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RESEARCH ARTICLE

Sedimentary characteristics and depositional evolution of carbonate platform during the Cambrian and Ordovician in eastern Tarim Basin, NW China

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Abstract The eastern Tarim Basin (Tadong Area) has gained wide attentions on large-scale marine carbonate reservoirs in Cambrian-Ordovician due to significant hydrocarbon discoveries. A systematic analysis combining thin sections, cores, wireline logs, and seismic data is conducted on Cambrian-Ordovician carbonate platform in the whole eastern Tarim Basin, including Gucheng area, Majiaer area, and western Luobopo rise (Luoxi area). The results show that 8 sub-facies and more than 10 micro-facies are developed including open platform, restricted/semi-restricted platform, reef-shoal around platform margin, drowned platform, foreslope, neritic platform, and deep-water basin. As both key areas for hosting petroleum reserves during the Cambrian and Ordovician, the Luoxi area is dominated by deep-water basin facies, while the Gucheng area is dominated by neritic platform facies and deep-water basin facies during the Lower Cambrian. The deposition evolution during the whole Cambrian is dominated by slope facies and deep-water facies, platform margin facies, and platform facies. In contrast, it is dominated by open platform facies during the whole Ordovician. The depositional evolution of carbonate platform is mainly controlled by paleo-geomorphology and sea-level changes. The distribution of paleo-geomorphologic units plays an important role in controlling types and distributions of carbonate platform facies. The transgression assists in growth of reef-shoal complex and lime mud mound in the Early Ordovician. However, with neritic platform and slope being to disappeared, in the Middle Ordovician, platform margin facies are well developed in Gucheng Area. Platform facies and deep-water basin facies are widely distributed. Finally, carbonate platform is drowned due to sea level rising in the Late Ordovician. The depositional evolution of carbonate platform coinciding falling and rising of sea-level changes can be beneficial for appropriate carbonate reservoirs identification and petroleum exploration.

Keywords carbonate platform, depositional evolution, sedimentary facies, Tarim Basin, the Cambrian-Ordovician

1 Introduction

The sedimentary characteristics and depositional evolution of carbonate platform has aroused wide-spread attentions in the last few decades (Pomar, 2001; Schlager, 2005; Lin et al., 2012; Wilson et al., 2019). The carbonate platform, where bunch of petroleum reserves are accumulated and discovered, is commonly a place with natural temporal-spatial boundaries (Red, 1985; Pomar, 2001). The boundaries of carbonate platform are generally constrained by fluxes of energy (light energy and chemical energy in compounds, kinetic energy in currents and mass flow) and matter (nutrients, carbonates, etc.). The interactive energy and matter usually lead to complex sedimentary characteristics and depositional evolution of carbonate platform (Pomar, 2001; Regnet et al., 2019; Gao et al., 2020). Understanding sedimentary characteristics and depositional evolution assists in establishing models of carbonate platform, predicting distributions of facies/micro-facies, providing insights of hydrocarbon exploration in sedimentary basins with similar settings.

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The Tarim Basin, as one of superimposed petroliferous basins that undergone complex tectonic deformation and evolution in NW China, covers an area of 56×10^4 km^2 (Lin et al., 2012; Dong et al., 2014). The eastern Tarim Basinis bounded by Kongquehe Fault to the north and Cheerchen Fault to the south (Han et al., 2009; Zhang et al., 2022). The coverage of eastern Tarim Basin approximately arrives at 12.57×10^4 km^2 (Han et al., 2009; Huang et al., 2017). During the Cambrian and the Ordovician, the carbonate and siliclastic deposits are widely distributed in eastern Tarim Basin (Feng et al., 2006, 2007; Zhang et al., 2007; Ren et al., 2014;). Furthermore, the sedimentary characteristics and depositional evolution are complicated (Feng et al., 2006, 2007; Han et al., 2009). So far, several giant oil/gas fields and petroliferous hydrocarbon indicators have been found in carbonate deposits in eastern Tarim Basin in the past few years by boreholes (GC6, GC8, TD2, and LX1) (Han et al., 2009; Huang et al., 2017). Therefore, the attentions to carbonate deposits, especially carbonate platform have been paid increasingly due to significant petroleum reserves. The extensive hydrocarbon exploration and exploitation has resulted in bunch of geological and geophysical data sets, including 2D/3D seismic lines/volumes, wireline logs, cores, and etc., which allows a systematic and integrated investigation of sedimentary characteristics and depositional evolution of carbonate platform. Previous studies predominantly focus on tectonic settings, sequence architecture and responses to controlling factors, and reservoir characteristics and mechanism (Feng et al., 2006, 2007; Lin et al., 2012, 2013; Shen et al., 2018; Zhang et al., 2019; Wang et al., 2020). In addition, the studies on carbonate facies mainly focus in local area (such as Gucheng Area or Luoxi Area or Tabei Area) or in single formations (the formations in Cambrian or the formations in Ordovician) (Feng et al., 2006, 2007; Lin et al., 2012, 2013; Ren et al., 2014) with limited data sets.

Presently, few studies concerning to sedimentary characteristics and depositional evolution of carbonate platform from the whole Cambrian to the Ordovician are conducted in the eastern Tarim Basin. To address the issues clearly, we employ 2D/3D seismic lines/volumes across eastern Tarim Basin, wireline logs from approximately 39 wells, cores and thin sections from approximately 16 wells to carry out comprehensive analysis. The purpose of this study is to make convincing and reliable sedimentary variation characteristics in the study area and to guide petroleum explorations.

2 Geological overview

2.1 Tectonic settings

The Tarim Basin, as one of petroliferous basins in northwestern China, is characterized by 1500 km in length and 700 km in width (Fig. 1(a)) (Lin et al., 2012; Laborde et al., 2019). The coverage of Tarim Basin approximately reaches 56×10^4 km^2 (Lin et al., 2013). It has undergone long-term geological evolution history, resulting the boundary of mountain ranges: Tianshan to the north, Altyn Tagh Range to the south-east, and Western Kunlun Range to the south-west in clockwise direction (Han et al., 2009; Zhang et al., 2013; Laborde et al., 2019). The eastern Tarim Basin refers to the region that is located in eastern part of Tazhong Uplift, including Tadong Uplift, Majiaer Depression, Western Majiaer Low Rise, Gucheng Low Rise, Luobupo Rise, and Kongquehe Slope (Fig. 1(b)) (Han et al., 2009; Dong et al., 2014). The eastern Tarim Basin was affiliated to Tarim Basin and evolved with the evolution of Tarim Basin (Xu et al., 2005; Dong et al., 2014). Therefore, the evolution of eastern Tarim Basin was complicated (Tang et al., 2003; Han et al., 2009). The basement rocks were developed in responses to Tarim Movement (before 800 Ma) before Sinian Period (Wu et al., 2002). Then, the Tarim Movement resulted in regional metamorphism of basement rocks to a large extent. The angular unconformity lied between overlying seal during Sinian Period and underlying basement rocks (Tang, 1994). The Tarim Basin was in an extensional setting during depositional period from the Sinian to the Ordovician with a time span of 361 Ma (Tang et al., 2003). The ancient Tarim Plate began to breakup and subside during the Sinian Period (He et al., 2008). The development of intracontinent rift basins within ancient Tarim Plate was related to mantle uplifting, crustal thinning, lithospheric extension (He et al., 2017a). In the Early Sinian, the rifting process was weak. The deposition only occurred at the basin margin with a set of terrigenous clastic rocks, tillites interbedded with volcanic rocks in shallow-marine environment (He et al., 2017b; Huang et al., 2017). The intensity of rifting started to increase during the Late Sinian. It received a set of carbonate rocks and clastic rocks in stable shallow-marine environment. The eastern Tarim Basin entered an unfilled sedimentary environment as the whole Tarim Basin was in an extensional tectonic environment during the Cambrian Period (Feng et al., 2006; He et al., 2008). The southern Tianshan Mountain and Altun Mountain acted as provenance which provided sediment supply to the basin (Feng et al., 2006; Liu et al., 2017). In addition, two sedimentary zones constrained by Kongquehe Fault were formed. The sedimentation had undergone an important transition since the Cambrian Period, forming an onlap unconformity over ancient Tarim Basin (Liu et al., 2005). The sediments were dominated by intraclast, lacking in terrigenous clastic deposits (Feng et al., 2006). The sea scope expanded during the Ordovician Period (Feng et al., 2007; Lin et al., 2012). The southern Tianshan Mountain shrank relatively compared to that during the Cambrian Period (Lin et al., 2013; Dong et al., 2014).

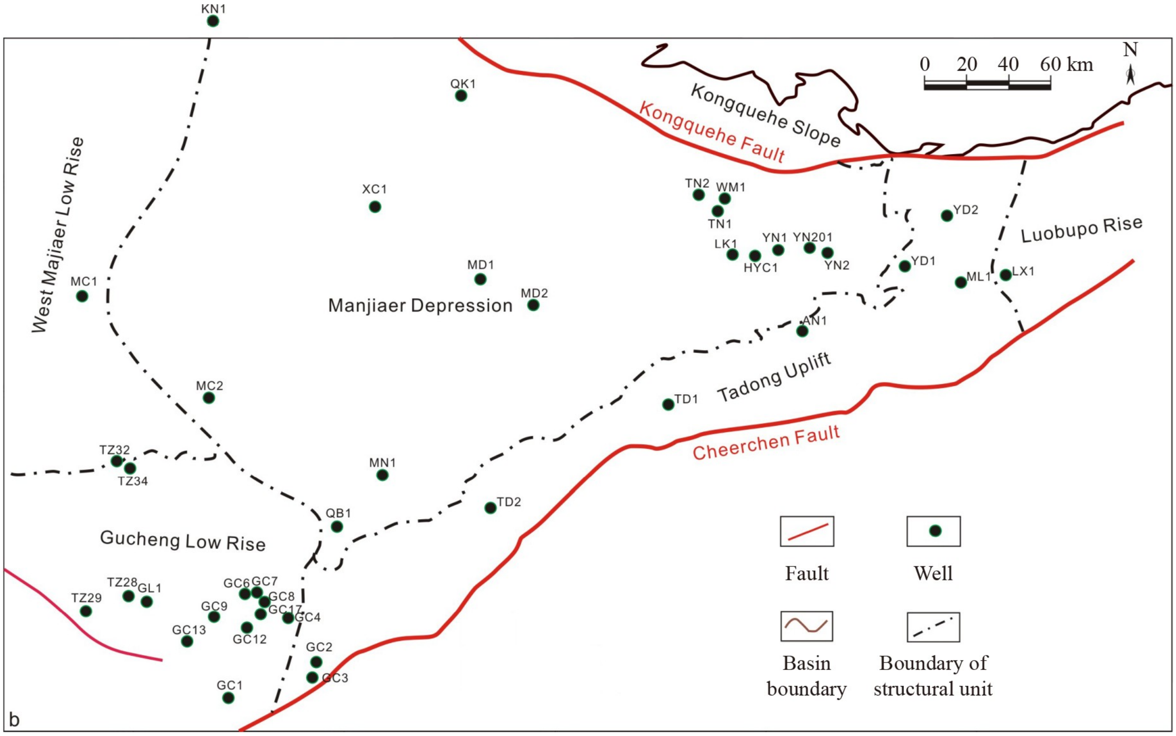

Fig. 1 Location, structural units, faults and database used in Eastern Tarim Basin.

The Altun Mountain was considerably drowned in the seawater (Lu et al., 2015). Therefore, there was not sufficient sediment supply.

2.2 Stratigraphy

The thickness of strata developed in eastern Tarim Basin can be up to 17000 m. It predominantly consists of the Sinian, the Cambrian, the Ordovician, and the Silurian in the Paleozoic, the Jurassic and the Cretaceous in the Mesozoic, the Paleogene, the Neocene, and the Quaternary in the Cenozoic in ascending order (Feng et al., 2006, 2007; Ren et al., 2014; Huang et al., 2017). However, some strata are missing, including the Devonian, the Carboniferous and the Permian in the Paleozoic, the Triassic in the Mesozoic (Tang, 1997; Wu et al., 2018). In addition, the distribution of the Devonian is relatively limited (Wu et al., 2018). Besides, the Carboniferous is distributed adjacent to Gucheng Area (Wu et al., 2018). In contrast, the Cambrian and the Ordovician is preserved in the north of Cheerchen Fault (Feng et al., 2006, 2007; Lin et al., 2012). The Silurian and the Devonian is only found in the north of eastern Tarim Basin (Wu et al., 2018). Compared with distribution of the Paleozoic and the Mesozoic, the Cenozoic is widely distributed in the study area, followed by the Cretaceous (Yu et al., 2010). In this study, the focus ranges from the Cambrian to the Ordovician. The strata encountered or penetrated the Ordovician by exploration wells in Gucheng Area and Luoxi Area follows the principle of stratification division in Tazhong-Bachu Area (Fig. 2). However, the strata encountered or penetrated the Cambrian by exploration wells in other parts of eastern Tarim Basin follows the principle of stratification division in Tadongbei Area (Fig. 2). The detailed descriptions of the Cambrian and the Ordovician are addressed as follows.

The Cambrian is encountered or penetrated by boreholes (TD1, TD2, ML1, YD2, and YD1) in the east of eastern Tarim Basin (Feng et al., 2006; Ren et al., 2014; Lu et al., 2015; Yang et al., 2020). The lithology associations are dominated by black micrite, microcrystalline dolomite, medium- to macro-crystalline dolomite, argillaceous rock, carbonolite, and siliceous carbonate rock (Wang et al., 2015; Wang et al., 2020). The Lower Cambrian consists of Xishanbulake Formation, Xidashan Formation from bottom to top (Fig. 2). The Xishanbulake Formation is dominated by grayish black microcrystalline dolomite, and siliceous dolomite (Lu et al., 2015; Wang et al., 2020). The lithology associations of Xidashan Formation consist of grayish black siliceous mudstone and muddy limestone interbedded with thin layered shale. It is continuously deposited with underlying Xishanbulake Formation (Lu et al., 2015; Yang et al., 2020). The lithology associations in the Middle Cambrian Moheershan Formation include gray and dark gray marl in upper part, and gray and dark gray dolomitic mudstone interbedded with marl in lower part (Zhang et al., 2015). The Upper Cambrian Tuershaketage Formation is dominated by a set of gray-black argillaceous or limy dolomite with parallel laminations. The dolomite is thicker than that in

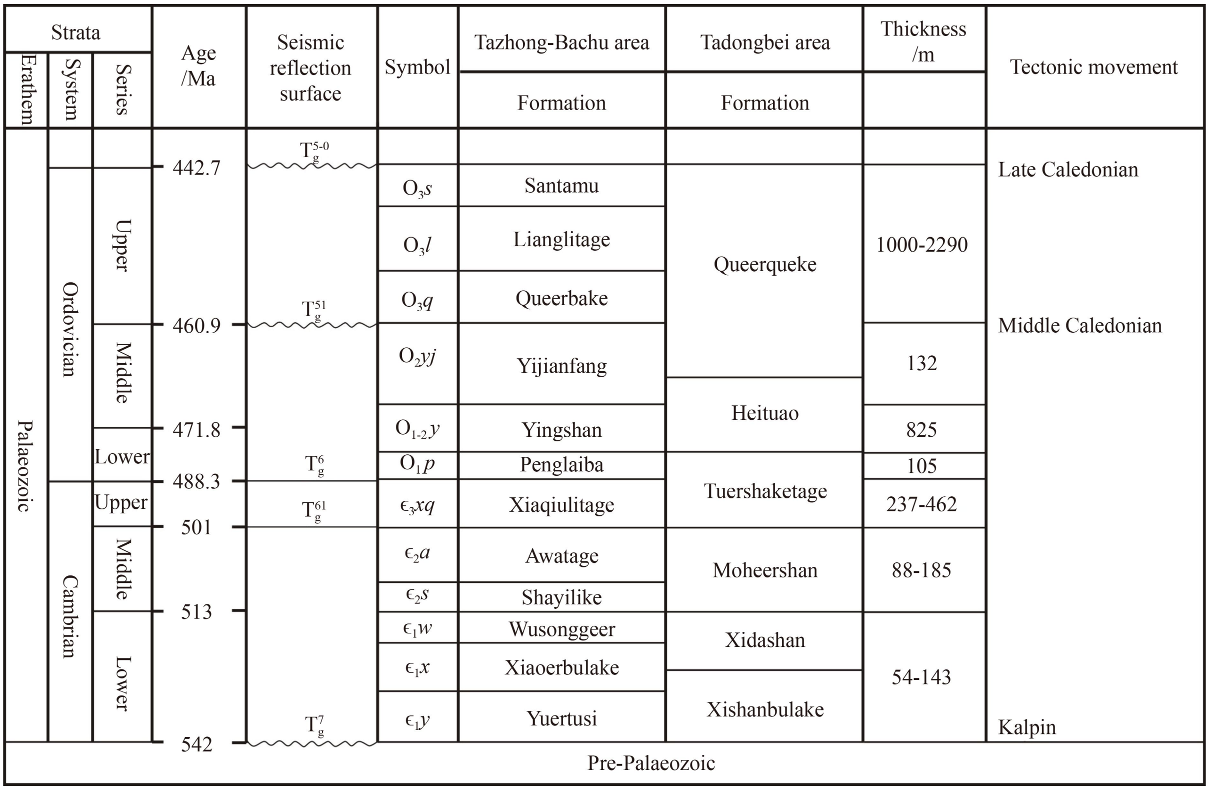

Fig. 2 The stratigraphic column of the Cambrian-Ordovician in Eastern Tarim Basin (cited and integrated from Research Institute of Petroleum Exploration and Development, PetroChina; Huang et al., 2017; Yang et al., 2020).

the Middle Cambrian. It shows conformity with underlying Moheershan Formation. In contrast, the Cambrian is encountered or penetrated by boreholes (GC4, GC7, GC8, and LX1) in the west of eastern Tarim Basin (Yang et al., 2020). The lithology associations are dominated by micro-crystalline-fine-crystalline dolomite, limy dolomite and dolomitic limestone with local micrite, macro-crystalline dolomite and calcarenite (Lu et al., 2015; Zhang et al., 2007).

The Middle and Lower Ordovician in the west of eastern Tarim Basin consists of Penglaiba Formation, Yingshan Formation and Yijianfang Formation in ascending order (Fig. 2) (Feng et al., 2007; Dong et al., 2014). The Upper Ordovician includes Queerbake Formation, Lianglitage Formation and Santamu Formation. Some boreholes (including LX1, GC4, GC6, GC7, and GC8) encounter or penetrate the Ordovician (Feng et al., 2007). The Penglaiba Formation in the Lower Ordovician mainly develops oolitic limestone, calcsparite calcarenite, calcsparite calcirudite, micro-crystalline, or fine-crystalline dolomite in upper part and medium-crystalline to micro-crystalline dolomite in lower part (Lin et al., 2012, 2013). The Yingshan Formation in the Middle-Lower Ordovician predominantly develops interbedded dolomite and limestone in the lower part. However, it mainly develops calcarenite, algal limestone, and micrite (Lu et al., 2015). The Yijianfang Formation in the Middle Ordovician is dominated by thin calcarenite, bioclastic limestone, and oolitic limestone (Ren et al., 2014). The Upper Ordovician is composed of bioclastic calcipulverite, bioclastic limestone, and knollenkalk, rich in small and thin shell organisms (Wang et al., 2014a; Zhang et al., 2020). The Middle and Lower Ordovician in the east of eastern Tarim Basin includes Heituao Formation and Queerqueke Formation from bottom to top (Fig. 2) (Zhao et al., 2009). All these two formations have been penetrated by boreholes, including ML1, YD1, YD2, TD1, and TD2 (Feng et al., 2007; Lu et al., 2015). The Heituao Formation is dominated by grayish black carbonaceous shale and siliceous shale in lower part and dark gray-black interbedded siltstone and mudstone. The Queerqueke Formation is composed of thick interbedded sandstone, siltstone, and grayish black mudstone (Wang et al., 2014b; Zhang, 2017; Yang et al., 2020).

3 Dataset and methodology

The data sets used in the study is provided by Exploration and Development Research Institute, Daqing Oilfield Company, PetroChina. It mainly includes 2D seismic lines/3D seismic volume, wireline logs, cores (9 wells), and thin sections (10 wells). The 2D seismic lines are totally 3599 km. The dominant frequency is about 30 Hz. The 3D seismic volume covers an area of 1620 km^2 with bin spacing of 25 m×25 m. The dominant frequency is approximately 35 Hz. The wireline logs come from 39 wells, including AC, DT, GR, SP, RD, RS, and DEN. The sampling rate is 0.125 m. The cores (327 pictures) from 9 wells ranges 113.49 m in total. The thin sections (455 pictures) are obtained under a polarizing microscope.

The lithology description of carbonate rocks adheres to the term and nomenclature of Dunham (1962) which is widely accepted in Tarim Basin. The interpretation of sedimentary facies/microfacies and summary of depositional model follow the principle of Wilson (1975) which is widely used around the world. The detailed workflows for study as follow. 1) Identification and description of facies/microfacies based on thin sections, cores, wireline logs, and seismic sections. The thin sections and cores provide micro-characters while wireline logs and seismic sections assist in macro-characters of facies/microfacies in carbonate platform. 2) Prediction of facies/microfacies distribution according to single well facies/microfacies analysis, well-tie-well correlation and well-tie-seismic interpretation. The scope of facies/microfacies is determined by well correlation and well-tie-seismic section interpretation. 3) Summary of depositional model with regarding to facies/microfacies distributions, sea level changes and regional tectonic settings.

4 Interpretations

4.1 The determination of division scheme in sedimentary facies/microfacies

Previous studies have demonstrated that carbonate facies model (including 9 facies) proposed by Wilson is widely accepted and used in sedimentary facies analysis of carbonate rocks (Wilson, 1975; Tucker and Wright, 1990; Flügel, 2009). The model elaborates the distribution and characteristics of carbonate facies from land to basin, including platform evaporite, restricted platform, open platform, platform marginal shoal, platform marginal reef, foreslope, neritic platform edge, neritic platform, and deep-water basin. In addition, it is widely accepted that carbonate depositional model proposed by Ma and Zhang (1999) is more suitable to carbonate setting in China. In this study, it integrates the model from Wilson (1975) and Ma and Zhang (1999) to propose facies concepts and describe facies characteristics based on actual sedimentary environments. Therefore, the carbonate facies in eastern Tarim Basin can be further divided into three facies zones, namely platform facies, platform margin facies, and deep-water basin facies (Fig. 3 and Table 1). In addition, several sub-facies and microfacies are identified based on integrated analysis of thin sections, cores, wireline logs and seismic reflections (Fig. 3 and Table 1). In general, well GL1 is predominantly deposited in platform facies during depositional period of the Cambrian-Ordovician. To be specific, it is dominated by restricted platform and semi-restricted platform in the Cambrian while it is dominated by open platform in the Ordovician. In contrast, the platform margin facies occupy the location of well GC4, GC6, GC7, and GC8 in the Cambrian-Ordovician. It mainly consists of platform marginal shoal and reef, interbank sea and drown platform from the Cambrian to the Middle Ordovician. The distribution of platform margin shifts due to sea level changes. It is dominated by neritic platform in the Upper Cambrian and Lower Ordovician, deep-water basin in the Middle and Lower Cambrian in well TD2, TD1, and YD1. Unlike well YD1, it is characterized by deep-water basin in well YD2 in the Middle and Lower Cambrian. However, it is dominated by foreslope in the Upper Cambrian and Lower Ordovician. It is composed of deep-water basin, neritic platform and foreslope from Lower Cambrian to Upper Cambrian in well ML1, which shows coarsening-up characteristics. It mainly includes platform margin facies from Lower Cambrian to Middle Ordovician in well LX1 (Fig. 3).

4.2 The types and characteristics of sedimentary facies/microfacies

It predominantly includes two carbonate platforms in

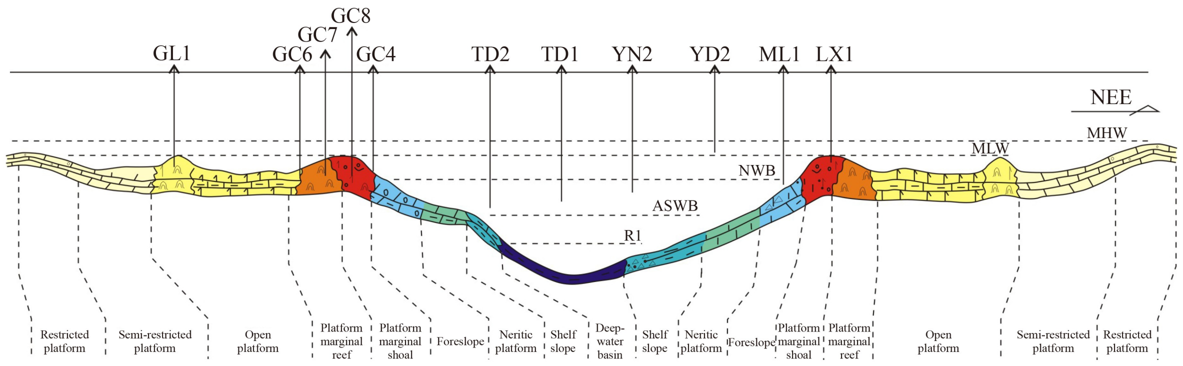

Fig. 3 The model showing facies zone during depositional period of the Cambrian-Ordovician in eastern Tarim Basin. NWB = normal wave base; ASWB = average storm wave base; RI = redox interface; MLW = mean low-tide base; MHW = mean high-tide base.

Table 1 The types and characteristics of carbonate platform resulted from different scholars during the Cambrian-Ordovician in eastern Tarim Basin

Facies	Sub-facies	Micro-facies (present study)	Micro-facies (Ren et al., 2014)	Micro-facies (Wang et al., 2015)	Micro-facies (Lin et al., 2013)	Micro-facies (Zhang et al., 2007)	Micro-facies (Yu et al., 2010)	Micro-facies (Li et al., 2005)
Platform facies	Open platform	Platform interior shoal	Platform interior shoal		Platform interior shoal	Platform interior shoal	Platform interior shoal	Platform interior shoal
						Platform interior cryptic		
			Platform interior cryptic			Interbank sea		
			Interbank hollow			Interbank hollow		
		Interbank sea			Interbank sea			Interbank sea
	Semi-restricted platform	Platform interior shoal			Platform interior shoal	Platform interior shoal		
		Interbank sea			Backreef/shoal hollow	Interbank sea		
	Restricted platform	Tidal flat	Tidal flat	Tidal flat		Tidal flat	Tidal flat	Tidal flat
		Lagoon	Lagoon			Lagoon	Lagoon	Lagoon
		Barrier	Barrier beach-bar		Barrier beach-bar			
	Drowned platform	Storm deposits						
	Evaporated platform			Salt hollow				Salt hollow
Platform margin facies	Platform marginal reef-shoal and lime mud mound	Platform marginal reef	Platform marginal reef	Platform marginal reef	Platform marginal reef	Platform marginal reef	Platform marginal shoal	Platform marginal shoal
		Platform marginal shoal	Platform marginal shoal		Platform marginal shoal	Platform marginal shoal		
		Lime mud mound	Reef-shoal complex	Backreef lagoon	Backreef lagoon	Lime mud mound	Lime mud mound	Lime mud mound
	Foreslope	Foreslope	Foreslope		Foreslope	Foreslope	Foreslope	Foreslope
Deep-water basin facies	Neritic shelf	Slope lime mud	Slope lime mud		Neritic mud	Slope lime mud	Slope lime mud	Slope lime mud
		Neritic mud	Neritic mud			Neritic mud	Neritic mud	Neritic mud
	Deep-water basin and basin floor fan	Mud in deep-water basin				Mud in deep-water basin	Mud in deep-water basin	Mud in deep-water basin
		Basin-floor fan				Basin-floor fan		Basin-floor fan

Gucheng (GC) Area and Luoxi (LX) Area, as well as associated carbonate platform margin area and basin area between them. The seismic sections and well correlations reveal existence of carbonate platform during depositional period of the Cambrian-Ordovician between Gucheng Area and Luoxi Area. It consists of platform facies in the east and the west, and deep-water basin facies in the center, as well as slope facies between platform facies and deep-water basin facies. It employs thin sections, cores, wireline logs and seismic volumes to systematically summarize the types and describe the characteristics of facies/microfacies in carbonate platform during the Cambrian-Ordovician. It mainly consists of 8 sub-facies and more than 10 microfacies from the Cambrian to the Ordovician, including open platform, restricted/semi-restricted platform, reef-shoal around platform margin, lime mud mound, drowned platform, foreslope, neritic platform, and deep-water basin (Table 1).

4.2.1 The characteristics of platform facies

The platform facies include Gucheng platform and Luoxi platform, which are mainly distributed in western Manjiaer Depression and Luobupo Rise. The platform facies in Gucheng Area and Luoxi Area extend toward the opposite. In addition, platform facies can be further divided into open platform, semi-restricted platform, restricted platform and drowned platform. The semi-restricted platform and restricted platform are widely distributed during depositional period of the Cambrian-Ordovician.

4.2.1.1 Open platform

The open platform is developed in shallow sea with normal or slightly high salinity, suitable seawater circulation, weak hydrodynamics and a variety of organisms. The open platform is well developed from the Middle to the Late Ordovician. The open platform is predominantly distributed in Gucheng Area and Luoxi Area. The lithology associations are dominated by granular limestone and marl, which can be further divided into platform interior shoal and interbank sea (Table 1). The open platform facies are limited distributed during depositional period of the Cambrian-Ordovician. Therefore, few wells encounter or penetrate it.

4.2.1.2 Semi-restricted platform

The semi-restricted platform is mainly developed during depositional period of Late Cambrian–Early Ordovician in the west of eastern Tarim Basin. It is developed in responses to poor seawater circulation and weak hydrodynamics between restricted platform and open platform. The lithology associations in semi-restricted platform mainly consist of argillaceous limestone, argillaceous granular limestone, calcisiltite, limy mudstone, and micritic limestone (Figs. 4 and 5). The lithology associations show the characteristics of semi-restricted platform with poor water flow and coexistence of high and low energy. The wireline responses show high gamma ray (GR) value and seriously serrated finger-shape stacking patterns, which reveal relatively strong hydrodynamics. It is characterized by medium amplitude, medium frequency and relatively continuous seismic reflections. The internal architecture of seismic reflections shows sub-parallel characteristics.

4.2.1.3 Restricted platform

The sedimentary environments where restricted platform sedimentation occurs is relatively closed with weak hydrodynamics, poor seawater circulation and high salinity. The lithology associations in restricted platform are composed of micro- to macro-crystalline dolomite with local calcite and dolorudite (Figs. 4 and 5). The wireline responses are characterized by medium GR value and slightly serrated finger-shape stacking patterns, which reveal relatively moderate hydrodynamics (Fig. 10). The seismic responses show strong amplitude, medium frequency and continuous seismic reflections (Fig. 11). In addition, parallel seismic reflections can be seen on seismic section (Fig. 11).

4.2.1.4 Drowned platform

The drowned platform is dominated by grayish green and purplish red knollenkalk filled with calcite, which indicates weak hydrodynamic in relatively deep-water environments (Fig. 7). The distribution of drowned platform is extremely limited only in Late Ordovician. Only two wells have encountered or penetrate it.

4.2.2 The characteristics of platform margin facies

The platform margin facies are located outside the platform, close to the basin and above normal wave base (FWWB), which is controlled by strong hydrodynamics

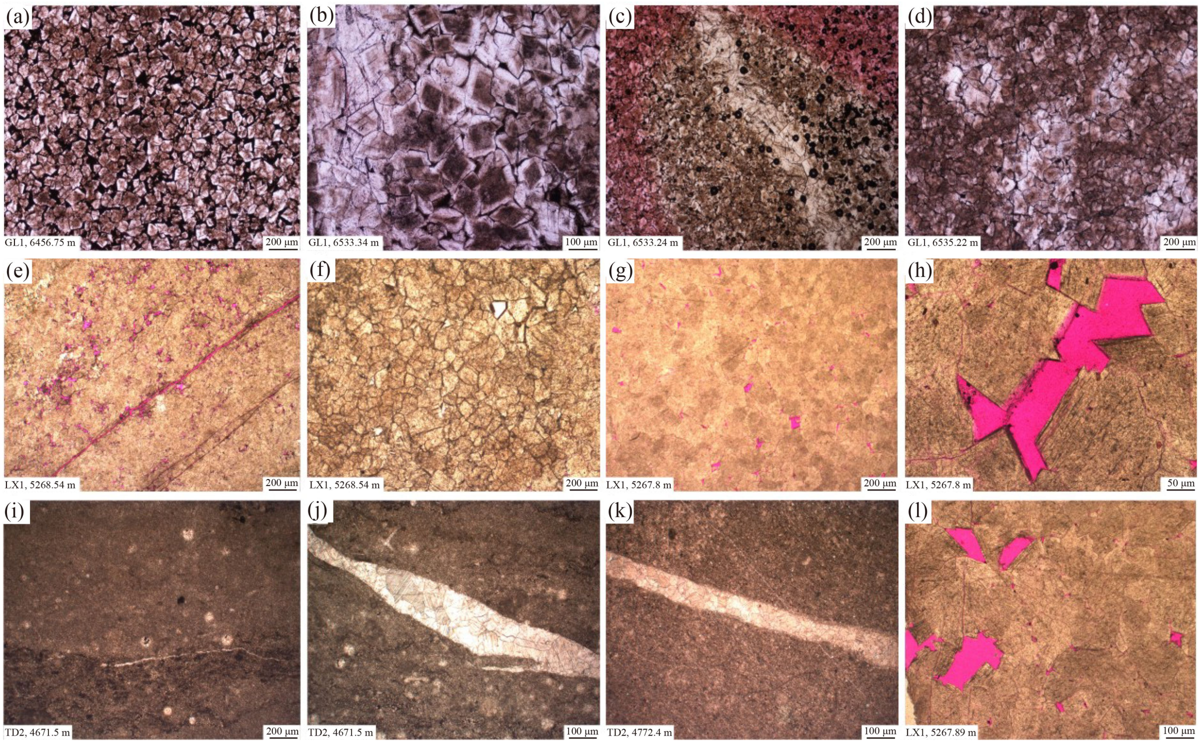

Fig. 4 The summary of thin sections showing the characteristics of platform facies during depositional period of the Cambrian-Ordovician in eastern Tarim Basin; (a) medium-crystalline dolomite; (b) macro-crystalline dolomite; (c) medium-crystalline dolomite; (d) medium-crystalline dolomite; (e) dolomite; (f) micro-crystalline dolomite; (g) dolomite; (h) medium-crystalline dolomite; (i) argillaceous limestone; (j) argillaceous granular limestone; (k) micritic limestone; (l) macro-crystalline dolomite.

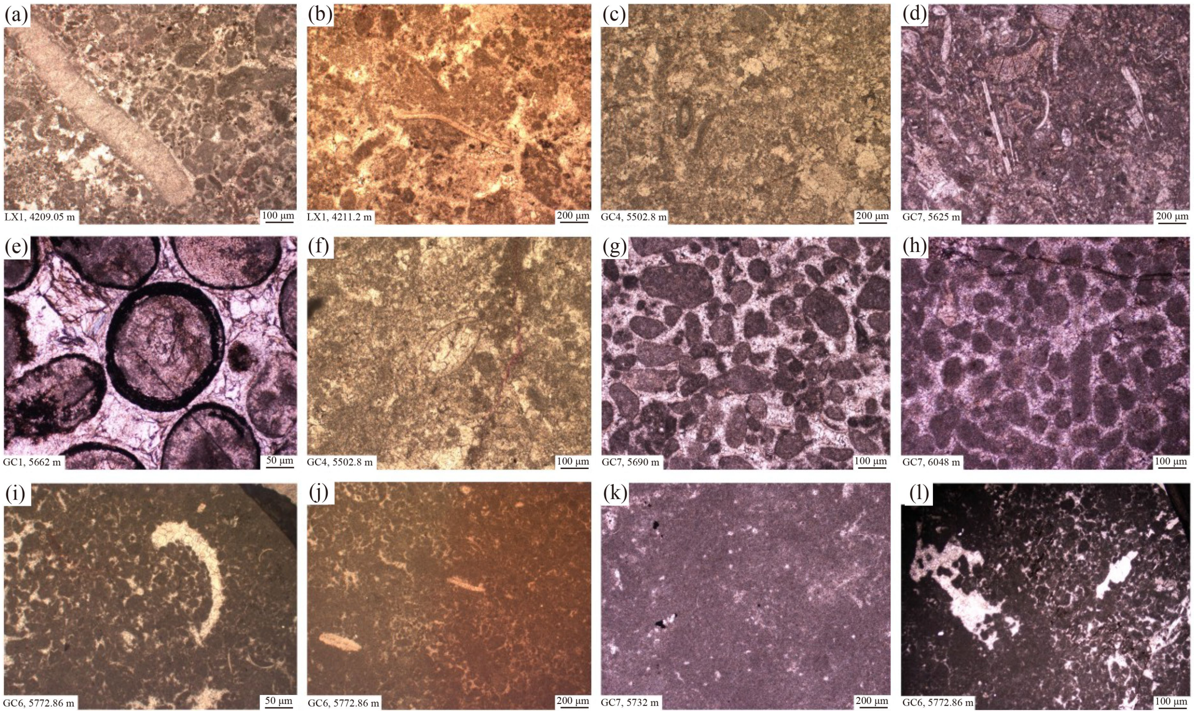

Fig. 5 The summary of thin sections showing the characteristics of platform margin facies during depositional period of the Cambrian-Ordovician in eastern Tarim Basin. (a) Calcsparite calcarenite with burrow; (b) calcarenite with burrow; (c) bioclastic shoal; (d) calcsparite calcarenite with bioclast; (e) calcsparite granular limestone; (f) calcarenite with Ostracoda; (g) calcsparite calcarenite; (h) oolitic limestone; (i) micritic limestone; (j) micritic limestone; (k) argillaceous limestone; (l) micritic limestone.

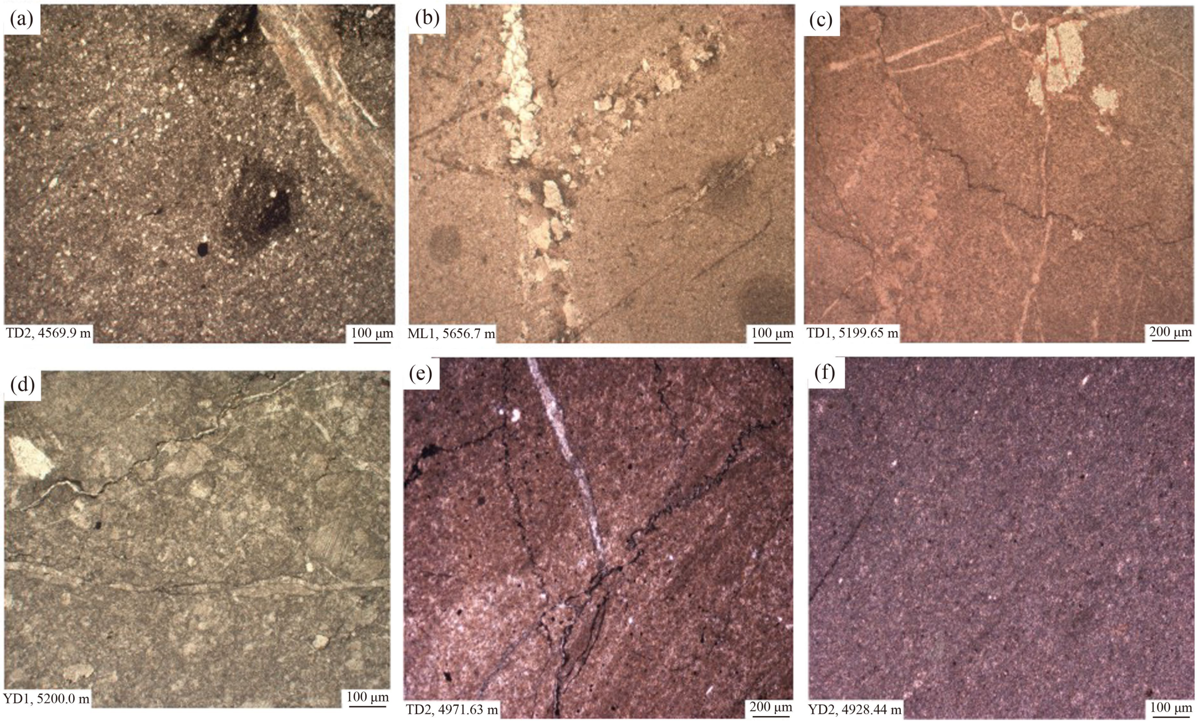

Fig. 6 The summary of thin sections showing the characteristics of deep-water basin facies during depositional period of the Cambrian-Ordovician in eastern Tarim Basin. (a) Micritic limestone; (b) micritic limestone; (c) argillaceous limestone; (d) micritic limestone; (e) limy mudstone; (f) mudstone.

in shallow water. The platform margin facies are widely distributed from the Cambrian to the Middle Ordovician.

The lithology associations in Yingshan Formation and Yijianfang Formation both in Gucheng Area and Luoxi

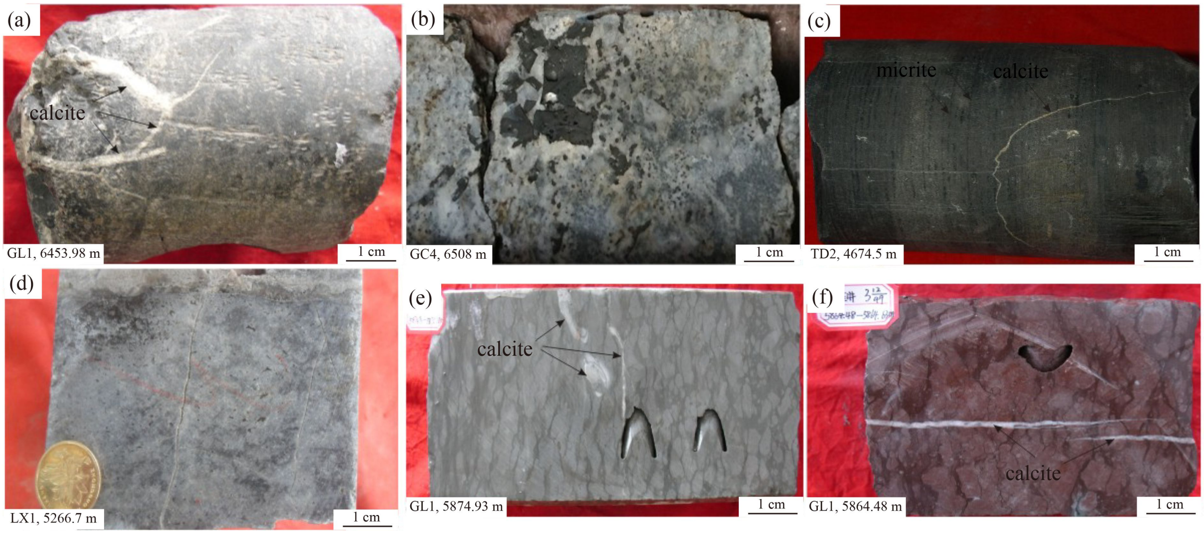

Fig. 7 The summary of cores showing the characteristics of platform facies during depositional period of the Cambrian-Ordovician in eastern Tarim Basin. (a) Yingshan Formation, dark gray dolomite filled with calcite; (b) Upper Cambrian, gray dolorudite; (c) Penglaiba Formation, dark gray clacisiltite interbedded with grayish black micrite; (d) Penglaiba Formation, limy mudstone; (e) Tumuxiuke Formation, grayish green knollenkalk filled with calcite; (f) Tumuxiuke Formation, purplish red knollenkalk filled with calcite.

Area are composed of calcsparite bioclastic limestone, calcarenite, oolitic limestone, and algal boundstone, which are characterized by strong hydrodynamics along platform margin.

4.2.2.1 Platform marginal reef-shoal complex

The sedimentary environments above average wave base (ASWB) with high hydrodynamics are easy for the

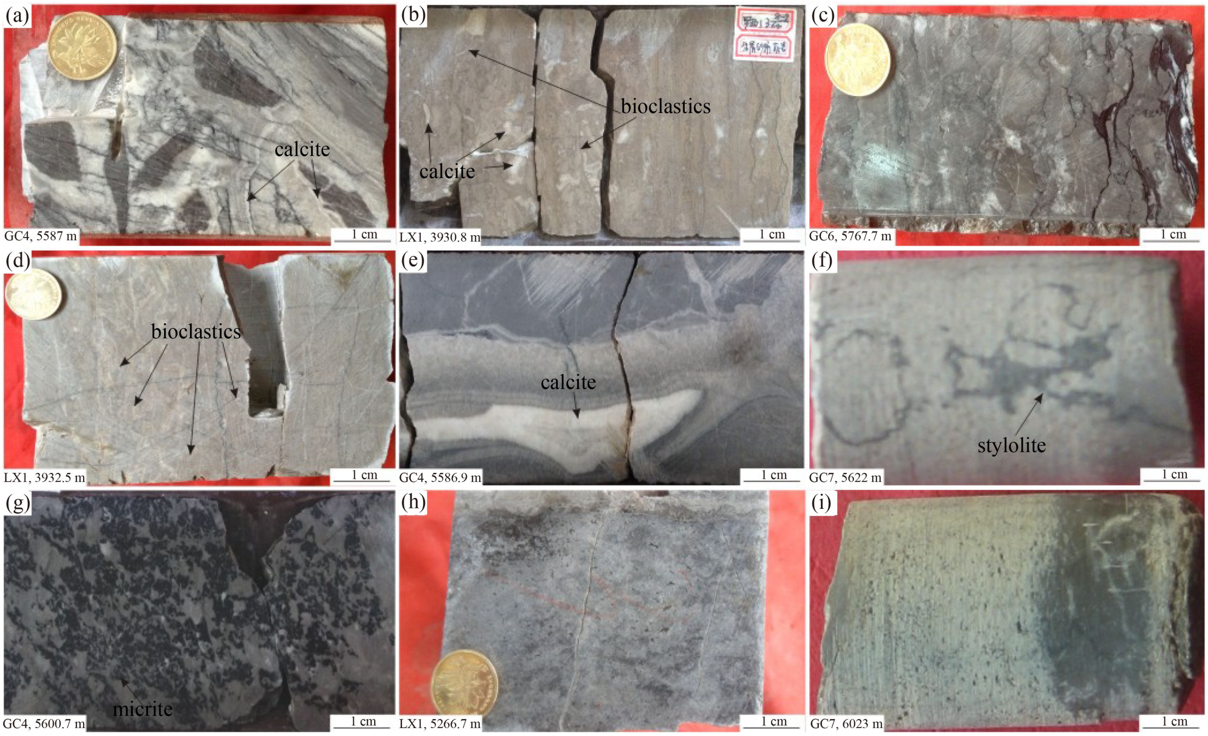

Fig. 8 The summary of cores showing the characteristics of platform facies during depositional period of the Cambrian-Ordovician in eastern Tarim Basin. (a) Yijianfang Formation, light gray calcarenite filled with calcite; (b) Yijianfang Formation, gray bioclastic limestone; (c) Yijianfang Formation, calcsparite calcarenite; (d) Yijianfang Formation, gray bioclastic calcarenite; (e) Yijianfang Formation, light gray calcarenite filled with calcite; (f) Penglaiba Formation, dark gray micrite with stylolite; (g) Yijianfang Formation, dark gray micrite; (h) Penglaiba Formation, limy mudstone; (i) Yingshan Formation, dark gray micrite with pinhole structure.

development of platform marginal reef-shoal complex. The lithology associations include calcsparite calcarenite, bioclastic shoal, calcsparite granular limestone, and oolitic limestone (Figs. 5 and 8). Usually it is filled with calcite, burrow, bioclast, and Ostracoda (Figs. 5 and 8). It shows medium-high gamma ray value which comprises cylinder-shape stacking patterns (Fig. 10). The wireline responses reveal strong hydrodynamics (Fig. 10). It shows mound shape, chaotic or blank seismic reflections on seismic section (Fig. 11). The trajectory of platform marginal reef-shoal complex migrates frequently during depositional period of the Cambrian-Ordovician. The main lithology associations in platform marginal shoal are granular limestone (especially macro-crystalline granular limestone).

4.2.2.2 Foreslope

The foreslope is located on the side toward the basin, where sedimentary interface is between average wave base (ASWB) and normal wave base (FWWB). The hydrodynamics is relatively low. The lithology associations are dominated by micritic limestone and limy mudstone, followed by argillaceous dolomite and micro-crystalline dolomite, which can be interpreted to be sedimentary environment of weak hydrodynamics (Figs. 5 and 8). The wireline responses are characterized by low gamma ray value. In addition, it shows cylinder-shape and funnel-shape stacking patterns, which indicates high energy (Fig. 10). The seismic responses contain medium-strong amplitude, medium-low frequency, discontinuous wedge-shaped seismic reflections. Furthermore, internal architecture shows oblique foreset and imbricate foreset reflections (Fig. 11).

4.2.3 The deep-water basin facies

The deep-water basin facies predominantly consist of neritic platform and deep-water basin, followed by shelf slope and basin-floor fan. The neritic platform is situated outside open continental shelf, where water depth increases while hydrodynamics weakens. The sedimentary environment is under redox interface (RI) with normal salinity. The lithology associations in neritic platform mainly include limy mudstone, carbonaceous mudstone and micritic limestone (Figs. 6 and 9). In

Fig. 9 The summary of cores showing the characteristics of platform facies during depositional period of the Cambrian-Ordovician in eastern Tarim Basin. (a) Middle Cambrian, limy mudstone filled with calcite; (b) Middle Cambrian, carbonaceous mudstone; (c) Middle Cambrian, gray micrite; (d) Yijianfang Formation and Yingshan Formation, grayish black mudstone filled with pyrite; (e) Yijianfang Formation and Yingshan Formation, black mudstone filled with calcite; (f) Tumuxiuke Formation, black carbonaceous mudstone filled with calcite; (g) Lower Cambrian, dark gray and black mudstone, gray medium-to fine-grained sandstone; (h) Tumuxiuke Formation, black limy mudstone filled with calcite; (i) Penglaiba Formation, gray micrite filled with pyrite and boulder clay.

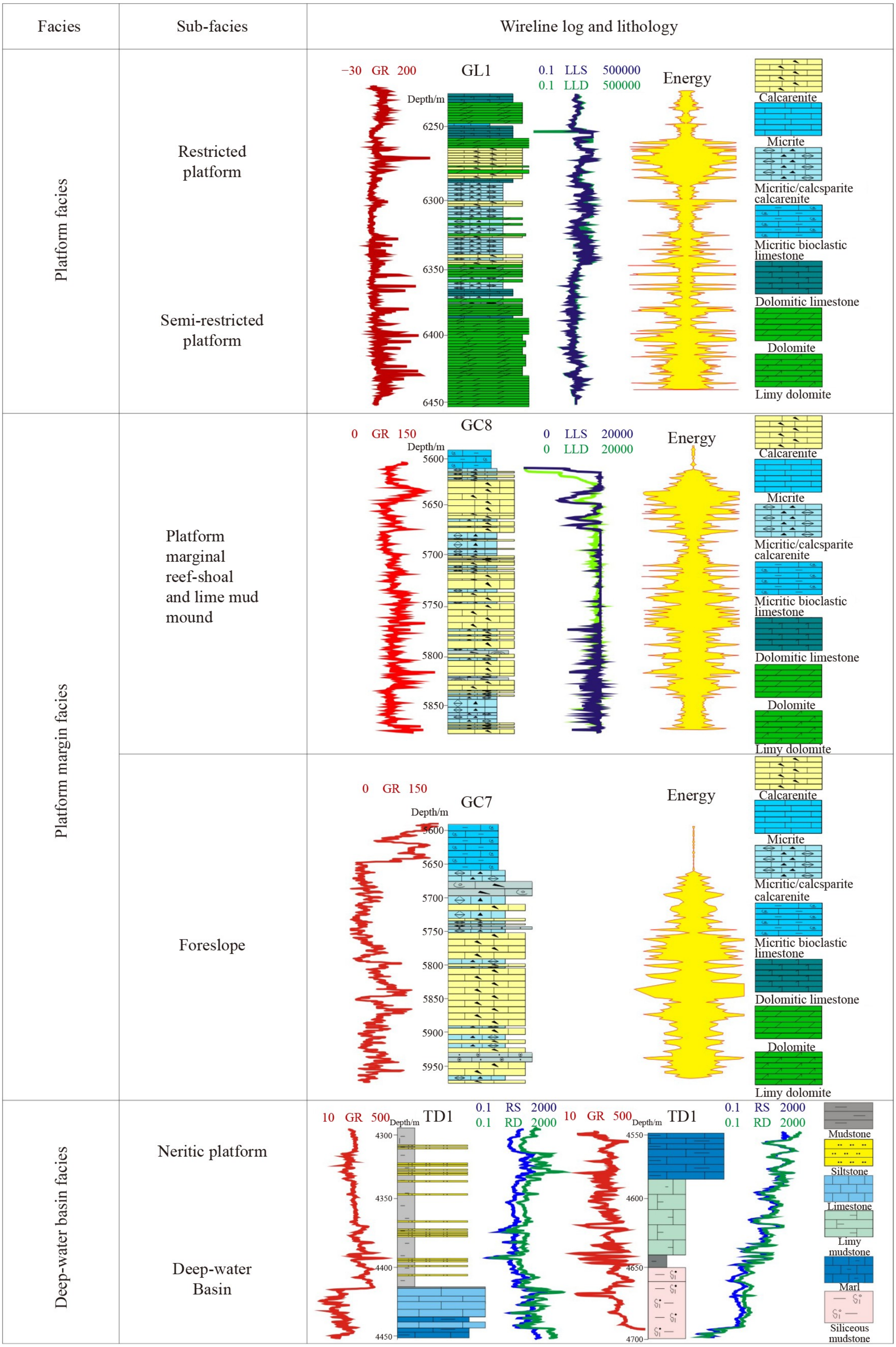

Fig. 10 The summary of wireline responses in various carbonate facies during depositional period of the Cambrian-Ordovician in eastern Tarim Basin.

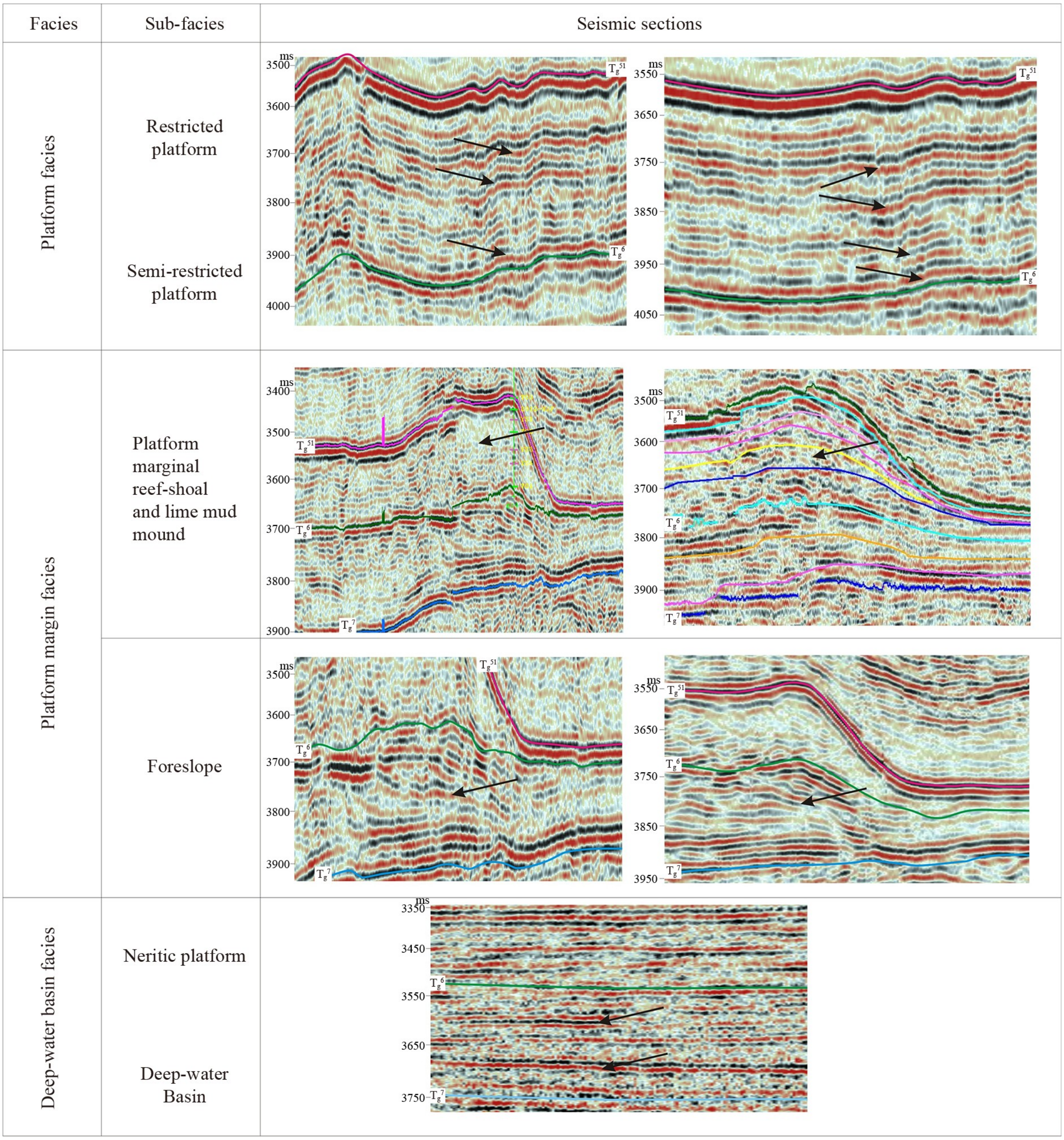

Fig. 11 The summary of seismic reflections in various carbonate facies during depositional period of the Cambrian-Ordovician in eastern Tarim Basin.

contrast, the lithology associations in shelf slope predominantly consist of micritic limestone, local pyrite and boulder clay (Figs. 6 and 9). In addition, the lithology associations in deep-water basin mainly comprise limy mudstone and siliceous mudstone (Figs. 6 and 9). The wireline responses are characterized by low-medium gamma ray value with serrated finger-shape stacking patterns, which reveals low hydrodynamics (Fig. 10). The seismic responses show weak-medium amplitude, medium-high frequency and continuous seismic reflections. The internal architecture shows parallel reflections (Fig. 11). The deep-water basin is mainly developed in Manjiaer Depression with deep water depth and few organisms.

4.3 The depositional evolution of carbonate platform during the Cambrian-Ordovican in eastern Tarim Basin

The integrated analysis of thin section, cores, wireline logs, and seismic volumes leads to determination of facies/microfacies types and prediction of facies/microfacies distributions.

4.3.1 The depositional evolution of carbonate platform during the Cambrian

The eastern Tarim Basin evolved in responses to extensively extensional setting during the Early Cambrian, with large-scale seawater transgression (He et al., 2005; Han et al., 2009; Lin et al., 2011). It was dominated by deep-water basin facies with depositional center around well TD1 and TD2. It predominantly consisted of dark gray and black siliceous mud and limy mud of the Cambrian in well TD2, TD1, ML1, and YD1, which were interpreted to be deep-water basin. The platform margin facies and slope facies (including upslope and downslope) were well developed with wide facies width and gentle slope gradient. In addition, platform marginal shoal was limited distributed in the north-east of eastern Tarim Basin (Fig. 12(a)). The sea level had begun to fall since the Middle Cambrian. The neritic platform was widely distributed. In contrast, the deep-water basin facies tended to shrink to the zone along well TD1 and TD2. It was dominated by restricted platform facies with platform margin migrating toward the basin and migration distance of about 20 km. It was composed of dark gray and black argillaceous limestone and calcareous mudstone interbedded with thin dolomite in well ML1, which was interpreted to be neritic platform facies. In addition, it consisted of black mudstone in lower part and black mudstone interbedded with thin marlstone and dolomite in upper part in well ML2, which was interpreted to be transition zone from neritic platform facies to deep-water basin facies. Furthermore, it included limy mudstone and argillaceous limestone in well TD1, which was interpreted to be deep-water basin facies. Finally, it was dominated by interbedded mudstone and limy dolomite in well TD2, which was interpreted to be neritic platform facies (Fig. 12(b)). Compared to platform marginal shoal during the Early Cambrian, it was relatively characterized by several isolated shoals along platform margin. The scale of shoals decreased toward the Gucheng Area. It shared similarity between the Middle Cambrian and the Late Cambrian. The sea level continued falling, resulting in further migration of platform margin toward the basin with decreasing width of platform margin. The coverage of deep-water basin facies continued to shrink. Therefore, the neritic platform facies were widely distributed during this period. The type of platform was still restricted platform with obvious buildups. The Upper Cambrian was encountered by well LX1, which was dominated by medium-thick limy dolomite, fine-crystalline dolomite and dolomitic limestone with residual algal lamina, which was interpreted to semi-restricted platform or restricted platform. The lithology associations in well ML1 included dark gray limy dolomite, argillaceous dolomite, which was interpreted to be slope facies. However, it was dominated by fine-crystalline dolomite and dolomite mudstone in well YD2, which was interpreted to be slope facies around platform margin. It was dominated by neritic platform facies in well YD1, which was characterized by fine-crystalline dolomite, limy mudstone, marlstone, and argillaceous dolomite. The well TD1 and TD2 encountered limestone, mudstone and argillaceous limestone, which was interpreted to be neritic platform facies (Fig. 13(a)).

4.3.2 The depositional evolution of carbonate platform during the Ordovician

The sea level began to rise slowly during the Early Ordovician Penglaiba Formation. The sedimentary characteristics shared similarity with that in the Late Cambrian. The type of platform was semi-restricted platform. The scope of platform margin in Gucheng Area and Luoxi Area started to shrink and narrow. The sea level rose significantly during late period of Penglaiba Formation, which was regional transgression period. Then, sea level fell during period of Yingshan Formation. The platform type transformed from semi-restricted platform to open platform. In addition, the hydrodynamics increased continuously. It was dominated by steep rimmed platform along Gucheng Area to the north of eastern Tarim Basin. Furthermore, it mainly developed reef-shoal complex along platform margin. The sand shoal along platform margin occupied slope belt of Luoxi Area in lower Yingshan Formation. The lithology associations predominantly included calcarenite and micrite. In

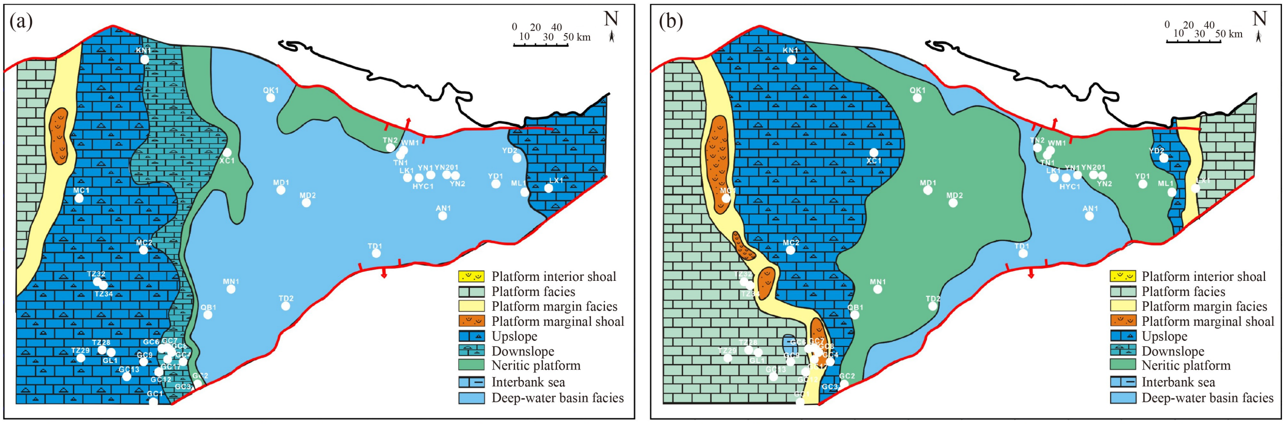

Fig. 12 The facies/microfacies distribution in eastern Tarim Basin. (a) Early Cambrian; (b) Middle Cambrian.

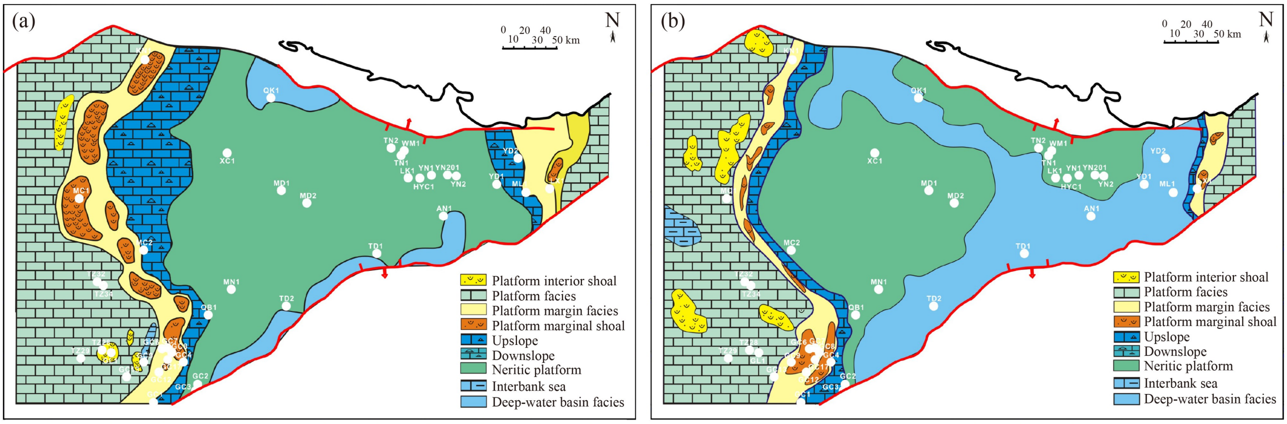

Fig. 13 The facies/microfacies distribution in eastern Tarim Basin. (a) Late Cambrian; (b) Early-Middle Ordovician.

contrast, it was characterized by reef-shoal complex in an obvious regression cycle from upper Yingshan Formation to Yijianfang Formation. The width of platform margin increased significantly. The well GC4, which was located on slope break zone, was dominated by sand shoal, oolitic limestone and bioclastic limestone, indicating intense hydrodynamics (Fig. 13(b)).

4.3.3 The depositional model of carbonate platform during the Cambrian-Ordovician

The whole Tarim Basin undergone several large-scale transgressions and regressions from the Cambrian to the Middle Ordovician, including transgression during the Early Cambrian, regression during the Middle-Late Cambrian, transgression during the Early Ordovician, and regression during the Middle Ordovician (Fig. 14). The depositional evolution was predominantly controlled by sea level changes, resulting in eastward-westward migration of facies belts, especially migration of platform margin facies and neritic platform facies. It was dominated by slope-deep-water basin in the Early Cambrian (especially in Gucheng Area and Luoxi Area) (Fig. 14). In addition, the deposits of deep-water basin were widely distributed, with deep-water carbonates, siliceous rocks and black shales. Then it developed platform margin and neritic platform in the Middle-Late Cambrian due to regression. The sedimentary facies consisted of semi-/restricted platform, open platform, platform marginal reef-shoal, foreslope, neritic platform, and deep-water basin. The sea level fell further in the Late Cambrian compared with that in the Middle Cambrian. The platform margin migrated toward the deep-water basin. The transgression occurred in the Early Ordovician, the reef-shoal complex and lime mud mound continued to grow. However, the neritic platform and slope tended to disappear. It was dominated by open platform, platform marginal shoal, foreslope and deep-water basin from the west to the east. The platform margin was well developed in Gucheng Area from Penglaiba Formation to Yijianfang Formation. The sea level began to fall in upper Yingshan Formation, and started to rise quickly in Yijianfang Formation. The carbonate platform was drowned (Fig. 15).

The slope break zone of platform margin determines the distribution of platform margin facies in marine carbonate depositional systems. The paleo-geomorphologic characteristics and its evolution controls the distribution of platform facies, platform margin facies and reef-shoal. In contrast, the sea-level changes control platform types, vertical change and horizontal migration of reef-shoal (Lin et al., 2012, 2013; He et al., 2016, 2017a; Chen et al., 2022).

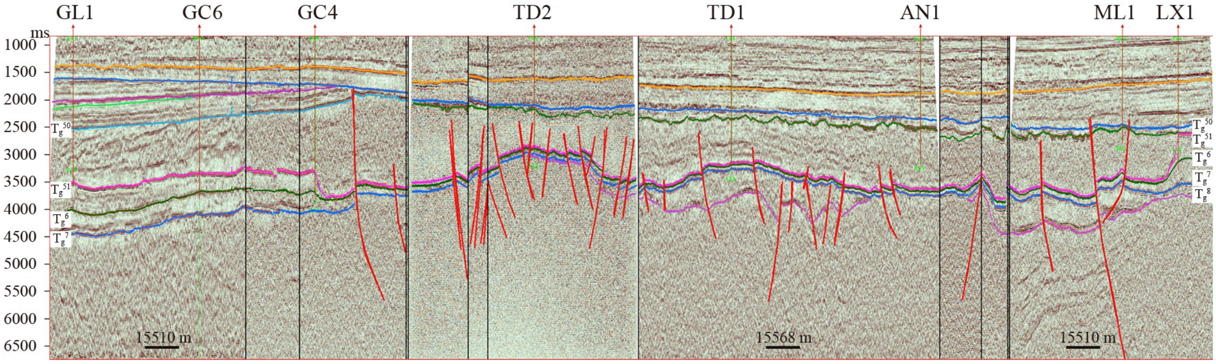

Fig. 14 The well tie seismic correlation showing depositional evolution of carbonate platform during the Cambrian-Ordovician in eastern Tarim Basin.

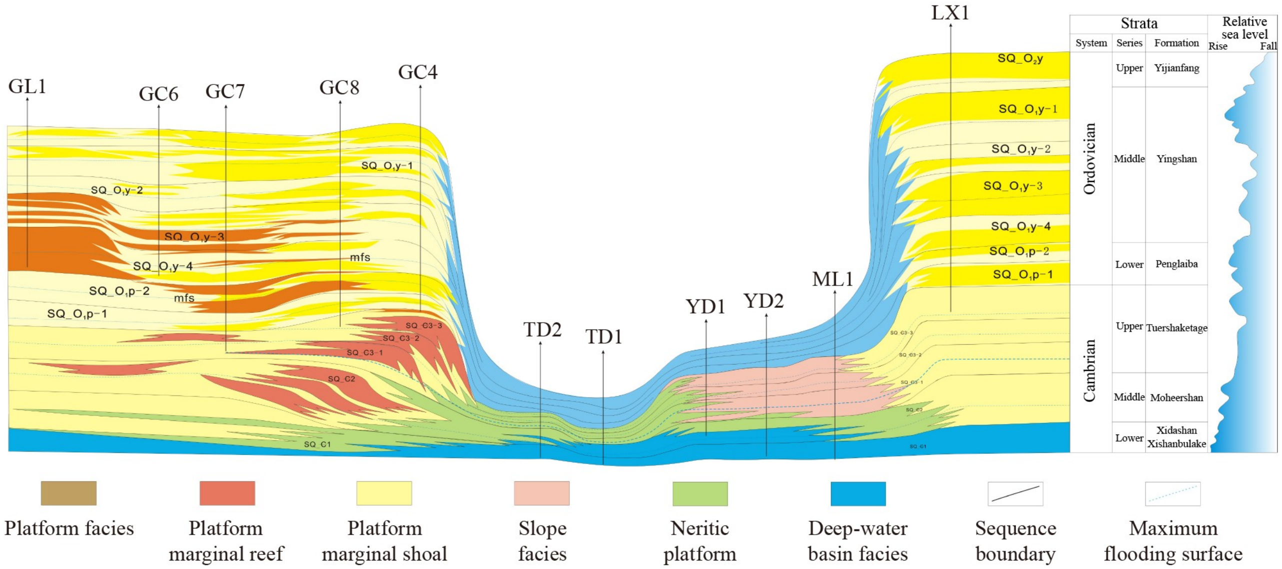

Fig. 15 The depositional model during the Cambrian-Ordovician in eastern Tarim Basin.

4.3.4 The paleo-geomorphologic units control on depositional evolution of carbonate platform during the Cambrian-Ordovician

Previous studies have demonstrated that several geomorphologic units can be identified in eastern Tarim Basin during the Cambrian-Ordovician, including high rise within platform, high rise along platform margin, slope around platform margin, slope within neritic shelf and deep-water zone (Lin et al., 2012; He et al., 2017b). All these geomorphologic units correspond to the distribution of platform, platform margin, foreslope, neritic platform and deep-water basin during the Cambrian-Ordovician which can be verified by borehole information (Figs. 12 and 13). In addition, two platforms are identified (Gucheng platform and Luoxi platform) which show slope break of different geometries and various scales from platform to deep-water basin (Lin et al., 2013; He et al., 2016; Chen et al., 2022). The reef-shoal is mainly distributed along platform margin slope break. The Gucheng platform and Luoxi platform develops two platform margin slope break which controls the distribution and evolution of platform margin facies. The platform margin facies changes with migration of platform margin slope break during the Cambrian-Ordovician (He et al., 2017b; Chen et al., 2022). In the early Cambrian, Gucheng platform and Luoxi platform was dominated by slope. Then the rise started in the middle-late Cambrian where platform margin facies (mainly reef-shoal) were deposited. In the early Ordovician, the paleo-geomorphology tended to be flat with no obvious platform edge. The development of platform edge started from the middle Ordovician. The platform margin slope became steep where platform margin facies were deposited along high rise of slope break zone (Lin et al., 2012, 2013; Chen et al., 2022).

4.3.5 The responses of depositional evolution of carbonate platform to sea-level changes during the Cambrian-Ordovician

The sea-level changes during the Cambrian-Ordovician in Tarim Basin are consistent with global sea level changes (Bao et al., 2006; Gao et al., 2006; Lin et al., 2012, 2013; He et al., 2016, 2017a; Zhang, 2017). During the early Cambrian, slight sea-level changes resulted in dominant slope facies-deep-water basin facies (Gao et al., 2006; Lin et al., 2012; He et al., 2017b). With continuous falling of sea level in the middle-late Cambrian, the whole facies margin migrated toward the east which resulted in previous platform margin evolving into restricted platform (Bao et al., 2006; He et al., 2017a). However, sea level started to rise during the early Ordovician, resulting in westward migration of platform margin and narrow facies zone (Bao et al., 2006; Gao et al., 2006; Zhang, 2017). Then, the sea level fell again during the middle Ordovician, resulting in eastward migration of platform margin and wide facies zone (Gao et al., 2006; He et al., 2017a; Zhang, 2017). Finally, the sea level underwent rapid rising to the highest during the late Ordovician which caused further wide platform margin and drowning of platform in Gucheng area and demise of platform margin (Bao et al., 2006; Gao et al., 2006; Lin et al., 2012, 2013; He et al., 2016, 2017b; Zhang, 2017).

5 Conclusions

1) The facies analysis indicates that 8 sub-facies and more than 10 microfacies are identified, including open platform, restricted/semi-restricted platform, reef-shoal around platform margin, drowned platform, foreslope, neritic platform, and deep-water basin.

2) The sedimentary environment during the Cambrian is characterized by slope facies and deep-water facies in Early Cambrian. Then platform margin facies in Middle Cambrian are developed, and the platform margin facies transits westward to semi-restricted platform/restricted platform and eastward to slope facies and deep-water facies. Restricted platform is dominated in Late Cambrian. The whole Ordovician is developed in response to open platform settings, including platform interior shoal and platform marginal shoal.

3) The development and evolution of carbonate platform coincides with sea-level fluctuations, which is characterized by migration of platform margin. The falling of sea level results in westward migration of platform margin with wide facie scope while the rising of sea level results in eastward migration of platform margin with narrow facie scope. The analysis of sea-level changes assists in regional reconstruction of paleogeography during the Cambrian-Ordovician and provides insights and understandings for petroleum exploration in the future.

4) The facies of carbonate platform are influenced by the distribution of paleo-geomorphologic units which largely determines types and distributions of carbonate platform facies. The high paleo-geomorphologic units usually control the development and evolution of platform facies and platform margin facies, while the low paleo-geomorphologic units commonly affect the development and evolution of deep-water basin facies. The interpretation and reconstruction of paleo-geomorphologic units help in the discovery of favorable carbonate reservoirs.

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Data availability statement The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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