Hindawi
Geofluids
Volume 2022, Article ID 5051804, 21 pages
https://doi.org/10.1155/2022/5051804

Research Article

Sedimentary Characteristics and Developmental Models of the Cambrian Dolostone-Evaporite Paragenesis System in the Sichuan Basin

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Received 16 June 2022; Revised 1 August 2022; Accepted 1 September 2022; Published 24 September 2022

Academic Editor: Dengke Liu

The Cambrian strata of Sichuan Basin, China, present many dolomite-evaporite paragenesis systems (DEPS), which contain oil and gas resources for industrial exploitation. However, despite their wide distribution, the formation models and influencing factors of DEPS remain poorly understood. By analyzing an abundance of literature from China, this study comprehensively summarizes the sedimentary characteristics, combination patterns of rocks, and formation models of DEPS. The research significance, research questions, and future research directions of DEPS are also clarified. Firstly, the distribution of DEPS is clarified based on published studies: DEPS are widely distributed in the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation of the eastern and southern Sichuan Basin. Evaporite and dolostone combination patterns in DEPS include the following modes: interbedding of dolostone and evaporite, evaporite overlying thick dolostone, thick dolostone mixed with thin evaporite, and thick evaporite mixed with thin dolostone. Secondly, five types of evaporites and five types of dolostones have been identified. Thirdly, spatiotemporal distribution, influencing factors, and developmental models are summarized. Studies on DEPS provide new insight into the origin of dolomite. Such research also provides theoretical guidance for the exploration of oil and gas resources in DEPS.

1. Introduction

Dolomites have been a focus of academic research since they were first proposed by the French scholar Deodal de Dolomieu in 1791. Numerous academic perspectives on the genetic model of dolomite have been proposed, and it is difficult to verify these under the natural or artificial conditions of today [1, 2]. Evaporite is a chemical sedimentary rock that formed by the continuous evaporation and concentration of sedimentary water in a confined environment [3]. Evaporite is often associated with the formation of dolomite, forming dolomite-evaporite paragenesis systems (DEPS) [4, 5].

DEPS are a common form of paragenesis systems, which are distributed across different geological historical periods around the world [5]. During the exploration and development of the Cambrian strata in the Sichuan Basin, China, large-scale DEPS have been discovered. These were found to contain good reservoir-caprock combinations, with a certain scale of oil and gas resources, promising good exploration potential. Scholars have previously carried out related research, examples of which are studies on the genetic model of dolomite ([5–21]. [22]), the controlling factors of dolomite reservoirs [23, 24], the genesis and types of dolomite reservoirs [13, 25, 26], evaporite characteristics and genesis [27, 28], evaporite accumulation conditions [29], paragenesis systems deposition model, and reservoir distribution [30]. These studies focused on dolomite or evaporite as a lithology. The temporal and spatial distribution, sedimentary characteristics, rock assemblage sequence, geochemical characteristics, and paleoclimate and paleoenvironmental records of the DEPS in the Sichuan Basin must be studied further. Such studies provide new concepts and guidance for the exploration of oil and gas resources in DEPS. Based on a review of the Chinese and international literature on the Cambrian in the Sichuan Basin, in this paper, the spatiotemporal distribution, rock sequence, developmental characteristics, geochemical characteristics, genetic models, influencing factors, practical significance, existing problems, and future research directions of the DEPS in the Sichuan Basin are discussed. The dolomite-evaporite paragenesis systems are mainly studied because the depositional environments of dolomite and evaporite in the pseudo-contemporaneous period and the formation process are similar. In the oil and gas exploration of marine basins, dolomite and evaporite form a good reservoir-caprock combination. Dolomite and evaporite are strongly correlated with the genesis of oil and gas. Therefore, terrigenous clastic rocks and rocks with a terrigenous clastic content greater than 50% are not considered in this study of DEPS.

2. Geological Setting

According to previous literature [31], the large-scale deposits of evaporites in the Sichuan Basin mainly happened in the Cambrian. The deep Cambrian in the Sichuan Basin is rich in resources. The Lower Cambrian Maidiping Formation and the Qiongzhusi Formation are mainly shelf facies, siliceous or carbonaceous shale, and dark mudstone, which are high-quality source rocks. The Canglangpu Formation belongs to the coastal area. The coastal shelf mixed platform facies deposits, while the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation are mainly a set of typical marine sedimentary rocks composed of carbonate rocks, sulphate rocks, halides, and thin sandy mudstones. In DEPS, the facies sedimentary system is widely developed in the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation [30]. Because DEPS are mainly distributed in the Middle-Upper Cambrian in the eastern and southern Sichuan Basin, the authors mainly use the Cambrian stratigraphic division and the same naming of the eastern and southern Sichuan Basin.

In terms of structure, after being subjected to the Jinning movement and the Chengjiang fold movement, the Sichuan Basin began to consolidate the basement as part of the Yangtze Plate. The Sichuan Basin also entered a stage of stable development [31]. A series of pre-Sinian rifts formed in the basin in NE direction, laying the foundation for the formation of the late Sinian-Early Cambrian rifts and affecting the distribution of later rifts [32] (Figure 1). The rifts that developed in the Sichuan Craton Basin provided the depositional conditions needed for the development of dolomite and evaporite.

Previous studies proposed the following sedimentary models for the Longwangmiao Formation: a slope-platform sedimentary model [9, 12], a traditional carbonate rimmed platform model [8, 17, 18, 33], a traditional carbonate gentle slope model [10, 13, 15, 20, 21, 34], a carbonate gentle slope "double shoal" depositional model [7, 35], a carbonate rimmed platform "three shoals" depositional model [16], and a carbonate gentle slope toward rimmed platform evolution model [19, 22]. The depositional facies of the Gaotai Formation were mainly identified as open platform facies-platform edge facies-slope facies [17]. The depositional mode of the Xixiangchi Formation was identified as a rimmed carbonate platform [32, 36].

3. Methodology

The data used in this study included research results of previous studies, well-logged data from 30 wells, core data from five wells, four surface outcrops in the western Sichuan Basin (including Leshan and Shapingzi in Leibo County, Heima in Ganluo County in the south, and Chongqing in the east), and more than 800 thin sections from five wells. Geochemical data of the study area from previous research were also used.

In this study, detailed core data and well-logging data of three wells in the unexposed area were used, and the rock assemblage sequence of DEPS was classified. A research-grade smart transflective polarizing microscope (Leica DM4 P Upright Polarizing Microscope, Leica Microsystems (Shanghai) Trading Co., Ltd.) at the Sedimentary Basin Experimental Center of Yangtze University, China, was used to observe more than 800 thin sections from five wells for detailed sedimentological and petrological analyses. All thin sections were stained with Alizarin red S to distinguish dolomite from calcite. The sequence stratigraphic interface was determined by wavelet transform technology and logging cycle analysis technology, and the sequence stratigraphic framework of the study area was established. The DEPS boundary was well drilled with dolomite and evaporite, and the residual thickness of DEPS was equal to the thickness of dolomite and evaporite. The sedimentary thickness of DEPS in the study area was calculated. The geneses of evaporite and dolomite are discussed in comparison with previous research results. Based on rock genesis, the geochemical characteristics of the study area, previous research data, and logging cycle analysis technology, the main controlling factors of DEPS are discussed, and a developmental model of DEPS is established.

4. Results

4.1. Lithological Association and Development Characteristics of DEPS

4.1.1. Lithological Association of DEPS. According to the classification of the lithological combination sequence of the DEPS [5] and in combination with the classification of the Cambrian gypsum-salt rock profile of the Sichuan Basin and that of dolomite [27, 29, 38, 39], the Cambrian DEPS lithologic combination sequence in the Sichuan Basin can be divided into four types (Figure 2): (A) Interbedding of dolostone and evaporite; (B) evaporite overlying thick dolostone; (C) thick dolostone mixed with thin evaporite; and (D) thick evaporite mixed with thin dolostone. Good correspondence was found between the classification of the gypsum-salt rock profile in the Sichuan Basin [27, 29, 38, 39] and

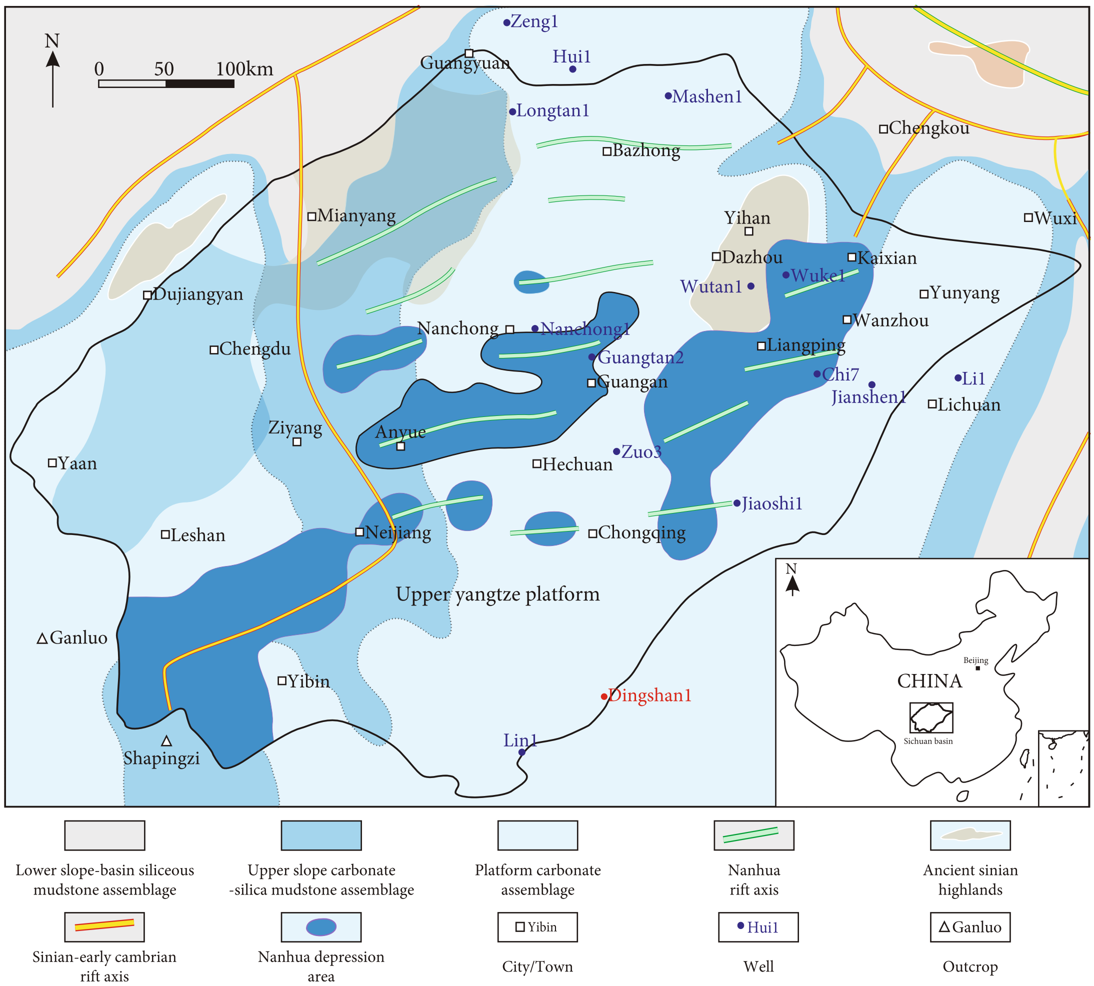


Figure 1: The Sinian-Early Cambrian uplift depression pattern of the Yangtze Craton [37].

the classification of the lithological combination sequence of the DEPS. The Gongshen type corresponds to the interbedding of dolostone and evaporite, the Dingshan type corresponds to thick dolostone mixed with thin evaporite, and the Jianshen type corresponds to thick evaporite mixed with thin dolostone.

(1) Interbedding of dolomite and evaporite (Figure 2(a)): This type of lithological combination is common in DEPS, and interbedding of dolomite and evaporite with unequal thickness is also common. For example, in the Gongshen 1 Well in the middle and upper part of the Longwangmiao Formation, dolomite and gypsum salt rocks form a rhythmic interbedding pattern. The single-layer thickness of gypsum salt rock is 21 m. This reflects that in a limited environment, the water body concentration increases because of evaporation and sedimentary diagenesis. A high-concentration water body in the later stage of the formation of gypsum-salt rock causes dolomitization, thus forming an interbed combination of dolomite and evaporite, which formed the upper part of the Longwangmiao Formation. The evaporite content increased, which indicates a progressively hot and dry environment

(2) Evaporite is overlaid with dolomite (Figure 2(b)): The formation of this type of lithological assemblage reflects two distinct situations. The first is that evaporite is directly deposited onto early dolomite, and the second is that evaporite is deposited on limestone, and later, this limestone is dolomitized [40]. For example, in Zuo 3, the deposition period of the Gaotai Formation belongs to a large-scale regression period. The sedimentary water body is shallow and mainly belongs to the tidal flat facies deposition. With intensifying regression, the evaporation of high-concentration fluids accelerated, and evaporites were gradually deposited on the dolomite that had formed in the early stage. This led to the formation of the interbedded combination of thick evaporite and thick dolomite, and the content of evaporite increased, reflecting a progressively hot and dry environment

(3) Thick dolostone mixed with thin evaporite (Figure 2(c)): Thin-layered evaporite is sandwiched

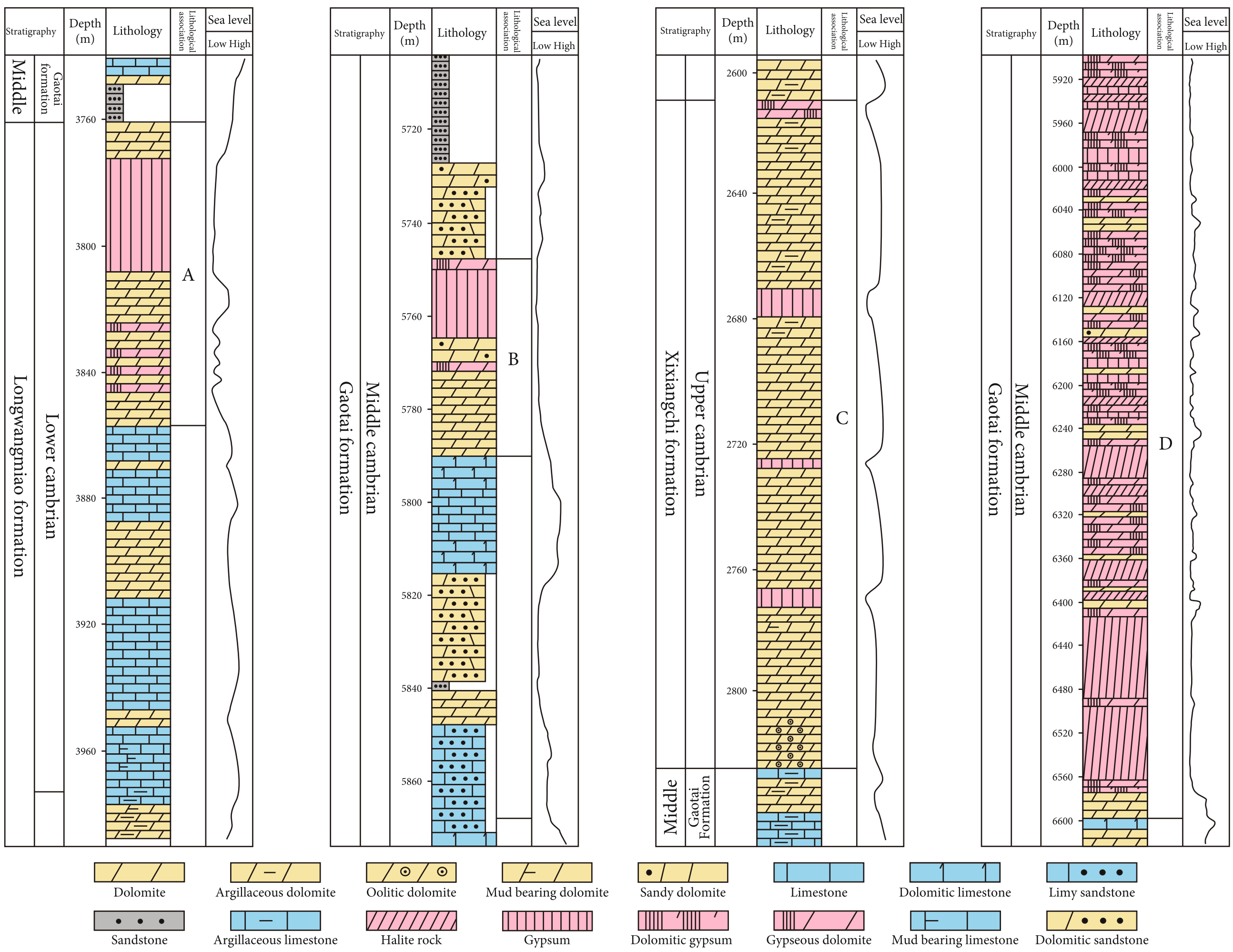


Figure 2: Lithological association of DEPS. (a) Interbedding of dolostone and evaporite (Gongshen 1 Well, Longwangmiao Formation). (b) Evaporite overlying thick dolostone (Zuo 3 well, Gaotai Formation). (c) Thick dolostone mixed with thin evaporite (Dingshan 1 well, Xixiangchi Formation). (d) Thick evaporite mixed with thin dolostone (Loutan 1 Formation) [27, 29, 38, 39].

between medium–thick-layered dolomite. For example, in Dingshan 1, during the depositional period of the Gaotai Formation, because of its proximity to the sea and the relative flatness of the terrain, small-scale and high-frequency sea transgression and regression often occurred, which led to the formation of this type of assemblage

(4) Thick evaporite mixed with thin dolostone (Figure 2(d)): Most thin-layered dolomite may be developed from evaporite by infiltration and reflux. For example, Loutan 1 of the Gaotai Group have many evaporites with a total thickness of 675 m, which implies that the sedimentary environment has been a restricted environment reflecting the dry and hot climate

4.1.2. Evaporite Development Characteristics of DEPS. The evaporites in DEPS mainly include gypsum rock and salt rock. According to the proportions of gypsum, salt, and dolomite, evaporite can be further divided into gypsum rock, dolomite-bearing gypsum rock, dolomite gypsum rock, gypsum rock, dissolved breccias, and salt rocks [11, 27, 29, 41]. These are detailed as follows:

(1) Gypsum rock (Figures 3(a) and 3(b)) is gray-grey and forms a dense block with a volume fraction of gypsum or salt greater than 90%. The main components are gypsum and anhydrite, and the rock also contains unequal amounts of dolomite, a small amount of clay minerals, quartz, and occasionally chalcedony, lapis lazuli, pyrite, organic matter, rhythm strips, lens, blocks, and waves. Pure gypsum rock is widely distributed in the wells in the basin. For example, in Jianshen 1, the pure gypsum rock in the Middle Cambrian Gaotai Formation is 56.5 m thick and has nine layers

(2) Dolomite gypsum rock (Figure 3(c)) is defined by a volume fraction of gypsum of 25–50%. Dolomite gypsum rock is mostly found when drilling, which may be due to the volume of gypsum in this type

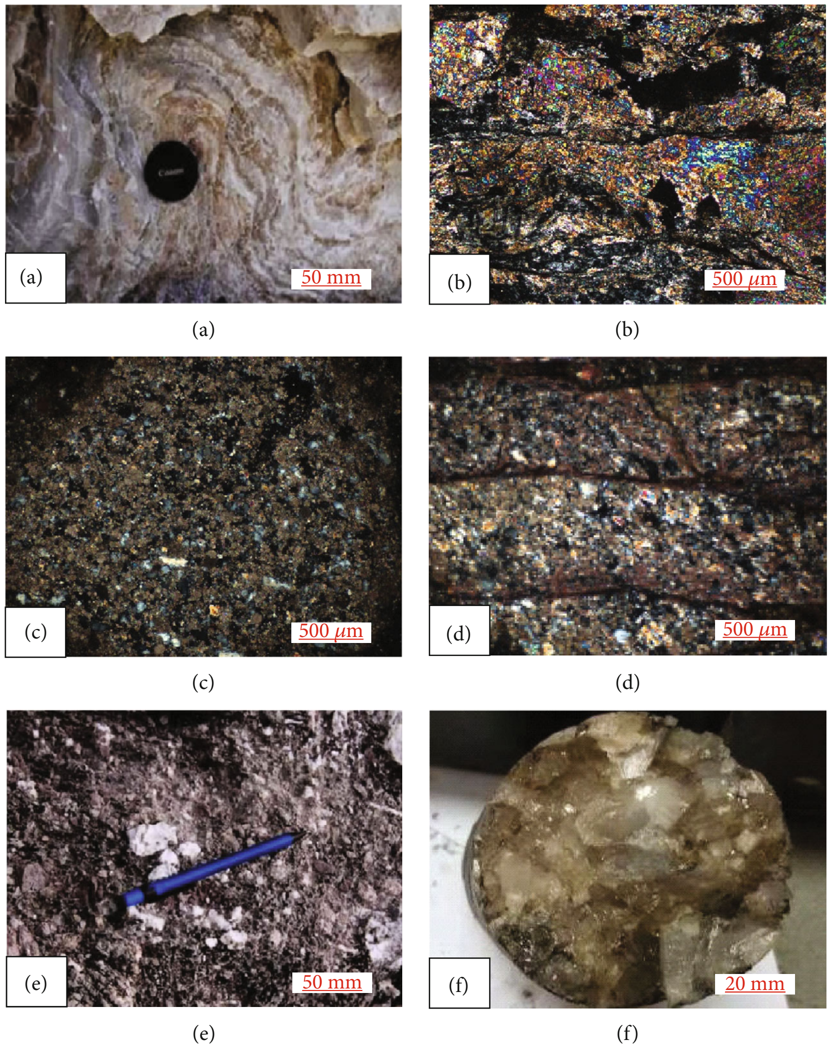


Figure 3: Petrological characteristics of evaporites in DEPS: (a) rhythmic banded gypsum, Shapingzi, Leibo County, Xixiangchi Formation [27]; (b) gypsum, Loutan 1 Well, 5595 m (+); (c) dolomite gypsum rock, Loutan 1 well, 5931 m (+); (d) dolomite-bearing gypsum rock, Loutan 1 well, Gaotai formation footwall, 6558 m (+); (e) Gypsum karst breccia, Heima, Ganluo County [27]; and (f) salt rock (potassium salt), Loutan 1 Well, 6050 m, core sample.

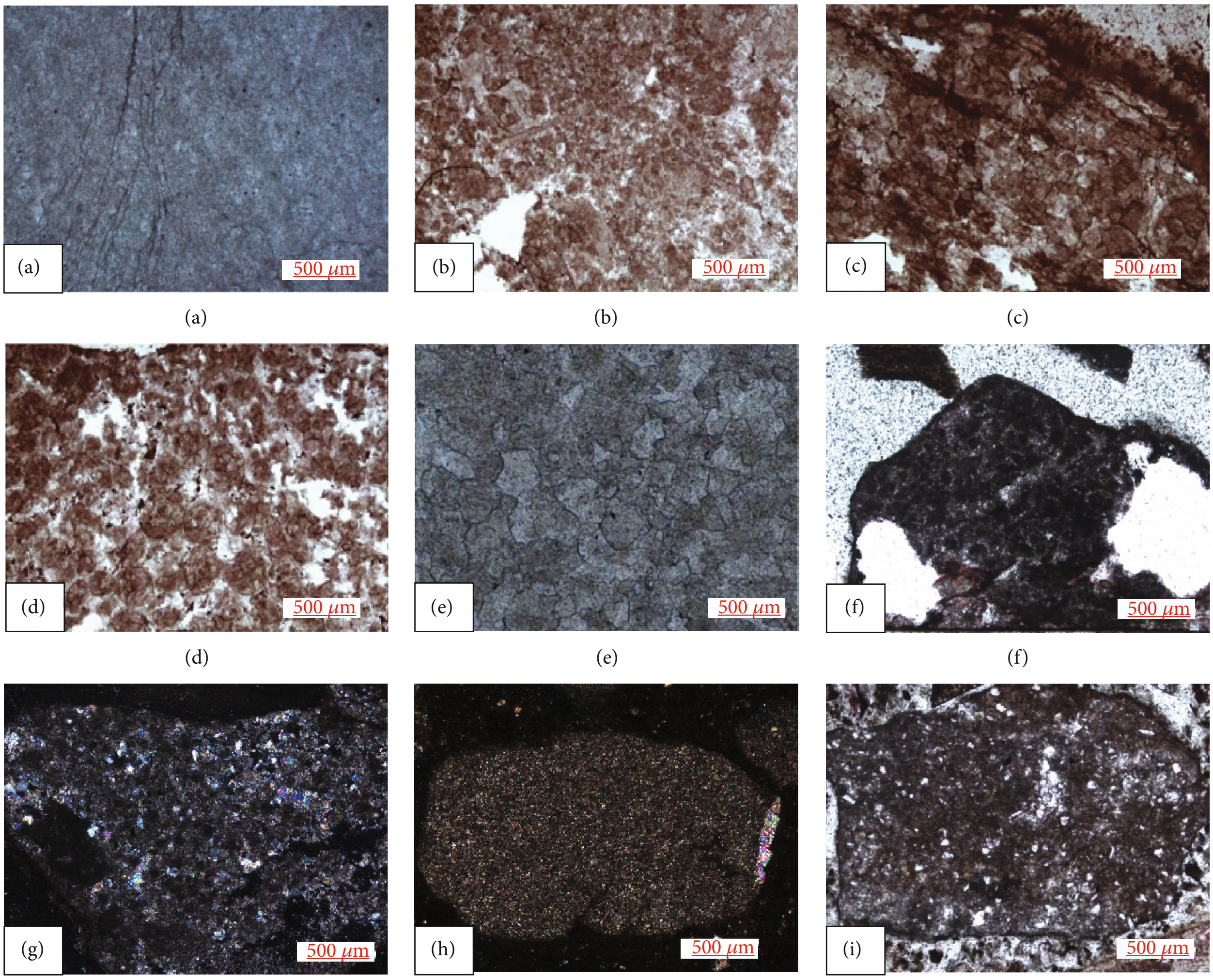
of rock. The scores are relatively large and not easily preserved under natural conditions. Dolomite gypsum rocks are mostly formed in confined environments with stable sedimentary water bodies

(3) Dolomite-bearing gypsum rock (Figure 3(d)) contains almost no clay, and the volume fraction of dolomite is higher than 50%. A volume fraction of gypsum of 10–25% defines gypsum-bearing dolomite. This kind of rock is rare under natural conditions. Similar to the formation of dolomitic gypsum rock, it formed in an environment with relatively limited water bodies

(4) Gypsum-dissolved breccia (Figure 3(e)) is commonly found in outcrops in Leshan and Leibo in the west of the Sichuan Basin and in Chongqing in the east of the Sichuan Basin. The formation of gypsum-solubilized breccia is related to surface dissolution. When soluble gypsum-salt rock is dissolved, the overlying rock collapses, thus forming gypsum-solubilized breccia

(5) The main component of halite (Figure 3(f)) is NaCl. Core samples can be found in Loutan 1, and halite pseudocrystals have also developed in the study area. Most of these rocks develop in a sedimentary environment where the water body is relatively limited, and the salinity gradually increases because of the strong evaporation environment

4.1.3. Evaporite Development Characteristics of DEPS. Common types of dolomite in the Cambrian DEPS in the Sichuan Basin include grain dolomite, granular dolomite, and gypsum dolomite. Grain dolomite can be further divided into argillaceous powder dolomite and fine-



(a) (b) (c) (d) (e) (f) (g) (h) (i)

Figure 4: Petrological characteristics of dolomite in DEPS. (a) Muddy-pink dolomite, Wutan 1 Well, 6265 m, Xixiangchi Formation, 10 × 5(-), chip stained thin section; (b) fine-crystal dolomite, residual grain phantom, dissolved pores, quartz crystal, Wutan 1, 6907 m, 10 × 5(-); (c) fine-grained dolomite, oolitic phantom, intercrystalline pores, Wutan 1 Well, 6921 m, 10 × 5(-); (d) oolitic dolomite, with intergranular and intergranular (dissolved) pores, asphalt impregnation, fine-grained structure, Wutan 1 Well, 6916 m, 10 × 5(-); (e) residual oolitic dolomite, Loutan 1 Well, 6903 m, 10 × 5(-); (f) sandy dolomite, Wutan 1 Well, 6562 m, Xixiangchi Formation, 10 × 5(-), cuttings stained thin section (g) gypseous dolomite, Loutan 1 well, 5325 m, (+); (h) gypsum-bearing dolomite, Loutan 1 well, 5665 m (+); and (i) gypsum-bearing dolomite, Wutan 1 Well, 6618 m (-).

medium crystalline dolomite, and granular dolomite can be further divided into oolitic dolomite and intraclastic dolomite (Figure 4).

(1) Muddy-powder crystal dolomite (Figure 4(a)): The volume fraction of the mineral composition of dolomite generally exceeds 90%, and the dolomite crystal is small with a low degree of crystallinity, usually accompanied by a small amount of mud sand and bioclasts. Lime composition caused the formation of muddy powder crystal dolomite during the quasi-contemporaneous period, because of dolomitization. In the Longwangmiao Formation, mud-powder dolomite reservoirs have often formed because of the development of dissolved paste mold pores [11, 41].

(2) Fine-medium crystal dolomite (Figures 4(b) and 4(c)) is also known as sugar-like dolomite. Dolomite crystals are large with a crystal size mostly ranging between 0.15–0.5 mm with a high degree of crystallinity. Most crystals are associated with dolomite facies that formed during the quasi-contemporaneous period

(3) Oolitic dolomite (Figures 4(d) and 4(e)): The most important reservoir rocks in the Longwangmiao Formation consist of oolitic dolomite, which gradually forms in an environment of slow precipitation and disturbed water bodies. During the burial process, oolitic dolomite mostly underwent diagenesis such as compaction and dolomitization. After full

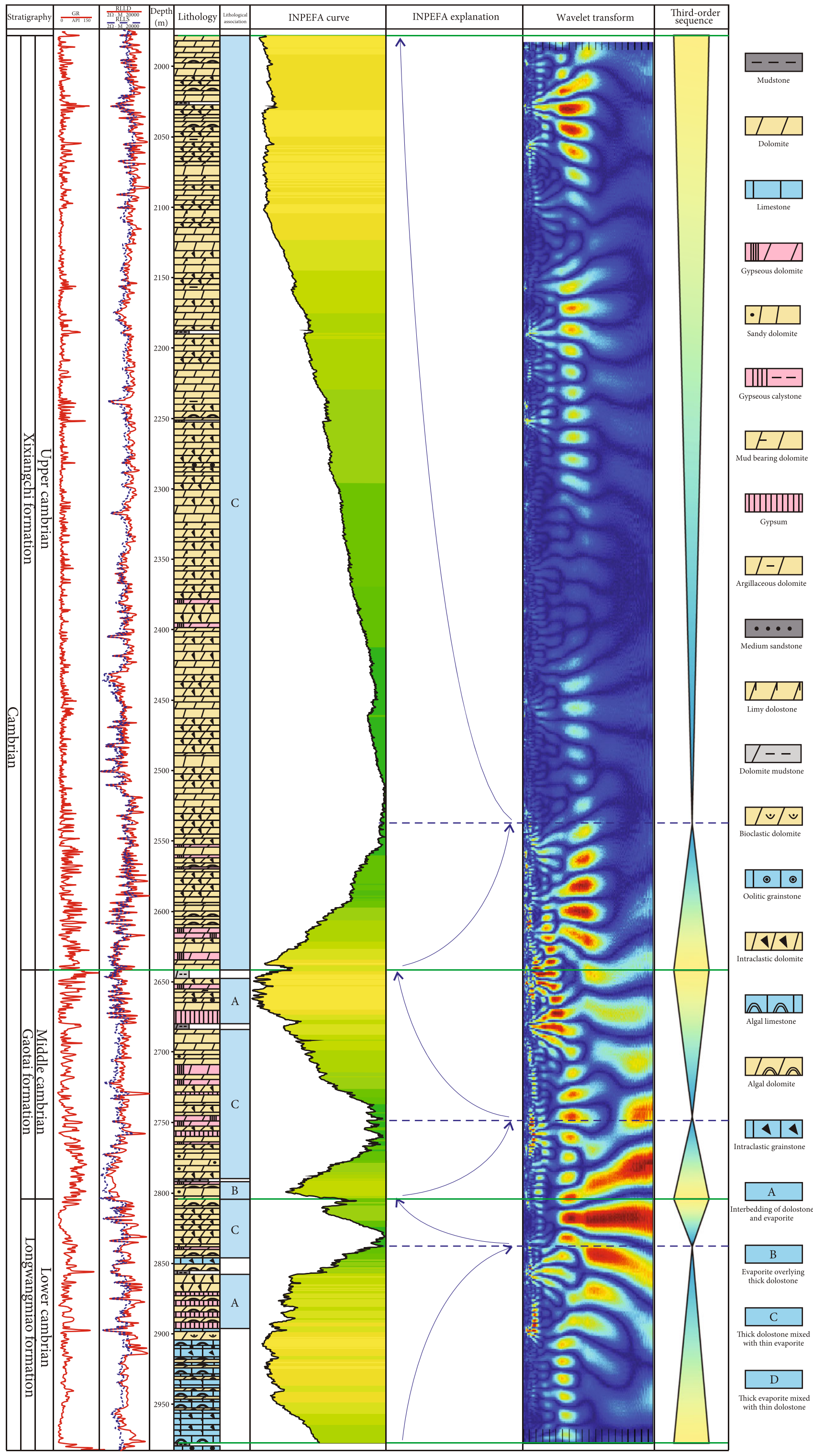


FIGURE 5: The Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation of Dingshan 1 well.

dolomitization, the oolitic structure disappears and changes to residual oolitic dolomite

(4) Intraclastic dolomite (Figure 4(f)): The main component of intraclastic dolomite (Figure 4(f)) is algal intraclastic. The particle size of the intraclastic is larger, and the degree of rounding and sorting of the sand in the Longwangmiao Formation is higher than that in the Xixiangchi Formation. Intraclastic dolomite is mostly the result of dolomitization of either intraclastic particles, cement, or both

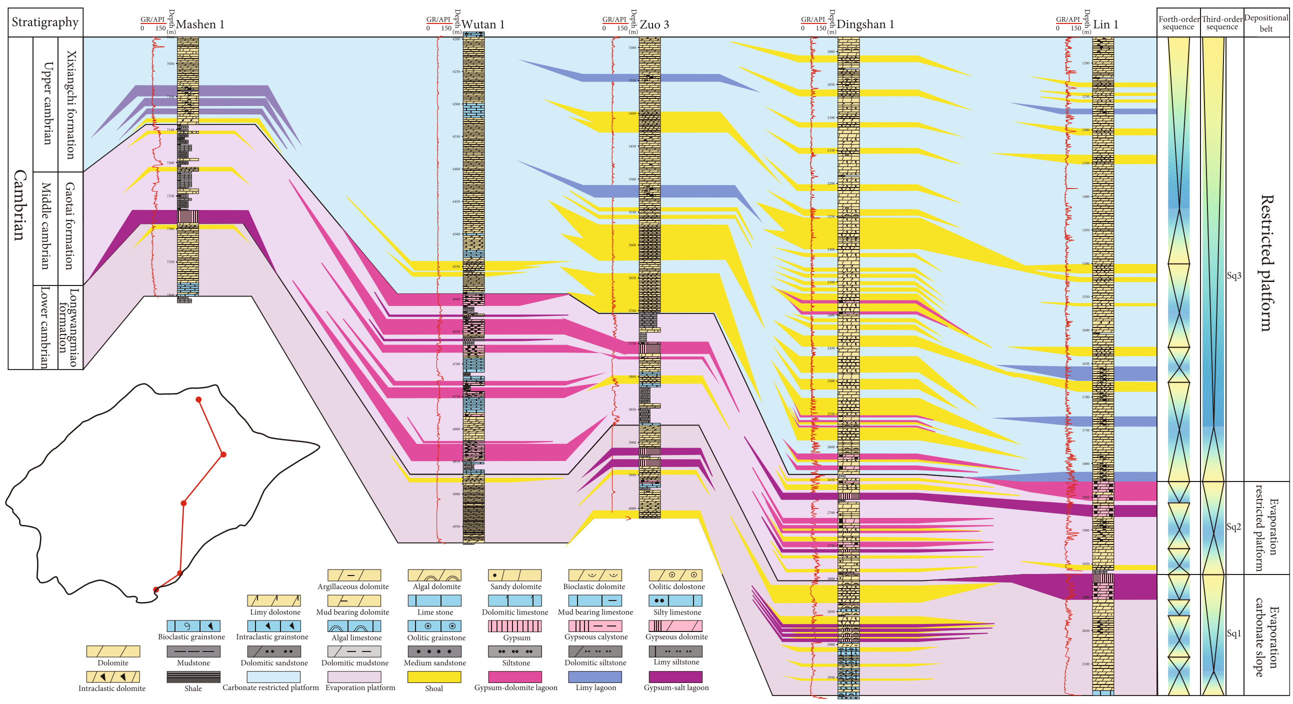


Figure 6: Sedimentary framework profile of the Cambrian DEPS in the Sichuan Basin.

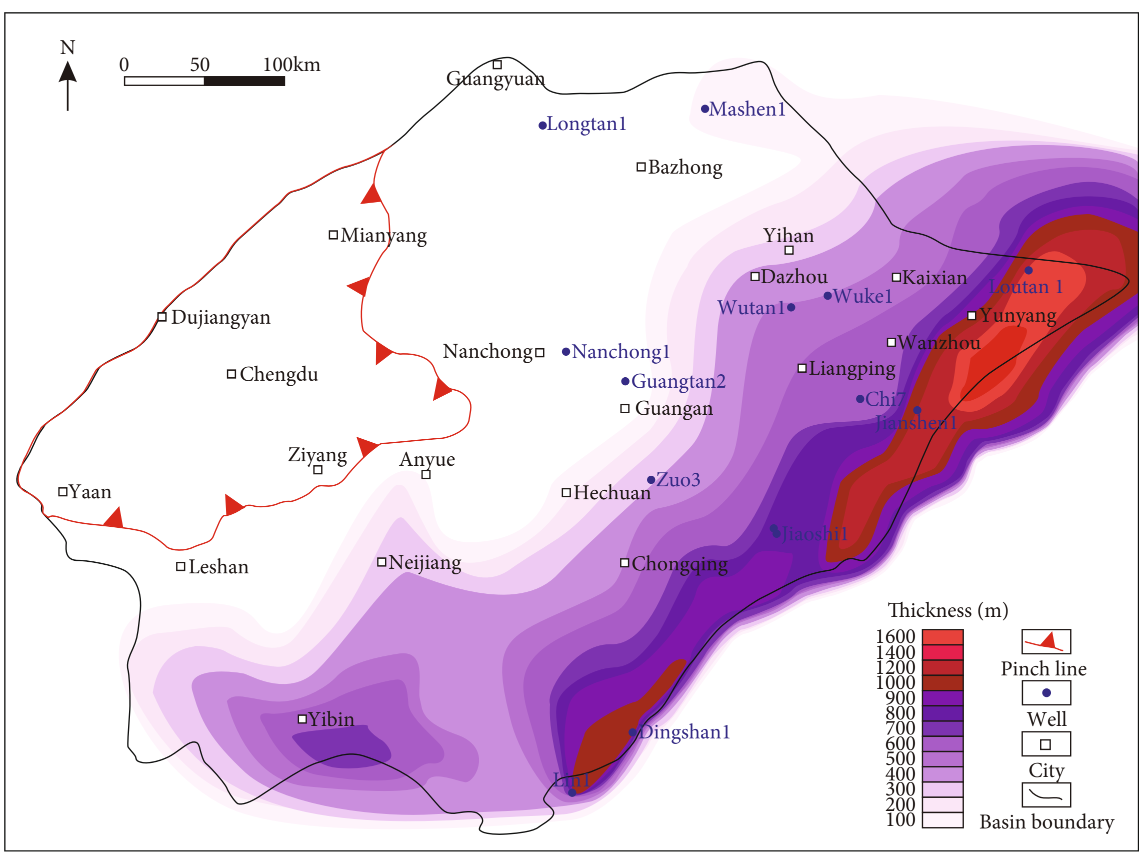


Figure 7: Residual thickness of the Cambrian DEPS in the Sichuan Basin.

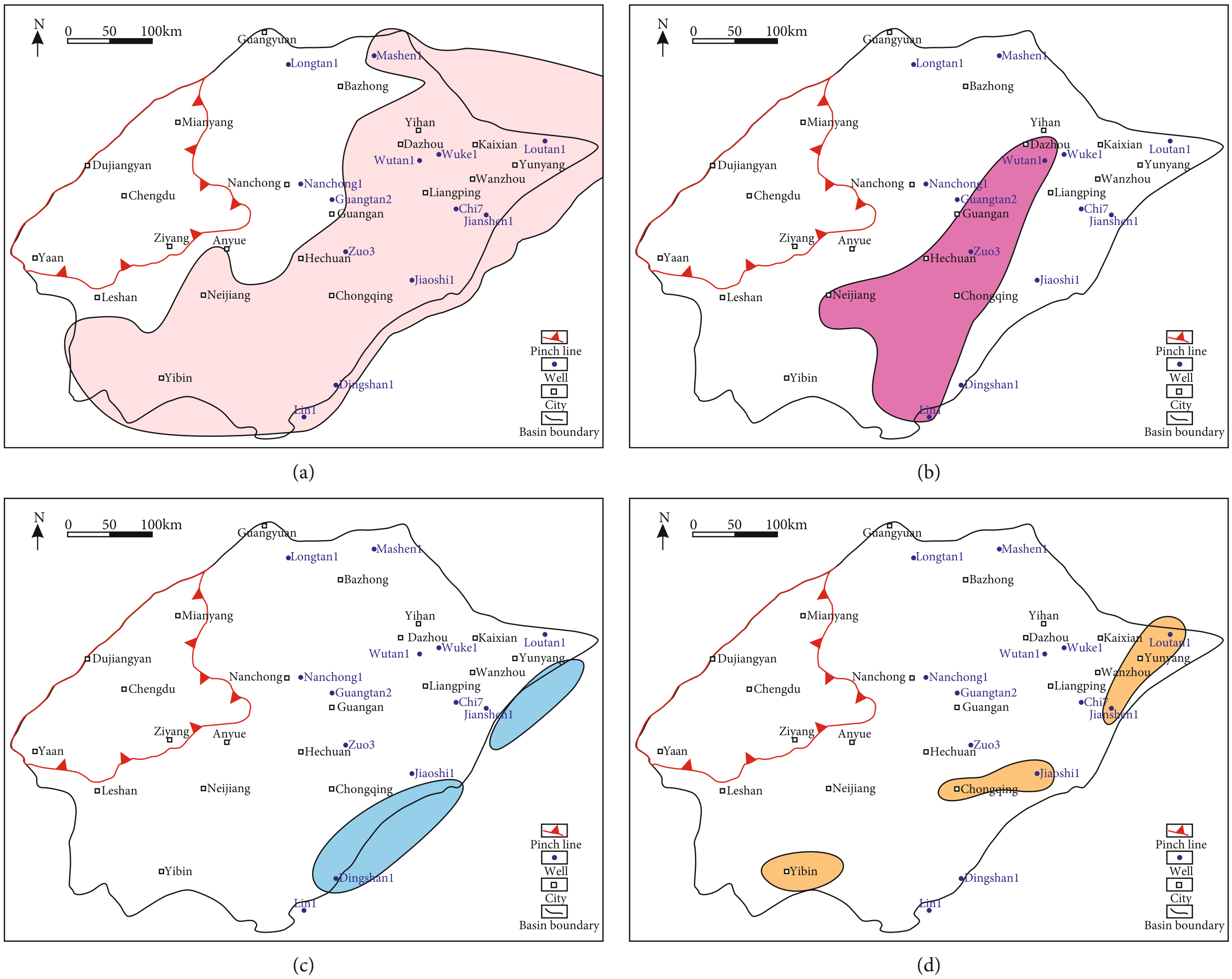


Figure 8: Distribution range of DEPS. (a) Interbedding of dolostone and evaporite; (b) evaporite overlying thick dolostone; (c) thick dolostone mixed with thin evaporite; (d) thick evaporite mixed with thin dolostone.

(5) Gypseous dolomite (Figure 5(g)) and gypsum-bearing dolomite (Figures 4(h) and 4(i)): In gypseous dolomite (Figure 5(g)) and gypsum-bearing dolomite (Figures 4(h) and 4(i)), the gypsum content is different. Gypseous dolomite has 25–50% gypsum, and gypsum-bearing dolomite has 10–25% gypsum. Gypseous dolomite and gypsum-bearing dolomite mostly develop in semiclosed lagoon environments. Because of the difference in deposition between dolomite and gypsum rock and salt rock, and because of the lack of gypsum rock source supplements, the dolomite content is relatively high. Gypsum-bearing dolomite is deposited easily

Microbial dolomite is less developed in the Cambrian paragenesis system in the Sichuan Basin, which may be due to the development of large salt lakes, high fluid salinity, and relatively limited environment. As it occurs only rarely, an environment with high salinity is not conducive to the development of microbial dolomite.

4.2. Spatiotemporal Distribution of DEPS

4.2.1. Longitudinal Distribution Characteristics of DEPS. The DEPS in the Sichuan Basin is mainly developed in the Cambrian Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation. In Dingshan 1 (Figure 5), for example, the use of wavelet transform technology (A. [42–44]) and logging cycle analysis technology [45] can be used to effectively identify unconformity surfaces and abrupt lithologic changes. These can be used to determine the sequence stratigraphic interface and classify the Cambrian Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation.

According to the DEPS rock assemblage sequence, mainly two types of paragenesis system, lithologic assemblage sequences have developed in the Cambrian Longwangmiao Formation. In the middle of the lithologic assemblage sequence, dolomite and evaporite are interbedded (Figure 5(a)). Thick layers of dolomite intercalated with thin layers of evaporite developed in the upper part (Figure 5(c));

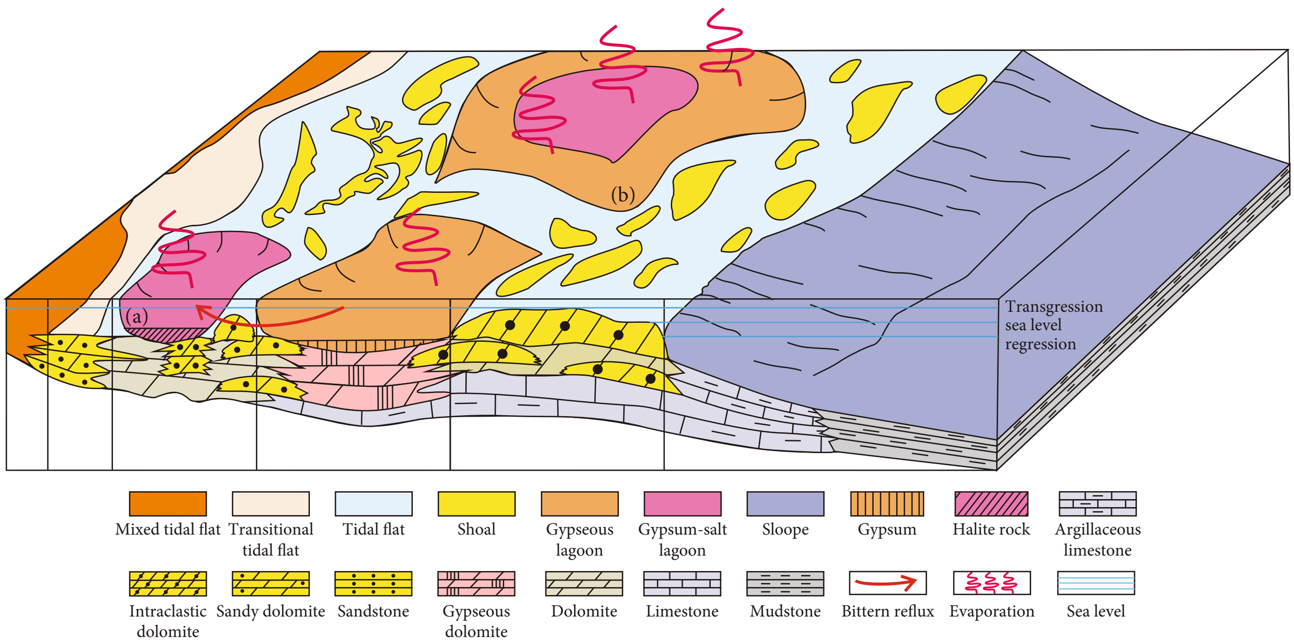


Figure 9: Genetic model of the Cambrian evaporite backflow in the Sichuan Basin.

there are many types of lithological assemblages in the Gaotai Formation paragenesis system: Thick dolomite overlies the evaporite in the lower part (Figure 5(b)), and thick dolomite is intercalated with thin evaporite (Figure 5(c)). Dolomite and evaporite are interbedded in the upper portion (Figure 5(a)). In the Xixiangchi Formation, thick dolomite is interbedded with thin layered evaporite (Figure 5(c)). In general, four types of lithological assemblages of paragenesis systems have developed in the Cambrian, Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation in Dingshan 1.

4.2.2. Lateral Distribution Characteristics of DEPS. Based on core, outcrop, drilling, and logging data, and combined with previous research results [30], the sequence stratigraphic framework and sedimentary were compared (Figure 6). The group is composed of sedimentary systems such as evaporative gentle slope platforms, mixed evaporative platforms, and carbonate limited platforms (from bottom to top). Three third-order sequences are developed, corresponding to Sq1–Sq3, among which Cambrian DEPS includes three regressive tertiary sequence cycles (Sq1–Sq3) that become shallower upward, and each tertiary sequence contains several subcycles. For example, the Longwangmiao Formation contains 3–4 subcycles that become shallower towards the surface. The Gaotai Formation contains 1–2 secondary cycles that become shallower, and the Xixiangchi Formation contains 3–4 secondary cycles that become shallower. Evaporites are mainly developed in the high stand domain of sequences Sq1–Sq3, namely, the Longwangmiao Formation and the Gaotai Formation, and a few are developed in the Xixiangchi Formation of sequence Sq3.

In the Sichuan Basin, the thickness of DEPS varies greatly, and gradually increases from north to south. Analysis of the stratum filling in the sequence framework, as well as the lateral distribution of sedimentary facies and evaporites, showed that the strata at the top of the Cambrian on the Palaeohigh in the central Sichuan Basin and the surrounding areas are completely absent. The residual strata are mostly thinner than 100 m, and evaporites are not developed. The sequence of the Cambrian in southern Sichuan Basin is relatively complete, and the bottom stratum has the characteristics of bottom super, with an evaporite thickness of 50–700 m. The Cambrian DEPS are thin in the west and thick in the east, and DEPS are mainly located in the eastern and southern regions of the Sichuan Basin.

4.2.3. Flat Distribution Feature of DEPS. The relevant data of DEPS development layers in the Sichuan Basin were assessed, a relevant database was established, and a systematic summary and comparison were carried out based on the data of single wells and consecutive wells. The DEPS of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation are widely developed in the Sichuan Basin. The boundary of DEPS was well drilled with dolomite and evaporite, and the residual thickness of DEPS reflected the thickness of dolomite and evaporite. Based on previous data [21, 30] and the drilling characteristics of the Sichuan Basin, DEPS in the Sichuan Basin are mainly distributed in the eastern and southern parts. A residual thickness map of DEPS in the Sichuan Basin is shown in Figure 7.

Based on the statistics of the DEPS, a distribution map of the range of the DEPS was drawn (Figure 8). (A) The distribution range of the interbedded rock combination sequence of both dolomite and evaporite is consistent with the distribution range of the DEPS. Compared with previous research results, it can be concluded that (A) is mainly related to the deposition of limited platform facies, which may indicate the distribution of tidal flat subfacies (Figure 8(a)). (B) The rock combination sequence of dolomite overlying evaporite is

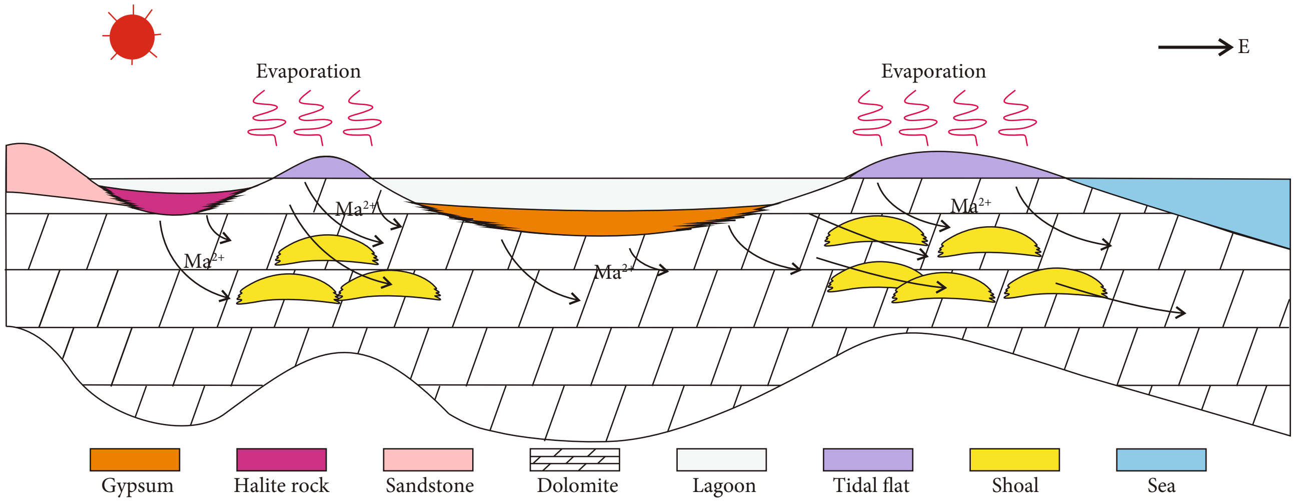


Figure 10: The genetic model of dolomite in DEPS.

distributed in the middle of the DEPS, and evaporite and granular dolomite can form a reservoir-caprock combination (Figure 8(b)). (C) The rock combination sequence of dolomite intercalated with thin-layered evaporite is distributed in the position of the platform margin and shoal. The limited environment between shoals is mostly sedimentary evaporite in arid and hot climate conditions, which is indicative of a reservoir (Figure 8(c)). (D) The rock combination sequence of thick evaporite and dolomite is distributed on the edge of the limited platform, which mainly reflects lagoon microfacies and carries indicative significance for the caprock (Figure 8(d)).

5. Discussion

5.1. Rock Origin of DEPS

5.1.1. Evaporite Origin of DEPS. Previous studies on the origin of evaporites in DEPS [5] and the origin of Cambrian evaporites in the Sichuan Basin [27, 29, 40, 46] have shown that the marine carbonate tidal flat-lagoon environment formed in a dry and hot climatic background. The Sabha genetic model and the genetic model of underwater concentration and sedimentation are the main models used to explain the development of Cambrian evaporites in the Sichuan Basin. The development of Cambrian evaporites in the Sichuan Basin satisfies the following three basic conditions: rich sources of salts, dry and hot paleoclimates, a process of continuous regression, and the limited environment of the unique shoal barrier conditions in the Sichuan Basin during this period. All these conditions accelerated the development of evaporites in DEPS.

The depositional environment changed from wet to dry, and the lithological sequence displays an evolution from carbonate rock to gypsum to halite to potassium and magnesium salts. In seawater, it displays an evolution of normal water concentration from salt water to salt water [47]. In this process, according to normal seawater evaporation experiments, the thickness ratio of gypsum rock to halite rock is about 1 : 21.79 [48]. However, judging from the interpretation of the Cambrian drilling data of the Sichuan Basin, the lithological transformation from the Longwangmiao Formation to the Xixiangchi Formation often manifests as a lack of internal sedimentary series during the depositional period. The thick salt rock of the Gaotai Formation in Loutan 1 directly overlying carbonate rocks (Figure 2(d)) shows a marked lack of gypsum rock deposits in the process from normal sea to salinized sea.

There may be two reasons for the abovementioned geological problems: First, before the deposition of halite, the gypsum rock was exposed in the corresponding position of the large-scale uplift basin. This caused leaching of the gypsum that had developed in the early stage, further resulting in a lack of gypsum in this section. Second, during the formation of halite, the products of the early stage of the salt lake, such as gypsum, were deposited in other lower parts close to the provenance. Based on current drilling and outcrop profiles, there is no apparent unconformity within the development range of the paragenesis system of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation. Therefore, the first proposed reason cannot explain the lack of the sedimentary sequence of the paragenesis system during the deposition of each group.

The authors believe that the above phenomenon is the result of the superposition of various factors such as regional tectonic movement and the rise and fall of the sea level in the Middle-Late Cambrian. In the DEPS of the Sichuan Basin, the phenomenon of missing gypsum rock in the sedimentary sequence (which can be observed in certain drilling wells) is a product of the backflow of bittern from multilevel basins under the background of regression (Figure 9). The regional tectonic event at the end of the Middle Cambrian, namely, the Leshan-Longnüsi paleo-uplift, led to an uplift of the crust and a substantial eastward retreat of seawater, inducing sedimentary responses to sea level fall events. Afterwards, with the end of the central Sichuan paleo-uplift, the basin entered a stage of stress relaxation, and large-scale subsidence occurred. Possibly because of the distance effect of

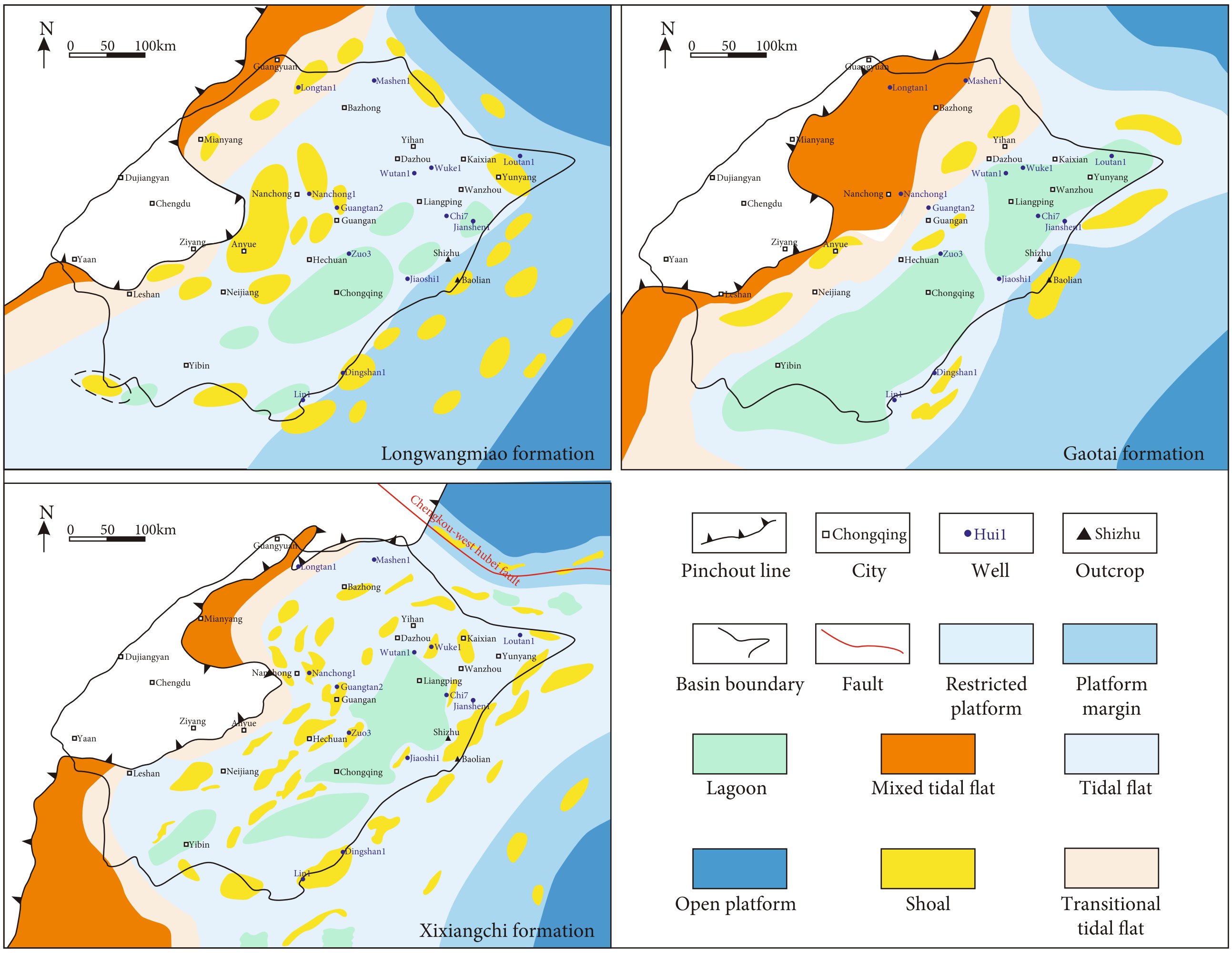


Figure 11: Sedimentary facies of the Cambrian Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation in Sichuan Basin.

tectonic stress, the subsidence amplitude of the eastern Sichuan Basin is larger than that of the central region, which has led to a sloping westward injection of seawater in the east. Because of the gradual transformation of the eastern Sichuan Basin from the carbonate rock gently slope platform to the carbonate rock rimmed platform structure [19, 20], seawater flows to the low-lying areas of the eastern Sichuan Basin [11, 49]. This accelerated the initial concentration of seawater in the rimmed mesa, resulting in extensive gypsum deposits, and bitterns with higher salinity eventually flowed through sediment pores into the nearer preparatory basin (Figure 9(a)). This, in turn, resulted in a significant lack of drilling in parts of the gypsum deposits of the study area. Salt rock gypsum rock, i.e., the rock sequence that does not lack gypsum rock, has a relatively limited formation environment. The high-concentration bittern after gypsum rock deposition cannot escape the limited environment and can only be deposited in the original basin. Under dry and hot climate conditions, a complete salt is formed in a rock-gypsum rock depositional sequence (Figure 9(b)).

Based on the above conditions, large-scale evaporites developed in the limited environment that was formed by the limited tidal flats, lagoons, tidal depressions, and beach barriers of the Cambrian in the Sichuan Basin.

5.1.2. Dolomite Origin of DEPS. Since the concept of dolomite was first proposed by the French scholar Deodal de Dolomieu in 1791, the origin of dolomite has been studied and has become a focus of academic attention. At present, many dolomite origin models have been proposed, such as the Sabha model [50], the osmotic backflow model [51], the mixed water model [52], the burial model [53], the thermal convection model [54], and the microbial model [55]. The genetic type of dolomite in the Cambrian DEPS in the Sichuan Basin is mainly related to the dolomitization of Sabha and osmosis reflux dolomitization. In the early stage, strong evaporation was beneficial to the increase of seawater concentration. Evaporite began to precipitate, the Mg/Ca of intergranular water in supratidal sediments increased [6], and this high Mg/Ca content led to the occurrence of aragonite or dolomitization of calcite. Long-term dolomitization consumed Mg/Ca from intergranular water in sediments, the Ca^{2+} concentration increased, and the Ca^{2+}-rich pore fluid provided an important material basis for the formation

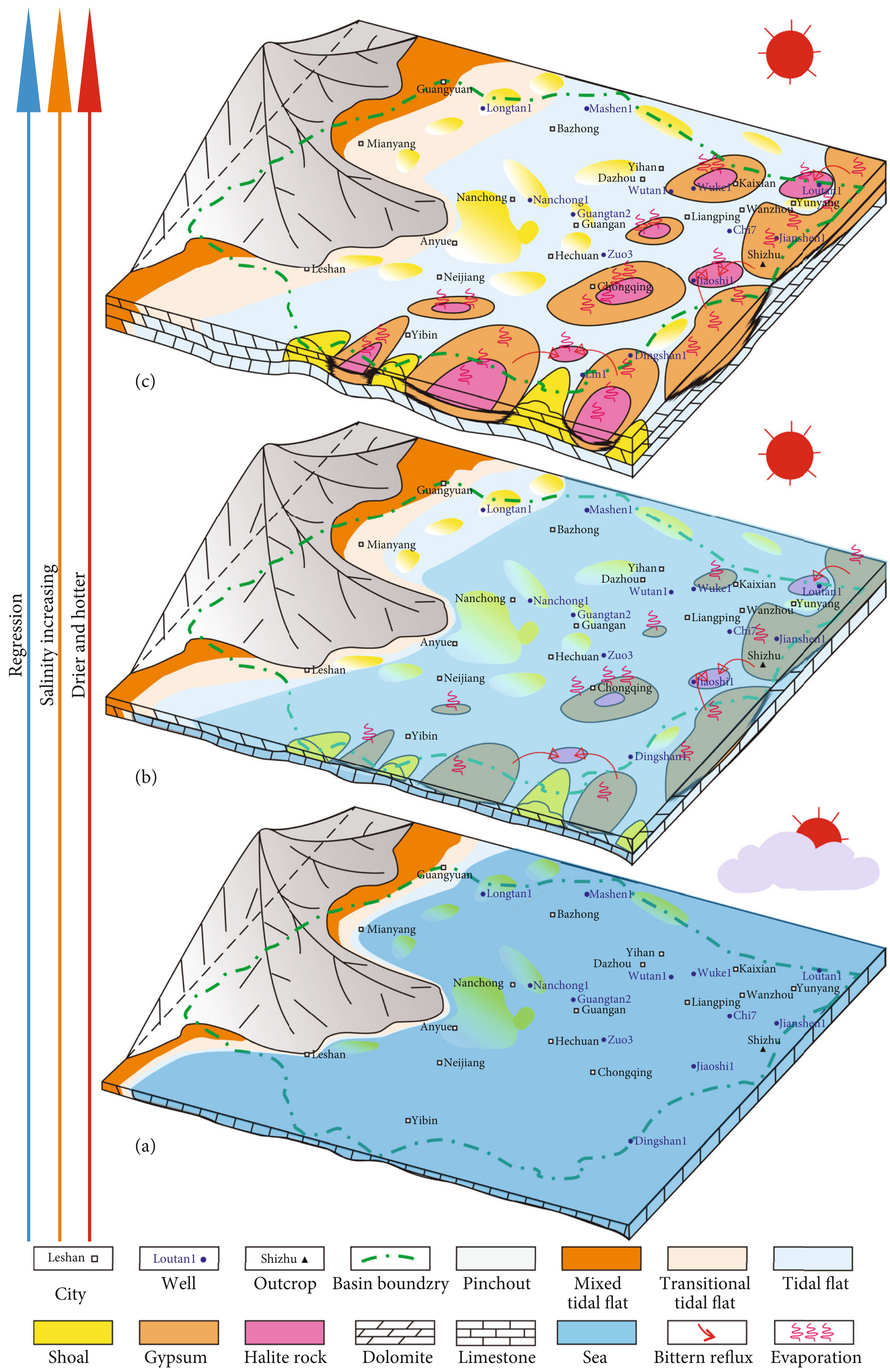


FIGURE 12: The formation mode of DEPC.

of evaporites [37]. With the periodic inflow of seawater into the sedimentary environment of the limited Sabkha bittern, the Sabkha environment continued to form dolomite because of the influence of dolomitization. With increasing salinity, the concentration of Mg^{2+} in pore water increased accordingly. Because of the influence of gravity and the concentration gradient in the pore fluid, the fluid with high Mg/Ca will flow back and infiltrate, causing the limestone infiltration in the lower layer to form dolomite [6]. However, because of the different geochemical conditions caused by the landform, in the environment of the ancient landform highland, namely, tidal flats, the formation of mud-powder crystal dolomite is caused by the evaporation pump (Sabuha), which is closely related to the dry and hot evaporation environment. However, the intraclastic dolomite in the particle shoal environment was mostly formed by backflow infiltration [13] (Figure 10).

5.2. Controlling Factors and Developmental Models of DEPS

5.2.1. Controlling Factors of DEPS. According to previous studies on the sedimentary facies and geochemical characteristics of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation, it can be assumed that the controlling factors of DEPS include sea level change, evolution of paleoclimate, and paleoenvironment [27, 29, 40, 41, 56, 57].

(1) Sea Level Change. At low sea level, under evaporation, infiltration, and backflow of fluid high in Mg/Ca often occur and form dolomite. In arid and hot environments, continuous evaporation leads to evaporite deposition [56]. When the sea level rises, the salinity of sea water decreases, and a new round of dolomitization begins. Therefore, dolomite and evaporite form in confined environments as a result of periodic seawater input [58].

The Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation developed shallow carbonate platforms. The shale content in the formation can reflect the depth of the water body during the deposition period. Therefore, this shale content can be used as a reflection of the depositional cycle of the formation. However, the natural gamma (GR) curve that can reflect the change of the shale content must be processed into an INPEFA curve by technical means [45]. The INPEFA curve can indirectly represent the depth of the water body [59]. Through the trend and inflection point of the INPEFA curve, the transgression process, the regression process, the flood surface, and the sequence boundary (or the characteristic boundary within the sequence) can be identified [60].

A negative bias of the INPEFA curve can be clearly observed in the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation in Dingshan 1 (Figure 5). This shows that the ocean portrayed stable regression conditions during the depositional period of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation. Analysis of the natural gamma (GR) and INPEFA curves of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation (Figure 5) shows that the overall INPEFA curve follows a decreasing trend and the value of the curve decreases from right to left. This indicates that the overall depositional environment is a rapid process of gradual sea regression in the context of invasion.

The geochemical characteristics of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation portrayed lower U and U/Th ratios, indicating that the dolomite experienced evaporation under oxidative conditions, and the U element was lost considerably [49]. This further indicates that during the deposition of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation, the sea level continued to decline.

(2) Evolution of the Paleoclimate. Previous studies suggested that dolomite generally develops under dry conditions and evaporite is the product of an extremely arid environment [4]. Therefore, the change of climate determines the lithological combination sequence of DEPS. For example, the lithology of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation in Wutan 1 shows gypsum rock, gypseous dolomite, and dolomite from bottom to top. The vertical change of lithology is clearly controlled by the influence of the climate and reflects a change of climate from an arid to a relatively humid environment during the depositional period. Previous geochemical studies showed that during the depositional period of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation, the $\delta^{18}O$ was low, and the average MgO/CaO was also low, indicating that the paleoclimate at that time was a relatively stable dry and hot climate [32, 61, 62].

(3) Paleoenvironment. Although there are many views on the sedimentary model of the Longwangmiao Formation, they did not originate from the background of the sedimentary model of shallow carbonate platforms. The results of comprehensive research and analysis imply that the Cambrian Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation are inherited and have similar depositional environments. The Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation developed shallow carbonate platforms in the Sichuan Basin (Figure 11).

There are two types of sedimentary environments with relatively limited water bodies: the supratidal zone of the tidal flat and the limited lagoon of the shallow-water carbonate platform. The tidal flat is favorable for dolomitization of the subtidal Sabha, while the limited lagoon is favorable for the dolomitization of infiltration and reflux. The subtidal Sabha is located in the high part of the platform, making it unlikely to be affected by sea water, which shows a limited dry environment. The intense evaporation caused by the hot and dry climate environment can increase the fluid concentration in the sediments of the Sabha environment and lead to the deposition of evaporites. This deposition of evaporites can cause a sharp increase in the Mg/Ca of fluids, which is beneficial for dolomite development [43]. The water body of the limited lagoon is relatively deep, and the salinity of this water body is relatively high and stable because of the relatively limited depositional environment. During the period of sea level decline, the limited lagoon was affected by the barrier imposed by the reef and the beach, and the water exchange between the limited lagoon, and the outer sea was limited. Because of evaporation, the salinity of the water gradually increased, and evaporite minerals gradually precipitated, promoting the downward infiltration of brine rich in Mg^{2+}, and the lower sediments undergo dolomitization, thus forming dolomite. Through geochemical research,

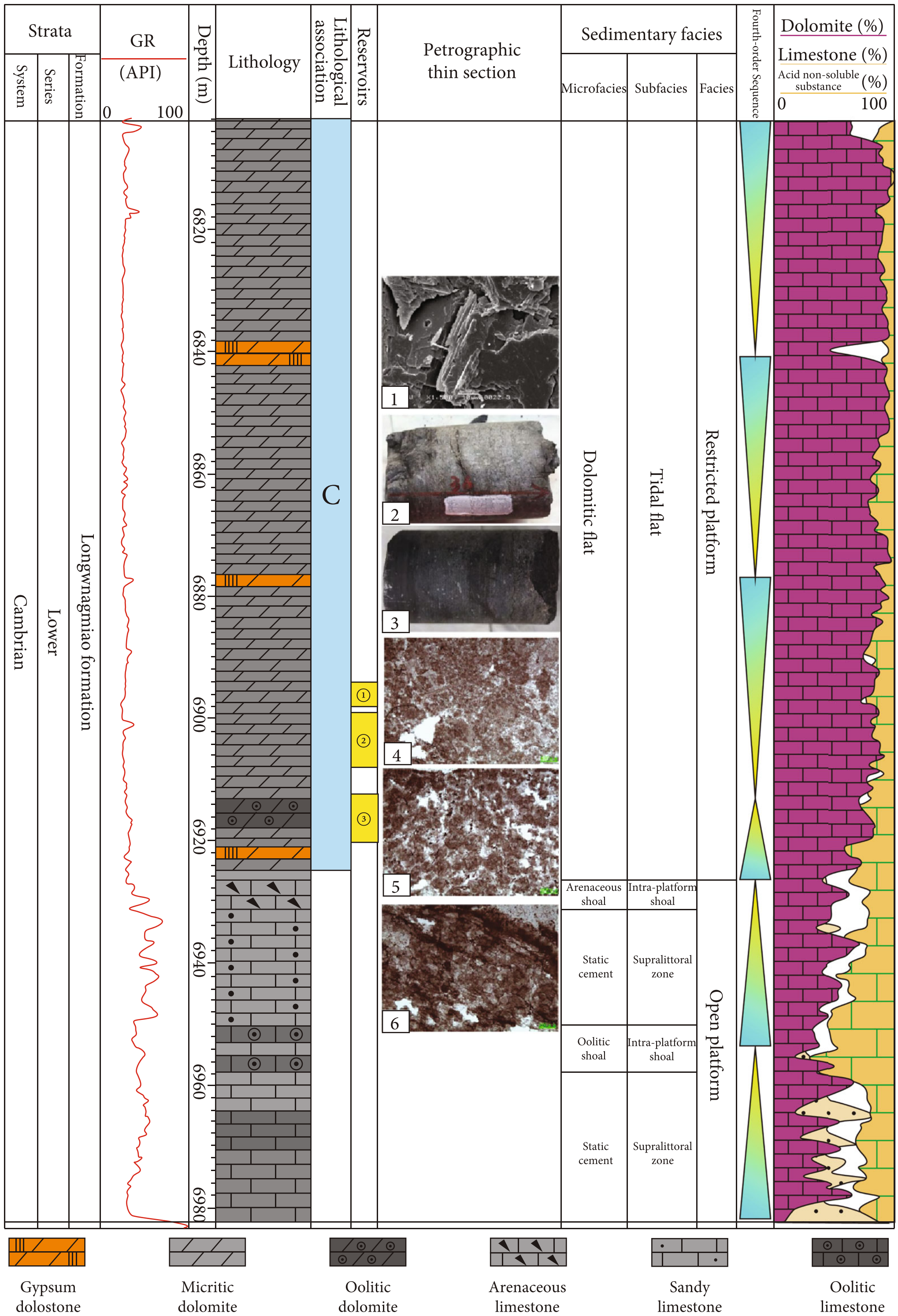


Figure 13: Comprehensive column chart of sedimentary reservoirs of Longwangmiao Formation in Wutan 1 Well, Sichuan Basin. 1.6895.52 m, microcrystalline dolomite, small amount of dolomite intercrystalline micro-hole slit, SEM; 2.6896.76 m, grey powder crystal dolomite, few dissolved pores, microcracks; 3.6900 m, dark grey powder crystal dolomite, dissolved pores; 4.6907 m, fine-grained dolomite, residual grains shadows, dissolved pores, quartz crystals, 10 × 5(-); 5.6916 m, oolitic dolomite, intergranular and intergranular pores, asphalt impregnation, fine-grained structure, 10 × 5(-); 6.6921 m, fine-grained dolomite, oolitic phantom, crystalline interhole, 10 × 5(-).

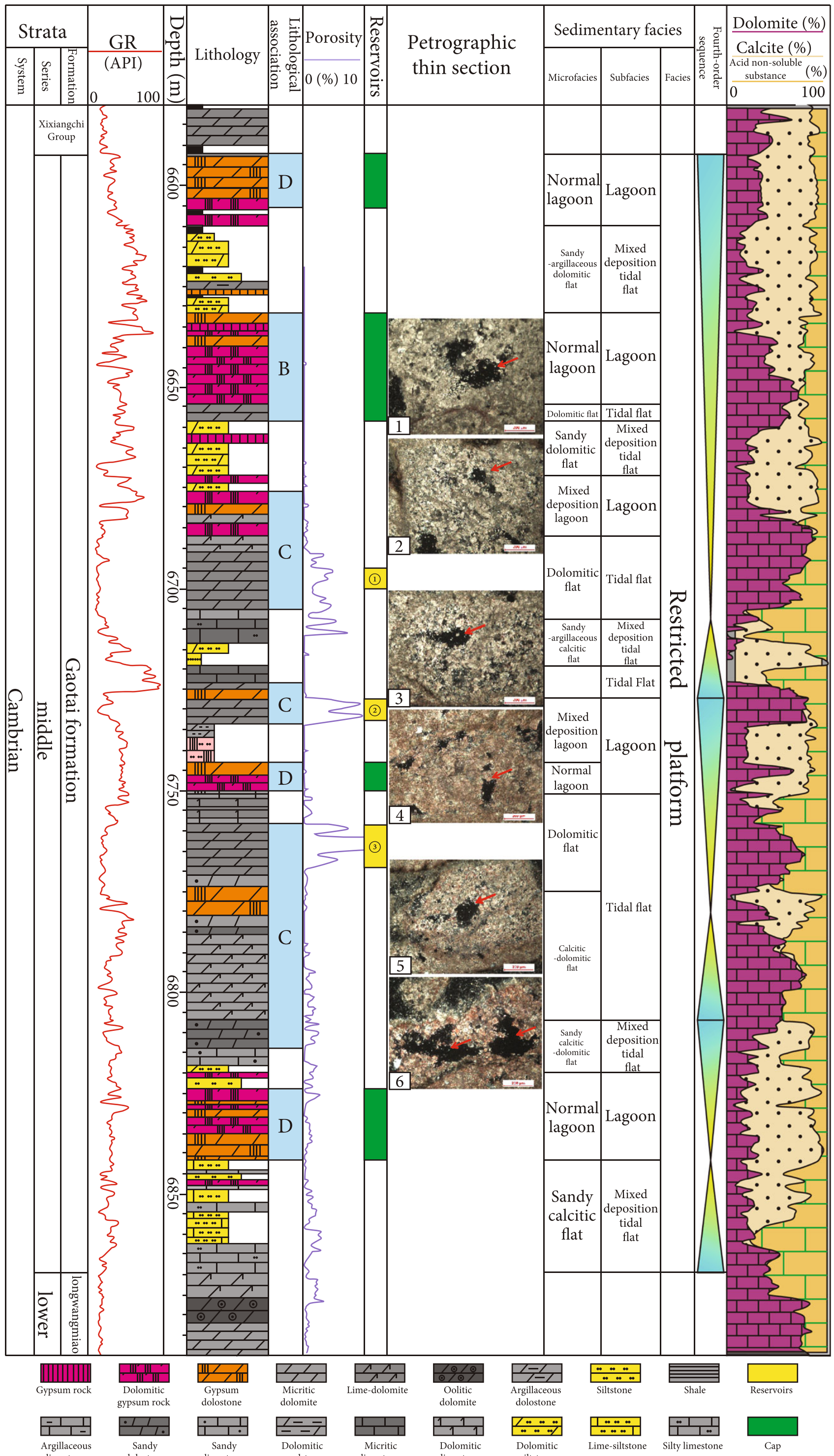


Figure 14: Comprehensive column chart of sedimentary reservoirs of the Gaotai Formation in Wutan 1 Well, Sichuan Basin. 1.6695 m, crystal powder dolomite, dissolved pores, dyed flakes, $10 \times 5(+)$; 2.6700 m, crystal powder dolomite, dissolved pores, dyed flakes, $10 \times 5(+)$; 3.6729 m, crystal powder dolomite, dissolved pores, dyed flakes, $10 \times 5(+)$; 4.6732 m, crystal powder dolomite, dissolved pores, dyed flakes, $10 \times 5(+)$; 5.6759 m, crystal powder dolomite, dissolved pores, dyed flakes, $10 \times 5(+)$; 6.6762 m, crystal powder dolomite, dissolved pores, dyed flakes, $10 \times 5(+)$.

predecessors found that during the depositional period of the Longwangmiao Formation, the Gaotai Formation, and the Xixiangchi Formation, Sr/Ba >1, indicating that the sedimentary environment as a whole was in a marine environment [61, 62], with a Z value higher than 120‰. This shows that the sedimentary period was in the surface sea

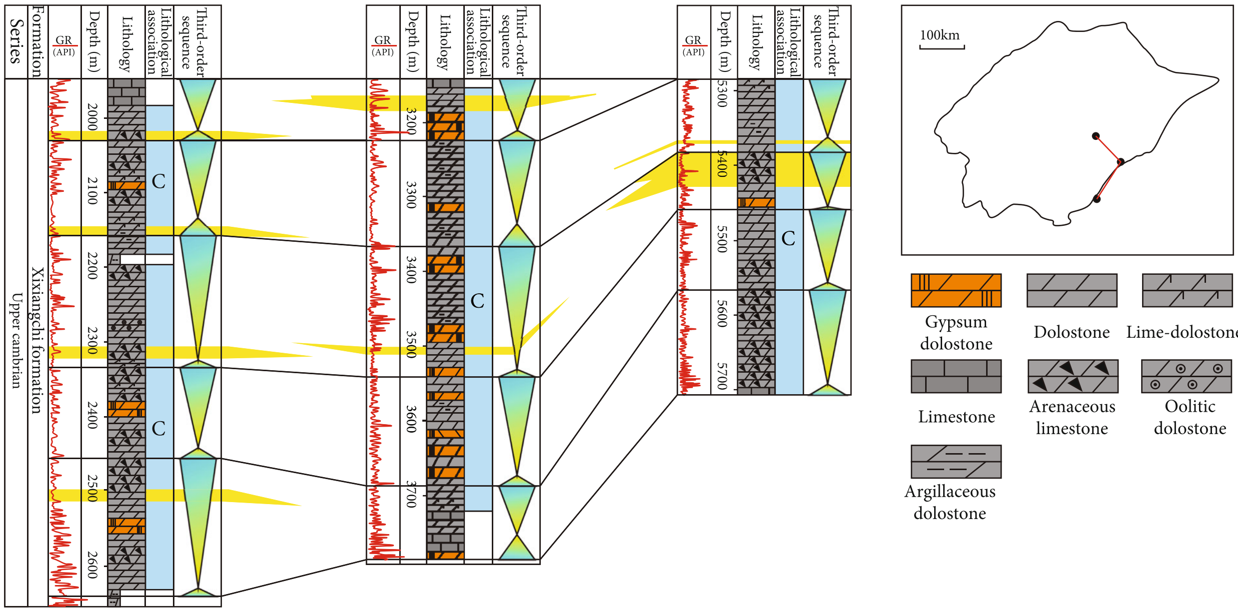


FIGURE 15: Well-tie section showing vertical reservoir distribution of the Xixiangchi Formation, Sichuan Basin.

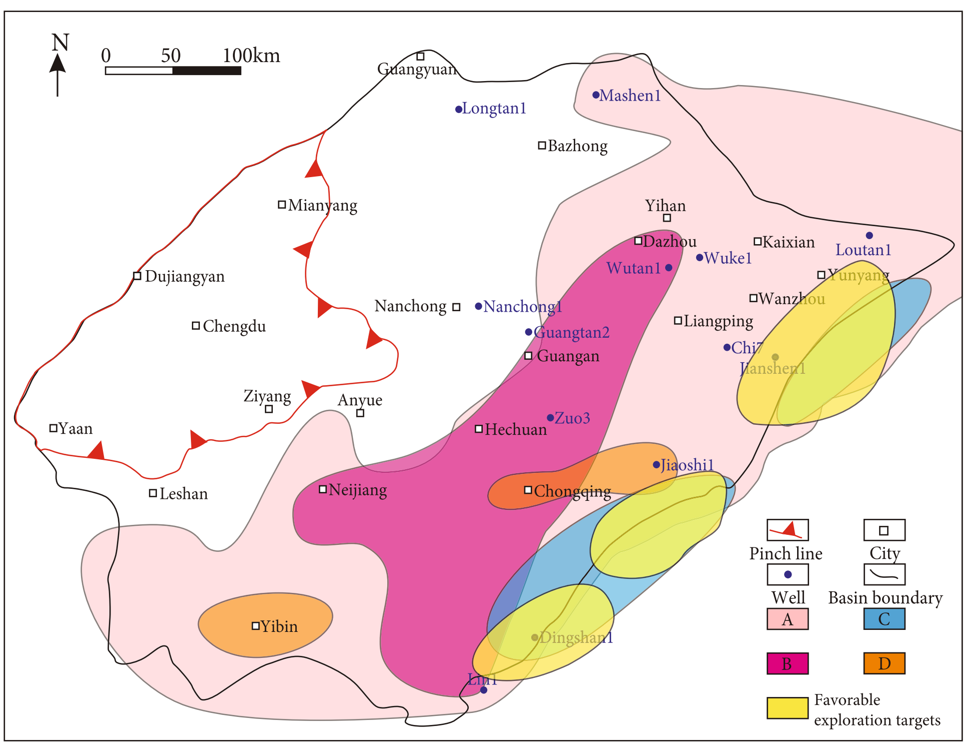


FIGURE 16: Distribution of favorable exploration zones of the Cambrian DEPS in the Sichuan Basin.

environment, the $\delta^{13}C$ value was generally positive, the $\delta^{18}O$ value was generally negative, and the average Sr/Ba was 4.75. The salinity of seawater can be inferred to be relatively high [16, 37, 49, 61, 62].

5.2.2. Developmental Models of DEPS. According to the Cambrian paleogeographic background of the Sichuan Basin and the results found by previous studies, the formation environments of evaporites and dolomite are mainly tidal flats, lagoons, and tidal depressions on carbonate gently sloping platforms or bordering platforms.

The cyclical up-and-down movement of the global sea level and the evolution of carbonate platforms affected the water exchange with seawater in the eastern and southern parts of the Sichuan Basin. During the transgressive period (Figure 12(a)), along with the rise of the sea level, mainly limestones of carbonate rocks were deposited and shoals developed. When the sea level began to drop again

(Figure 12(b)), most of the Sichuan Basin developed a limited environment of shallow-water carbonate platform facies, and the exchange of water between the platform and seawater became difficult. The hot and dry climate led to the initial concentration of tidal flat lagoon water, which, in turn, led to gypsum rock deposition and the formation of evaporite. There are two scenarios regarding the movement state of bittern with higher salinity: In the first scenario, bittern, with its higher salinity, leaves the original lagoon and migrates along sediment pores to a low-lying platform with relatively close location, good connectivity, low water level, and strong evaporation. Later, as the climate continues to be dry (Figure 12(c)), bittern, which had a higher concentration in depressions, deposited thick layers of salt rocks, missing gypsum rocks because of evaporation, and the supply of original lagoon salts, thus forming thick evaporite layers with thin dolomite layers. In the original lagoon, because of the deposition of evaporite and the departure of high-salinity bittern, the Ca^{2+} in the water body is greatly reduced, and the content of Mg^{2+} in the pore fluid is relatively increased. This rich high-salinity pore fluid tends to migrate downwards, leading to dolomitization of limestone sediments. This resulted in the formation of dolomite and the formation of a rock combination sequence of evaporite overlying thick dolomite. This seawater that can promote dolomitization is assumed to have the characteristics of high Mg/Ca, high temperature, and high salinity [63]. In the second scenario, because of the relatively limited and closed conditions of the lagoon, bittern with high salinity can only flow in the lagoon and sediment pores. There is no suitable bittern deposition environment outside the lagoon, causing the bittern to mainly circulate in the lagoon. Later, as the climate continues to be dry (Figure 12(c)), if the sea level fluctuates periodically, a rock combination sequence of interbedded evaporite and dolomite would form in the lagoon. If sea levels continue to rise, the lagoon is shrinking, the range and thickness of gypsum rock decrease, and a rock combination sequence of thick evaporite mixed with thin dolostone will form in the lagoon. On tidal flats, beaches mostly develop around lagoons, thus forming a barrier-limited environment that gradually accelerates the development of DEPS.

Therefore, the DEPS of the Cambrian in the Sichuan Basin originated from the formation of dolomite and the precipitation of evaporites under high salinity. Because of the influence of water bodies with high salinity, the development of DEPS was not affected by many biogeochemical processes.

6. Relationship between the Cambrian DEPS and the Reservoir

6.1. Reservoir Development of the DEPS

6.1.1. The DEPS Longwangmiao Formation Reservoir. The lithology of the DEPS dolomite reservoir of the Longwangmiao Formation mainly includes oolitic dolomite, fine-crystalline dolomite, and powder-crystalline dolomite. The reservoir space mainly consists of intercrystalline (dissolved) pores, intergranular (dissolved) pores, and fractures. The main reservoirs are almost all related to the dolomitic tidal flats that developed in the grain shoals and shoal tops, which are mainly of the fracture-pore type. For example, the reservoir of the Longwangmiao Formation in the Wutan 1 Well (Figure 13) has strong heterogeneity, with maximum, minimum, and average porosities of 6.26%, 0.1%, and 1.89%, respectively. Such reservoirs are controlled by facies, and shoal facies form the basis for the development of the reservoirs of the Longwangmiao Formation. In the restricted platform with relatively strong hydrodynamics, evaporite development is relatively low and is present as a rock combination sequence of thick dolomite intercalated with evaporite layers. Both the dolomite reservoir and the tight dolomite in the upper layer form a good reservoir-caprock combination.

6.1.2. The DEPS Gaotai Formation Reservoir. The lithology of the DEPS dolomite reservoirs of the Gaotai Formation mainly consists of powder crystal dolomite. The reservoir space mainly consists of intercrystalline (dissolved) pores and intergranular (dissolved) pores. Based on the porosity and permeability test data of core samples of the Gaotai Formation in the Wutan 1 Well (Figure 14), the powder crystal dolomite reservoirs in the Gaotai Formation can be divided into the following reservoirs: ① reservoirs with an average porosity of 3%, ② reservoirs with an average porosity of 5.4%, and ③ reservoirs with an average porosity of 9.7%. Type ③ reservoirs have the best reservoir characteristics, and type ② reservoirs have the largest thickness. The Gaotai Formation reservoirs were greatly transformed by later diagenesis. During the deposition of dolomite, the depositional environment was a limited-evaporative platform, and evaporites were mostly developed because of the hot and dry paleoclimate. Dolomite and evaporite form a good reservoir-caprock combination.

6.1.3. The DEPS Xixiangchi Formation Reservoir. The Xixiangchi Formation exploration area of the DEPS in the Sichuan Basin is located in the high-steep structural belt in the eastern Sichuan Basin (Figure 15). Anticline traps have developed in the area, and shoal facies reservoirs are thick and widely distributed, showing favorable reservoir conditions. The exploration of Well Pingqiao 1 in the area has confirmed that the well has a daily gas production of 25.13 $\times 10^4$ m^3 in the Xixiangchi Formation. There are good reservoirs in the DEPS of the Xixiangchi Formation.

This study found that reservoirs are mainly developed in the DEPS C and the DEPS B and D can be used as caprock for oil and gas. Based on research on the lithofacies and the paleogeographical characteristics of the Cambrian in the Sichuan Basin, as well as the C-plane distribution of the DEPS, a comprehensive analysis of the geological conditions of natural gas accumulation was conducted, and favorable exploration zones of the DEPS are predicted (Figure 16). These are located in the East–Southeast Sichuan Basin promising exploration area and the Northeast Sichuan Basin favorable exploration area.

7. Conclusions

(1) The combination patterns of DEPS in the Cambrian strata of Sichuan Basin include the interbedding of dolostone and evaporite (A), evaporite overlying thick dolostone (B), thick dolostone mixed with thin evaporite (C), and thick evaporite mixed with thin dolostone (D). The DEPS in the Cambrian strata of the Sichuan Basin is thin in the west and thick in the east, and its main distribution is in the eastern and southern parts of the Sichuan Basin

(2) The origin of evaporite in the Cambrian DEPS of Sichuan Basin is the Sabuha genetic model and the underwater concentration and sedimentation genetic model. The genetic models of dolomite are mainly the Sabha genetic model and the returning permeability dolomitization genetic model

(3) The DEPS in the Cambrian strata of Sichuan Basin developed in the shallow-water carbonate rock platform with relatively limited water bodies. Geochemical analysis mostly identified a tidal flat lagoon environment with hot and arid climate, strong evaporation, and high water salinity

(4) In the Cambrian DEPS of the Sichuan Basin, reservoirs are mainly developed in C, B and D can be used as good regional caprocks, C as tight dolomite, and B and D can form a good reservoir-caprock combination. Promising exploration areas of the Cambrian DEPS in the Sichuan Basin are located in the eastern–southeastern Sichuan Basin and the northeastern Sichuan Basin, which are potential backup exploration areas in the Sichuan Basin

Data Availability

No data were used to support this study.

Conflicts of Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, "Sedimentary Characteristics and Developmental Models of the Cambrian Dolostone-evaporite Paragenesis System in the Sichuan Basin."

Acknowledgments

This research was financially supported by the "Thirteenth Five-Year Plan" National Major Project "Key Marine Strata Sedimentary Facies Research" (No. 2016ZX05007002).

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