Sequence stratigraphy and lithofacies paleogeography of the Middle–Upper Cambrian Xixiangchi Group in the Sichuan Basin and its adjacent area, SW China

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Abstract: Based on isotopic, lithologic and electrical data and logging cycle analysis technique, stratigraphic sequences in the Middle–Upper Cambrian Xixiangchi Group in the Sichuan Basin and its adjacent area are divided, and its sedimentary characteristics and evolution are analyzed. The Xixiangchi Group can be divided into 5 third-order sequences (Sq1–Sq5), of which sequences I to III (Sq1–Sq3) are relatively complete, sequences IV and V are denuded in the Late Cambrian because of the Dian-Chuan paleo-uplifts. Third-order sequences of the Xixiangchi Group in this area have the characteristics of thin in the west and thick in the east, showing that the Caledonian paleo-uplift is a synsedimentary paleo-uplift and the paleogeomorphology in the platform is a gentle slope. Sequence I develops high stand systems tract and transgressive systems tract. The other third-order sequences are dominated by highstand systems tracts, and the transgressive systems tracts last shortly in time and are limited in area. The basic features of evaporative-restricted platform of gentle slope type developed continuously in the sedimentary period of the Xixiangchi Group, its sedimentary environment of “high in west and low in east” and the change of micro paleogeomorphology in the platform control the continuous development of sedimentary facies. Open platform is developed only in sequence I and sequence II, and the inner beach of the platform and the edge beach of the platform are mostly developed in sequence II and sequence III. It indicates that there are two platform margin zones in the study area, a relatively stable, large-scale platform marginal zone in NE Guizhou–Western Hunan and Hubei, and a moving and small-scale platform marginal zone in North Chongqing–Western Hubei.

Key words: Sichuan Basin; Middle–Upper Cambrian; Xixiangchi Group; sequence stratigraphy; third-order sequence; carbon isotope composition; lithofacies paleogeography; sedimentary environment evolution

Introduction

After the gas discovery from the Xixiangchi Group in Weiyuan field South Sichuan, industrial gas flows are obtained in this group from multiple wells in Gaoshiti, Moxi, and its northern area, demonstrating a substantial potential for gas exploration. The Xixiangchi Group is mainly a set of dolomite deposits[1–3] thin in the west and thick in the east[4–6]. Lack of fossils, its stratigraphy division and sedimentary evolution have long been controversial. Studies have shown that the middle-upper part of the Xixiangchi Group basically corresponds to the Furongian Series, and the middle-lower part corresponds to the third Series or Wuling Series[6–7]. It is far from enough to depict hundreds even over one-thousand meter thick Xixiangchi Group by one lithofacies paleo-geomorphic map. Furthermore, there is disagreement on the third-order sequences classification. Research based on Well Hanwei 1 in Sichuan Basin shows it contains four third-order sequences[6–8], while studies based on outcrops around the basin show it can be divided into three to seven third-order sequences[9–10]. Obviously, the difference on its sequence division is due to the different strata developed inside and around the basin. It directly hinders the detailed description of the sedimentary facies.

In this study, sequence stratigraphy division framework from inner basin to peripheral basin is preliminarily established based on the identification of the base of the Furongian Series[6], isotopic data[6–8], using of the INPEFA technique[8,11], lithological and electrical characteristics, and the relative frequency of sea level changes[12]. In the meantime, lithofacies paleo-geomorphologic maps of the Sichuan Basin and its adjacent area are compiled in third-order sequence units by investigating outcrop and drilling lithology and electrical characteristics and the features of the microfacies, to reveal sedi-
mentary evolution characteristics and pattern in the study area.

1. Sequence stratigraphy

The sequence stratigraphy division of the Xixiangchi Group is a difficult task, as the group in most area is unified in lithology and with rare fossils, but also has unclear electrical cutoff. Peng Shanchi et al. [13–15] and other authors considered that the Middle Upper Cambrian consists of the fifth Stages to tenth Stages, in total six stages, which are generated in the time of 510–488 Ma from now. The Xixiangchi Group covers the Gaotai Formation (or Douposi Formation) of the Middle Cambrian. So the sedimentary process of the Xixiangchi Group should be between 504–488 Ma. However, the division of sequence stratigraphy by the unit of formation (member) [16–18] usually needs to take unconformities as basis, and mostly focuses on identifying system track. The time of each sequence is always between 3.0–0.5 Ma [17] or 5.25–1.60 Ma [19]. Due to lack of unconformities and long-time gaps, it is more suitable to divide the Xixiangchi Group into five or six third-order sequences.

1.1. Markers of sequence division

To make it much more reliable, markers of carbon isotope, INPEFA logging sequence, lithology, electrical characteristics, and unconformity etc. are considered in this division. Carbon Isotope Composition Marker. By analyzing the oxygen and carbon isotope composition of the Xixiangchi Group, the basement of the Furongian Series is determined by the base of a carbon isotope positive shift event [6–7]. Argillaceous dolomite with a negative GR peak corresponding to this base is the most obvious sequence boundary in the middle Xixiangchi Group and the most important lithologic transforming surface, which is traceable across the whole region (Figs. 1–3). INPEFA Logging Sequence Marker. INPEFA logging sequence analysis reduces the influence of uncertainty in manually sequence division, and enables the transition of sequence division from qualitative to half quantitative and quantitative [10]. Based on analysis of spectrum trend characteristics in INPEFA logging sequence of many drillings, the maximum flooding surface, and lithologic transforming surface of third-order sequences are sought out accurately. The first, second, third, fourth and fifth maximum flooding surfaces in the Xixiangchi Group of Well Taihe 1 are at around 4710 m, 4599 m, 4405 m, 4217 m and 4073 m respectively; and the first, second, third, fourth and fifth lithologic transforming surfaces are at 4601 m, 4410 m, 4218 m, 4074 m and 4010 m respectively (Fig. 3). These five lithologic transforming surfaces are also the top of third-order sequences. Apparently, except the bottom maximum flooding surface, other surfaces are all 1–5 m above lithologic transforming surfaces, indicating that all the transgression processes are quite brief.

Electrical Marker. Electrical marker considered in this study is the change of GR curves. As it is difficult to define sequence boundary solely based on the electrical marker, GR negative peak corresponding to carbon isotope composition marker and INPEFA logging sequence marker can be found. The bottom of the low values in the negative peak is the lithologic transforming surface, the middle of the high values in the negative peak is the maximum flooding surface (Fig. 3). Furthermore, electrical marker of the base of the Xixiangchi Group is mostly defined based on the bottom of a comb shape GR.

Lithology Marker. It is one of the most difficult issues in sequence stratigraphy division of the Xixiangchi Group. The specific markers can only be identified by the integrated assistance of carbon isotope composition marker, INPEFA logging sequence marker, and electrical marker, otherwise the third-order sequence boundaries can only be defined by well correlations. The five lithologic transforming surface of third-order sequences in the Xixiangchi Group are all surfaces shifting from dolomite to argillaceous dolomite, dolomitic mudstone, shale, and mudstone. The five maximum flooding surfaces are mostly argillaceous dolomite or dolomitic mudstone, with minor shale or mudstone. Besides, the base of the Xixiangchi Group is usually marked by dolomites located at the bottom of a set of thin argillaceous dolomite or dolomitic mudstone interbedded with dolomite corresponding to the comb shape GR. Below it is the thicker argillaceous dolomite, dolomitic mudstone, or gypsum-bearing dolomitic mudstone of the Gaotai Formation (or Douposi Formation) with higher GR [5–6].

Unconformity Marker. The Xixiangchi Group only develops unconformity at the top, mostly in parallel unconformable contact with the Ordovician [5–6, 9].

1.2. Third order sequences and their basic characteristics

Based on the above mentioned markers of maximum flooding surfaces and lithologic transforming surfaces, it is concluded that the Xixiangchi Group has four to five third-order sequences in east Sichuan–west Hubei and Hunan–north Guizhou area where it is fairly complete with little erosion. While it comprises four third-order sequences in central Sichuan–Weiyuan area with severe erosion, and one to three third-order sequences in the west pinch-out zone.

1.2.1. Basic characteristics of Sequence I

Sequence I is the bottom third-order sequence in the Xixiangchi Group, developing evident transgressive systems tract (TST) and high stand systems tract (HST) (Figs. 1–3). Consisting of dolomite and argillaceous dolomite interbeds primarily, this sequence is thick in the east and thin in the west with comb-shaped GR curves [5]. Except the central Sichuan and Well Taihe 1 area, this sequence has carbon isotope composition lightening from bottom to top. It basically corresponds to the Xi 1st Member [6–7], and exists wherever the Xixiangchi Group develops, indicating extensive transgression when this sequence deposited led to inundation of the
Fig. 1. Third-order sequence division and cross section of Xiexiangchi Group in Northwest Sichuan-East Chongqing-Southwest Hubei. HST—Highstand systems tract, TST—Transgressive systems tract.
Fig. 2. Third-order sequence division and cross section of Xixiangchi Group in Southwest Sichuan–Weiyuan–Central Sichuan–East Sichuan–South Shaanxi. HST—Highstand systems tract, TST—Transgressive systems tract.
Fig. 3. Third-order sequence division and cross section of Xixiangchi Group in North Yunnan–North Guizhou–South Chongqing–Northeast Chongqing–West Hubei. HST—Highstand systems tract, TST—Transgressive systems tract.
whole Upper Yangtze Platform under sea level. It is thick in the east and thin in the west, indicating that the terrain in the platform was high in the west and low in the east. It is 30–50 m thick in Well Longtan 1–Mashen 1 in the northwest of the basin, 150–180 m thick in Well Wuke 1–Chi 7–Taihe 1 in the east; and over 200 m thick in Jiaoshiba, Yongshun Xiafu, Dayong Guzhang Luoyixi in the east part of the basin.

The lower part of Sequence I is dominated by transgressive systems tract (TST). The sequence within Sichuan Basin was deposited in continuous regression after transgression\(^{[30]}\). The basement of Sequence I is a layer of pure dolomite or dolarenite, which is especially obvious in central Sichuan to East Sichuan area. For instance, there is a 19 m thick gypsum-bearing dolomite and dolomite layer in Well Weihi 1, and 18 m thick dolarenite and 15 m thick dolomite layers in the bottom of Well Guangtan 2 and Wutan 1, indicating that the restricted evaporation and shallow water environment of the early stage transfers to the deeper water depositional environment in later stage. The sequence varies in lithologic composition in areas around the Sichuan Basin. For instance, it consists of calcarenite and limestone in Yubei Chengkou; oolitic dolomite, dolomite and dolomitic mudstone in Wuxi; breccia dolomite with chert nodule, limestone, and marls in Baxian County, south of Shaanxi; gypsum-bearing dolomite, dolomite, and shale in Wushan Lake Shenlongjia, west of Hubei; sandstone, siltstone, limestone, breccia limestone, and shale in Yangjiaping and Baiguoping, west of Hubei; breccia arenaceous dolomite, argillaceous dolomite in Jinsha Yankong of north of Guizhou; and dolarenite, dolomite, and limestone in Yanhe Ganxi, north of Guizhou. It is composed of dolomite and dolarenite in Yongshun Xiafu West of Hunan; shale, marls, and limestone in Guzhang Luoyixi slightly different with above lithology. INPEFA logging cycle analysis of Well Lin 1 in Xishui, north of Guizhou; a large set of argillaceous dolomite, dolomite and limey dolomite in Baiguoping, southwest of Hubei; large set of dolomite in Yangjiaping; limestone in Jinsha Yankong in north of Guizhou; limestone and dolomite in Ganxi; marl and limestone in Luoyixi, west of Hunan.

Both of TST and HST are developed in Sequence I symmetrically all over the region, reflecting the transgression and regression both develop slowly.

### 1.2.2. Basic characteristics of Sequence II

Sequence II is a third-order sequence in the lower part of the Xixiangchi Group, dominated by HST (Figs. 1–3). It is mainly composed of dolomite and is thick in the east and thin in the west. The GR curves of drillings feature in low flat or minor sawtooth shape. The isotopic composition turns heavier from bottom to top\(^{[8]}\). Basically it corresponds to the Xi2 member\(^{[6–8]}\), occurs all across the Upper Yangtze Platform. The variation of the thickness of the sequence reflects that the terrain is high in the west and low in the east. It is thinner in Caledonian Paleo-uplifts such as Leshan–Longnüsi and northwest Sichuan. For instance, it is around 50 m thick in Well Longtan 1 in northwest Sichuan, Well Nanchong 1 and BaoLong 1 in Nanchong of central Sichuan, and outcrop in Fandian, southwest Sichuan. It becomes thicker in east Sichuan. For instance, it is 180–220 m thick in Well Wutan 1, Wuke 1, Taihe 1, Jianshen 1 in east Sichuan, and Well Lin 7, Dingshan 1 in southeast Sichuan. The thickness reaches a maximum at the margin of platform in now western Hunan, for instance, it is 350 m thick in Baiguoping and Yangjiaping, and 346 m thick in Xiufu. Then it becomes thinner on the slope-basin area outside of the platform margin, for instance it is around 50–60 m thick in Wuxi, north of Chongqing, Shenlongjia in west of Hubei, Baxian County in south of Shaanxi.

Sequence II is dominated by HST, only shortly developed TST in the early stage. The thickness of the TST only about 10 m in most area, and is diverse in lithology, including shale, argillaceous dolomite, dolomite with mud, marl, limestone, and dolomite. But the TST is well developed in some areas. For example, it is interbedded deposit of shale and thin dolomite in Wushanhu Shenlongjia, west of Hubei; dolomite and argillaceous siltstone, mostly thin to medium thickness dolomite in Xujia County, north of Chongqing; complex in lithology in Well Jianshen 1, east of Chongqing, including argillaceous dolomite, dolomite, and dolomitic limestone; interbedded argillaceous dolomite and dolomite, mostly dolomite in Well Lin 1 in Xishui, north of Guizhou; a large set of argillaceous dolomite (over 80 m) in Zhenxiong Yangchang, north of Yunnan; continuous argillaceous dolomite (43 m) in Xinsha Yankong, north of Guizhou; a large set of thin marl (176 m) in Luoyixi West of Hunan; breccia limestone and algal limestone (76 m) in Baiguoping, southwest of Hubei. Moreover, INPEFA logging cycle analysis of Well Lin 1 and Jianshen 1 shows that the maximum flooding surface after Sequence II TST is at the argillaceous dolomite corresponding to the middle-lower part of the negative peak on GR. INPEFA logging cycle analysis of Well Taihe 1 shows that the maximum flooding surface of Sequence II is at the argillaceous dolomite corresponding to the bottom negative peak on GR (Fig. 3). It indicates a poorly developed TST.

HST in the upper part of Sequence II is well developed in the Sichuan Basin, with thickness increasing from west to east. It is mostly composed of dolomite, with some special rocks. It
consists of limestone and thin shale in Zhuazhuayan Leibo County, Lianshanzhou, Sichuan; dolomite, dolarenite, limestone, argillaceous dolomite, karst granular limestone in Jiaoshiba, east of Chongqing; dolomite, dolarenite, marls, and limestone in Well Li 1; nodules and breccia limestone with marls at the bottom in Baxian County; limestone, clastic limestone, dolomite in Chengkou; 45 m thick dolarenite in Well Guangtang 2 in central Sichuan; 51 m thick dolarenite at the bottom of Well Zuo 3 in east of Sichuan; dolarenite 73 m thick, argillaceous dolomite, and dolomite in Sanhui outcrop of Nanchuan, south of Chongqing; gypsum-bearing dolarenite, limestone, dolarenite, and dolomite in Ganxi, north of Guizhou, with gypsum-bearing dolarenite occurring in the upper part; 178 m thick dolarenite in Xufu, west of Hunan, occurring in the upper part; limestone with marl interlayers of 136 m thick in Luoyiixi, west of Hunan; dolomite with intercrystalline pore in Jinsha Yankong, north of Guizhou.

Sequence II develops TST–HST asymmetrically, indicating a short fast transgression and slow regression sedimentary process.

1.2.3. Basic characteristics of Sequence III

Sequence III is a third-order sequence in the middle of the Xixiangchi Group, with clear features of HST. Dominated by dolomite, it is thick in the east and thin in the west and features low flat minor sawtooth shape and low peak on GR\(^6\). The carbon isotope composition turns lighter from bottom to top. It basically corresponds to the Xi 3 Member\(^6–8\). It has slightly larger erosion area in northwest–central Sichuan, and is incomplete and thinner in Caledonian Paleo-uplifts. For instance it is only 28 m and 23 m thick in Well Longtan 1 and Mashen 1 respectively in northwestern Sichuan, 48 m thick in Well Nanchong 1 in central Sichuan, 50–75 m thick in most central and east Sichuan; 150–200 m thick in southeast Sichuan, east Chongqing, and west Hunan; and 70–80 m thick in Chengkou, north Chongqing and west Hubei. These indicate that the platform has a certain slope during the deposition of this sequence and inherits the terrain features of high in the west and low in the east.

The Sequence III is also dominated by HST, with restricted TST. TST in the lower part of the sequence is very limited, with argillaceous dolomite mostly less than 10 m thick, suggesting a very short sedimentary period. INPEFA logging cycle analysis of Well Lin 1, Taihe 1 and Jiashen 1 shows that TST is very short in time, with maximum flooding surface corresponding to the bottom of argillaceous dolomite (Fig. 3). There are also some areas with well developed TST, showing a deepening water characteristic. For instance, karst granular limestone, oolite limestone, and algal limestone developed from bottom to top in Jiaoshiba East Chongqing, with a total thickness of 48 m; medium thickness dolomite and dolarenite, interbedded of thin dolomite and thin dolarenite developed from bottom to top in Wushanhu Shengnongjia West Hubei, with a total thickness of 70 m; dolomite and dolarenite with muddy siltstone developed from bottom to top in Xujia County Wuxi North Chongqing.

HST in the upper part of Sequence III consists of medium thickness dolomite and thin layer argillaceous dolomite generally. Special lithologies occur in some local areas. For instance, it is composed of argillaceous dolomite, dolomite and dolarenite interbeds in Well Taihe 1 in east Sichuan and Lin 1 in north Guizhou; interbedded argillaceous dolomite and dolomites in Well Lin 7 in south Sichuan and Well Jianshen 1 in east Sichuan; dolarenite, algal dolarenite, and breccia dolomites in Xujia County of north Chongqing; thin dolarenite and oolitic dolomite in Wushanhu of west Hunan; limestone and marl in Luoyiixi, west Hunan; 30 m, 150 m, and 50 m thick dolarenite respectively in Well Wuk 1, Yongshun Xufu outcrop, and Sanhui outcrop in south Sichuan; 75 m thick gypsum-bearing dolomite and gypsum-bearing dolarenite in Ganxi, north Guizhou; dolarenite, dolomite, limestone, and marl in Well Li 1 in northeast Sichuan; dolomite with intercrystalline pore in Jinsha Yankong, north Guizhou.

In Sequence III, HST also takes dominance, and TST only occurs in limited areas in northeast peripheral of the basin and east Chongqing, representing asymmetrical TST–HST. It indicates that the transgression is short and fast, and the regression process is slow.

1.2.4. Basic characteristics of Sequence IV

Sequence IV is a third-order sequence in the middle – upper part of the Xixiangchi Group, still with evident HST characteristics. Thin in the west and thick in the east, it consists of dolomite and thin argillaceous dolomite interbeds, and has both low flat minor sawtooth shape and low peak on GR\(^6\). Its carbon isotope composition is ~3‰–0, and turns lighter from bottom to top or shows minor sawtooth shape characteristic. It is basically correlated with the lower Xi 4 Member\(^7–8\). It has a much larger erosion area in West Sichuan and is thin on the slope of Caledonian Paleo-uplifts. For example, it has been eroded completely in Well Longtan 1 and Mashen 1 in north-west Sichuan, and Well Nanchong 1 in central Sichuan, it is 15–30 m thick in Well Gaoshi 26, Longbao 1, and Fanbian Leshan in southwest Sichuan; 50–70 m thick in most south, central, and east Sichuan; 150–200 m thick in southeast Sichuan, east Chongqing, and west Hunan; while in Chengkou and west Hubei, controlled by slope sedimentary environment, it is thinner and the thickness about 70–80 m. Therefore, the Upper Yangtze Platform still has a slope during this sedimentary period, and the terrain is high in the west and low in the east as before.

In Sequence IV, HST is highly developed, and TST is limited. The TST is represented by only 5–10 m argillaceous dolomite, and even doesn’t occur in some areas, with siliceous shale and limestone in local area. The TST mostly developed in southeast Sichuan, north Yunnan, and west Hubei. In Well Lin 7, south Sichuan and Lin 1, north Guizhou, it is composed of dolarenite, dolomite, and argillaceous dolomite; 18 m thick...
limestone in Zhuazhuayan Leipo, north Yunnan; two layers of 10 m thick siliceous shale in Baiguoping, southwest Hubei; and dolarenite and dolomite in Wushanhu, west Hubei. INPEFA logging cycle analysis of Well Zhonglin 1 shows that the maximum flooding surface after transgression is in the middle-upper part, corresponding to the low peak of upmost section of the GR low peak interval (Fig. 3).

HST in the middle-upper part of the Sequence IV is dominated by medium to thick dolomite, and dolarenite with thin argillaceous dolomite interbeds. But in some areas, it is composed of special rocks. In Luoyixi, west of Hunan, marls and limestone in it are over 200 m thick; dolarenite and gypsum-bearing dolarenite are over 133 m thick in Ganxi in north Guizhou; dolomite in Well Zuo 3 in Sanhui, Chongqing and in east Sichuan is 50 m thick; and dolomite with intercrystalline pore is 35 m thick in Jinsha Yankong, north Guizhou. Besides, INPEFA logging cycle analysis of Well Taihe 1 and Jianshen 1 show that the maximum flooding surface of this sequence is at its bottom (Fig. 3), indicating most of Sequence IV is HST sedimentary deposit.

The Sequence IV is evidently missing in most area of west Sichuan, and HST is well developed.

1.2.5. Basic characteristics of Sequence V

Sequence V is a third-order sequence at the top of the Xixiangchi Group, showing HST characteristics. This sequence mostly develops dolomite, dolarenite, with thin argillaceous dolomite, and limestone in restricted area, showing a topography of thin in west and thick in east, corresponding to micro saw shape and low peak GR characteristics in exploration wells[6]. Its carbon isotope composition turns heavier and then lighter gradually from bottom to top. This sequence is basically corresponding to the upper Xi 4 Member[7–8]. Under the influence of the long term erosion of the Caledonian Paleo-uplift after the Cambrian, it is largely eroded in central, western, and part of eastern Sichuan. For example, it is missing in well Longtan 1, Nanchong 1 Northwest Sichuan, well Guangtan 2, Baolong 1, Gaoshi 26, Nanchong 1 in central Sichuan, well Weihan 1 and Lin 7 in south Sichuan, and well Lin 1 in north Guizhou; its residual thickness is only 20–70 m in well Wake 1 in northeast Sichuan; 50–150 m in east margin of the Sichuan Basin; 80–220 m in west Hunan, Hubei and north Guizhou; and 20–70 m in west Hubei and north Chongqing. Despite the erosion effect, it is still high in the west and low in the east, inheriting the paleo-topography.

HST still dominates Sequence V, with limited TST. TST is restricted or undeveloped at the lower part of the Sequence, which is represented by less than 10 m thick of argillaceous dolomite, and siliceous shale, limestone, marls in locals. TST is extensively developed in north Guizhou, west Hunan and Hubei, and south Shaanxi. It consists of 40 m limestone in Yanhe Ganxi, north Guizhou, 10 m thick calcareous clay in Jinsha of Yankong, two layers of 10 m thick calcareous clay in Baiguoping of southwest Hubei, 10 m thick argillaceous strip limestone in Luoyixi, west Hunan, 41 m thick mudstone in Baxian County Pingli District, south Shaanxi.

HST in upper Sequence V consists of medium to thick dolomite, dolarenite, with thin argillaceous limestone interbeds in some areas. For instance, it is composed of interbedded marls, limestone, and shale over 80 m thick in Guizhang Luoyixi outcrop, west Hunan; 100 m thick dolarenite in Xiafu, west Hunan; 150 m thick dolarenite, dolomite, and limestone in Ganxi, north Guizhou; 35 m thick dolomite with intercrystalline pore in Jinsha Yankong; 15–18 m thick limestone at the top part in some parts of south Sichuan.

Sequence V is missing in most western to central Sichuan and part of eastern Sichuan, and still features HST, with TST developed in limited areas.

To sum up, the Xixiangchi Group is divided into five third-order sequences (I–V) in Sichuan Basin and its adjacent area, of which Sequence I, II, and III occur in all the areas where the residual Xixiangchi Group exists, erosion area of Sequence IV and V gradually extends to east Sichuan. Sequence I clearly shows symmetrical TST–HST characteristics, indicating a slow transgression and slow regression sedimentary process, Sequence II–V third-order sequences within the platform all show asymmetrical TST–HST characteristics, indicating a fast transgression and slow regression process. All the third-order sequences are thinner in the west and thicker in the east, showing that paleo-topography in the platform was a gentle slope during the deposition of the Xixiangchi Group.

2. Sedimentary and lithofacies paleogeography

Monotonous in lithology, the Xixiangchi Group of the Middle – Upper Cambrian in the Sichuan Basin has long been taken a whole in sedimentary and lithofacies paleogeography study, making it difficult to find the sedimentary variation vertically and horizontally. Especially in eastern Sichuan Basin and its adjacent area, it is hundreds and even over one thousand meter thick, sedimentary and lithofacies paleogeography study by the unit of group can’t characterize its basic characteristics and variation pattern, let alone satisfying the need of exploration and production. Previous studies show that the Xixiangchi Group is a set of regression sedimentary sequence, dominated by platform deposits[20–26], which could compare to platform in North America[27]. As transgression process in the Upper Yangtze Region is small in scale and short during this depositional period, TST is poorly developed, and HST takes dominance under the background of TST[5–24]. In this study, its sequence stratigraphy is examined and divided, which will provide foundation for sedimentary and lithofacies paleogeography study of each member or each third-order sequence. Also via HST dominated characteristics of each third-order sequence, the development characteristics of carbonate platform[28–29], and sedimentary evolution pattern of inner platform and platform margin beach are revealed.
2.1. Sedimentary and lithofacies paleogeography characteristics of Sequence I

Mixed tidal flat, evaporative-restricted platform, open platform, platform margin, slope, and basin deposits are developed in Sequence I of the Xixiangchi Group in Sichuan Basin and its adjacent area (Fig. 4). The inner platform is characterized by small intraplatform grain beach and gypsum lagoon developing on a gentle sloped evaporation-restricted platform, while small intraplatform grain beach takes dominance at the margin of platform. This sequence is seen all over the Sichuan Basin and its adjacent area, except in the west and north of Mianning–Yaan–Leshan–Suining–Mianyang–Guangyuan section where it is eroded.

Mixed tidal flat deposits of Sequence I mostly occur in northwest and southwest areas of Sichuan. It is composed of carbonate and clastic interbeds in well Longtan 1 and Mashen 1 in northwest Sichuan; dolomite and dolomitic mudstone in well Longtan 1; dolomite, argillaceous dolomite, and dolomitic mudstone in well Mashen 1; grey dolomite, dolarenite with purple-red mudstone in Huili Qingshui River outcrop of western Sichuan; grey dolomite, argillaceous dolomite, with thin or strip sandy mud in Emei[30-31]; dolomite with dolomitic sandstone, argillaceous siltstone strip at the bottom of Fandian outcrop in western Sichuan[32]; dolomite and gypsum-bearing dolomite primarily, with siltstone and silty mudstone of 42 m thick at the bottom in well Shenwo 1, showing characteristics of nearshore mixed tidal flat deposits.

Evaporative-restricted platform deposits of Sequence I exist in most areas of Sichuan, eastern Chongqing, northern Guizhou, and northern Yunnan, and is composed of extensive dolomite, restricted thin dolarenite and gypsum dolomite. It is sand debris beach deposits in early TST in Guangan, Nan-chong, Gaoshiti, Luoguanshan, and Hechuann, with 2–10 m thick dolarenite, 68 m thick in Sanhuida. Due to evaporation environment in the middle to late stage of Cambrian[5,32-33], gypsum lagoon in Sequence I only develops at the bottom vertically, and is small in scale with thickness of only 1–2 m, represented by gypsum dolomite. Gypsum lagoon deposits in small scale also occur in Weiyuan, Yanggaosi South Sichuan, Wubaiti East Sichuan, Enshi West Hubei, while evaporation plateau in large scale only developed in the south of Changning-Gulan area[34] (Fig. 4). Moreover, desalinating lagoon limestone deposits develops in Leibo Zhuazhuayan outcrop, with only dolarenite at the bottom, indicating mainly desalinated lagoon deposits.

Platform margin facies of Sequence I occur in two zones, one Ganxi in northeast Guizhou, Huatan in west Hunan–Yongshun–Dayong, Wufeng Baiguoping–Yangjiapiang in southwest Hubei; and the other Chengkou in north Chongqing–Wuxi–Wushanhu West Hubei. These two zones mostly have microfacies such as sandy beach, gravel beach, oolite beach,
algal shoal, and intertidal microfacies, with desalinating lagoon deposits partially. The platform margin is relatively thin, at 5–10 m thick, and could reach 30 m thick in individual places, and consists of clastic limestone, dolarenite, oolitic limestone, oolitic dolomite, with algal debris dolomite in local parts. There are also semi-deep water sediments in the platform edge, for example, three layers of black shale of 6–10 m thick each in Wushanhu, and one layer of black shale 18 m thick in Baiguoping in southwest Hubei.

Open platform deposits of Sequence I mostly develop in East Chongqing–West Hubei area. Well Li 1 East Chongqing has limestone, marls, dolarenite of clastic platform microfacies, and dolomite and argillaceous dolomite of shoal sea and muddy lake microfacies in open shallow water environment, indicating interactively developed restrictive and open platform characteristics. In well Jianshen 1, the sequence is composed of laminated thin argillaceous dolomite and medium to thick dolomitic limestone, and dolomitic limestone and calcareous clay, indicating open platform dominated sedimentary environment. At Baiguoping outcrop in southwest Hubei, the sequence is composed of calcirudyte, gravel limestone, algal limestone, and dolomite, indicating intertwinement platform margin and open platform. There is also thin clastic beach in open platform, for instance two layers of dolarenite 5 m and 8 m thick respectively in well Li 1 in east Chongqing, and two layers of dolarenite 4 m and 6 m thick respectively in well Jianshen 1.

Slope-basin facies of Sequence I mostly develop in northeast Guizhou–west Hunan and Hubei, south Shaanxi–west Hubei areas. Thin marl and black shale develop in Luoyixi outcrop, west Hunan, indicating a relatively deep water slope and deep water basin sedimentary environment; calcirudyte, thin limestone and marl in Baxian County outcrop in south Shaanxi, indicating characteristics of slope carbonate deposit in fairly deep water and clastic flow of carbonate rock.

Overall Sequence I has all facies, including extensive evaporation inner platform-restricted platform, fairly developed open platform, and poorly developed high energy beach. Grain beach and gypsum lagoon in the inner platform was developed in the early stage of TST, mostly disperse in distribution, and the platform margin beach is also small in scale.

2.2. Sedimentary and lithofacies paleogeography of Sequence II

Inner platform of Sequence II in the Xixiangchi Group has characteristics of small to large scale inner platform breccia beach and gypsum lagoon developed on a gentle sloped evaporative–restricted platform, within which mixed tidal flat, platform margin, and slope to basin developed successively, while previous open platform transferred into semi-restricted platform, and the distribution of platform margin evidently increases, and the erosion area is similar to that in Sequence I (Fig. 5).

Mixed tidal flat of Sequence II occurred in northwest and southwest Sichuan, reducing slightly in area. It is dolomite...
Area of evaporative-restricted platform deposit of Sequence II is similar to that of Sequence I, but high energy grain beach in inner platform is changed. It is mainly thin clastic beach still in Gaoshiti, Moxi and its adjacent area, but large scale grain beach deposit occurs in central Sichuan–Guangan–Huayingshan Tianba, Leshan Fandian in southwest Sichuan–Dawoding, Well Mashen 1 of northwest Sichuan. There is 45 m thick dolarenite in Well Guangtan 2, and 16–25 m thick dolarenite in Fandian outcrop–well Woshen 1. East edge of the basin has a relatively large to large inner platform beach, represented by 26 m thick dolarenite in well Lin 1, 72 m thick dolarenite in Sanhui outcrop Chongqing, 75 m thick dolarenite and 20 m thick karst granular limestone in Jiaoshiba outcrop, and 45 m thick dolarenite in well Li 1. Gypsum lagoons in the platform developed in southern Basin and northern Guizhou area, and were larger in scale individually than those in Sequence I. At Jinshayankong outcrop, dolomite with intercrystalline pore is 80 m thick, with pseudocrystals salt rock and large number of corroded crystalline pores, representing dolomite of evaporation facies; gypsum dolarenite in Ganxi outcrop section Northeast Guizhou is 40 m thick. During this period, inner platform beach extended outwards to the peripheral, and move eastwards from Paleo-uplift, and the gypsum lagoon was more developed in the southeast. Besides, Leibo Zhuazhuayan outcrop in southwest Sichuan shows the water slightly deepened, earlier clastic beach disappeared, and thin black shale deposited, suggesting a desalinating lagoon environment.

Semi-restricted platform facies of Sequence II is developed in east Chongqing to southwest Hubei area. The open platform in Sq1 in this area changed slightly. One change is the transform to restricted platform in well Jianshen 1 area, and second is the transform to semi-restricted platform in Jiaoshiba, in well Li 1 and Jiaoshiba Sq2 it is a large scale grain beach deposit.

Sedimentary facies of platform margin in Sequence II is still developed in northeast Guizhou–west Hunan and Hubei area, and north Chongqing–west Hubei area, but the scale of platform margin beach remarkably increased. Sq2 has 175 m thick dolarenite at Xiafu outcrop, 88 m thick breccia limestone and 40 m thick algace limestone, 15 m thick breccia dolomite at Baiguoping outcrop in southwest Hubei. Platform margin doesn't change much in north Chongqing–west Hubei during this time. One evidence is argillaceous siltstone and breccia beach overlying at Wuxi outcrop, another is thin dolomite with thin shale interbeds transferring to dolarenite from bottom to top at Wushanhu outcrop, indicating slope transferring to platform margin sedimentary environment. These findings show that platform margin in southeast area built up fast, and north Chongqing–west Hubei area transferred from slope area to platform margin.

Slope-basin facies of Sequence II is still developed in east Chongqing–west Hunan and Hubei area, and south Shaanxi–west Hubei area. In Luoixi of west Hunan, the Sequence is dominated by marl of slope facies, with limestone and breccia limestone interbeds of platform margin facies. In Baxian town of south Shaanxi it consists of slope facies marl and flint-bearing gravel-clastic limestone, with gravity flow carbonate deposit containing slump structure; in Wushanhu of west of Hubei, it is composed of slope facies thin dolomite with basin facies thin black shale deposits.

In platform of Sequence II is dominated by HST slope type carbonate restricted platform, within which high energy grain beach is mostly developed in HST stage, and grain beaches in the platform are smaller in the west and large in the east in scale, in east Chongqing–west Hubei the sedimentary facies turned into semi-restricted platform, in northeast Chongqing–west Hunan and Hubei platform margin increased significantly in scale, in north Chongqing–west Hubei platform margin is also observably developed, gypsum lagoons mainly occurred in the southeast of the basin and its peripheral and are larger in scale than earlier stage.

2.3. Sedimentary and lithofacies paleogeography of the Sequence III

In platform, Sequence III of the Xixiangchi Group is still dominated by small to large scale inner platform grain beach and gypsum lagoon on a gentle slope evaporative-restricted platform, within which mixed tidal flat, half restricted platform, platform margin, and slope to basin subfacies are still developed successively, but open platform disappeared, and large scale platform margin are developed (Fig. 6). The erosion area of this sequence gradually extends towards east, with the following main changes: (1) In well Longtan 1 and Mashen 1 in northwest Sichuan, the facies transferred from platform to mixed tidal flat, and gypsum dolomite was found in well Longtan 1, showing mixed-evaporation tidal flat characteristics. (2) In local area of Huayingshan–east Sichuan exist gypsum dolomite and thick pelitic dolomite, proving there is large scale clastic beach in the east of Huayingshan Tianba, hence, thick argillaceous dolomite of lagoon subfacies 20 km away was found in Well Zuo 3, but due to the obstruction of clastic beach in east of Tianba, gypsum lagoon deposit of evaporation environment is occurred in the west side. (3) Wubaiti structural belt is a large scale clastic beach, but with the water deepening, the southwest part of Wubaiti transferred from restricted platform to semi-restricted platform, with fairly thick limestone. (4) Platform margin in Northeast Chongqing is evidently thickened in Wuxi, reaching 45m. (5) Slope in Baxian town of south Shaanxi develops marls, with no carbonate clastic gravity flow.

2.4. Sedimentary and lithofacies paleogeography characteristics of Sequence IV

In the platform, Sequence IV of the Xixiangchi Group is still
Fig. 6. Sedimentary and lithofacies paleogeography of Sequence III (Xi 3 Member) in Sichuan Basin and its adjacent area.

...developed poorly. The erosion area of this sequence clearly extends towards east, mixed tidal flat was basically eroded away, and other lithologies are developed successively. This sequence has the following main changes from the underlying sequence: (1) Medium to small size grain beach developed in platform, with dolarenite 5–15 m thick, up to 30–60 m thick in local parts. For example, dolarenite is 30 m thick in Well Guangtan 2, and 60 m thick in Sanhui outcrop of Chongqing. (2) Platform margin is mostly poorly developed, with a thickness of 10–20 m, only in Ganxi the dolarenite and gypsum dolarenite are 130 m thick. (3) Half restricted platform totally withdrew from east Chongqing, in Well Wutan 1, Jiaoshiba, Lichuan the sedimentary facies transferred to restricted platform from pervious semi-restricted platform. (4) In Wuxi Xujia town of east Chongqing, the deposit is transferred from platform margin clastic beach dolomite to platform margin dolomite with slump structure towards slope facies. (5) In slope environment in Baxian town of south Shaanxi, gravel limestone containing flintstone nodules occurs again, indicating sedimentary characteristics of carbonate clastic flow. (6) In Baiguoping of southwest Hubei, this sequence contains thin black siliceous shale, in Yangjiaping it consists of breccia dolomite, showing signs of transform from platform margin to slope-basin.

2.5. Sedimentary and lithofacies paleogeography of the Sequence V

In the platform, Sequence V of the Xixiangchi Group is still dominated by gentle slope evaporative-restricted platform in slightly deeper water environment (Fig. 8), inner platform beach and platform margin beach is developed poorly. It has erosion and missing area extending extensively towards east, and is eroded in most central–western Sichuan Basin and northwest Yunnan–southwest Sichuan, but residual deposits in the east still is inherited development features. This sequence shows the following changes compared to the underlying sequence: (1) Its residual deposit of evaporative-restricted platform is mostly distributed in east Sichuan–east Chongqing–west Hunan and Hubei–north Guizhou–northeast Yunnan, beaches in platform are mostly small to medium scale, and occur in east Sichuan–east Chongqing–Southeast Chongqing, with dolarenite 20–25 m thick generally, especially thicker in some individual sites, for instance, 50 m thick karst grain dolomite and oolitic limestone at Jiaoshiba outcrop. (2) Platform margin is poorly developed and 10–20 m thick in general, and reaches 30 m thick only in northeast Guizhou–west Hunan area. But the 30 m thick dolarenite has bioclastic limestone and thick limestone interbeds, indicating the water body deepened...
slightly. In Xiafu of northeast Guizhou, the dolarenite is 100 m thick, showing the transform from undeveloped to developed platform margin beach; the Wushanhu outcrop in Shennongjia shows clear features of platform margin deposit, with 36 m thick dolarenite. (3) The half restricted platform entirely withdrew, most of Sichuan Basin and its adjacent area transferred into restricted platform. (4) Slope in Baxian town of south Shaanxi had clearly deeper water environment, evidenced by dark grey marl and black shale of half deep water depositional environment. (5) Gypsum lagoon in platform had large changes, one is that the gypsum lagoon increased in scale in Jinsha Yankong, where the dissolution crystalline porous dolomite is 52 m thick, much thicker than that in Sequence IV; another is Ganxi outcrop area transferred into platform margin deposit, from previous gypsum lagoon to inter-beach sea and shallow water deposit. This is similar with the previous understanding that the middle upper part of Loushanguan Group in Middle Upper Cambrian, northern Guizhou had mainly restricted platform inner beach sea, muddy-dolomitic lagoon, and evaporative flat deposits.

In summary, development and sedimentary evolution of the five three-order sequences of the Xixiangchi Group in the Sichuan Basin and its adjacent area have the following characteristics: (1) In the platform, the gentle slope evaporative-restricted platform landscape has been kept, the high in the west and low in the east depositional environment and inner platform micro-paleo-facies controls the continuous development of sedimentary microfacies. (2) Sequences II and III are the periods when inner platform beach and platform margin beach are developed and inherited well, of which inner platform shallow beach is controlled by Paleo-uplift of central Sichuan, micro paleo-topography at the margin of east Sichuan Basin, and sea level changes, and moved towards east. (3) Sequences IV and V are the period when inner platform beach and platform margin beach are fairly developed and changed. (4) The gypsum lagoon in the platform goes through a gradual expansion and then shrinkage process. (5) Open platform of north Chongqing–southwest Hubei area gradually transfers to half restricted platform, showing the sea turned shallower gradually. (6) Platform margin of northeast Chongqing–west Hubei and Hunan is relatively stable, and larger in scale, while platform margin in north Chongqing–west Hubei migrated and were smaller in scale, largely different from the former.

3. Conclusions

Based on isotope composition, lithology, logging data, the Xixiangchi Group in the Sichuan Basin and its adjacent area can be divided into five third-order sequences. Sequences I, II and III exist in most area, and eroded only in Yaan–Lezhi–Mianyang–Guangyuan area and its west. While the erosion areas of Sequences IV and V gradually extend to northwest
and east Sichuan. Thus, the paleo-uplift at the end of the Cambrian should be named as the large scale Yunnan–Sichuan Paleo-uplift, instead of the Leshan-Longnüsi paleo-uplift.

The entire Xixiangchi Group is dominated by HST, with slight differences between the third-order sequences. Sequence I shows an outstanding symmetrical TST–HST characteristic, indicating a slow transgression and slow regression depositional process; the other third-order sequences in the platform all show asymmetrical TST–HST characteristic, indicating a short period fast transgression and slow regression in the platform.

Gentle slope evaporative–restricted platform has been the major topographic feature of the Xixiangchi Group. All facies are developed and evolved on the northeast, east and southeast dipping gentle slopes controlled by Leshan-Longnüsi uplift, with the micro paleo-facies, and sea level changes. Thus the residual thickness, and distribution and migration pattern of all the facies in the sequences show characteristics of carbonate gentle slope, which is the most distinctive feature from classic rimmed platforms, carbonate gentle slopes in China and abroad.

In Sequences II and III of the Xixiangchi Group, inner platform beach and platform margin beach are well developed and inherited. Inner platform is not only developed around Paleo-uplift and micro paleo topography at the east margin of Basin, but also moved towards east. They are the sequences with well developed facies-controlled reservoirs. In contrast, inner platform beach and platform margin beach are fairly developed in Sequence IV and V, with fairly developed facies-controlled reservoirs.

There are two platform margin beach belts in Xixiangchi Group, of which, the northeast Guizhou–west Hunan and Hubei belt is relatively stable and larger in scale, while north Chongqing–west Hubei belt is migrative and smaller in scale. It indicates that carbonate platforms northeast and southeast of the paleo-uplift might have some differences.

References


