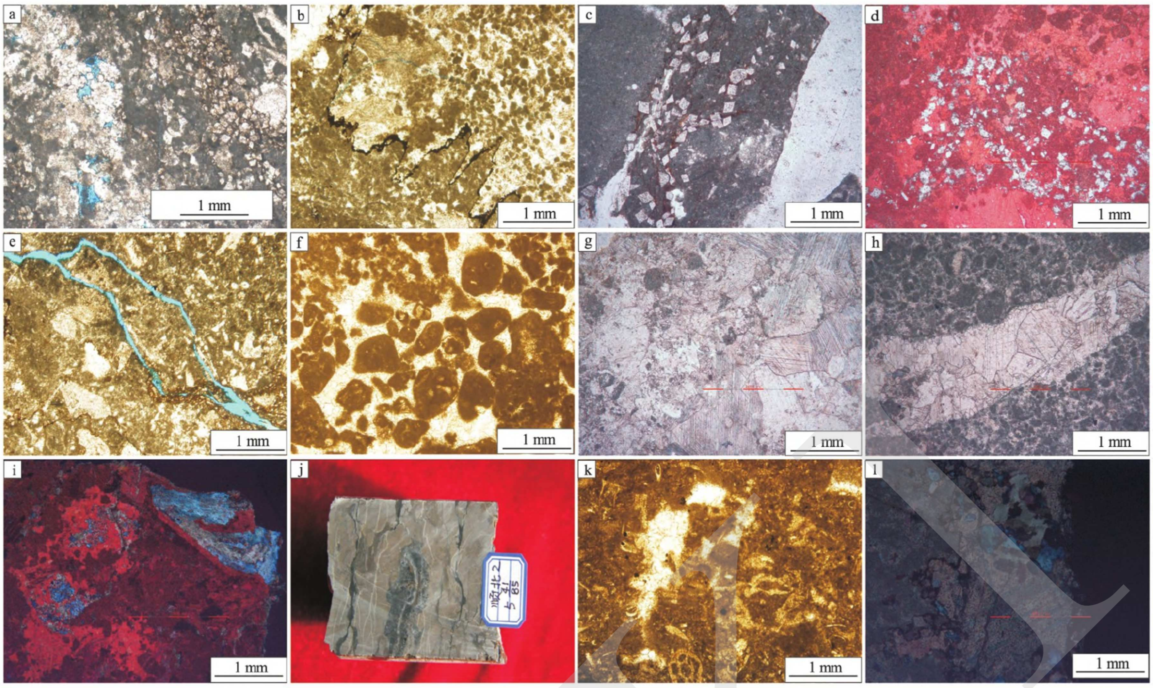

Fig. 2 Typical diagenesis and diagenetic facies of Yijianfang Formation, Shunbei area, Tarim Basin

a. The sample is from Well Shunbei 2 at 7 442.45 m; it is packstone, with some micritic recrystallization and suture lines, accompanied by intergranular pores induced by atmospheric freshwater dissolution; the bioclastic mainly includes brachiopods and spines; b. The sample is from Well Shunbei 2 at 7 444.94 m; it is grainstone subject to burial dissolution; dissolution pores are filled with asphaltenes and few dolomite crystals; brachiopods are observed; c. The sample is from Well Shunbei 1-3 at 7 466 m, with the fracture-dissolution subfacies; dolomitization develops along the dissolution fractures in the late stage, belonging to the burial dolomitization; d. The sample is from Well Shunbei 1-3 at 7 354 m, with bird-eye structure, and dolomite is scattered in the micrite matrix; e. The sample is from Well Shunbei 2 at 7 362.80 m; it is bioclastic micrite in fracture facies; the fractures are not filled; f. The sample is from Well Shunbei 2 at 7 446.37 m; it is arenaceous grainstone, with fibrous and ctenoid calcite cement; g. The sample is from Well Shunbei 1-3 at 7 308 m; it is grainstone with atmospheric freshwater dissolution pores; it is cemented by calcite in the late stage; h. The sample is from Well Shunbei 1-3 at 7 358 m; it is grainstone subject to burial cementation; i. The sample is from Well Shunbei 1-3 at 7 352 m; hydrothermal fluid destroyed calcite cement, and then quartz cement is formed; j. The sample is from Well Shunbei 2 at 7 522.65 m; it is gray calcarenite; strong dolomitization occurred along the suture rim; siliceous nodules are observed; k. The sample is from Well Shunbei 2 at 7 355.96 m; it shows cemented hydrothermal facies, with micron-sized pyrite and a small amount of sparry calcite cement; l. The sample is from Well Shunbei 1-3 at 7 346 m; it shows dolomitization-cementation-hydrothermal facies, forming the quartz cement.

2.5 Composite diagenetic facies

(1) Fracture-hydrothermal facies: The thermal fluids destroyed the original structure and created dissolution pores, and then new cements were formed. The specific cement type is determined by the composition of thermal fluid. The study area is characterized by the thin-layered siliceous rocks formed by siliceous metasomatism, which are filled with idiomorphic calcite, a large amount of granular pyrite and a small number of algal and bioclastic grains (Fig. 2i).

(2) Cementation-hydrothermal facies: Cementation is the main factor that causes the low porosity of reservoirs in the study area. The intrusion of thermal fluids will destroy the existing cements, and the siliceous bulks and sporadic pyrite particles will be formed simultaneously. The siliceous bulks observed in the core have the diameter of about 3–10 cm, and the pyrite particles have a diameter of about 3 μm (Figs. 2j, k).

(3) Fracture-dissolution facies: The edges of fractures are not clear and often accompanied by clastic particles of residual surrounding rocks. The fractures are basically unfilled. It is the most favorable diagenetic facies for reservoir development in the study area (Fig. 2e).

(4) Fracture-cementation facies: This facies is widely developed in the study area. Due to fluid intrusion or the influence of the diagenetic environments, the existing fractures are mostly cemented by calcite (Fig. 2h).

(5) Dolomitization-cementation facies: The calcite cementation in the burial environments flees to suture lines, and the burial dolomitization occurs along the suture lines. Then fluids flow through this place and creat quartz cement. The occurrence of the composite diagenetic facies indicates the larger burial depth, and it is the product of burial environments (Fig. 2l).

3 Logging response identification bases of diagenetic facies

Different diagenetic facies differ from each other in terms of structures, mineral compositions and physical properties, resulting in various response characteristics on the logging curves. Although the overall response of logging curves of the carbonate strata is weaker than that of the clastic rocks, the physical characteristics of curves such as density, resistivity, acoustic velocity, hole diameter and neutron are the main manifestations of rock diagenetic strength, reflecting the degrees of cementation, compaction and secondary pores/fractures development [14,18]. Therefore, this paper determines the strength of diagenesis according to the characteristics of those logging curves. Five curves, i.e., interval transit time (AC), hole diameter (CAL), natural gamma (GR), natural potential (SP) and neutron logging (CNL) are selected for their high sensitivity to diagenetic facies, and the logging curve markers of different diagenetic facies are established. For direct expression of the diagenetic facies, a spider web diagram is used to integrate the diagenetic facies and the logging data. It uses the parameters of AC, CAL, GR, SP and CNL logging curves as the radiation axes for point projection respectively, and characterizes the logging response characteristics of diagenetic facies through graphical partitioning (Fig. 3).

4 Discussion

Li et al. [32] believed that Ordovician reservoir space in Tarim Basin was developed with the joint effort of tectonic-fluids, sedimentary facies and diagenesis, and the diagenetic facies was directly controlled by tectonic-fluids and sedimentary factors. Therefore, the study on the distribution of dominant diagenetic facies will help predict the effective reservoir spaces.

4.1 Influential factors on planar distribution of diagenetic facies

4.1.1 Tectonics

The fractures controlled by strike-slip faults are mainly developed in the Shunbei and adjacent areas. The cores near the fault zone show the large steep-angle–near-vertical fractures, most of which are filled with calcite, silica and pyrite cements. It indicates that these fractures are often accompanied with cementation. Additionally, these fractures provide pathways for diagenetic fluids, so dolomitization, dissolution and hydrothermal action may easily occur, forming fracture-dissolution subfacies, dolomitization facies, and tectonic hydrothermal facies (Figs. 2j, 3k). There are many vertical joint seams in the cores obtained in wells far from the fault zone, and most of them are not opened; a small number of low-angle fractures are usually filled with calcite, dolomite and asphalt. In summary, the structure has a great influence on the type and distribution of diagenetic facies.

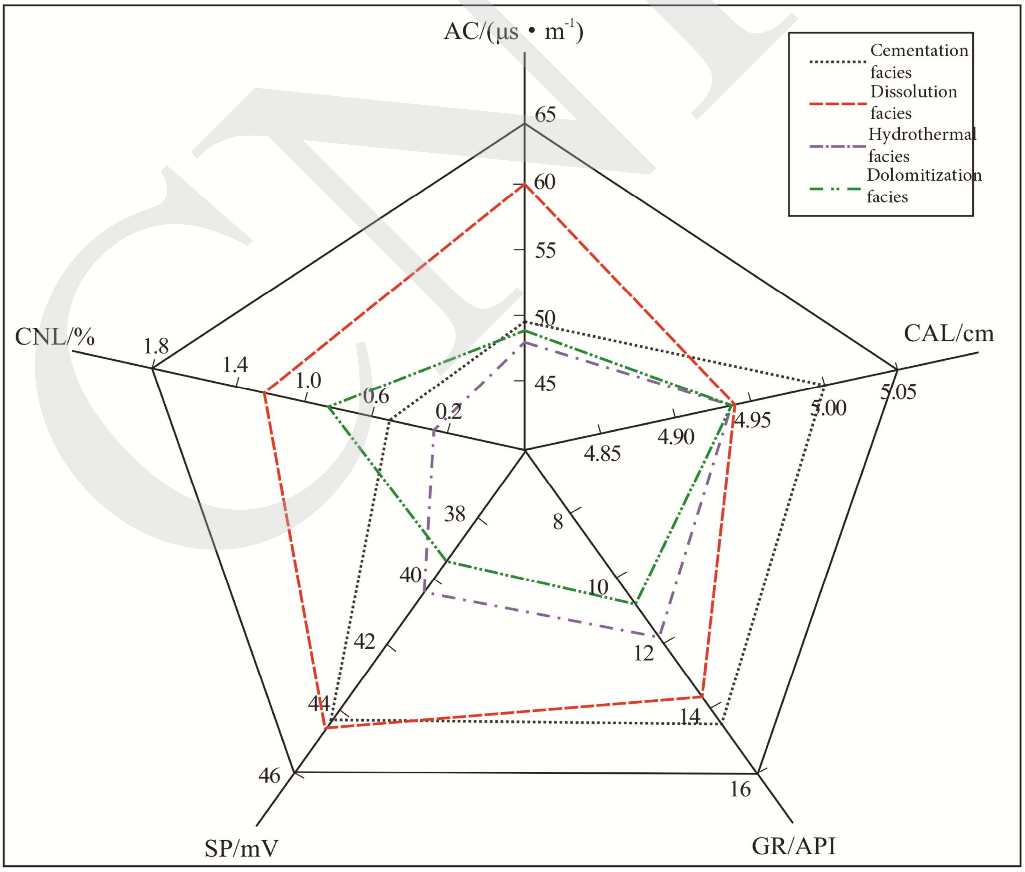

Fig. 3 Logging responses of diagenetic facies of Yijianfang Formation, Well Shunbei 2, Shunbei area, Tarim Basin

4.1.2 Sequence

The previous studies suggested that Yijianfang Formation could be divided into a third-order sequence [33]. Through studying cores, thin sections and logging data and with the classical theory of sequence stratigraphy [34–35], this paper considers that Yijianfang Formation in the study area can be divided into a third-order sequence and four fourth-order sequences. From bottom to top, they are successively the sql–sq4 (Fig. 4). As shown in Fig. 4, below the sequence interface (the T_7^4 interface of the seismic reflection marker), the depth is 7 360.45 m, and the lithology is dominated by grainstone, with dissolution pores and fractures developed; it usually shows the non-fabric selectivity, in the form of the dissolution of particles and the expansion-dissolution along the tectonic fractures. They belong to dissolution facies and fracture-dissolution facies (Fig. 5a). In the area of transgressive system tract, the single-well depth is about in the range of 7 352–7 360.45 m, and it is at a sea-level ascending stage during the initial transgression. In the thin sections, the freshwater dissolution fractures (Fig. 5b) and the intergranular dissolution pores are developed in the lower part of this depth range, and the complete brachiopod bioclast is preserved properly (Fig. 5c); as the sea level rises, sporadic dolomite gradually appears in the micrite matrix (Fig. 5d), and calcite cement is developed along the edge of particles. It is mainly developed with the subsea cementation subfacies and the dolomitization subfacies. Near the marine flooding surface (about 7 333.95–7 352 m), the lithology is dominated by micrite. The natural gamma in the logging curves shows a turning point towards a high value. At this time, hydrothermal fluid destroys calcite cement, and then the quartz cement is formed (Fig. 5e) and better developed below the suture line (Fig. 5f). Therefore, the diagenetic facies can be divided into tectonic hydrothermal facies, fracture hydrothermal facies and cementation facies. In summary, the evolution of diagenetic facies is subject to the influence of the vertical evolution of sequences, so the distribution of diagenetic facies shall be analyzed within the established sequence stratigraphic framework.

4.1.3 Sedimentary facies

In the Shunbei area, Yijianfang Formation is located on an open platform with weak carbonate rim, and three types of sedimentary subfacies can be identified in this platform: intra-platform beach, interstitial marine and intra-platform reef. Controlled by local geomorphology, the intra-platform subfacies extend as an NW-strike strip, and its area is larger than that in the sedimentary period of the Yingshan Formation. The intra-platform reef subfacies are developed in the high position inside the platform, which is mainly subject to the influence of waves and tidal effects. Meanwhile, the hydrodynamic conditions are strong, and storms also generate great influence. On the basis of the core description and thin-section analysiss of the study area, the intra-platform subfacies are mostly developed with atmospheric freshwater dissolution subfacies, atmospheric freshwater cementation subfacies, and a small amount of tectonic-hydrothermal facies. The interstital marine subfacies are formed below the normal wave base, but generally does not exceed 50 m, and the hydrodynamic conditions on the sea floor are weak. The lithology is dominated by micrite and dolomitic calcisiltite, and burial dolomitization subfacies, dissolution facies and cementation facies are developed. The intra-platform reef subfacies can be presented on the scales of cores and thin sections, and it mainly consists of bioclastic limestone, framestone, algae-bonded limestone and bioclastic algae-bonded limestone. It is generally formed in the deep water, with the atmospheric freshwater dissolution and atmospheric freshwater cementation subfacies (Table 1).

Table 1 Comparison between sedimentary microfacies and diagenetic facies of Yijianfang Formation, Shunbei area, Tarim Basin

Sedimentary facies	Subfacies	Microfacies	Characteristics of lithofacies	Diagenetic facies	Diagenetic subfacies
Open platform	Intra-platform beach	Gravel beach Sandy beach Oolitic beach Algae clastic beach	Micritic spherulitic calcisiltite, calcisiltite	Dissolution facies, dolomitization facies, tectonic-hydrothermal facies	Atmospheric freshwater dissolution subfacies, burial dissolution subfacies, penecontemporaneous dolomitization subfacies
	Interstitial marine	Limestone terrace Dolomitic limestone terrace	Bioclastic sparry calcarenite, bioclastic calcisiltite, silty calcarenite, algal limestone	Cementation facies, dissolution facies, dolomitization facies	Mixed water dolomitization subfacies, burial dolomitization subfacies, burial dissolution subfacies, atmospheric freshwater dissolution subfacies, atmospheric freshwater cementation subfacies
	Intra-platform beach	Point reef	Algae-bonded limestone, framestone, bio-bonded limestone	Dissolution facies, cementation facies	Atmospheric freshwater dissolution subfacies, atmospheric freshwater cementation subfacies

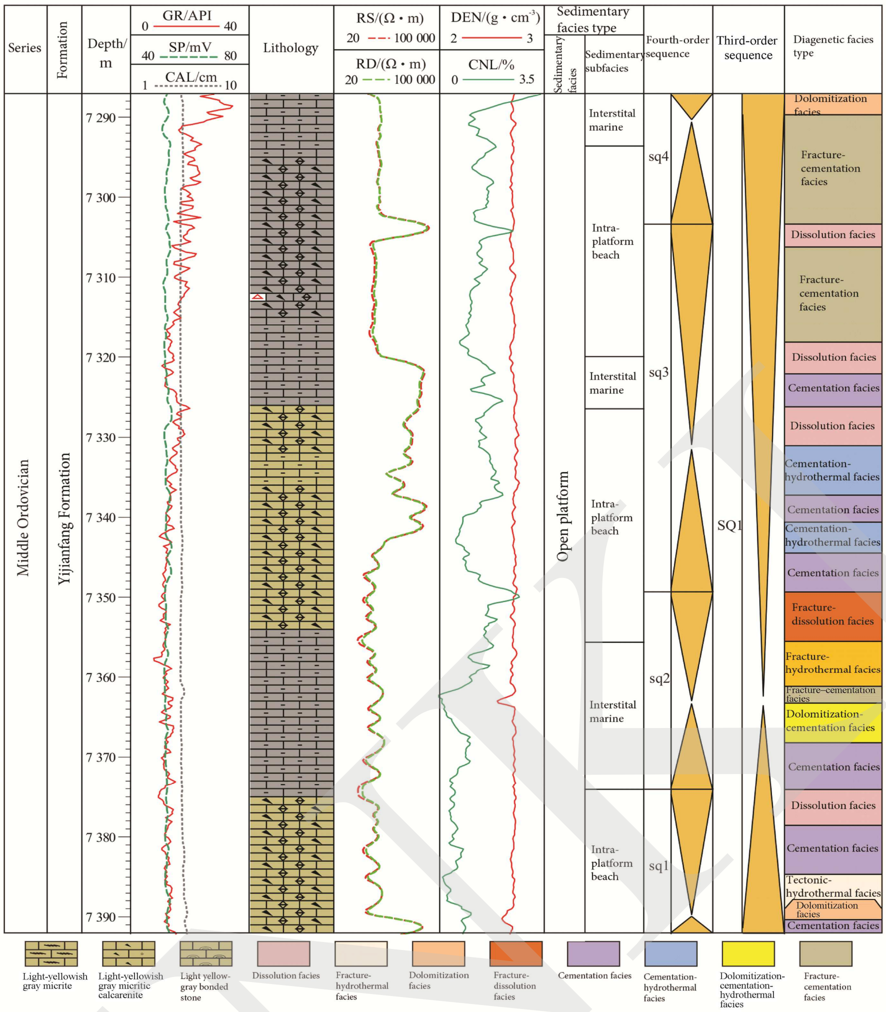

Fig. 4 Diagenetic facies columns of Yijianfang Formation, Well Shunbei 1-3, Shunbei area, Tarim Basin

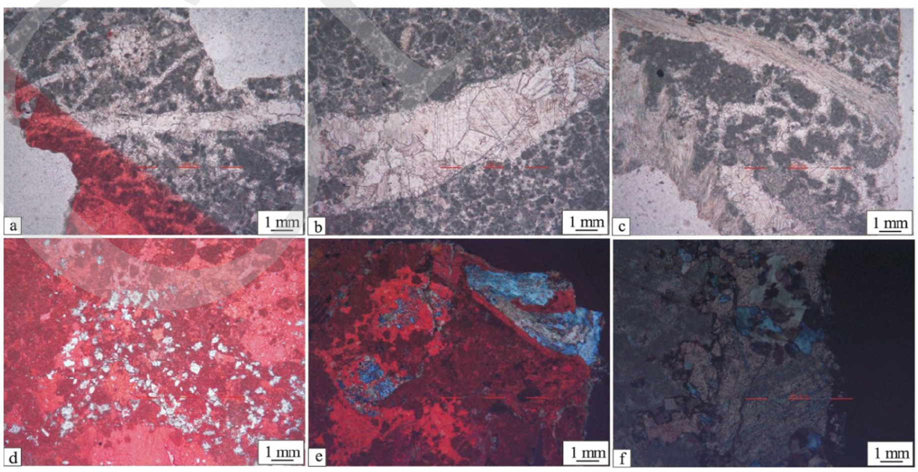

Fig. 5 Diagenetic characteristics under sequence control in Yijianfang Formation, Well Shunbei 1-3, Shunbei area, Tarim Basin

a. It is arenaceous grainstone obtained from 7 360 m, with dissolution fractures/pores and dissolution along fractures; b. It is grainstone obtained from 7 358 m, with freshwater dissolution fractures; c. It is grainstone obtained from 7 358 m, with dissolution caves developed and two well-preserved brachiopods; d. It is algae-bonded limestone obtained from 7 354 m, with dolomite scattering in the micritic matrix and metasomatic micritic particles; e. It is algae-bonded limestone obtained from 7 352 m, where hydrothermal destroyed calcite cement and the quartz cement is formed; f. It is algae-bonded grainstone obtained from 7 350 m, where suture lines are well developed. They are usually observed in the areas without developed bulky sparry calcite, indicating that the formation of sutures is later than that of calcite

4.2 Determination method of planar distribution of diagenetic facies

4.2.1 Point diagenetic facies

After the diagenetic facies in the Yijianfang sequence framework of Wells Shunbei 1-3, Shunbei 1 and Shunbei 2, the diagenetic facies can be identified by points. This paper takes Well Shunbei 1-3 as an example (Fig. 4). In this well, the 7 366–7 378 m section of Yijianfang Formation is dominated by micrite, which is developed with dolomitization-cementation facies and cementation-hydrothermal facies; the 7 301–7 366 m section is developed with grainstone of the intra-platform reef facies, and the diagenetic facies include fracture-hydrothermal facies, cementation-hydrothermal facies, and dolomitization-cementation facies; the lithology of 7 256–7 301 m section is dominated by bioclastic mudstone–microcrystalline limestone and micrite, which mostly contain pyrite and quartz. It indicates that the transformation by hydrothermal fluids. The diagenetic facies is also dominated by tectonic hydrothermal facies, and the fracture-hydrothermal facies and the fracture-cement facies are developed as well.

4.2.2 Line diagenetic facies

The well-tie analysis under the control of sequence framework is conducted to the typical single-well diagenesis in this study area. It, combined with the paleo-geomorphology, can clearly analyze the lateral distribution characteristics of diagenetic facies by lines. As shown in Fig. 6, the favorable diagenetic facies such as dissolution facies, fracture-dissolution facies, and fracture-hydrothermal facies are relatively developed near the sequence interface, and the connectivity is strong. Many thick layers of cementation facies and fracture-cementation facies are developed in the area close to the marine flooding surface, indicating that the sequence interface has a strong controlling effect on the development of diagenetic facies [36–37]. Therefore, the well-tie comparison on diagenetic facies in the sequence framework can be taken as an important basis for studying the diagenetic facies distribution.

4.2.3 Surface diagenetic facies

The prerequisite for the establishment of surface diagenetic facies is to determine the paleo-geomorphology of the study area. Generally, the water in the high structural part is relatively shallow, and the carbonate rock sediment is thick, which is largely affected by the penecontemporaneous atmospheric freshwater. The water in the low structural part is deep, and the carbonate rock sediment is thin, which is less affected by atmospheric freshwater. The terrain in the study area gradually ascends from southwest to northeast, well matching with the well-tie distribution of diagenetic facies in Wells Shunbei 2–Shunbei 1–Shunbei 1-3. Among them, Wells Shunbei 1-3 and Well Shunbei 1 are located in the high structural part, where the water is shallow and the sediments are thick. They are significantly affected by the penecontemporaneous atmospheric freshwater, which are developed with the dissolution facies and the penecontemporaneous dolomitizaiton facies. Well Shunbei 2 is located in the low structural part, where the water is deep and the sediments are thin. It is less affected by the atmospheric freshwater, which is widely developed with the cementation facies and the hydrothermal facies. Therefore, combining diagenetic facies, sequence and tectonic paleo-geomorphology can greatly improve the prediction accuracy with regard to diagenetic facies distribution.

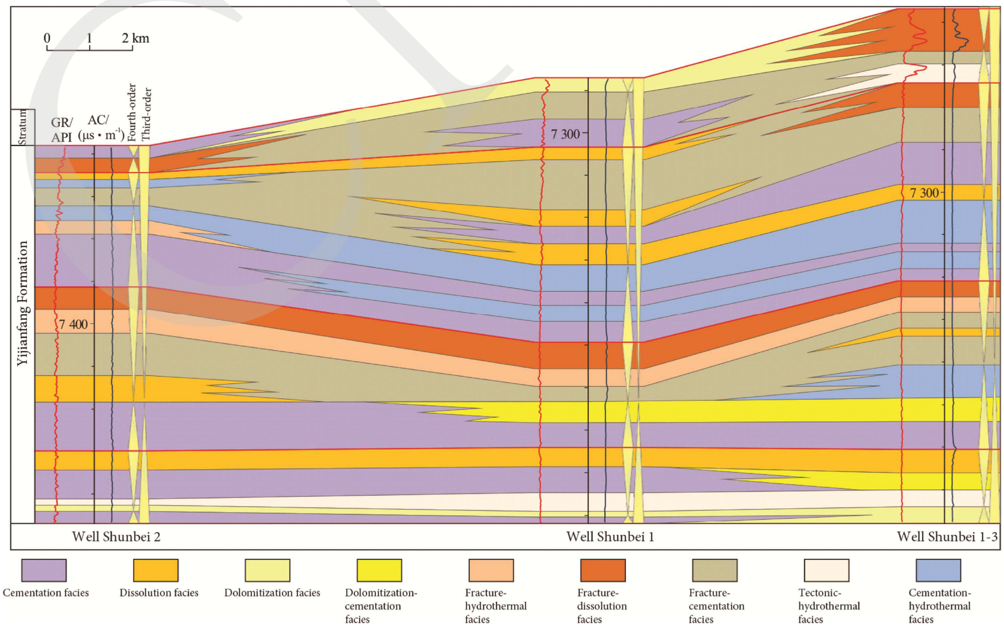

Fig. 6 Diagenetic facies section across Wells Shunbei 2, Shunbei 1 and Shunbei 1-3, Shunbei area, Tarim Basin

Root mean square (RMS) can well reflect the distribution of effective reservoir spaces and favorable physical properties, including reservoir spaces of micro-fractures and dissolution pores. As shown in Fig. 7, the red and yellow patches indicate the distribution areas of favorable physical properties, while the green and white patches represent the areas with relatively weak reservoir properties. Therefore, this paper has made point-to-line study in the previous part. The study on the planar distribution of diagenetic facies shall also rely on the sensitivity of seismic attributes to reservoirs, and make plane projection along the sequence interface, so as to obtain the planar distribution of diagenetic facies at each sequence interface. Furthermore, the RMS attributes are applied, and this distribution can be extended beyond the controlled area of wells, thus obtaining the distribution characteristics of diagenetic facies in the study area.

4.2.4 Planar distribution of diagenetic facies

The planar layout of favorable diagenetic facies in the study area can be indentified (Fig. 8) from the above analysis of the single-well/well-tie diagenetic facies characteristics, the distribution characteristics of tectonic geomorphology and the RMS amplitude attributes in the sequence frameworks. A represents the bottom interface of sq1, at a depth of 7 378 m. The well-tie diagenetic facies profile illustrates that the dolomitization facies is widely developed during this period. Therefore, it is believed that the distribution range of favorable reservoir physical properties in the RMS attributes at this interface belongs to the dolomitization facies (Fig. 8A). B indicates the top interface of sq1, at a depth of 7 360.45 m. In this period, the physical properties in the whole region qre generally good. The sediment thickness varies slightly, and the dissolution effect is developed. It can be inferred that the water in this period is shallow and it is significantly affected by atmospheric freshwater. The distribution of dissolution facies at this interface (Fig. 8B) is obtained with the range of favorable physical properties in RMS attributes during this period. C refers to the marine flooding surface of sq2, at a depth of 7 376 m. During this period, the water is deep, and it is weakly affected by the atmospheric freshwater; dissolution is not strong, and the favorable reservoir physical properties are poor. The well-tie diagenetic facies profile illustrates that the cementation facies and the cementation-hydrothermal facies are mainly developed, and the dissolution facies are widely developed near Well Shunbei 2. They transform into the cementation facies and the cementation-hydrothermal facies successively towards the northeast. The diagenetic facies distribution at this interface can be obtained (Fig. 8C) on the basis of the distribution of favorable physical properties in RMS attributes, which is relatively better developed in the southwest while underdeveloped in the northeast. D shows the top interface of sq4, with a depth of 7 287 m. During this time, strong regression is found, and it shows the geomorphic features of low in the southwest while high in the northeast under the control of tectonic topography. Therefore, the water in this area is relatively shallow. However, the water shows a tendency of deepening in the southwest. The well-tie diagenetic facies profiles suggest that Well Shunbei 1-3 is developed with the contiguous dissolution facies, and it gradually transforms into the dolomitization facies in Well Shunbei 1; all of them are the facies belts favorable for reservoir spaces. The RMS amplitude energy in Well Shunbei 2 is relatively weak, in the form of cementation facies. The diagenetic facies distribution in Fig. 8D is determined according to the fact that the areas with favorable physical properties as shown by RMS attributes are located in the middle and northeast of this block.

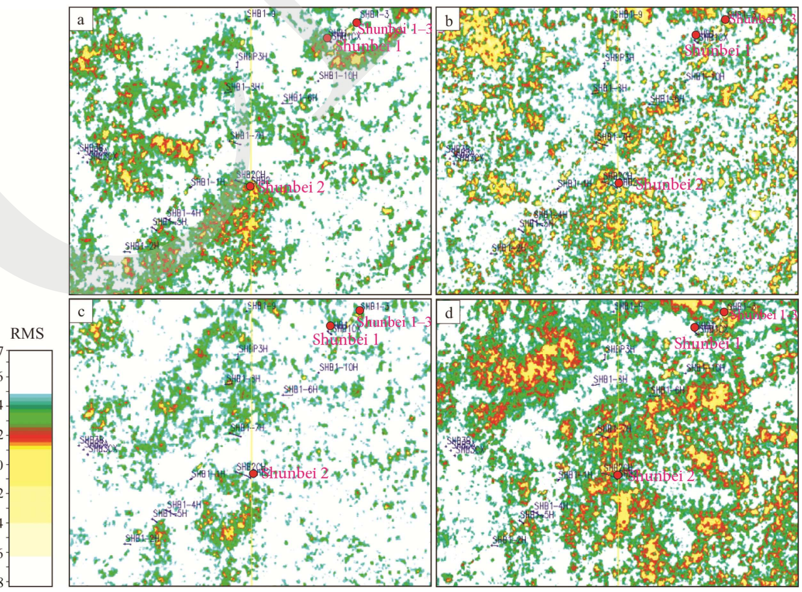

Fig. 7 RMS attributes of Yijianfang Formation, No.1 fault zone, Shunbei area, Tarim Basni

The location of the study area is shown in Fig. 1.

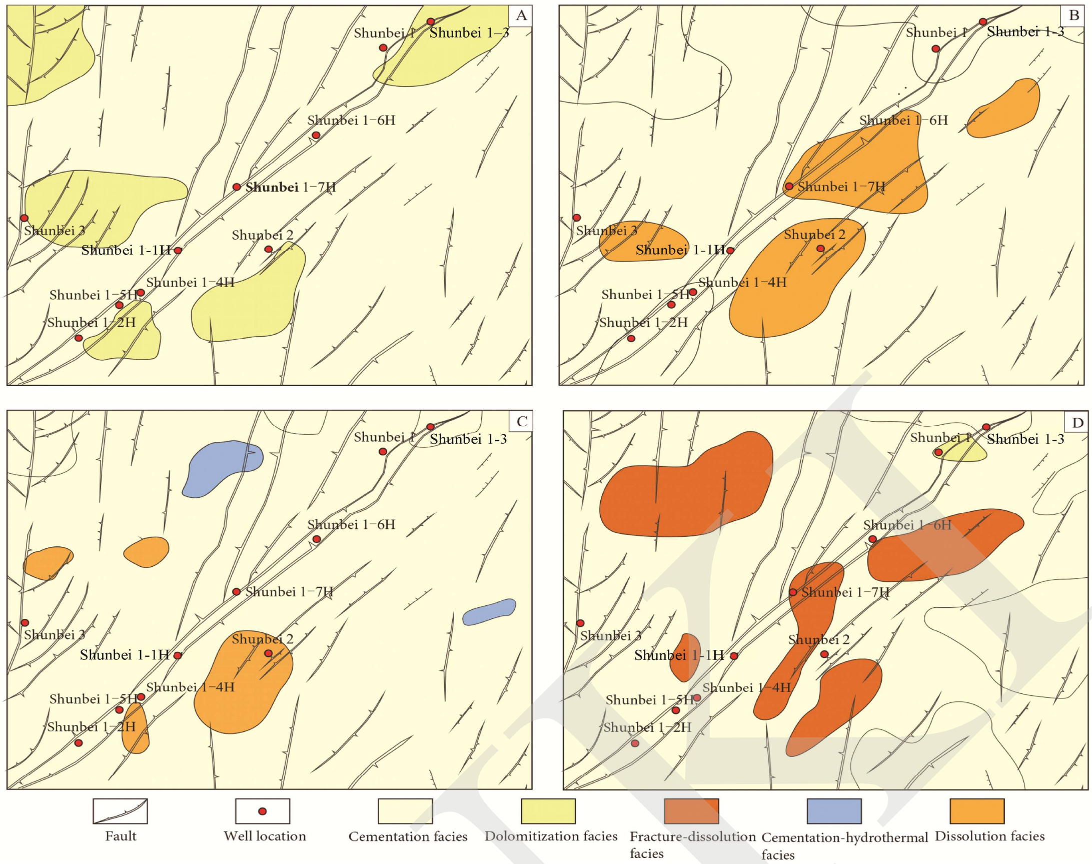

Fig. 8 Planar distribution of diagenetic facies of Yijianfang Formation in 3D seismic survey block of No. 1 fault zone, Shunbei area, Tarim Basin

According to the distributions of diagenetic facies in those four periods, the favorable diagenetic facies in the study area are mainly dolomitization facies, fracture-dissolution facies, and dissolution facies. Among them, the fracture-dissolution facies is the most conducive to the reservoir development, and it is mainly distributed in the middle–northeast parts of this study area in Fig. 8D. It is followed by the dissolution facies, which shows the largest development area and good continuity in Fig. 8B, and develops SW-NE strike along the Shunbei No. 1 fault zone. The distribution of favorable diagenetic facies is gradually transiting from the southwest to the northeast. In the late sedimentary stage of Yijianfang Formation, the favorable diagenetic facies belts are basically concentrated in the middle and northeast parts of the study area, and the area is relatively large, which can be selected as the exploration targets in the future.

5 Conclusions

(1) The diagenetic facies in the study area can be divided into dissolution facies, dolomitization facies, fracture facies, cementation facies and hydrothermal facies. For the different forming environments of dissolution facies, dolomitization facies and cementation facies, they can be further divided into eight diagenetic subfacies, namely atmospheric freshwater dissolution, burial dissolution, fracture-dissolution, penecontemporaneous dolomitizaiton, burial dolomitization, subsea cementation, freshwater cementation and burial cementation. Also, five composite diagenetic facies are identified: cementation-hydrothermal, fracture-dissolution, fracture-cementation, fracture-hydrothermal and dolomitization-cementation facies.

(2) On the basis of core description, thin section analysis, logging trace and seismic data, and control of sequence framework and sedimentary facies on diagenetic facies distribution, it is believed that the transgressive system tract is developed with the subsea cementation diagenetic subfacies; in the high system tract, the tectonic hydrothermal facies, the fracture hydrothermal facies and the cementation facies are developed. The intra-platform subfacies is mostly developed with the atmospheric freshwater dissolution subfacies, the atmospheric freshwater cementation subfacies, and a small amount of tectonic-hydrothermal facies. The interstital marine subfacies are developed with the burial dolomitization subfacies, the dissolution facies and the cementation facies. The intra-platform reef subfacies are developed with the atmospheric freshwater dissolution and atmospheric freshwater cementation subfacies.

(3) The comprehensive analysis of the single-well/well-tie

diagenetic facies characteristics, tectonic paleo-geomorphology and RMS amplitude attributes will contribute to the identification of the planar distributions of favorable diagenetic facies in this study area. The favorable diagenetic facies in the sq1–sq4 periods are mainly dolomitization facies, fracture-dissolution facies, and dissolution facies. Among them, the fracture-dissolution facies are the most conducive to reservoir development, and exhibit a migration trend from southwest to northeast. The favorable diagenetic facies belts in the late sedimentary stage of Yijianfang Formation are mainly concentrated in the middle and northeast parts of the study area, which can be selected as the exploration targets in the future.

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