Type and evolution of carbonate platforms in Jixian Period Mesoproterozoic: southwestern margin of Ordos Basin

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Abstract The Ordos block experienced extension in the Mesoproterozoic, during which the Longshan–Kuanping and Haiyuan rifts developed on its southwest margin. The Jixian Group (1.6–1.4 Ga) is mainly exposed on the rimmed and ramp-type platforms at the Qishan County, southwest of the Ordos block. The deposition associated with the rimmed platform margin consists of platform facies, platform edge facies, and slope facies, which are characterized by small tidal creeks, mud cracks and scour troughs, rockfalls, respectively. The ramp-type platform is dominated by platform edge facies, shelf facies and slope facies and featured by intraclastic dolostones, tempestites and debris flow sediments respectively. The syndepositional normal faults were well developed at the early stage of the rifting. Fault-related cracks and folds present in the adjacent strata. The uplift of the footwall rimmed the platform. The drag structures determine the local sedimentary environment. In the final stage of the rifting, the fault movement stopped. The surrounding rocks were undeformed. The slope became less steep, resulting in the formation of ramp-type platform. The study area in the Jixian period, Mesoproterozoic is located at a palaeo-

continental margin, which has already shown good petroleum prospectivity. A clear study on the type of carbonate platforms and the evolution of the platforms can help reduce exploration risks by improve the understanding of the presence of the source rocks.

Keywords Carbonate platform · Fault · Sedimentary facies · Mesoproterozoic · Ordos

Introduction

The Ordos block is located in the southwest of the North China plate and has undergone multiple tectonic settings. The Weihe rift was developed at the southern margin of Ordos block in the late Mesozoic–Cenozoic. The ca. 1.6–1.4 Ga Middle Proterozoic Jixian Group, which is exposed at the edge of the block and composed mainly of dolostones and silica rocks, presents as a good chance to study the type of the carbonate platforms and the transition between different types. The Ordos block was adjacent to the Qin-Qi Sea to the southwest during the Jixian Period. The sedimentary environment of the Qin-Qi Sea is shallow marine (Yan et al. 1989) or tidal flat of marginal marine (Deng et al. 2009). However, the spatial distribution of sedimentary facies remains poorly understood.

This paper aims to provide clear understanding of the type and the depositional environments of carbonate platforms, as well as their relations with the syn-depositional normal faults. This study can play significant role in understanding the spatial distribution of the source rocks and thus reducing risks in exploration activities in the Ordos basin. Besides, it may also be taken as a good reference for the study of carbonate platforms elsewhere in the world.

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Geological setting

The Ordos block was formed at the early Proterozoic era (Bai 1993), after which it underwent extension stage, and abundant failed rifts and strata of shallow and littoral facies aged ca. 1.8–1.6 Ga were reported on the periphery of the Ordos block (Zhang 1983; Sun et al. 1985; Tang et al. 1993; Zhao and Zhou 2009; Peng 2010). After a transient uplift (Wu 2002), the southwestern margin of Ordos block were affected by Longshan–Kuanping and Haiyuan rift in the Mesoproterozoic (Huo and Zheng 1988; Yan et al. 1989; Di 2003; Li et al. 2006; Dong et al. 2014). The carbonate platforms were developed in these rift events.

The Jixian Group in or around Ordos block exposes mainly in Luonan–Huayin county, Long county, Qishan county, Helan mountain and Qinglong mountain. The typical stratigraphic section in Luonan county is divided into four Formations from bottom to top: Longjiayuan, Xunjiansi, Duguan, Fengjiawan (Yan et al. 1989). Revealed by drilling data and outcrops observation (Yan et al. 1989; Deng et al. 2009), the thickness of Jixian Group increases from the block center to margin and the western margin is thicker than the eastern margin. Compared with the typical section, the Fengjiawan Formation is absent in

the study area, and the thicknesses of Longjiayuan Formation and Xunjiansi Formation are greater (Figs. 1, 2).

A lot of asphalt in algae dolomite of Jixian Group was discovered in Chongxin county (Gansu Province) in the southwest of Ordos block, and was believed to stem from the algae dolomite (Li et al. 2011). This place has similar sedimentary environment and tectonic setting compared with our study area in Jixian Period.

Methodology

The study area is situated in the southwestern margin of the Ordos block, and is about 30 km away from the Qinling block (Fig. 1). More than 1000-m thick Jixian Group was deposited in the study area. A fieldtrip was conducted to observe the general sedimentary facies and structural features of the Jixian Group, as well as to take samples for further study. The microscope analysis was implemented for samples taken from the field to determine the rock microstructures.

Mesoproterozoic Jixian Group is a monoclinical structure dipping towards NW, unconformably overlaid by the Cambrian rocks. The observation line started at point 1, which is near the boundary of Jixian Group, and extends

Fig. 1 **a** Location map of Ordos in North China Craton (study area is in southwest margin of Ordos). **b** Simplified geological map of study area (modified from GBSP 1966), with observation line in blue

Fig. 2 Lithological histograms of Jixian System in Qishan, Luonan and Jixian (modified from Di 2003; Gao et al. 2008)

along SEE to point 2, where the rockfalls appeared. Then it goes along NNE to point 3, where debris flow occurs, at which it turns to NW, ending at point 4 (Fig. 1). The points 1 and 2 are topographically lower than 3 and 4, with an altitude difference of 150 m. A syn-depositional fault of about 3.5 km in length is identified in the study area, trending NE–SW, dipping to SE with an angle of 64°–80°. It separates carbonate platforms from gravity flow deposits.

Sedimentary facies and fault activity

The rimmed shelf edge is in high elevation due to the development of the organic reefs. It has a steep slope in higher-energy depositional environment. The ramp-type platform was located in deep water with gentle inclination. The carbonate sedimentary facies in this study is determined based on the criterion of Wilson (1975). The sedimentary microfacies of rimmed shelves edge include restricted platform lagoon, platform-margin reef, and talus breccias on slope. While the ramp platform margin

includes tidal-flat, ooid-pellet shoal, open marine shelf and gravity flows on slope (Read 1985).

The four stratigraphic columns in Fig. 3 correspond to 1, 2, 3, 4 observation points in Fig. 1. Their sedimentary structure will be addressed in the following.

Sedimentary facies pattern of rimmed platform margin and fault activity

Platform facies

The platforms, behind rimmed shelf margin reef, are usually in the intertidal-subtidal zone, showing tidal creeks. Small tidal creek often suggests low lateral migration speed of the creek itself, but strong vertical erosion. The geometry of every single creek is concave downwards. The small tidal creeks were formed in alternate erosion and deposition filling process, and the creeks in different ages are overlapping each other (Scholle et al. 1983; Zhang et al. 1984).

Fig. 3 Stratigraphic columns of the four observation points (locations see Fig. 1)

Fig. 4 **a** Photograph showing the boundary of tidal creeks. **b** Amplified photograph of the boundary, highlighted in red rectangular in **a** (each phase of tidal creek in concave shape). **c** Medium-thick

bedded grain dolomites near the red circle in **b**. **d** Graded structure in grain dolomites in **c**. **e** Photomicrograph of **d**

Tidal creeks presents at the bottom of observation point 1 (Fig. 3), around 8 m in height. It is surrounded by thin dolostones interbedded with chert bands. The shape of the sedimentary bodies is irregular lenticular (Fig. 4a).

Each tidal creek has a rough downwards-concave boundary, and the deposits borne in the creek are composed of the conglomerate at the bottom, collapse breccia at the creek margin and the uniform dolomite surrounded

(Fig. 4b). The small tidal creeks have relative poor lateral continuity (Zhang et al. 1984). Sedimentary units of different ages overlap each other and form lens-shape. The widths of tidal creeks decrease from bottom to top. The gravels are composed of dolostone and siliceous rocks, with 0.5–70 cm (20 cm mean value) in size, and spherical to sub-angular in shape. These gravels have groundmass of small amount of mud and sand.

The grain dolomite is easily recognized within the platforms, where the hydrodynamic energy is moderate to low. At the upper column of observation point 1, a about 14-m thick, medium-bedded grain dolomite layer (Fig. 4c) presents containing a set of black graded debris sediments (Fig. 4d). Under the microscope, the debris rocks are mainly made up of dolostone and silicalite, with grain size of 0.2–2.5 mm (0.3 mm on average) (Fig. 4e).

Platform edge facies

The platform edge shoals are adjacent to ramps and approximately at the mean sea level. As shown by point 2 in Fig. 3, grey black and grey white thin-bedded

dolostones with stratiform algae present alternately (Fig. 5a). Algae is diagnostic for aquatic environment, and the stratiform algae in the shallow water is mostly found in supratidal zone (Hoffman 1976), which has medium flow intensity. A number of 0.1–2 cm angular or subangular breccias were seen in the stromatolitic dolostones (Fig. 5b). They are probably formed by the flow entrenchment on the unconsolidated formation. The sedimentary structures are scour troughs and mud cracks (Fig. 5c, d), indicating that the beds was exposed in the air during the process of deposition. All these prove that the sedimentary sub-environment of the point 2 is the rimmed platform edge shallow.

Slope facies and fault activity

Rockfalls, slides and sediment gravity flows are well developed on continental slope (Varnes 1978). Slides can induce brittle and plastic deformation (Varnes 1978; Scholle et al. 1983). In southeast of point 2 (Fig. 1), the slope sediments were divided into two parts by the normal fault. The upper part of the slope developed sliding

Fig. 5 a Stratiform stromatolite. b Stromatolitic dolostones containing a number of breccias. c Scour troughs on the surface of dolostone. d Mud cracks

Fig. 6 **a** Photograph showing sedimentary architecture of the slope, the *a1-b1* and *b1-f1* represent the *upper* and *lower* part of the slope near the rimmed shelf, respectively. The rockfalls are encircled by *white lines* in *b1-f1*. **b** Details of the *upper* part of the slope, *a2-b2* equals to *a1-b1*. The cleavages in mud are marked by *ice blue dashed line*. The *white rectangle* shows a deformation zone of the fault. **c** Faulted related folds in *white rectangle*, *orange dashed lines* represent the bedding surfaces. **d** Dynamic recrystallization of calcites in the fold core. **e** Rockfall, original strike is labelled by *white line*. **f** Collapse breccia at the rear of *f1* in **a**. **g** Details of the mud cleavages in the *left segment* of **b**, the cleavages are denoted with *black dashed lines*

structures (a1-b1 of Fig. 6a, a2-b2 of Fig. 6b), while the lower part formed rockfalls (b1-f1 of Fig. 6a).

During normal fault development, fault propagation folds are formed to accommodate the variation of the displacement between the faulted beds and the unfaulted beds above the fault tips. They usually exhibit normal-drag geometry, with anticlines at the footwalls and synclines at the hanging walls. The amplitudes of the downwarping of the hanging wall and the upwarping of the footwall, as well as the subsidence and uplift at each wall respectively, increase with the fault dip and displacement (Erslev 1991; White and Crider 2006). As a consequence, the topographic variation is produced, which predominantly control the sedimentary environments. Hence, the propagation and evolution of the normal fault is the controlling factor for the carbonate rocks facies distribution.

During the early period of rifting, the intense tectonic movements produced high-angle normal fault, and drag anticline at its footwall. Its back limb extended into deep sea and formed the upper slope. As a result of subsidence of the back limb, the sedimentary environment was changed. A dolostone layer of 2–3 m in thickness and a mudstone layer of 1–2 m in thickness were deposited (Fig. 6g). Cleavages are found in mud, suggesting that slide took place along beds surfaces (Fig. 6b, g).

Breaks and minor folds are developed at the footwall close to the fault plane (Fig. 6b, c). A large number of dynamic recrystallization of calcites present in fold core (Fig. 6d). They indicate the fault had experienced intense activity.

Rockfalls and collapse breccias are seen in the lower slope (Fig. 6e, f). The size of rocks are several meters (encircled by white lines in b1-f1 of Fig. 6a). The original strike of rockfalls intersects strata with a high angle on the upper slope (Fig. 6e). The presence of siliceous dolomite, dolomite, algae dolomite and silicate in rockfalls suggests continental shelf provenance. The other parts of lower slope, far away from the fault, are covered by Cenozoic strata.

Depositional model

At the early stage of rifting, the syndepositional normal faults were active intensively. The footwall uplift and normal drag anticline were developed. The footwall's uplifting rate exceeded increasing of the sea level, and the rimmed shelves edge was elevated above the water, where rocks are weathered and easier to collapse (Hunt and Tucker 1995).

Seawardly, the depositional facies near rimmed platform margin are platform, platform edge and slope, corresponding to small tidal creek, mud cracks and scour troughs, slides and rockfalls respectively (Fig. 7).

Sedimentary facies pattern of ramp type platform margin and fault activity

Platform edge facies

Intraclastic dolostones usually present in the strata of ramp-type carbonate platform edge shoals. As shown in the upper of stratigraphic column in point 4 (Fig. 2), the debris compositions are siliceous and dolomitic, with a size of 2–60 mm (Fig. 8a). Most of the rock fragments have long axis parallel to bedding surface, and the intraclastic dolostones incised into underlying bedded dolostones (Fig. 8a). The siliceous breccias are in radial arrangement at the top of this deposition unit (Fig. 8b). Intraclastic dolostones and bedded dolostones appear alternately, indicating the dynamically intense shallow-water environment.

In the middle of column (Fig. 3), cross beddings are well developed with an angle of 25°–40° with the sediment unit boundary (Fig. 8c). The hoary medium bedded oolitic dolomiticrites exist in point 3 (Fig. 8d), and the ooids type contains compound ooids and radial ooids, with a size between 0.2 and 1 mm (Fig. 8e). The radial ooids are included in compound ooids. The presence and characteristics of the cross-beddings and ooids suggest shoal micro-environment.

Shelf facies

Open marine shelves locate above the storm wave base in high-energy environment, and accumulate medium-thick bedded dolomite, thin-bedded siliceous dolomite and dolomite containing nodular cherts. As shown at point 3 (Fig. 3), tempestite sequence which includes three segments (erosion bottom, parallel bedding and hummocky lamination) emerges at the lower part (Fig. 9a). Compared with typical tempestite sequence, it lacks the graded bedding, interrupted laminae and mudstone in the study area (Aigner 1982). The tempestite's breccias are fan-shaped, and such kind of tempestites is regarded as in situ and deposition between fair-weather wave-base and storm wave-base, where presents strong hydrodynamic environment (Qiao 2001). Based on the presence of the tempestites and their adjacence to gravity flow deposits on outcrops, the tempestites here indicate the shelf environment.

As shown in the middle segment of the column at point 3 (Fig. 3), the nodular stromatolites are overlain by the bedded dolostones (Fig. 9b). The stromatolite suggests intertidal-subtidal depositional environment, with stronger hydrodynamics (Hoffman 1976). A dolomite lens presents close to the slope, with obvious sliding traces around it. Some fractures display at both the periphery and interior of the lens (Fig. 9c). The evidence of slide in local strata as a result of steep slope are the sedimentary structures, wavy

Fig. 7 Depositional model of rimmed platform margin in study area. Some symbols of lithology and sedimentary structure are seen in Fig. 3

laminations and loop bedding siliceous nodule, present in the middle-upper of the column (Fig. 9d, e). Though, the loop bedding nodules are thought to form by tensile stress along the layers as they are often arranged next to each other (Rodriguez-Pascua et al. 2000; Qiao and Li 2009), the nodules in the study area show remote distance from each other and lack tensile deformation. These features might be coherent with storm eddies (Ma et al. 2011). On the basis of all above, these sediments are settled in sub-tidal and high-energy environment.

Slope facies and fault activity

Carbonate debris flow deposit, often composed of carbonate clasts and micritic matrix, is a common type of sediment gravity flow deposits along the canyons or channels developed at the edge of the passive continental shelf (McHargue et al. 2011; Puga-Bernabéu et al. 2013). The gravity flow deposits are massively distributed and unsorted, and the deposits within the canyons and/or channels are lenticular (Scholle et al. 1983; Macauley and Hubbard 2013).

The observation at point 3 (Fig. 1) suggests the normal fault separates the open-marine shelf from the sediment gravity flow deposits on the slope (Fig. 10b). The formations in footwall are undeformed, suggesting that the fault activity has attenuated impacts on the footwall. The hangingwall is consisted of hoary massive debris flow sediments with matrix-supported fabric. The debris components are long-strip or ellipsoidal dolomites and silicites in size of 1–100 mm, which show disordered arrangement (Fig. 10c). Lenticular channels or canyons are overlapping each other, and are enclosed by the gravity flow deposits (Fig. 10a). The thicknesses of the lenses are commonly 0.3–1.5 m (Fig. 10d). In the matrix, the large particles of debris are floating in the size of 1–100 mm (Fig. 10e), comprised of the dolomitic and siliceous gravels (Fig. 10f).

Depositional model

The syn-depositional normal faults became inactive during the late stage of the rifting, and facilitated a ramp-type carbonate platform. From landward to seaward, the

Fig. 8 **a** Intraclastic dolostone. **b** The larger scale map of yellow rectangle in **a**. **c** Cross beddings in dolostones highlighted by dashed yellow lines. **d** Oolitic dolostone. **e** Photomicrograph of **d**, including compound ooids and radial ooids

depositional facies at the ramp-type platform margin are platform edge, shelf and slope, correspondingly with main characteristics of: (1) intraclastic dolostones, oolitic dolostones; (2) tempestites, nodular stromatolites, dolostones with wavy laminations and loop bedding; (3) debris flow sediments, respectively (Fig. 11).

Discussions

The impacts of tectonism on carbonate platform

Sea-level fluctuations can influence the type of carbonate platform and characteristics of gravity flow deposits (Read 1985; Reijmer et al. 2012; Phelps et al. 2014). Many studies have been focused on the sea-level changes of the Jixian Period of Mesoproterozoic at the eastern North

China plate, but few studies try to address the problem from the southern margin of the North China plate. According to presence and features of stromatolites, the Jixian Group, are contemporary with the Wumishan Formation in the east (Yan et al. 1989; Di 2003). The deposition of the Wumishan Formation records a sea level increase (Gao et al. 1996; Mei et al. 1999, 2000), which was caused by tectonism rather than climate change (Gao et al. 1996). The tectonics and eustatic events are likely to match in the study area.

In Mesoproterozoic Jixian Period, the southwest of Ordos block is modified by the Longshan–Kuanping rift and the Haiyuan rift, while the southeast is only effected by the former (Huo and Zheng 1988; Wu et al. 2002; Di 2003; Li et al. 2006; Dong et al. 2014). The tectonic subsidence is more intense and the Jixian Group is thicker in the southwest (Di 2003). In this study, the rimmed and ramp type

platforms presents, and sediment gravity flow deposits are well developed on the slope in the southwest. On the contrary, the ramp platforms dominated in the southeast, and the related sediment gravity flow deposits are poorly developed (Lu et al. 2013). All of above suggests that tectonics plays an important role in defining the type of carbonate platform in late Mesoproterozoic.

The carbonate platform types are divided mainly based on the paleotopography, composition and distribution of sediments, tectonic settings, and sealing of the platform

Fig. 10 **a** Channel or canyon deposits on slope circled by *black line*. **b** The fault between open-marine shelf deposits and debris flow deposits on slope. **c** Boundary of the debris flow (the *left*) and the channel deposits (the *right*), location “*b*” refer to **a**. **d** Channel lenses marked by *yellow dashed lines*, location “*a*” refer to **a**. **e** Dolomite and silicalite debris floating in lenses. **f** Photomicrograph of **e**

margin to the seawater inside (Wilson 1975; Read 1985; Mei et al. 1997; Bosence 2005; Gu et al. 2009). Concretely, tectonic movements primarily manipulate

Fig. 9 **a** Tempestites. **b** Nodular stromatolites. **c** Sliding deformations highlighted by *dashed yellow line*. **d** Wavy laminations. **e** Loop bedding

Fig. 11 Depositional model of ramp-type platform margin in study area. Symbols of lithology and sedimentary structure are seen in Fig. 3

paleotopography, which determines the composition and distribution of sediments, thus the platform's types (Vail et al. 1991; Mei et al. 1997; Gómez and Fernández-López 2006).

Faults, as a major form of rifting movements, control the architecture and depositional sequences of fault-block carbonate platform (Bosence et al. 1998; Preto et al. 2011), and impact depositional environment and facies distributions of hangingwall and footwall (Wilson 1999). The platform boundary fault affects the type of slope sediments and platform geomorphology (Yilmaz 2006; Lü et al. 2013; Quiquerez et al. 2013). Therefore, syn-depositional faults could be a key factor when judging the type of the carbonate platform.

The effect of tectonism on source beds

Tectonism may control the sedimentary environment of source beds as well as its distribution. At the early stage of rifting, the activity of faulting at the margin of platform may lead to the exposure of the shelf edge and the

formation of islands, which limited the water exchange on the platform and was conducive to the preservation of organic matter. At the late stage of rifting, the weakened activity of faulting made it easy to form open marine shelves. Meanwhile, the presence of tempestite suggests water upwelling from deep ocean may have occurred. This water movement can bring rich nutrients up to facilitate the productivity of organic matter in euphotic zone. Theoretically, an anoxic environment created by degradation of dead organic matter benefits the generation and preservation of organic matter itself in shelf. Although, the observation line is confined by landform, the conclusion that the link between distribution of source beds with tectonism still needs to be further proved.

Conclusions

This study presents a detailed description of the impacts of fault activity on the sedimentary facies of carbonate platform margin and the types of slopes. At the early stage, the

syn-depositional normal faults acted intensely, causing the uplift of its footwall and the formation of high steep rimmed platform. The local depositional environments were affected by the fault propagation folds. The related depositional environments were platform, platform edge and slope successively. At the late stage, the fault activity weakened, and the platform was transformed to a ramp-type with the gradient decrease of the slopes. The depositional environments of this period are platform edge, shelf and slope respectively.

In conclusion, the study area was a transition zone between the edge of the continental shelf and the slopes during Mesoproterozoic Jixian period. And tectonic movements induced the conversion of the carbonate platform from rimmed type to ramp type. Also, tectonism controls the depositional environment and distribution of source beds.

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