Analysis of Hybrid Facies, Hybrid Sequence, and Its Controlling Factors of the Devonian Yangmaba Formation in the Northwestern Sichuan Basin, Southern China

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ABSTRACT: Abundant hybrid sediments composed of clastic rocks and carbonate rocks were deposited in the Devonian Yangmaba Formation in the northwestern of Sichuan Basin. Based on the measurement of the Ganxi section in detail, combined with the observation of the 30 slices, the hybrid facies, and hybrid sequence, the hybrid deposit mechanism and its controlling factors of the Yangmaba Formation were analyzed. It shows that the hybrid facies consists of the hybrid shore at the lower and clastic hybrid shelf and carbonate hybrid shelf deposits at the middle-upper of the Yangmaba Formation. The hybrid sequence, which can be divided into four sedimentary system tracts: the shelf-margin systems tract (SMST), the transgressive system tract (TST), the early highstand systems tract (EHST), and the late highstand systems tract (LHST), was developed in the Yangmaba Formation. There are three hybrid mechanisms including punctuated mixing, facies mixing, and in situ mixing, and the first two are the main types in the Yangmaba Formation. The punctuated mixing and in situ mixing are the main hybrid mechanisms of hybrid shore and clastic hybrid shelf deposits, and the facies mixing is the main hybrid mechanism of clastic hybrid shelf and carbonate hybrid shelf deposits. The hybrid mechanisms are different among the system tracts: the punctuated mixing is the main mixing manner in the SMST and LHST and the facies mixing developed in the TST and EHST. Storm action is the most important controlling factor of punctuated mixing of the Yangmaba Formation. Relative sea level change, carbonate productivity or the rate of terrestrial clastic supply, and climate change are factors that control and affect hybrid deposits. SMST and HST are mainly related to changes in the relative sea level, while TST is controlled by sedimentary source recharge, and climate change affects the hybrid action of system tracts to varying degrees.

1. INTRODUCTION

The hybrid deposits of siliciclastic and carbonate rock have been recognized since 1950, but with a long period, people always separate the study of siliciclastic rocks and carbonate rocks. The mixing of siliceous and carbonate clasts is narrow hybrid deposits, which refers to the fabric mutual doping of siliceous and carbonate clasts, or relatively pure in composition of rock cyclic thin interlayers, or sedimentation of sideways crossing each other. The definition includes two aspects of hybrid deposits: (1) the mixing of siliciclastic and carbonate sedimentary facies and (2) the mixing of siliciclastic and carbonate sediments in structure and composition. In terms of mixing mode, the former is punctuated mixing deposition, while the latter is in situ mixing. Hybrid deposits have various controlling factors, such as global sea level change, regional tectonic activity, relative sea level change, climate, sedimentary source recharge, deposition rate, rate of carbonate production, and so on. The latter may also affect and interact with each other. Compared with the hybrid facies, the controlling and influencing factors of hybrid rocks with composition and structure are more complicated, such as hydrodynamic conditions of the sedimentary environment and storm action, and other factors affect the mixing of siliciclastic rocks and carbonate rocks in structure and composition. Among the many controlling factors of sedimentation, global sea level change, regional tectonic activity, climate, and sedimentary source recharge are also the main controlling factors of sequence stratigraphic development. Therefore, combining hybrid deposits and sequence stratigraphy to carry out hybrid deposit studies in sequence stratigraphy can not only better analyze the controlling factors of hybrid deposits, but also improve the

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reliability of the study of sequence stratigraphic division and sedimentary facies in the hybrid sedimentary development area.8,12,13

The hybrid sedimentary development of the Early Devonian to the Middle Devonian in southwestern China is an ideal place for conducting hybrid deposit studies.11,14,15 In this paper, the Yangmaba Formation of the Ganxi Devonian is taken as the research object in the northwestern of Sichuan Basin; based on the field survey of the section, the hybrid sedimentary and sequence stratigraphic development characteristics are analyzed in detail. The study of mixed deposition helps to explain the sedimentary dynamics, climate, provenance, sea level change, and their interchanges and can also be used to analyze the structure and basin properties.

2. GEOLOGICAL SETTING

The section of the Devonian Yangmaba Formation is an important component of the Guixi-Shawozi Devonian International Standard Profile (commonly known as Ganxi section) in Longmenshan area, Sichuan Province.16,17 It is located in Shigouli Village, 3.5 km southeast of Ganxi Village, Guixi Township, Jiangyou City, northwest of Sichuan Basin, and 500 m northwest of Yuanwang Cave (Figure 1). The strata are well distributed along the highway and are located in the northwestern edge of the Yangtze platform of South China.18 The Devonian strata in this area were deposited on a continental margin where no significant tectonic events occurred throughout the Devonian.16 The Lower Devonian is composed of ascending order siliciclastic, mixed siliciclastic-carbonate, and carbonate rocks, which formed in marine environments ranging from nearshore to the outer shelf.16,17,19,20

According to the stratigraphic division criteria of the Devonian in the northwestern of Sichuan Basin,21,16,17,21 The Lower Devonian consists of Pingyipu Formation, Bailuping Formation, Ganxi Formation, Xiejiawan Formation, and Ertai Formation, while the Middle Devonian consists of Yangmaba Formation, Jinbaoshi Formation, and Guanwushan Formation (Figure 2). The target layer Yangmaba Formation is in conformable contact with the Lower Devonian Ertai Formation. The Yangmaba Formation is equivalent to the B84-B94 layer of the Devonian section of the Guixi-Shawozi in Beichuan County (Figure 2),17 which was deposited in the late Emsian stage to the early Eifelian stage,16,17 mainly composed of carbonate rocks, sandy carbonate rocks, quartz sandstone, silty claystone, and claystone.22–24 According to the lithology characteristics, this study subdivided the Yangmaba Formation into 39 layers (Figure 3), each of which is continuously exposed, with sedimentary structures developed and abundant biological fossils. The bottom-up lithology is mainly composed of bioclastic limestone mixed with silty claystone, carbonate rocks developed upward, and organic reefs and inter-reef breccia appeared. The upper clastic composition increases to form the stratigraphic features of the hybrid sequence dominated by the hybrid shelf of sandy carbonate rocks affected by frequent storms (Figure 3).

3. METHODS

Based on research of the stratigraphy,17,20 sedimentary environments,17 and faunas,16 the field profile of Yangmaba Formation in the Shigouli section among the Ganxi section was measured in detail, and a comprehensive histogram (82.65 m in length) of the field stratum was established, including the succession characteristics of lithology and the detailed description of stratum characteristics (Figure 3). The description of the field profile includes the color, lithology, grain structure, and typical sedimentary structure of the sediments.

In this study, through the actual measurement of the outcrop of the Yangmaba Formation in the Shigouli section, the high-frequency cycle of section was established, and the Yangmaba Formation was divided into 39 high-frequency cycles (Figure 3). The minimum thickness of the cycle is 0.40 m, the maximum thickness is 4.60 m, and the average thickness is 2.07 m. Using the Fischer plot,25,26 the Fischer plot of the Yangmaba Formation was drawn and then to analyze its accommodation space variation.
4. RESULTS

4.1. Hybrid Facies and Types. Hybrid deposits refer to the intermixing of terrigenous clastics and carbonates in the same sedimentary system or background. On the basis of the sedimentary background, the hybrid types can be divided into: (1) the mixed claystone shore at the lower of Yangmaba Formation with claystone as sedimentary background and (2) the mixed sandy and carbonate shelf, mixed reef, and shoal at the middle-upper of the Yangmaba Formation with powder-fine sandstone or limestone as the sedimentary background. The sedimentary types that form hybrid deposits include punctuated mixing, facies mixing, in situ mixing, and source mixing. In the Yangmaba Formation, the punctuated mixing of storm current transport, mixing, and deposition is mainly developed, the facies mixing of carbonate rocks and clastic rocks is mainly intersected and interbedded, and in situ mixing is based on biological shell enrichment. The hybrid deposits of the Yangmaba Formation...
Figure 3. Comprehensive column of sedimentary facies and sequence stratigraphy, the Devonian Yangmaba Formation, and Ganxi section of the northwestern of Sichuan Basin.
can be subdivided into hybrid shore, hybrid clastic shelf, and hybrid carbonate shelf in which the hybrid shelf can be further divided into hybrid facies types such as sandy hybrid shelf and carbonate hybrid shelf (Table 1).

Table 1. Division, Characteristics, and Distribution Layers of the Hybrid Facies of the Yangmaba Formation

| hybrid facies       | microfacies     | sedimentary characteristics                                                                 | hybrid mechanism       | distribution layers |
|---------------------|-----------------|------------------------------------------------------------------------------------------------|------------------------|---------------------|
| hybrid shore        | hybrid lagoon   | thin layers of claystone is intercalated with oolitic bioclastic limestone and ferruginous oolitic limestone | facies mixing punctuated mixing | 1−3                 |
| clastic hybrid shelf| hybrid tidal flat| thin layers of sandy bioclastic limestone is intercalated with silty claystone                  | punctuated mixing      | 4−5                 |
|                     | proximal-source sandy storm current | silt-fine sandstone is intercalated with a thin layer of claystone and argillaceous siltstone | punctuated mixing in situ mixing | 20−21, 27−30, 36−39 |
|                     | hybrid shelf mud | gray-dark gray thin layers of claystone, argillaceous siltstone, are intercalated with thin layers of marl and shell limestone lenses | in situ mixing         | 19                  |
| carbonate hybrid shelf | hybrid bioclastic shoal | gray medium-thick bioclastic limestone is intercalated with thin layers of claystone and argillaceous siltstone | facies mixing punctuated mixing in situ mixing | 6−11, 22−26 |
|                     | hybrid reefs     | gray thick layer of coral reef limestone is intercalated with gray lime claystone and breccia reef limestone | facies mixing punctuated mixing in situ mixing | 12−13               |
|                     | deep water shelf mud | dark gray claystone and lime claystone                                                                 | weak in situ mixing    | 13                  |
|                     | distal-source hybrid storm current | thin layer of sandy bioclastic limestone is intercalated with thin layers of claystone | in situ mixing         | 14−16               |
|                     | proximal-source hybrid storm current | silt-fine sandy calcarenite is intercalated with thin layers of claystone and argillaceous siltstone | facies mixing punctuated mixing in situ mixing | 17−18, 31−35 |

4.1.1. Hybrid Shore Facies. The hybrid shore facies develops at the bottom of the Yangmaba Formation is a shoal-barrier coast sedimentary system that can be subdivided into two microfacies: lagoon and hybrid tidal flat.
4.1.1. Hybrid Lagoon. Located at the bottom of the Yangmaba Formation, the sedimentary unconformity covers the ancient exposed surface of reef and shoal facies limestone on the top of Ertaizi Formation (Figure 4a). The microfacies lithology is mainly composed of grayish green thin layers of claystone and silty claystone and is intercalated with bioclastic limestone and ferruginous oolitic limestone (Figure 4b).

The limestone in the stratum is mainly composed of bioclasts, containing unequal amounts of iron ooid, which are lenticularly produced, with thicknesses ranging from 10 to 40 cm (Figure 4c). Ferruginous oolitic limestone is layered, brightly colored, and reddish brown with a thickness of 40 cm (Figure 4d). The bottom of the limestone often has a scour surface and gutter cast that reflect the characteristics of storm deposition (Figure 4e). It is a sedimentary background of hybrid sediment in the mixed claystone shore, which is formed by a mixture of facies mixing and punctuated mixing.

4.1.1.2. Hybrid Tidal Flat. It is developed on the fourth to fifth layer of the Yangmaba Formation. The lithology is interbedded with intermediate layered sandy microcrystalline bioclastic limestone and siltstone and silty claystone (Figure 4f). The rock is rich in sea lily stem fossils followed by brachiopods and trilobites. It is a facies mixing effect of alternating interbedded layers of terrigenous clastic rocks and carbonate rocks.

4.1.2. Clastic Hybrid Shelf. This type can be divided into two sedimentary microfacies: hybrid shelf mud and proximal-source sandy storm current in the middle-upper part of Yangmaba Formation.

4.1.2.1. Hybrid Shelf Clay Microfacies. This microfacies is distributed on the 19th layer and consists of a thin layer of gray silty claystone and dark gray claystone, with horizontal bedding.

4.1.2.2. Proximal-Source Sandy Storm Current Microfacies. This microfacies is mainly developed in layers 20−21, 27−30, and 36−39, which is the most developed type of hybrid facies in Yangmaba Formation. The lithology is mainly grayish white thin-medium fine-grained quartz sandstone and is an intercalated thin layer of claystone (Figure 5a). The scour surface is often developed at the bottom, and large hummocky cross-stratification (HCS), swaley cross-stratification (SCS), and parallel bedding (Figure 5b). The storm sequence is composed of a scour surface at the bottom, graded bedding, HCS, and horizontal bedding (Figure 5b,c).
Multiperiod storm sequences were superimposed to form sand bodies with huge thickness (Figure 5b,c). The storm deposition sequence of the microphase has a large sequence thickness, ranging from 50−100 cm, wherein the HCS is large in scale, with a wavelength of 100−200 cm and a wave height of 30−60 cm (Figure 5b,c). The argillaceous sediment during the storm intermission is rich in bioturbation structures and trace fossils, such as Zoophycos, Chondrites, and Skolithos (Figure 5d).

Calcareous cementation is well developed in sandstone (Figure 5e) and may also be rich in bioclasts (Figure 5f), which are formed by typical punctuated mixing.

4.1.3. Carbonate Hybrid Shelf Facies. Carbonate hybrid shelf is developed in the middle-upper parts of the Yangmaba Formation, which can be subdivided into microfacies types such as hybrid bioclastic shoal, hybrid reefs, proximal-source hybrid storm current, distal-source hybrid storm current, and deep water shelf mud.

4.1.3.1. Hybrid Bioclastic Shoal Microfacies. This microfacies is mainly developed in the 17−18 and 31−35 layers. Similar to the proximal-source sandy storm current, the carbonate proximal-source hybrid storm current also develops the bottom structure such as the scour surface and the gutter cast and the bedding structures such as HCS, graded bedding, parallel bedding, and current bedding (Figure 6a−c).

The graded bedding is composed of the brachiopod shells, which are mostly convex upward and in a layered distribution (Figure 6a,b). There are two types of storm sequence thicknesses: ① between 50 and 100 cm, and the HCS with a scale of meters, a wavelength of 80−150 cm, and wave height of 20−50 cm (Figure 6a,b), mainly distributed in the upper 31−35 layers of Yangmaba Formation and ② between 20 and 50 cm, the HCS has a decimeter scale with a wavelength of 30−80 cm and a wave height of 10−30 cm (Figure 6c). The scale is relatively small, mainly distributed in layers 17−18 of the upper part of the Yangmaba Formation. It was formed by the storm surge impact of strong alternating punctuated mixing and in situ mixing.

4.1.3.2. Distal-Source Hybrid Storm Current Microfacies. The microfacies are mainly developed in layers 14−16, located proximal to the storm wave base with a greater water depth, and have a longer extension distance than the proximal-source storm current,18 with significant changes in biological debris. The obvious thinning of bioclasts and of sequence thickness indicates the far source characteristics. The lithology is a yellow-gray thin layer of bioclastic limestone, which develops small groove cast,
HCS, and wave-ripple bedding. The thickness of the storm sequence is small, ranging from 10 to 30 cm, and the HCS has the centimeter-scale, with a wavelength of 10–30 cm and a wave height of 5–15 cm, which is small in scale (Figure 6d). Five small storm deposition sequences can be developed per meter.

**4.1.3.3. Deep Water Shelf Clay Microfacies.** The microfacies are developed in layer 13, and the lithology is relatively pure thin dark claystone and silty claystone with a high organic matter content. It is the deposit sediment of the major flooding period, and the sedimentary environment is quiet and low-energy.

**4.1.3.4. Hybrid Reef Microfacies.** The microfacies are mainly developed in layers 12–13, and the lithology is mainly a gray heavy layer-massive layer of sandy stromatoporoid-coral reef limestone (Figure 6e,f). In the upper part of the biohermal limestone, a breccia layer of reef limestone 50 cm thick is developed. The breccia with a diameter of 10–20 cm is irregularly distributed in the calcilutite, which is mainly composed of coral fragments, which is the damage caused by the storm on the organic reef. It has a hybrid effect of facies and weak punctuated mixing.

**4.1.3.5. Proximal-Source Hybrid Storm Current Microfacies.** The microfacies are mainly developed on the layers 6–11 and 22–26, and the lithology is mainly a gray heavy layer-massive layer of microcrystalline-sparry sandy bioclastic limestone, intercalated with thin layered claystone and muddy limestone (Figure 6g). The limestone is rich in fossils such as stromatoporoids, sea lilies, brachiopods, and corals and is most abundant with sea lilies and corals (Figure 6h,i). It has a hybrid effect of facies mixing and weak punctuated mixing; this microfacies type is formed in a higher energy deposition environment.

**4.1.4. Hybrid Facies Model.** From the above analysis of the hybrid facies and microfacies characteristics of the Yangmaba Formation, it is possible to synthesize the hybrid shore-hybrid shelf model of the Yangmaba Formation (Figure 7), and the hybrid shore, clastic rocks, and carbonate hybrid shelf can be developed successively from the shore to the shelf.

**4.2. Characteristics of the Hybrid Sequence.**

**4.2.1. Sequence Interface Identification.** The bottom sequence interface of the Yangmaba Formation is a type-II sequence interface, which is a transitional surface from the paleo-karst exposed surface to a wide regional transgression. Below the interface is the reef and shoal facies on the top of the Yangmaba Formation, which is a gray-green claystone containing tentaculite intercalated with hematite and biological gravels. The top interface of the sequence is the lithology and lithofacies transitional surface. Under the interface is the pale yellow quartz sandstone with cross-bedding and parallel bedding development, which belongs to the proximal-source storm deposits, and above the interface is micritic limestone. This interface is the boundary between Emsian and Eifelian and belongs to the type-II sequence interface. The condensed section is located on the 13th layer and is a black shale with only a small amount of thin shell tentaculite.

**4.2.2. Sequence Stratigraphic Division and Accommodation Space Analysis.**

**4.2.2.1. Sequence Stratigraphic Division.** Using the research method of sequence stratigraphy, based on the sequence interface and the characteristics of each system tract, the vertical and horizontal changes of sedimentary facies and facies sequence, combined with the tectonic framework, tectonic evolution, time of sequence formation, and so on, are obtained. The sequence and system tract of the Devonian Yangmaba Formation in the northwestern of Sichuan Basin are divided into one III-order sequence (Figure 3), and the shelf-margin systems tract (SMST) and transgressive system tract (TST), early highstand system tract (EHST), and late highstand system tract (LHST) are developed from the bottom up, and each system tract is composed of 1–3 fourth-order sequences and 2–6 fifth-order sequences (Figure 3).

**4.2.2.2. Sequence Stratigraphic Division.** In the course of time, the stacking patterns of sediments and the development of sedimentary systems also change periodically with the periodic variation of the accommodation space. The variation of
accommodation space is the essential factor for the formation of sedimentary sequences, and a sequence boundary is formed during the relatively slow growth rate of the accommodation space. Therefore, the analysis of the change history of the accommodation space is a relatively objective method to classify the sequence level and perform the sequence comparison. The current Fischer plot is one of the most important methods for analyzing the accommodation space. In recent years, it has been proved that the Fischer diagram is a simple and practical method to study the sedimentary cycles, relative sea level changes, and division of sequence order of different types of sedimentary basins. It can be seen from Figure 8 that the Yangmaba Formation in the study area develops a complete and large-scale actual accommodation space cycle, representing a significant sea level rise-down cycle, which has a good correspondence with the III-order sequence classified in this paper. This not only verifies the correctness of the sequence division but also demonstrates the practicality and objectivity of the Fischer diagram cycle analysis technique to a certain extent and also shows that the relative sea level change is an important controlling factor for the sequence development.

4.2.3. Hybrid Characteristics of the System Tract. 4.2.3.1. Shelf-Margin System Tract. The SMST develops in 1−5 layers (Figure 3) and is 14.85 m thick. At the bottom for the type-II sequence interface, overlining on the reef limestone of Ertaizi Formatin, which is a hybrid shore sediment, hybrid lagoon and hybrid tidal flat microfacies develop. The lower hybrid lagoon deposits are gray-green thin-medium layered calcareous siltstone, silty claystone, and claystone and intercalated with layered or lenticular ferric oolitic bioclastic limestone and ferruginous oolitic bioclastic limestone. The bottom of the bioclastic limestone often has an erosion surface and gutter cast, reflecting the characteristics of storm deposition. There are many types of bioclastics, mainly corals, brachiopods, and sea lily fragments, which are generally an upwardly deepening and thinning retrogradation sequence.

Figure 8. Fischer diagram of the Devonian Yangmaba Formation, Ganzhi section of the northwestern of Sichuan Basin.

Figure 9. Models showing three types of mixing processes in the Yangmaba Formation. WB, Wave base; SWB, Storm wave base.
tidal flat in the upper part is composed of gray thin layered sandy microcrystalline bioclastic limestone intercalated with thin-layer silty claystone, and it is a relatively stable weak progradation sequence.

4.2.3.2. Transgressive System Tract. The TST develops in 6–13 layers and is 16.1 m thick. The system tract contains a hybrid shelf dominated by carbonate rocks; from bottom to top, the hybrid bioclastic shoal microfacies composed of gray thin-medium layered sandy microcrystalline-sparite bioclastic limestone and organic reef microfacies composed of gray coral reef limestone are developed. Coral breccia was broken up by storms developed in inter-reef. The black-gray calcilutite, which is 10 cm in the upper part of the system tract, represents the maximum flooding surface in which the sea level rises to the highest position in the system tract.

4.2.3.3. Highstand System Tract (HST). The maximum flooding surface is the bottom boundary, and the top boundary is the lithology and facies transitional surface. Developed in 14–39 layers and 52.4 m thick, it is composed of superposition of the EHST and LHST.

Early highstand systems tract: The lower and upper parts are hybrid shelf deposits dominated by carbonate rocks. The lower part is gray sandy bioclastic limestone, which belongs to carbonate distal-source storm current microfacies and is developed in 14–16 layers. It develops small HCS, graded bedding, and wave-built cross bedding. The bioclastic content and particle size increased upward, and the scale of the storm gradually increased. It was a carbonate proximal-source storm current microfacies, which developed in layers 17–18. The middle part is black-gray claystone, which belongs to the mud microfacies, developed in 19 layers. The upper part is gray thick massive calcareous powder fine-grained quartz sandstone, and it is a microfacies of proximal-source distal carbonate strom current and develops in 20–21 layers. The upper part is a dark gray medium-thick layer sandy microcrystalline bioclastic limestone intercalated with a thin layer of calcareous claystone, which is hybrid bioclastic shoal microfacies, which develops in the 22–26 layers.

Late highstand systems tract: The system tract is deposited in a hybrid shelf environment. The lower part (27–30 layers) and the upper part (36–39 layers) are sedimentary microfacies of clastic strom current, and the lithology is dominated by gray-white thin-middle layered fine-grained quartz sandstone intercalated with a thin layer of claystone. The bottom has an erosion surface, and large-scale HCS, SCS, and parallel bedding are developed. Multiple storm sequences are superimposed to form a thick sand body, with rich trace fossils such as Zoophycos. The 31–35 layers are in the central part of the carbonate proximal-source strom current sedimentary microfacies, and the lithology is gray sandy bioclastic limestone, rich in coral, brachiopod and sea lily stem fragments, and storm sedimentary structures developed.

5. DISCUSSION

5.1. Hybrid Mechanism. The hybrid sediments of the Yangmaba Formation are developed in the shore and shallow shelf, and the main hybrid mechanisms are punctuated mixing, facies mixing, and in situ mixing (Figure 9).

5.1.1. Punctuated Mixing. Punctuated mixing is the process of transporting a sediment to another sediment by sudden events. For example, the terrigenous sand is transported into the carbonate sediments, and it is essentially a doping of a component structure. Storm wave action, turbidity current, and gravity current are the main driving factors for punctuated mixing. The storm wave is the most important driving force for the punctuated mixed sedimentation of the shore and the shallow shelf in the Yangmaba Formation. The proximal-source clastic storm current microfacies, proximal-source, and distal-source carbonate storm current microfacies developed in the HST hybrid shelf are the result of punctuated mixing (Figure 9a). Quartz sandstone is rich in bioclastics (Figure 5f), and calcareous cement is developed (Figure 5e), while the bioclastic limestone contains a large amount of quartz and other clastic grains (Figure 6h), which are mutually doped with two different compositions. The storm wave and storm backflow generated by the storm bring the shore sand into the shelf to form a proximal-source storm deposit with graded bedding, HCS, and ripple bedding, while a large number of faunal assemblages living in the shelf make the bottom seawater rich Ca. In addition, the proximal facies located in a higher energy zone, and the storm can also bring a small amount of shoreline sand into the carbonate deposits to form a hybrid carbonate shelf deposit. Of course, the high-frequency storm waves and their backflow bring a lot of sand or clay, which makes the sea water turbid and inhibits the continued growth of the faunal assemblages. At the same time, the strong storm action can also break up corals and other reef-building organisms (Figure 6b), which is not conducive to the development of biological reefs, which may be the reason why organic reefs are hard to see in hybrid carbonate storm sediments.

5.1.2. Facies Mixing. The sediments are mixed along the boundary between the different facies, which are interdigitated and interbedded between different deposits. That is to say, the hybrid sedimentary facies under the action of the hybrid mechanism are staggered in the plane or overlap in the vertical direction. With the relative sea level rise and relative stability stage, the supply of clast is relatively reduced. In the shallow shelf, the shore zone may develop low-diversity, high-abundance benthic brachiopod community or sea lily and produce and precipitate a large number of carbonates or corals and other reef-building organisms proliferate to form biological reefs. The hybrid bioclastic shoal and hybrid reefs developed in the TST of the Yangmaba Formation are the result of mixing. When the relative sea level declines, the supply of clast increases, and the fine-grained quartz sandstone is formed by winnowing, which overlaps on the shoal bioclastic limestone. Such reciprocation can constitute the characteristics of intersecting facies mixing and subsequence superposition.

5.1.3. In Situ Mixing. In situ mixing refers to sediment mixtures related to contemporaneous availability in space and time of the two heterolithic siliciclastic and carbonate fractions. This type of mixing process results in a bed-scale mixing (Figure 9c). In Yangmaba Formation, with the siliciclastic sediment inputting, the sediments deposited on the shelf where autochthonous faunal assemblages could live. The siliciclastic combining with bioclastic composed the compositional mixing (Figure 6h,i).

5.2. Controlling Factors of Sequence Hybrid Deposits. It is concluded that the hybrid deposits and hybrid mechanism in the various system tracts of the Yangmaba Formation can be seen that the factors controlling and affecting the hybrid deposits mainly include the relative sea level change, carbonate productivity or the rate of terrestrial clastic supply, climate change, and so on are not independent of each other, but are mutually restrained and mutually influential, and the storm exacerbates the mixing of clastic rocks and carbonate rocks.
Located at a low latitude in Ganxi, Longmenshan area, the reef-building organisms such as corals and the formation of reefs. Failure to form large-scale reefs in this area is inhibits the formation of reefs. It may be the main reason for the mixed into the interstitial material of reef limestone, which formed in inter-reef. Second, the terrigenous quartz sand is mixed into the reef limestone. The Devonian Yangmaba Formation in Ganxi, Longmenshan area at low latitudes is in warm climatic conditions, which is conducive to the massive growth of reef-building organisms such as corals and the formation of reefs. Located at a low latitude in Ganxi, Longmenshan area, the Middle Devonian is a greenhouse stage in history with a PCO₂ concentration of 900 ppm, causing frequent storms and destroying the growth of reefs. Large amounts of reef breccia are formed in inter-reef. Second, the terrigenous quartz sand is mixed into the interstitial material of reef limestone, which inhibits the formation of reefs. It may be the main reason for the failure to form large-scale reefs in this area.

5.2.2. Controlling Factors of TST Hybrid Deposits. There are relatively few TST hybrid sediments in the Yangmaba Formation, mainly carbonate hybrid bioclastic shoal and hybrid reefs. The main controlling and influencing factors are sedimentary source recharge and climate change. Along with the rapid rise of the sea level in the TST stage, the supply of terrigenous materials is rapidly reduced, which is conducive to the rapid growth of biomes and the formation of bioclastic limestone. The Devonian Yangmaba Formation in Ganxi, Longmenshan area at low latitudes is in warm climatic conditions, which is conducive to the massive growth of reef-building organisms such as corals and the formation of reefs. Located at a low latitude in Ganxi, Longmenshan area, the Middle Devonian is a greenhouse stage in history with a PCO₂ concentration of 900 ppm, causing frequent storms and destroying the growth of reefs. Large amounts of reef breccia are formed in inter-reef. Second, the terrigenous quartz sand is mixed into the interstitial material of reef limestone, which inhibits the formation of reefs. It may be the main reason for the failure to form large-scale reefs in this area.

5.2.3. Controlling Factors of HST Hybrid Deposits. In the EHST stage, during the relatively high water level, shelf deposits are dominated by a thin layer of rhythmic plaster, and the basin is in starvation. The Yangmaba Formation mainly develops carbonates in EHST. Because of the impact of storms, the development of distal-source and proximal-source carbonate storm sedimentary microfacies occurs. In the LHST stage, the sea level decline provides a prerequisite for mixed sedimentation: terrigenous materials can be adequately supplied, controlled by storm deposits, and clastic storm deposition under punctuated mixing was developed. If carbonate production is favorable under the right climate, the punctuated mixing of terrigenous clastics and carbonates is increasing, forming carbonate proximal-source storm microfacies.

6. CONCLUSIONS

(1) The Devonian Yangmaba Formation in the northwestern of Sichuan Basin develops a hybrid shore-hybrid shelf deposit, which can be divided into three types of hybrid facies: hybrid shore, clastic rocks hybrid shelf, and carbonate hybrid continental. Further divided into hybrid lagoon, hybrid tidal flat, hybrid shelf mud, distal-source carbonate storm current, proximal-source carbonate storm current, hybrid bioclastic shoal, and hybrid reefs microfacies.

(2) The mixed claystone shore at the lower with claystone as sedimentary background, and the mixed sandy and carbonate shelf, mixed reef, and shoal at the middle-upper of the Yangmaba Formation. The hybrid mechanism includes punctuated mixing, facies mixing, and in situ mixing, and the first two are the main types.

(3) The hybrid sequence of the Yangmaba Formation can be divided into four sedimentary system tracts: SMST, TST, EHST, and LHST. All system tracts developed different hybrid deposition controlled by various hybrid mechanisms. The punctuated mixing is the main mixing manner in the SMST and LHST, and the facies mixing developed in the TST and EHST.

Among the controlling factors such as relative sea level change, terrestrial clastic supply, the rate of carbonate productivity, deposition rate, and storm action, the first two factors are the most important factors controlling the formation of different hybrid facies. In the systems tracts of Yangmaba Formation, the relative sea level change and carbonate productivity control the facies mixing, and terrestrial clastic supply and deposition rate dominate the in situ mixing. Storm action is the most important controlling factor of punctuated mixing of the Yangmaba Formation.

(4) Relative sea level change, carbonate productivity or the rate of terrestrial clastic supply, and climate change are factors that control and affect hybrid deposits. SMST and HST are mainly related to changes in the relative sea level, while TST is controlled by sedimentary source recharge, and climate change affects the hybrid action of system tracts to varying degrees.

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Notes
The authors declare no competing financial interest.

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