

Lithofacies palaeogeography, depositional model and shale gas potential evaluation in the O_3–S_1 Wufeng–Longmaxi Formation in the Sichuan Basin, China

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Lithofacies palaeogeography, depositional model and shale gas potential evaluation in the O_3-S_1 Wufeng-Longmaxi Formation in the Sichuan Basin, China

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A B S T R A C T

The black shales of Wufeng and Longmaxi Formation (Late Ordovician-Early Silurian period) in Sichuan Basin are the main strata for marine shale gas exploration, which have a yearly shale gas production of 228×10^8 m^3 and cumulative shale gas production of 919×10^8 m^3. According to the lithological and biological features, filling sequences, sedimentary structures and lab analysis, the authors divided the Wufeng /Guanyinqiao and Longmaxi Formations into shore, tidal flat, shoal, shallow water shelf and deep water shelf facies, and confirmed that a shallow water deposition between the two sets of shales. Although both Formations contain similar shales, their formation mechanisms differ. During the deposition of Wufeng shale, influenced by the Caledonian Movement, the Central Sichuan and Guizhou Uplifts led to the transformation of the Sichuan Basin into a back-bulge basin. Coinstantaneous volcanic activity provided significant nutrients, contributing to the deposition of Wufeng Formation black shales. In contrast, during the deposition of Longmaxi shale, collisions caused basement subsidence, melting glaciers raised sea levels, and renewed volcanic activity provided additional nutrients, leading to Longmaxi Formation black shale accumulation. Considering the basic sedimentary geology and shale gas characteristics, areas such as Suijiang-Leibo-Daguan, Luzhou-Zigong, Weirong-Yongchuan, and Nanchuan-Dingshan are identified as key prospects for future shale gas exploration in the Wufeng-Longmaxi Formations.

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1. Introduction

In recent years, shale gas exploration in South China has deepened significantly. In 2021, China's annual shale gas production reached 228×10^8 m^3, with cumulative production totaling 919×10^8 m^3. The potential of the black shales in Wufeng-Longmaxi Formations (Late Ordovician-Early Silurian) in Sichuan Basin is huge. By the end of 2020, there are seven proven shale gas fields in the Wufeng-Longmaxi Formations in Sichuan Basin with geological reserves of 2.0×10^{12} m^3 and recoverable reserves of about 4700×10^8 m^3. They represent crucial horizons for future natural gas production growth and exploration in China (Guo XS et al., 2014, 2016, 2019; Ma YS et al.,2018; Zou CN et al., 2015, 2022).

Many studies have been conducted on the sedimentary facies and models of the black shales of Wufeng and Longmaxi Formations in Late Ordovician and Early Silurian. It is widely accepted that these formations were predominantly deposited in deep water shelf facies. Based on shale lithology, mineral composition, biological fossils, micromorphology, and logging responses, various microfacies types have been identified (Zou CN et al., 2015; Mou CL et al., 2016, 2023; Pu BL et al., 2020; Shi ZS et al., 2022; Wang HY et al., 2023; Guo W et al., 2022; Hu ZQ etal., 2022). The sedimentary models of the black shale can be divided into the inheriting standing water shelf center, the

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inheriting standing water shelf slope, upwelling sedimentary models (Wang YM et al., 2018) and the shallow water onlap model (Chen L et al., 2023).

The black shales of the Wufeng-Longmaxi Formations are known for their substantial thickness and consistent distribution, often referred to collectively as the "Big Longmaxi Formation" in shale gas exploration. However, these formations actually consist of two distinct sets. Between these sets lies a thin layer of shallow water shelf facies, commonly referred to as the Guanyinqiao Formation or Guanyinqiao Member. This formation or member is widely distributed in Sichuan Basin and is characterized by the presence of the cold water Hirnantia Fauna, which holds significant environmental importance. The Hirnantia Fauna occurred and flourished in the ecological location of benthic assemblage BA2–3, mainly BA3, which was not deeper than 60 m (Fang YT et al., 1993; Rong JY, 1984; Rong JY and Chen X, 1987). The lithological features also indicate that the sedimentary water of Guanyinqiao Formation is shallower than that of Wufeng and Longmaxi Formations (Chen C, 2018; Li GP et al., 2009; Liu W et al., 2012; Mou CL et al., 2014; Wang YC, 2016; Wang YC et al., 2015, Su XH, 2017; Ge XY, 2020). This confirms that although both the Wufeng and Longmaxi Formations consist of black shales, their formation processes and the primary factors controlling organic matter enrichment differ significantly.

To better understand the organic matter enrichment mechanism of black shales in Wufeng and Longmaxi Formations, the authors selected continuous Wufeng-Longmaxi Formations shale section and drills to conduct detailed sedimentary facies and lithofacies paleogeography studies. The goal of this study was to identify the primary controlling factors of organic matter enrichment in these black shales and provide a more solid theoretical foundation for the exploration of shale gas in China.

2. Geological setting

Sichuan Basin belongs to the Upper Yangtze Block structurally, which is a superposition basin developed on the basis of the Upper Yangtze Craton Basin. According to the regional structural characteristics, present tectonic features and previous research (Bureau of Geology and Mineral Resources of Sichuan Province, 1991), based on the boundary of Huaying Mountain and Longquan Mountain faults, the basin is divided into three tectonic zones and subdivided into six secondary tectonic zones, which are high dipping anticline belt in eastern Sichuan, lower gentle anticline belt in Southern Sichuan, ancient uplift belt in southwestern Sichuan, lower flat belt in central Sichuan, broad gentle anticline belt in northern Sichuan, lower uplift belt in western Sichuan (Wang XP et al., 2015; Fig. 1). In the long process of tectonic and sedimentary evolution, Sichuan Basin has experienced multi-stage and multi-direction marginal deep fault activities, which reflects the characteristics of multi-tectonic cycles.

Since Nanhua Period, the Yangtze Block started making its way into the cratonic basin stages (Huang FX et al., 2011). During the Sinian-Silurian period, the Middle and Upper Yangtze Block experienced two evolutionary phases that changed from extension to compression mechanism. In Cambrian the study area deposited lots of carbonates and formed the carbonate ramp and then evolved into a rimmed carbonate platform in Early Ordovician (Xu XS et al., 2001; Mou CL and Xu XS, 2010; Mou CL et al., 2011, 2014, 2019; Hu FX et al., 2011;Chen HD et al., 2009; Yu Q et al., 2011; Yan DT et al., 2011; Yan JF et al., 2010). In the Middle-Late Ordovician, as the compression and collision between the Yangtze and Cathaysia blocks intensified, the Central Sichuan, Central Guizhou, and Xuefeng uplifts constantly expanded, and the sea level rose relatively. The rimmed carbonate platform developed in Middle-Upper Yangtze Area was submerged and transformed into a carbonate ramp, and finally developed into the back-bulge basin confined by the marginal uplifts (Mou CL and Xu XS, 2010, Mou CL et al., 2011, 2014, 2015; Liu W et al., 2010, 2012; Wang JP et al., 2012; Ge XY, 2020; Ge XY et al., 2021) and the lithology changed from carbonate rocks to the black shales.

3. Stratigraphical features

The black shales of Wufeng-Longmaxi Formations span two epochs-Ordovician and Silurian periods, which are internationally divided by graptolite biozone. Wufeng, Guanyinqiao and Longmaxi Formations across Katian, Hirnantian, Rhudannian, Ellonian and Trechian five stages, and 13 graptolite biozones (Chen X et al., 2006, 2015, 2017, 2018; Fan JX et al., 2011).

The Katian stage contains three graptolite biozones, which are *Foliomena-Nankinolithus* zone, *Dicellograptus complexus* zone and *Paraorthograptus pacificus* zone from the bottom up. The *Paraorthograptus pacificus* zone is further divided into three subzones: *Lower Subzone*, *Tangyagraptus typicus* and *Diceratograptus mirus*. The Hirnantian stage contains two graptolite zones. The bottom is the *Normalograptus extraordinarius* graptolite biozone, which corresponds to the top part of the Wufeng Formation, and the upper is the *Persculptograptus persculptus* graptolite biozone, which corresponds to the black shale at the bottom of Longmaxi Formation. The Rhudannian stage contains four graptolite biozones, which are *Akidograptus ascensus*, *Parakidograptus acuminatus*, *Cystograptus vesiculosus* and *Coronograptus cyphus* in ascending order. The Ellonian stage consists of three graptolite zones, namely the *Demirastrites triangulatus*, *Lituigraptus convolutus* and *Stimulograptus sedgwickii* from the bottom up, and the Trechian stage contains two graptolite zones, which are *Spirograptus guerichi* and *Spirograptus turriculatus* (Fig. 2). According to the present data, only the *Spirograptus guerichi* zone at the bottom of Trechian stage is found in the black shales of Longmaxi Formation in Yangtze Platform. In order to facilitate the division and comparison of strata of Ordovician and Silurian black shales, Dr. Xu Chen used WF and LM to refer to the corresponding graptolite

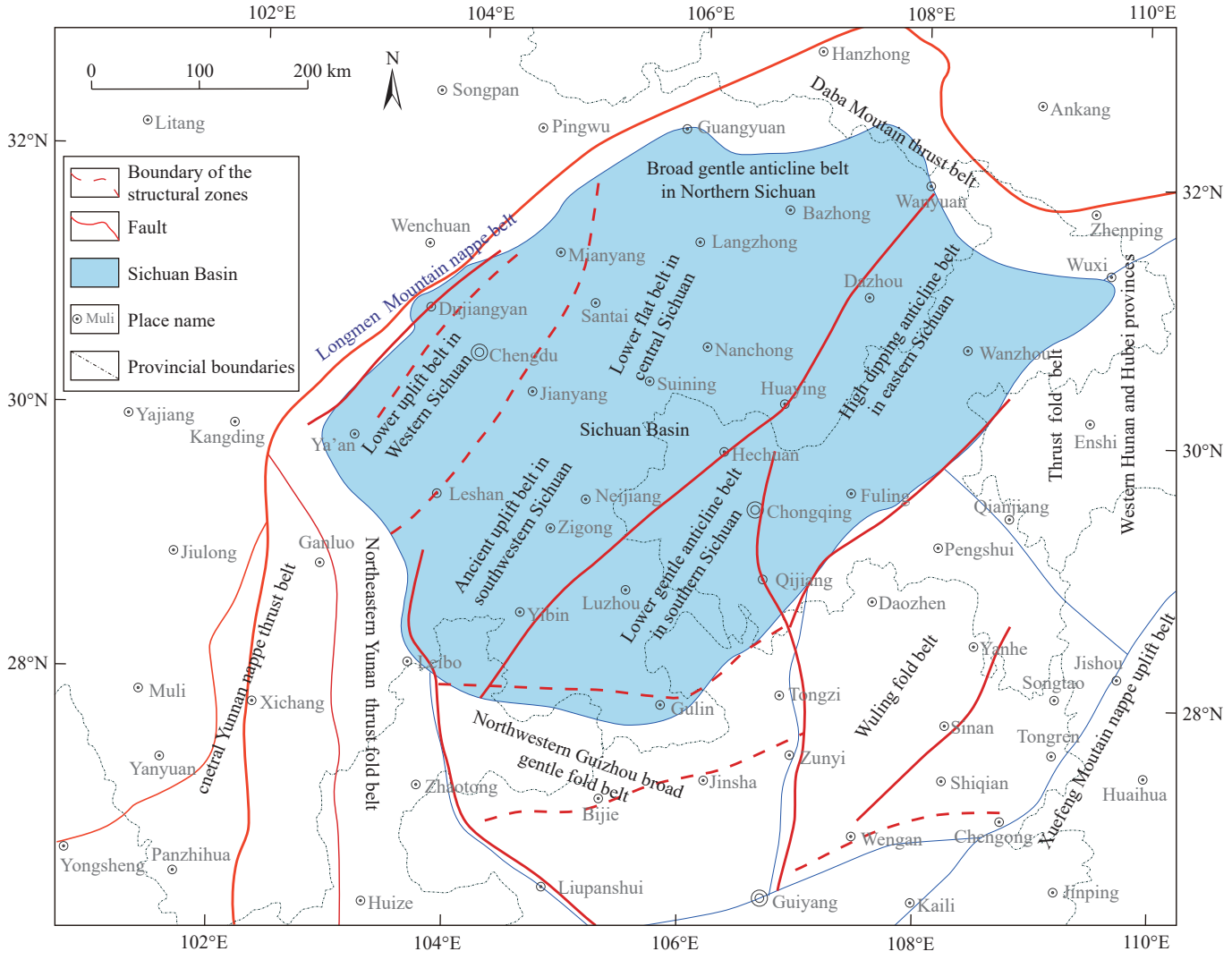

Fig. 1. Distribution of major faults and division of structural areas of Sichuan Basin, China.

biozone (Chen X et al., 2015, 2017), and then used to divide and compare the two sets of black shales of Wufeng Formation and Longmaxi Formation. For example, WF3 was called "Wu threemember", that is, the third graptolite biozone of Wufeng Formation. LM2 is called "Long two member", that is, the second graptolite biozone of Longmaxi Formation.

The lithological features of the Wufeng, Guanyinqiao and Longmaxi Formations are summarized from bottom to top as follows:

The Wufeng Formation, which is characterized by black carbonaceous shale and siliceous shale, is widely distributed in the Yangtze area. In eastern Sichuan, this formation is in conformable contact with the underlying Linxiang Formation or Jianchaogou Formation and overlying Guanyinqiao Formation, generally 0.3 m to 30 m thick, and is mainly composed of graptolites, a few brachiopods and radiolarian. There are some gray-white, brown-yellow and purple-gray bentonites distributed among these shales, with single-layer thickness ranging from 0.1–40 cm (Ge XY et al., 2019, 2021; Ge XY, 2020).

The Guanyinqiao Formation is a set of shell facies deposition, which is mainly composed of biological limestone, calcareous siltstone, mudstone or calcareous dolomite, and is a remarkable sign for division of Wufeng and Longmaxi Formations. The Guanyinqiao Formation, mainly a few dozen centimeters thick with the largest more than ten meters, is characterized by the Hirnantia-Dalmanitina Fauna (Rong JY and Chen X, 1987; Zhou MK et al., 1993; Zhan RB et al., 2010).

The Longmaxi Formation, is in conformable contact with the underlying Guanyinqiao Formation and overlying Luoreping Formation in western Sichuan, Xiaoheba Formation in eastern Sichuan and Shiniulan Formation in Sourhwestern Scihuan. The Longmaxi Formation can be divided into two parts by lithology (Fig. 3). The lower part of the Longmaxi Formation, is mainly dominated by black carbonaceous shale, and siliceous shale interbedded with gray-black calcareous mudstone. The thickness of this formation is 10–200 m, accounts for 10%— 30% of the sedimentary thickness of Longmaxi Formation. The lower part black shales of Longmaxi Formation and the black shale of Wufeng Formation together constitute the black shale with relatively stable thickness, which is the key horizon of shale gas exploration in Sichuan Basin at present. The lithology of

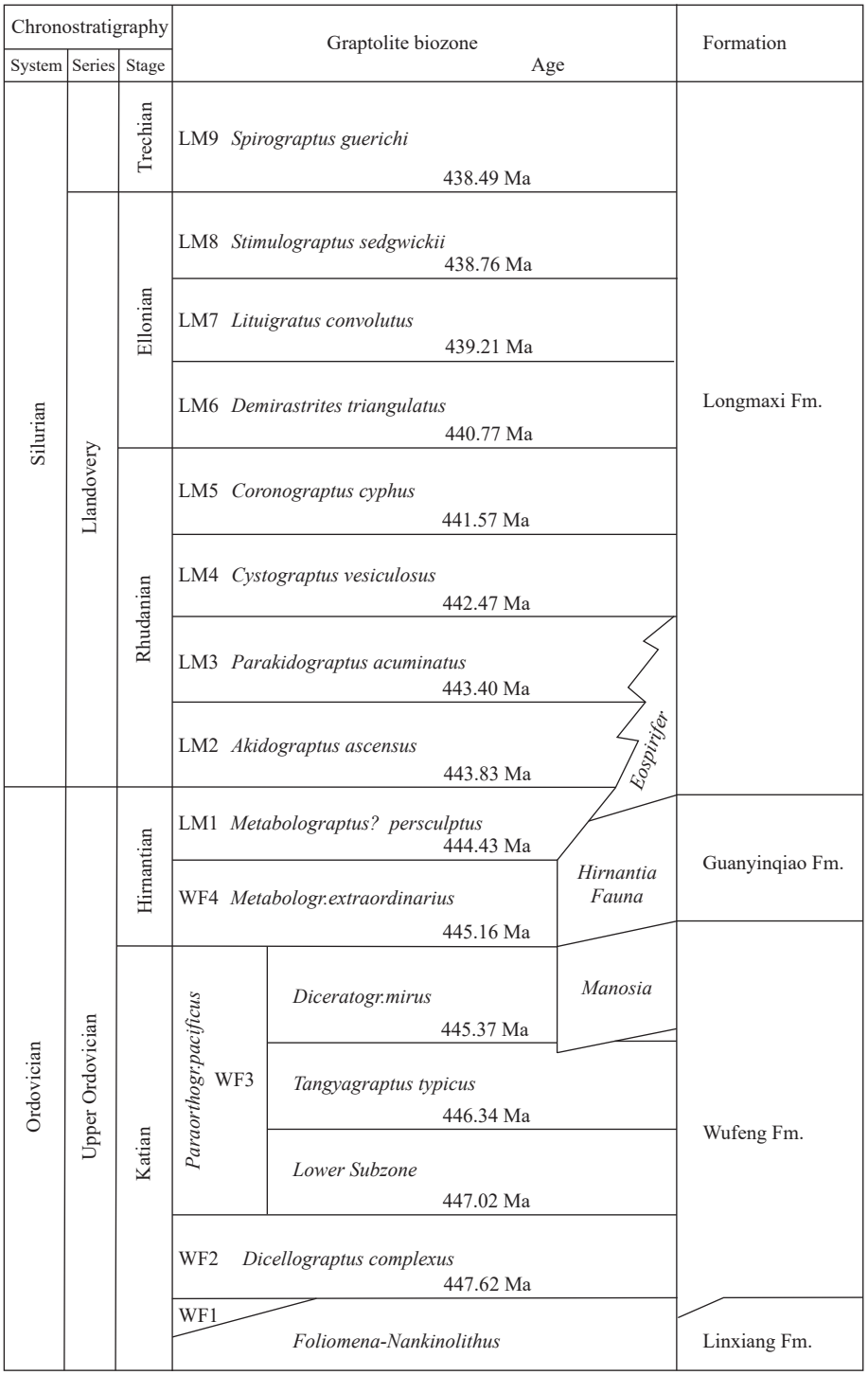

Fig. 2. Graptolite biozones of Upper Ordovician-Lower Silurian (after Chen X et al., 2015, 2017).

the upper part of Longmaxi Formation which is a non-black rock series, is mainly grey-green, yellow-green mudstone, silty mudstone and siltstone, usually interbeded with argillaceous limestone lens.

4. Types of sedimentary facies

Based on lithological, sequential, sedimentary structural, and biotic assemblage characteristics, the Wufeng, Guanyinqiao, and Longmaxi Formations in the Sichuan Basin were classified into five distinct facies types: Tidal flat, shoreline, shoal, shallow-water shelf, and deep-water shelf.

4.1. Tidal flat facies

The tidal flat facies developed in gently sloping coastal areas, where cyclic tidal interactions played a dominant role, and is mainly composed of fine clastic material (clay, silt) and carbonate rock. The Wufeng and Longmaxi Formations are typified by gray-gray black silty sandstone and argillaceous limestone, exhibiting distinctive bedding features including flaser bedding, wavy bedding, lenticular bedding, and small-

scale flow ripple laminations. (Fig. 4).

The tidal flat facies of Guanyinqiao Formation is distributed in the periphery of the central Guizhou Uplift, and the lithology is composed primarily of silty limestone, silty argillaceous limestone and bioclastic mudstone. The silty content is relatively high in the nearshore area of the central Guizhou Uplift, whereas in the offshore direction, the silty content progressively decreases, giving way to an increase in muddy sediments. The tidal flat facies of the Guanyinqiao Formation is characterized by a relatively thin bedding and lacks a discernible sedimentary structure. In terms of paleontology, the facies yields a limited fossil record, including brachiopods (Fig. 5), as well as a few specimens of lamellibranchias, trilobites, crinoids, bryozoans, and gastropods, along with calcareous algae (Li Y et al., 2005, 2008).

4.2. Shore facies

The coastal zone refers to the area between the maximum tidal surface and the wave base. Along the barrier-free clastic

Sichuan Basin and its adjacent area						
Stratigraphic system		Stratigraphic subregion: Western Sichuan	Southwestern Sichuan	Southeastern Chongqing	Northern Guizhou	Northeastern Sichuan
Overlying strata		Liangshan Fm.	Liangshan Fm.	Liangshan Fm.	Liangshan Fm.	Liangshan Fm.
Silurian	Upper-Middle Silurian		Huixingshao Fm.	Huixingshao Fm.		
	Lower Silurian	Shamao Fm.	Daluzhai Fm.	Hanjiadian Fm.	Hanjiadian Fm.	Hanjiadian Fm.
		Luoreping Fm.	Shiniulan Fm.	Xiaoheba Fm.	Shiniulan Fm.	Xiaoheba Fm.
		Longmaxi Fm.	Longmaxi Fm.	Longmaxi Fm.	Longmaxi Fm.	Longmaxi Fm.
Ordovician	Upper Ordovician	Guanyinqiao Fm.	Guanyinqiao Fm.	Guanyinqiao Fm.	Guanyinqiao Fm.	Guanyinqiao Fm.
		Wufeng Fm.	Wufeng Fm.	Wufeng Fm.	Wufeng Fm.	Wufeng Fm.
		Linxiang Fm.	Linxiang Fm.	Jiancaogou Fm.	Linxiang Fm.	Linxiang Fm.
		Baota Fm.	Baota Fm.	Baota Fm.	Baota Fm.	Baota Fm.

Fig. 3. Lithostratigraphic units of Upper Ordovician-Lower Silurian in Sichuan Basin and adjacent areas.

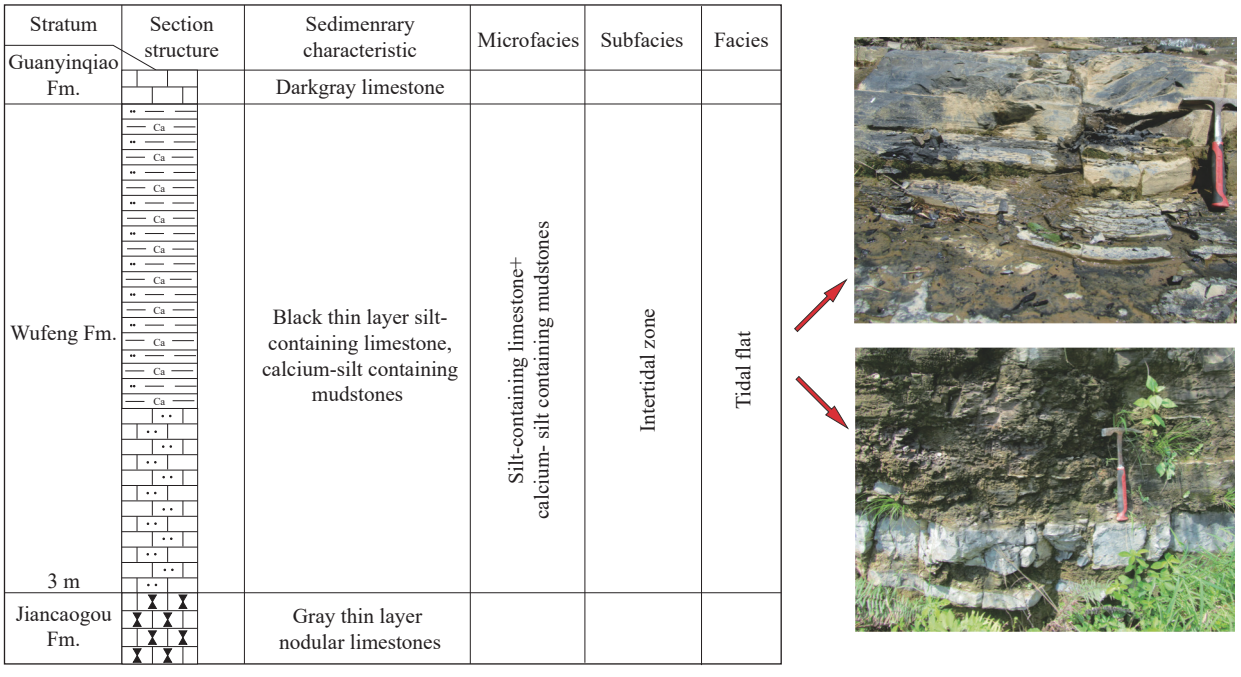

Fig. 4. Sedimentary sequence of tidal flat facies in Wufeng formation of Huanggexi section, Daguan county, Yunnan Province.

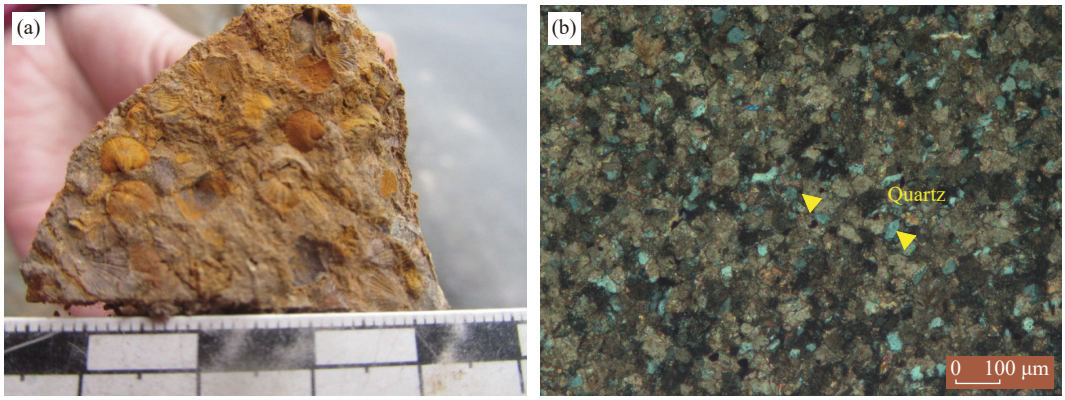

Fig. 5. Sedimentary sequence of tidal flat facies in Guanyinqiao Formation. a–Fenghuang section, Youyang county, Chongqing City; b–Xiadian section, Dejiang county, Guizhou province.

littoral, a wide coastal plain exists, which is directly influenced by wave action and is characterized by the deposition of beach sediments. Typical shore facies deposits are found in Guanyinqiao Formation around the Hannan Oldland and Central Sichuan Uplift. The Guanyinqiao Formation is relatively thin and lacks prominent sedimentary structures. The shore facies around the Central Sichuan Uplift is mainly calcareous siltstone, and the representative section is Xihe in E'bian. Small oblique bedding and parallel bedding are found in the gray-white thin-layered siltstone, and the quartz particles are predominantly circular and elliptical in shape, with only a few exhibiting subangular. The Guanyinqiao Formation in Wuxing Village, Xiaoyang Town, Zhenba County, Shaanxi Province, is dominated by pebbly sandstone, mud-containing quartz sandstone, calcareous sandstone and quartz sandstone. At the base of the formation, parallel bedding is evident, with a scale of approximately 5 mm. Additionally, a small bottom erosion structure was identified at the boundary between the Wufeng and Guanyinqiao Formations in the Fucheng section (Fig. 6).

4.3. Shoal facies

The shoal facies refers to the intertidal zone of the tidal flat facies of Guanyinqiao Formation. This environment experienced frequent fluctuations in water level, leading to the development of areas with higher hydrodynamic conditions, which ultimately gave rise to the shoal facies. In the Fenggang and Renhuai areas of northern Guizhou, the Guanyinqiao Formation is characterized by grainstones, including sparite sandclastic limestone, bioclastic limestone (featuring brachiopods and crinoids), coral reef limestone, and oolitic limestone.

The Dongkala section in Fenggang County boasts the thickest deposition of the Guanyinqiao Formation, comprising sparite sandclastic limestone and oolitic limestone. In contrast, the lower part of the Guanyinqiao Formation at the Zhongshu section in Renhuai County is characterized by calcareous mudstone with limestone nodules (Zhan RB et al., 2010), which is the main producing position of the Hirnantia Fauna. The upper portion of the Guanyinqiao Formation is comprised of bioclastic and reef limestones, which are characterized by a dominance of corals, as well as a few trilobites, brachiopods, and bryozoans (Fig. 7).

4.4. Shallow marine shelf facies

The shallow marine shelf, situated within the photic zone (i.e., between the low-tide line and 200 m below), is characterized by a pronounced marine environment, as demonstrated by the prevalence of sunlight and benthic organisms. Sedimentological analysis reveals that this zone is dominated by fine-grained terrigenous clastic sediments and biochemical deposits, which are replete with biological remains, burrows, and bioturbation structures. Generally, it is dominated by dark mud shale with silty-fine sandstone and argillaceous limestone.

Through an examination of sedimentary sequence and structural characteristics, it becomes evident that the study area can be partitioned into two distinct depositional environments: Shallow water shelf and deep water shelf. In this investigation, The authors utilize the storm wave base as a proxy for determining the boundary between these two zones, with the upper region corresponding to the shallow water shelf and the lower region corresponding to the deep water shelf.

4.4.1. Shallow water shelf facies

The shallow water area, bounded by the storm wave base and the normal wave base, is characterized by the presence of storm deposits. The shallow-water shelf is characterized by a lithological assemblage dominated by gray-green to gray-dark carbonaceous silty mudstone, which occasionally yields thin intervals of layered gray muddy siltstone, silty mudstone, or argillaceous limestone. The sedimentary structures observed in this zone include horizontal bedding, symmetry-asymmetric ripples (Fig. 8), and small-scale ripple lamination or cross-bedding.

The lithology of shallow water facies in the Wufeng Formation is composed of gray, dark gray carbon-containing calcareous mudstone, carbon-containing silty mudstone, carbon-containing siltstone, dolomite-silt containing carbonaceous mudstone. In the Weixin, Wuchuan, and Dejiang regions, dark gray carbonaceous calcareous mudstone and carbonaceous silty mudstone predominate, whereas in the northern sector proximal to the Central Guizhou Uplift,

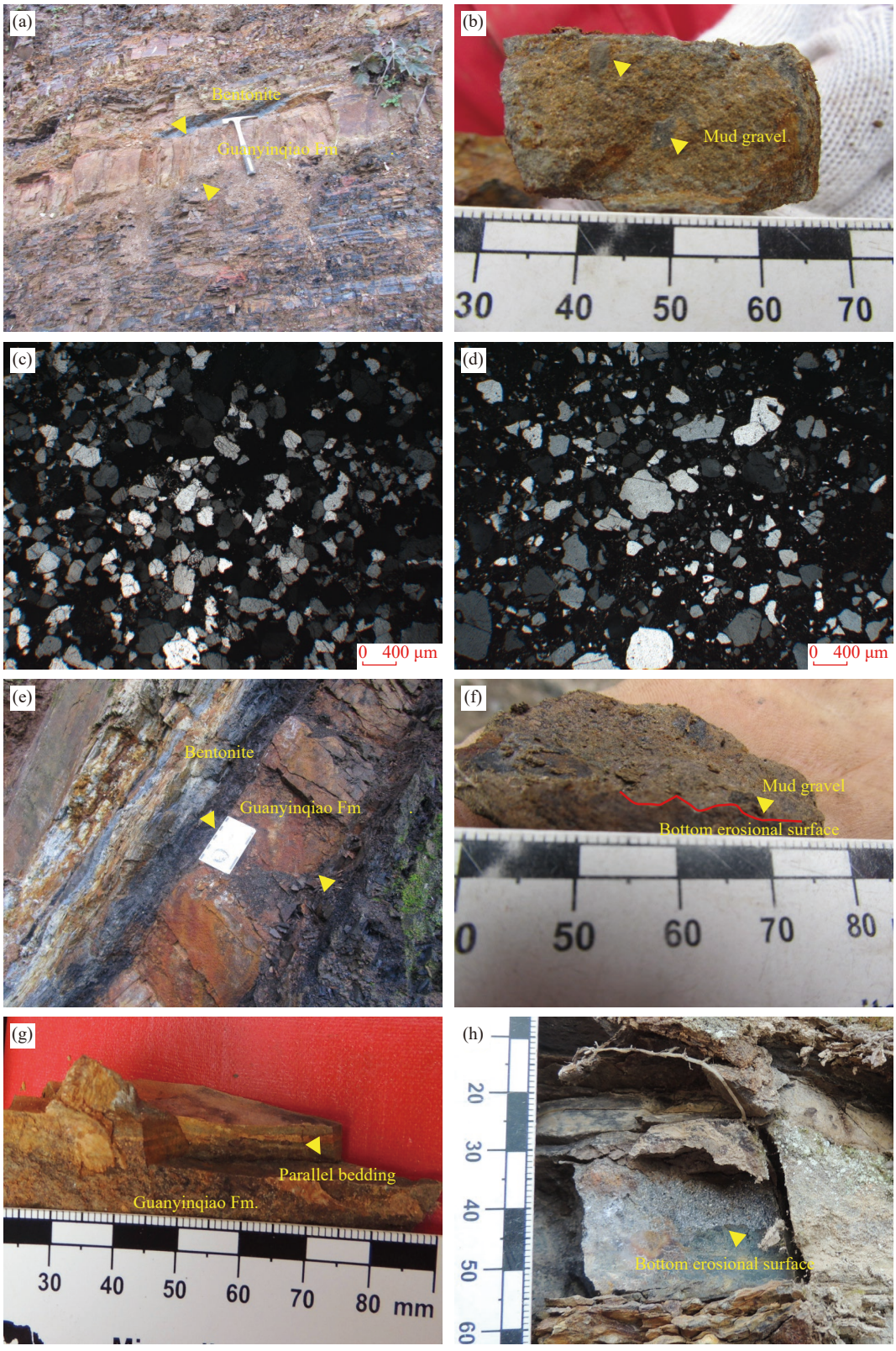

Fig. 6. Characteristic features of shore facies in Guanyinqiao Formation. a–thick beded pebbly sandstone in Liangbai, Zhenba County; b–mud gravel in the quartz sandstones in Fucheng section, Nanzhen County; c–quartz siltstones in Fucheng section, Nanzhen County; d–quartz sandstones in Liangbai section, Zhenba County; e–boundary of Wufeng and Guanyinqiao Formations in Wuxing section, Zhenba County; f–bottom erosion structure between the Wufeng and Guanyinqiao Formations in Shuanghui section, Wangcang County; g–parallel bedding in sandstones of Guanyinqiao Formation in Wuxing section, Zhenba County; h–bottom erosion structure at the bottom of Guanyinqiao Formation in Fucheng section, Nanzheng County.

carbonaceous calcareous mudstone or argillaceous limestone are the primary lithofacies.

The lithology of shallow water facies in the Guanyinqiao Formation is composed of dark gray silt-containing mudstone,

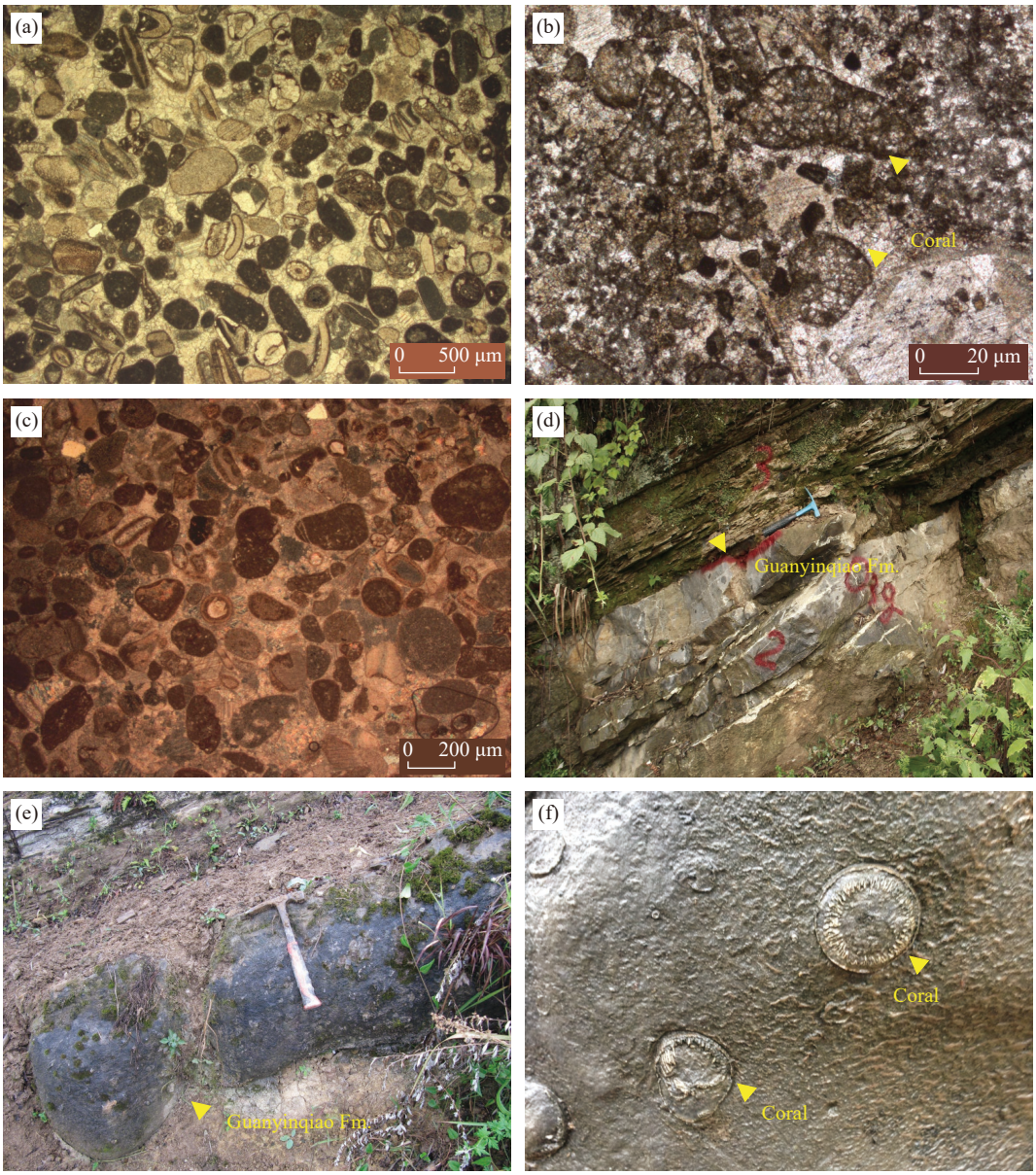

Fig. 7. Characteristic features of shoal facies in Guanyinqiao Formation. a–oolitic limestone of Guanyinqiao Formation in Dongkala section, Fenggang County; b–coral developed in the biological limestones of Guanyinqiao Formation in Zhongshu section, Renhuai County; c–oolitic limestone of Guanyinqiao Formation in Yonghe section, Fenggang County; d–boundary of Wufeng, Guanyinqiao and Longmaxi Formations in Yonghe section, Fenggang County; e– macroscopic character of the Guanyinqiao Formation in Zhongshu section, Renhuai County; f– corals of the Guanyinqiao Formation in Zhongshu section, Renhuai County.

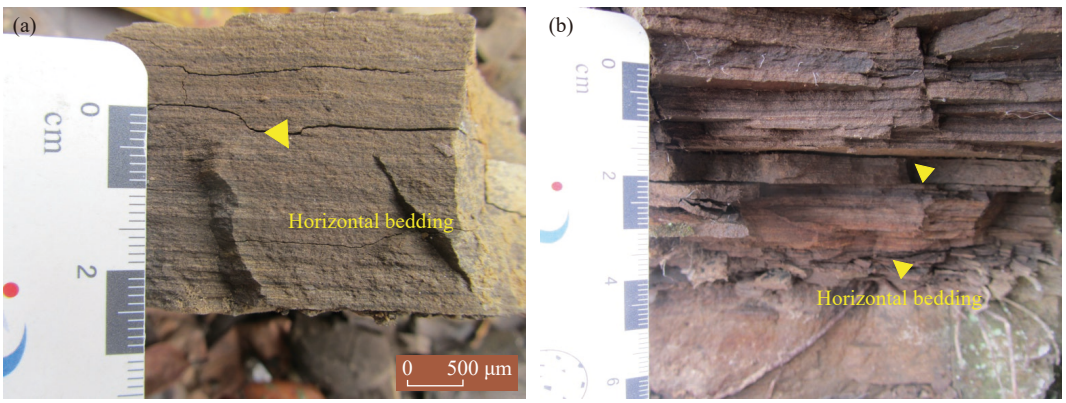

Fig. 8. Horizontal beddings developed in the carbonaceous silty mudstones of Wufeng formation in Xiadian section, Dejiang County, Guizhou Province.

silty mudstone, carbon-containing mudstone, argillaceous limestone and bioclastic-containing argillaceous limestone. Silt-containing mudstone and carbon-bearing mudstone were mostly distributed in the northern and central parts of the Sichuan Basin and developed Hirnantia brachiopods and a few trilobites. In the northern Guizhou area near the central Guizhou Uplift, the lithology was dominated by limestones and bioclastic-containing limestones, and developed brachiopods (Fig. 9), trilobites, crinoids, gastropods, and hornstones.

The shallow-water shelf facies of Longmaxi Formation is widely distributed in the restricted basin bounded by central Guizhou Uplift, Central Sichuan Uplift and Hannan Oldland, and composed of siltstone, silty mudstone and silt-containing shale (Fig. 10). Since affected by storms, tides and ocean currents intermittently, the sediments in the shallow water are easy to be transformed. The shallow water shelf generally consisted of dark gray and gray silty mudstone and silt-containing mudstone with horizontal bedding, small ripple lamination and cross-bedding. The types of biological fossils are mainly graptolites, a few brachiopods and corals.

4.4.2. Deep water shelf facies

In terms of depth, it is deeper than the shallow water shelf, mainly located in the shallow marine area below the storm wave base, and mainly composed of still water deposits. The Wufeng Formation and the lower part of the Longmaxi Formation all developed deep water shelf facies. The lithology consisted of gray-black and black carbonaceous mudstone, carbonaceous silty mudstone and siliceous mudstone (Figs. 11, 12) with horizontal bedding. In addition, the organic carbon content is generally greater than 1.0%. This facies is a very important hydrocarbon generating zone in the process of shale gas exploration.

The deep water shelf of Wufeng Formation and Longmaxi Formation mainly deposited carbonaceous silty mudstone, silt-containing calcareous carbonaceous mudstone, carbonaceous mudstone and siliceous mudstone and developed horizontal bedding. The abundance and differentiation of graptolites are relatively high, with scattered occurrences of corals and brachiopods.

Pyrite typically exhibits a banded or lenticular morphology in the carbonaceous mudstone, and radiolaria fossils can be seen in the siliceous mudstone under the microscope with the content of 10% to 20%. The shape of the radiolaria is mostly spherical or elliptic, with a diameter between 0.05 mm and 0.3 mm. Besides, most of the siliceous radiolarian shells have been dissolved and destroyed, and then filled with opals or quartz. Despite this intense alteration, it is still possible to identify the circular and elliptical shape of these fossils in siliceous rocks. In summary, it is concluded that the deep-water shelf environment is quiet and less biodisturbed by benthic animals which is beneficial to the burial and preservation of organic matter, and is a very important shale gas exploration facies area in the whole Sichuan Basin.

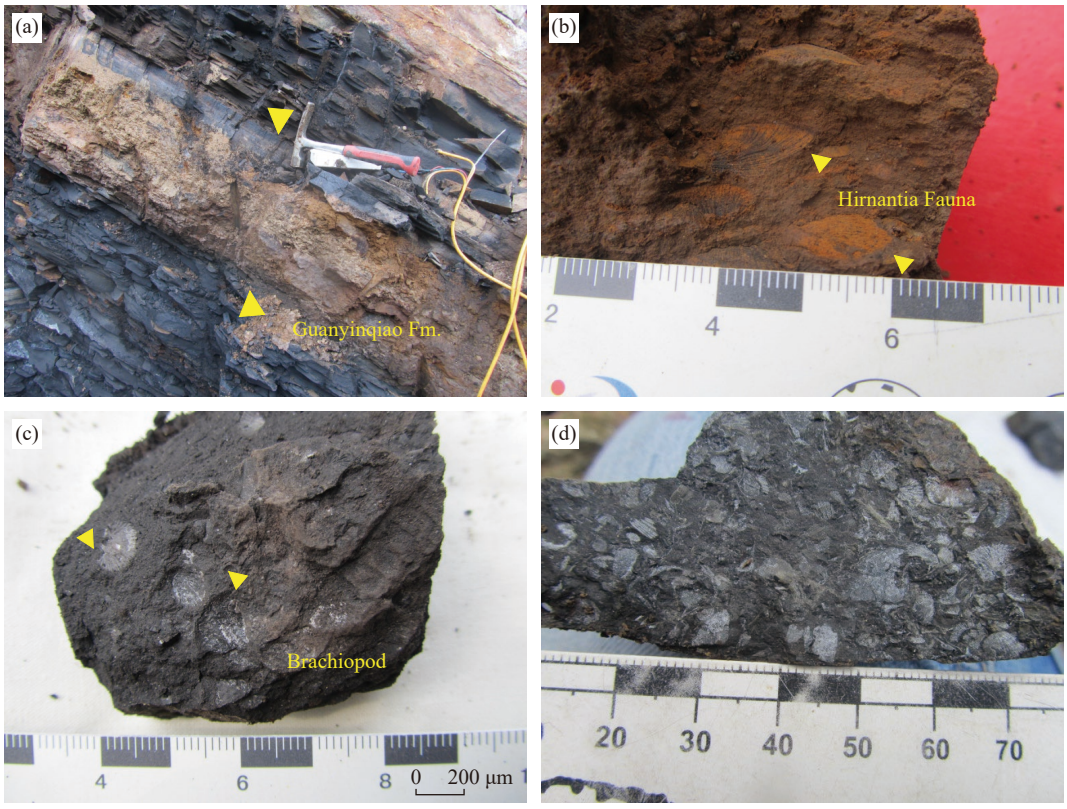

Fig. 9. Characteristic features of shallow water shelf facies in Guanyinqiao Formation. a–bioclastic-containing mudstone of Guanyinqiao Formation in Huangcao section, Wulong County; b–hirnantia brachiopods of bioclastic-containing mudstone in Huangcao section, Wulong County; c–hirnantia brachiopods of bioclastic-containing argillaceous limestone in Liangcun section, Xishui County; d–hirnantia brachiopods of bioclastic-containing argillaceous limestone in Dalianghui section, Wangcang County.

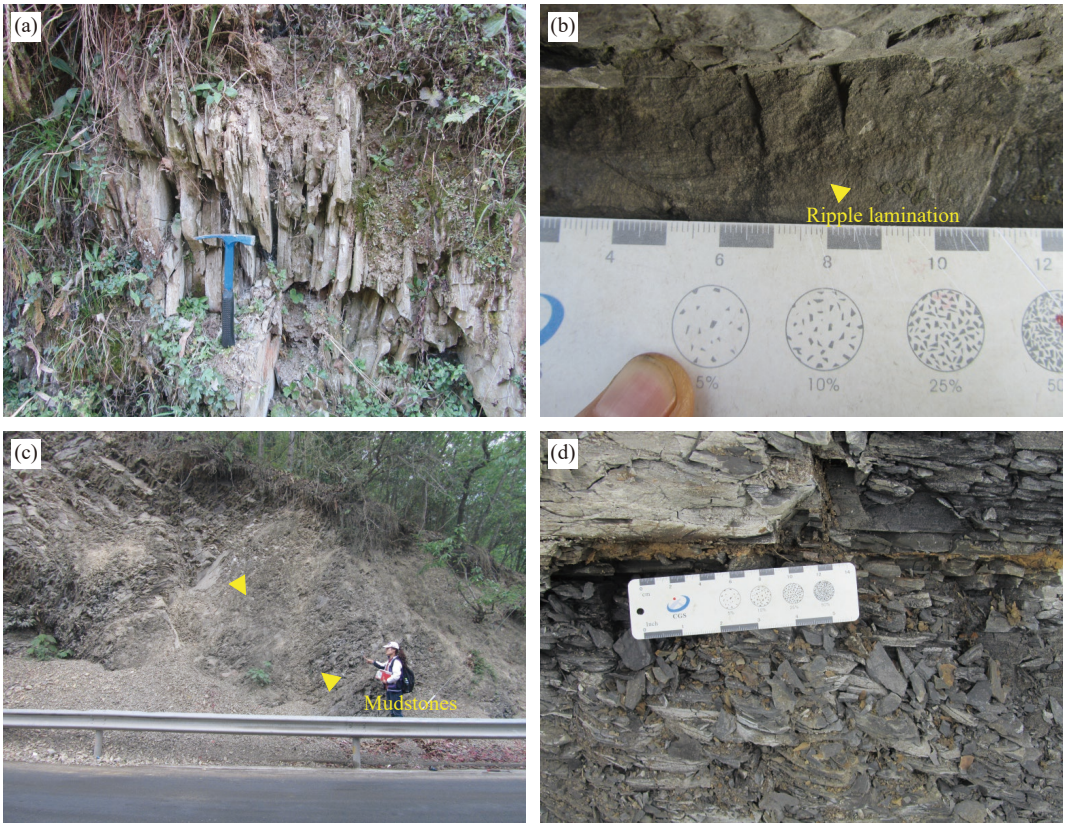

Fig. 10. Characteristic features of shallow water shelf facies in Longmaxi Formation. a–gray-green silty mudstone of Longmaxi Formation in Tuping section, Zhengan County; b–small ripple lamination developed in the silty mudstones of Longmaxi Formation in Tuping section, Zhengan County; c–gray-green shales of the upper part of Longmaxi Formation in Huangcao section, Wulong County; d–graygreen silt-containing mudstone of Longmaxi Formation in Hanjiadian section, Tongzi County.

Two east-west profile lines of Wufeng-Longmaxi Formation in Sichuan Basin are selected for comparison: One line is Shizhu Qiaoliao-Jiaoye 1 well - Xindi 1 well - Yongdi 1 well - Yongshan Yunqiao - Jinyang Xinzhaizi - Butuo Pobowu, the other is Pengye 1 well - Wulong Huangcao - Dingshan 1 well - Lin1 well - Xuyong Macheng - Junlian Luomurou - Leibo Bajiaotan (Figs. 13, 14). The distribution of sedimentary facie of the two east-west Wufeng-Longmaxi Formations are basically the same. Taking Shizhu Qiliao-Jiaoye 1 well-Xindi 1 well- Yongdi 1 Well-Yongshan Yunqiao - Jinyang Xinzhaizi -Butuo Pobowu as an example.

There are deep-water shelf of carbonaceous and siliceous shales with a thickness of 6 m in Wufeng Formation of Qiliao section, Shizhu County. The Guanyinqiao Formation is a set of biological argillaceous limestones with 1 m thick, the black shales of the lower part of the Longmaxi Formation is 56 m thick, and the upper part of Longmaxi Formation are dark gray, light gray muddy siltstone and siltstone. The lithology of Wufeng, Guanyinqiao and Longmaxi Formations in the vicinity of Jiaoye 1 well, Fuling is basically the same as that of Qiliao section, Shizhu county, but the thickness of the black shale of Longmaxi Formation is about 60 m larger than that of Qiliao. It is dominated by calcareous carbonaceous mudstone with marl lens, which is obviously shallower than the eastern side and mainly dark gray in sedimentary lithology color. The lithology of Xindi 1, Yongdi 1, Yongshan Yunqiao, Xinzhaizi, Pobowu of Wufeng and Longmaxi Formations has the tendency of increase in terms of carbonate content, and consists of calcium-containing carbonaceous mudstone with limestone lens.

In contrast to the eastern part of the Sichuan Basin, the water depth decreases and the rock color is darker gray in the southwestern region. From the perspective of the overall sedimentary pattern of Sichuan Basin, the eastern area is concave-shaped pattern confined by the Central Sichuan Uplift and the central Guizhou Uplift. From the southeast direction of the Central Sichuan Uplift to the Qiliao section, Shizhu County and Jiaoye 1 well, Fulong County, the thickness of the black carbonaceous shale is the highest. Continue to the southwest to Xindi 1 well, Yongdi 1 well, Yongshan Yunqiao, Xinzhazi and Pobowu, the thickness of the black shale gradually thinned and the carbonate rocks such as argillaceous limestone gradually increased. The lower part of Longmaxi Formation is also dominated by carbonaceous calcareous mudstone. On the whole, the sedimentary water body in the Sichuan Basin from northwest to southeast became shallower, showing the characteristics of deep in the northeast and shallow in the southwest.

5. Lithofacies paleogeography

5.1. Lithofacies paleogeography of the organic rich shales in Wufeng Formation

At the end of the Middle Ordovician, the tectonic

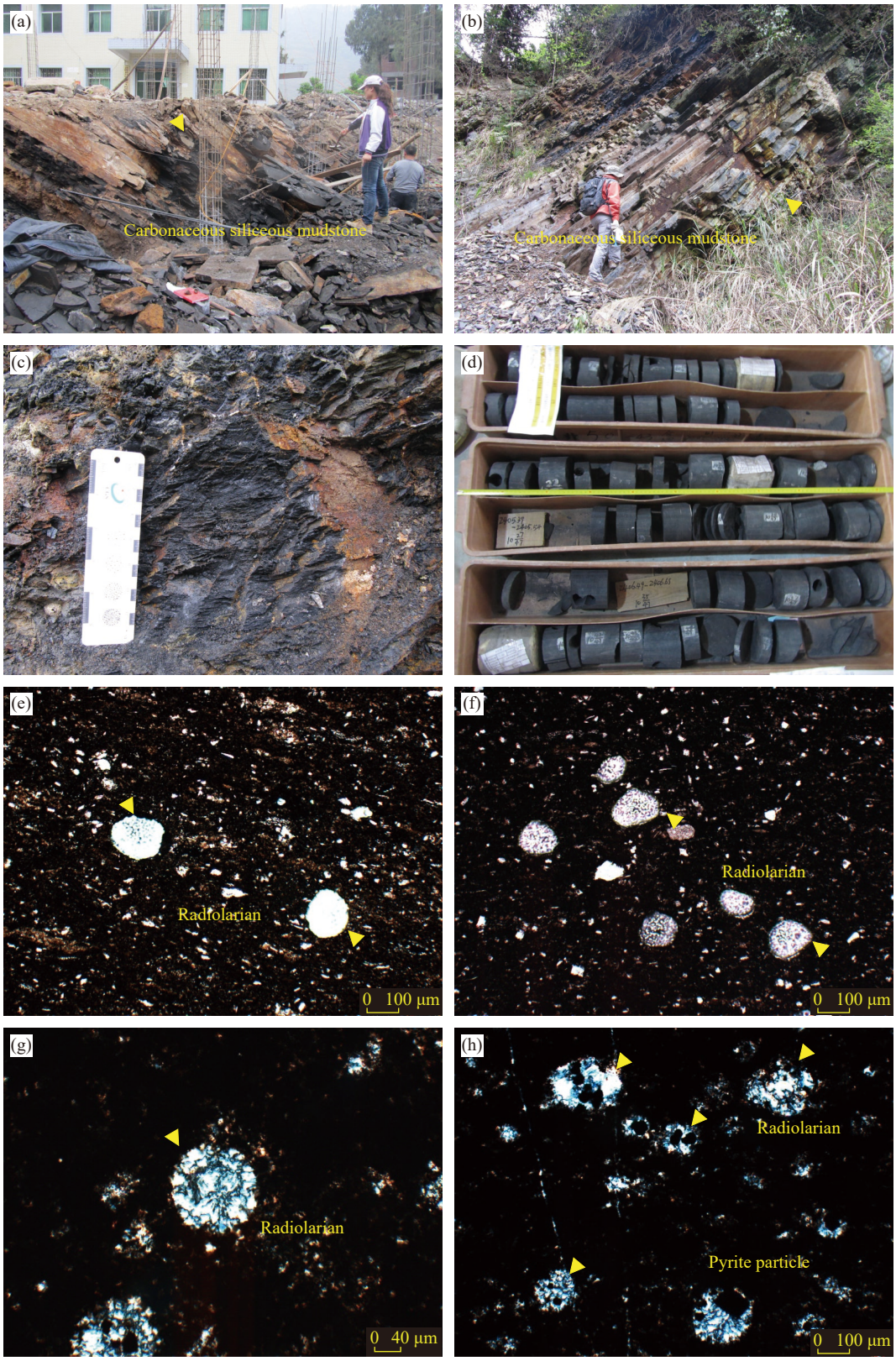

Fig. 11. Characteristic features of deep water shelf facies in Wufeng and Longmaxi Formations. a–d–macro characteristics of the black carbonaceous and siliceous mudstones; Longmaxi Formation, a–Huangcao section, Wulong County; b–Qiliao section, Shizhu County; c–Guanyinqiao section, Qijiang County; d– Jiaoye 1well; e–h–radiolaria developed in carbonaceous and siliceous mudstones; Wufeng Formation, e–Huangcao section, Wulong County; f–Huangyingxiang section, Wulong County; g–Fucheng section, Nanzheng County; h–Shuanghui section, Wangcang County.

compression intensified continuously in South China plate affected by the Caledonian Movement (Zhou MK et al., 1993; Liu BJ et al., 1993, 1994; Xu XS et al., 1996, 2004; Shu LS et al., 2008, 2012; Yan DT et al., 2010; Charvet J et al., 2010;

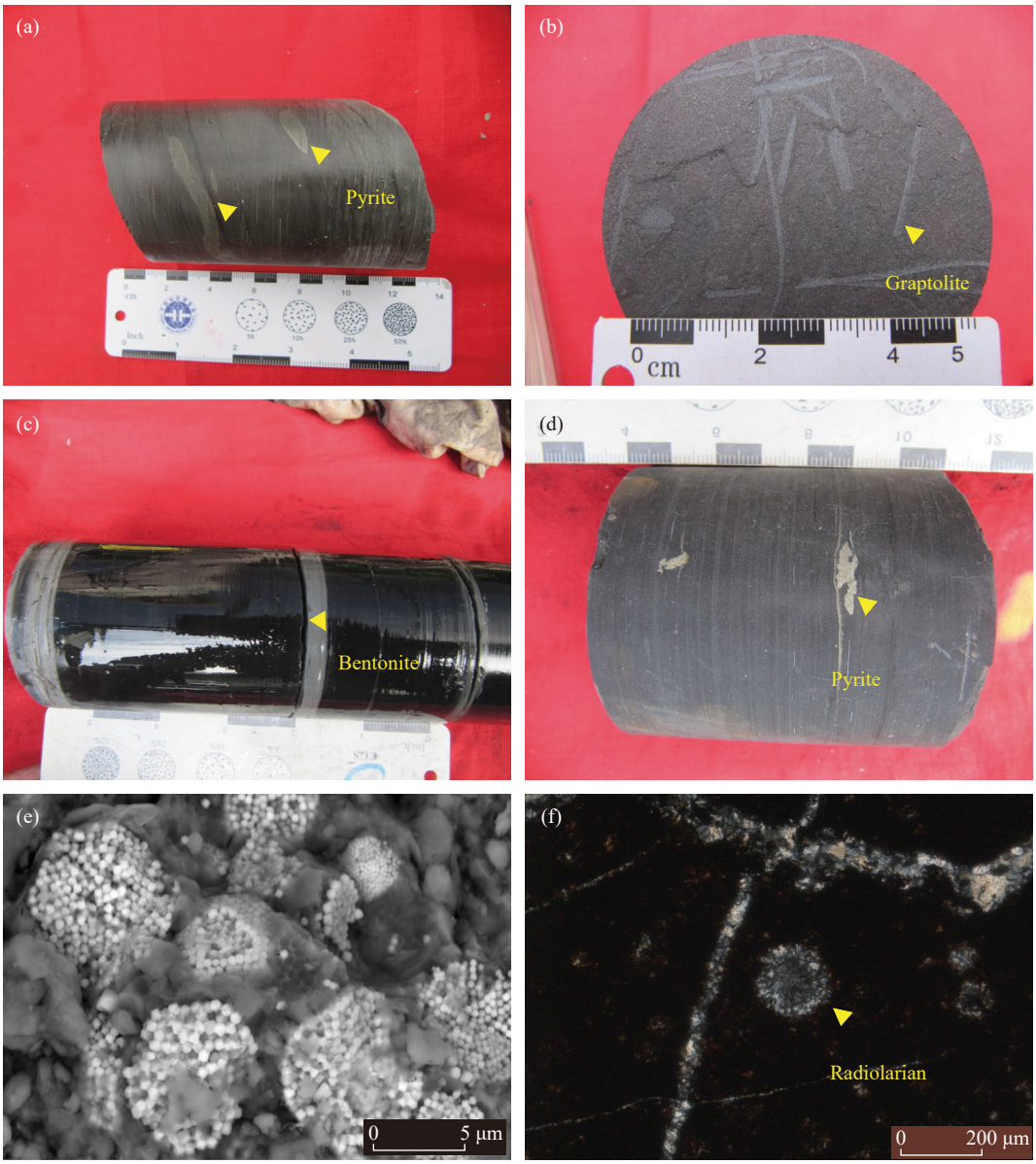

Fig. 12. Characteristic features of deep water shelf facies in Wufeng and Longmaxi Formations of Huadi 1well and Xindi 2well. a–pyrite nodules developed in the black shales (Huadi 1well, Wufeng Formation); b–graptolite developed in the black carbonaceous and siliceous mudstones (Huadi 1 well, Longmaxi Formation); c– bentonites developed in the black shales(Xindi 2well, Wufeng Formation); d–pyrites developed in the black shales (Xindi 2well, Longmaxi Formation); e–pyrite framboids developed in the black shales (Huadi 1well, Longmaxi Formation); f–radiolaria developed in the black shales (Huadi 1well, Wufeng Formation).

Faure M et al., 2009). Central Guizhou uplift, Xuefeng uplift and Central Sichuan Uplift increased continuously, and the Yangtze block changed from the craton basin to the back-bulge basin confined by the marginal uplifts and the lithology changed from pure carbonate rocks to the black shales. During this period, uplift, tidal flat, shallow water shelf and deep water shelf developed successively in Sichuan Basin and adjacent areas (Fig. 15).

The periphery of each uplift is tidal flat facies, dolomitic shales and argillaceous limestones are deposited in the periphery of Hannan Oldland, Central Sichuan Uplift. The shallow shelf facies roughly follows Hannan Oldland to the south of the Ningqiang-Nanjiang-Zhenba area and is composed of dolomitic mudstone and silty mudstone. The facies follows Central Sichuan Uplift to the east to Jiange-Langzhong-Yingshan-Weiyuan-Leibo line, the Western Sichuan-Central Yunnan-Central Guizhou-Xuefeng Uplift to the north to Weixin-Renhuai-Wuchuan-Youyang-Longshan line, and the lithology is mainly carbon-containing siltstone, carbon-containing shale, dolomitic mudstone and silty mudstone. Deep water shelf facies mainly develops on the outside of shallow shelf facies and is bounded by the Junlian-Chishui-Qijiang-Nanchuan-Wulong-Qianjiang line. To the north, the rocks are carbonaceous and siliceous mudstone, while to the south, due to its proximity to the Central Guizhou Uplift, the carbonate rock composition increases and the carbonaceous mudstone and calcareous mudstone are dominated.

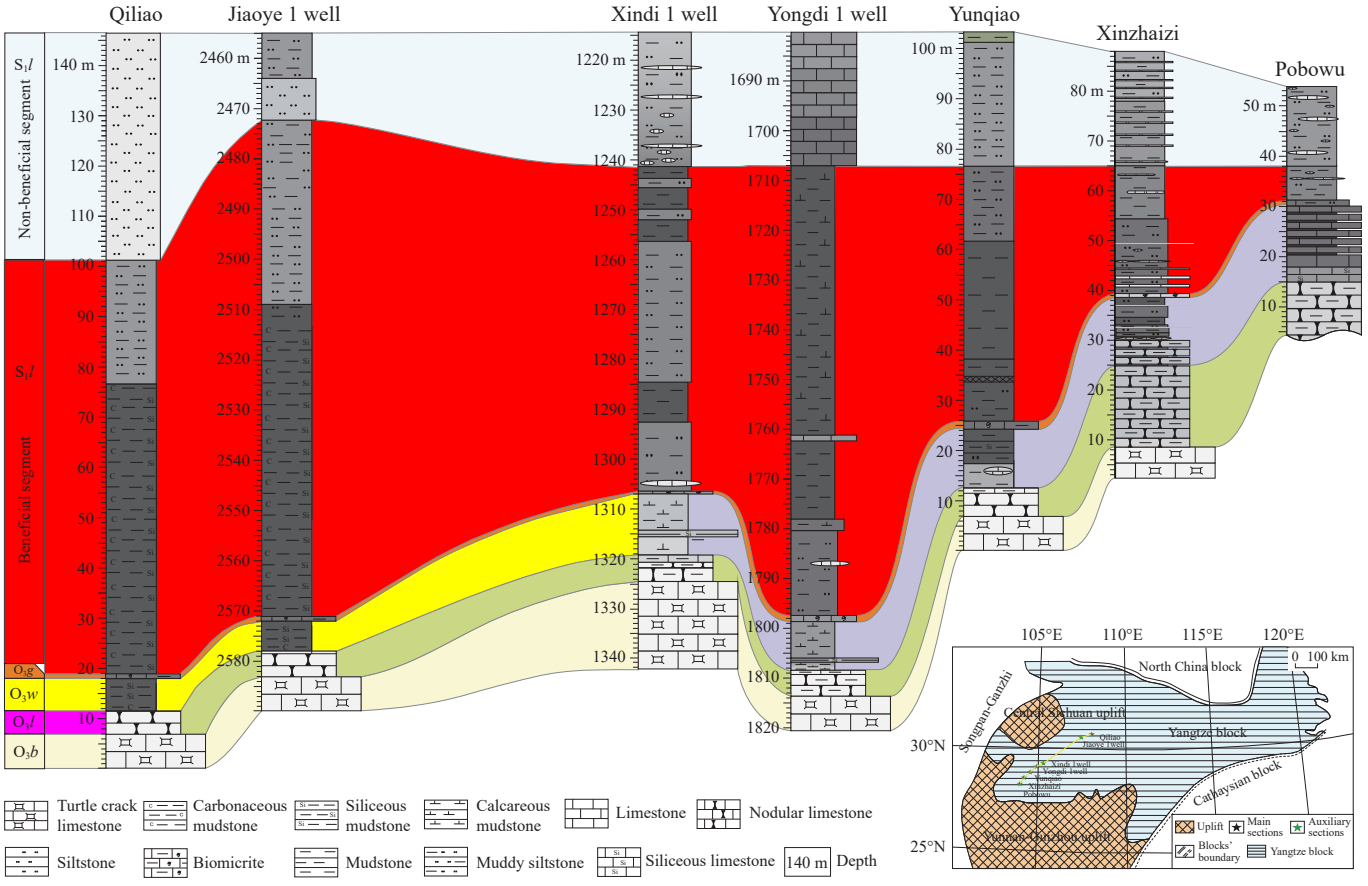

Fig. 13. Sedimentary correlation diagram of the north east-south west direction in Sichuan Basin and its adjacent areas (the palaeogeography map were modified from Ge XY, 2020).

5.2. Lithofacies paleogeography of the Guanyinqiao Formation

In the middle Hirnantian, the global eruption of Gondwana glaciation caused a significant drop in sea level, and the graptolite shale facies of Wufeng Formation was replaced by the shallow-water shell limestone facies of Guanyinqiao Formation. The Guanyinqiao Formation, with a thickness of only ten centimeters to several meters and a maximum of only ten meters, began to be deposited above on the black shale. During this period, the area of the Western Sichuan-Central Yunnan-Guizhou Uplift also increased, and the edges of the uplifts are still tide-flat facies (Fig. 16). The periphery of the Central Sichuan Uplift is mainly developed biological limestone, which is roughly located between the Baoxing - Ya'an - Laolong1 well - Anyue - Nanchong - Yanting - Mianyang and Yingjing - Woshen 1 well - Qianwei - Zizhong - Huaying lines. The periphery of the Central Yunnan-Central Guizhou Uplift deposited dolomitic shale and argillaceous limestone. In the east tidal flat, such as Fenggang Dongkarla, Renhuai Zhongshu sections are high energy shoal facies deposits. The Dongkala area develops sparry oolitic limestone, sand-clastic limestone, and the Renhuai Zhongshu section is dominated by coral reef limestone.

The shore facies is located outside of Hannan Oldland and composed of quartz coarse sandstone, calcareous coarse sandstone, mud-containing coarse quartz sandstone and pebbly coarse sandstone. There are fine gravels in Nanzheng Fucheng, and Zhenba Liangbai sections. Hirnantia brachiopods are found in Wuxing section, and a set of biogenic mudstone developed above the mud-containing coarse-grained quartz sandstone of Liangbai section, containing trilobites, brachiopods and other organisms. Clastic shallow-water shelf facies is situated between Zhenba-Fucheng-Ningqiang and Nanjiang-Wanyuan lines and made up of argillaceous siltstone and mudstone. A wide range of shallow water shelf facies were deposited outside the tidal flat facies of the Central Sichuan Uplift and the Central Yunnan-Central Guizhou Uplift. The rock associations of shallow water shelf facies are diverse. The Xingjing - Woshen 1 well - Qianwei - Zizhong - Huaying and Hanyuan - Leibo - Changning - Luzhou - Yongchuan - Linshui - Yingshan - Jiange lines are still dominated by carbonate deposits, which are mainly bioclastic-containing argillaceous limestone and argillaceous limestone. On the south side, the shallow-water shelf facies around the Western Sichuan-Central Yunnan-Central Guizhou Uplift is bounded by the Ganluo - Butuo - Jinyang - Daguan - Weixin - Tongzen - Daozhen - Wulong - Shizhu - Enshi line, which is dominated by sedimentary clastic rocks, which are argillaceous siltstone and silty mudstone. The facies between Ganluo - Butuo - Jinyang - Daguan - Weixin - Tongzi - Daozhen - Wulong - Shizhu - Enshi and Hanyuan - Leibo - Changning - Luzhou - Yongchuan - Linshui - Yingshan - Jiange lines are dominated

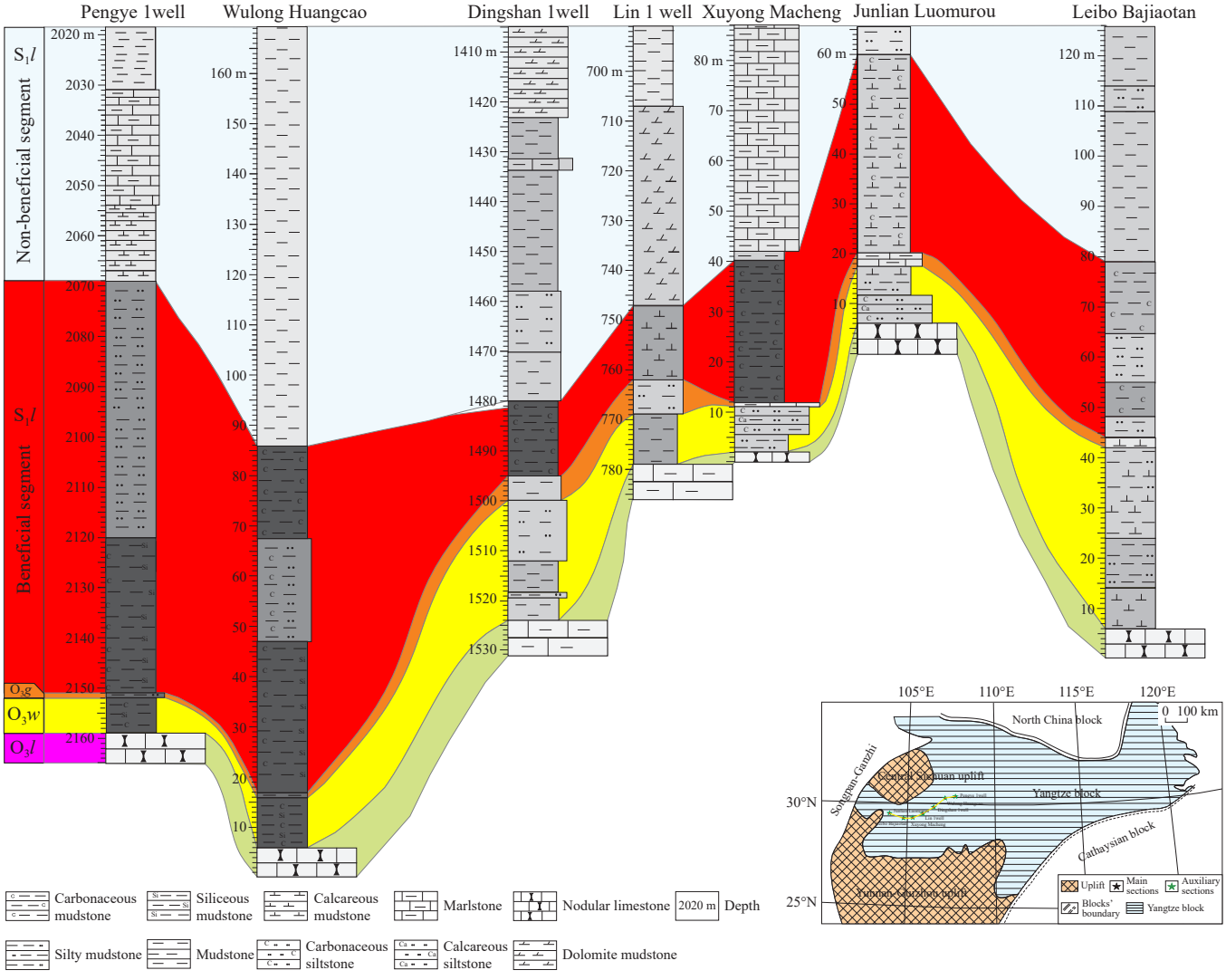

Fig. 14. Sedimentary correlation diagram of the nearly east-west direction in Sichuan basin and its adjacent areas (the palaeogeography map were modified from Ge XY, 2020).

by mixed shelf deposits, which are biological argillaceous limestone, calcareous shale and mudstone.

5.3. Lithofacies paleogeography of the organic rich shales in the lower part of Longmaxi Formation

At the end of the Hirnantian, the glaciers began to melt, the temperature gradually warmed, and the relative sea level rose significantly. In the early Rhuddanian of the Early Silurian, large-scale transgressions occurred worldwide, black carbonaceous shale with stable thickness widely distributed at the bottom of the Longmaxi Formation. The paleography distribution of this period, as illustrated in Fig. 17.

Since the late Late Ordovician, with the intensification of collision in South China, the areas of Central Guizhou Uplift, Xuefeng Uplift and Central Sichuan Uplift Hannan Oldland and Kangdian Oldland have been enlarged. The periphery of the uplifts were narrow tidal flat zones of clastic and carbonate rocks. In the north distributed in circularity in the periphery of Hannan Oldland. The lithology is dominated by carbon-containing silty mudstone and siltstone with horizontal bedding and lenticular bedding. The shallow-water shelf facies is deposited outside tidal flat and composed of carbonaceous mudstone and silty mudstone. According to the old well data of the periphery of Central Sichuan Uplift, the uplift area extends to the Baoxing - Leshan - Jingyan - Ziyang - Nanchong - Mianyang line. Perhaps affected by late weathering and denudation, no tidal flat deposits have been found around the Central Sichuan Uplift. The lower part of the Longmaxi Formation in the Hanyuan - Yingjing area is mainly a set of gray-black mudstone, silty mudstone and siltstone with low organic carbon content, which has the characteristic of shallow water shelf facies. However, the boundary between the shallow water shelf and uplift can not be accurately determined, so the Central Sichuan Uplift is still called the denudation area. A small range of shallow water shelf deposits outside the uplift. According to the surface profile data of the Luding-Hanyuan area, three small uplifts are developed near Luding and Hanyuan, and shallow water shelf deposits dominated by carbon-containing silty mudstone and silty mudstone is deposited on the periphery of the uplifts. The southernmost Kangdian Oldland, Central Guizhou Uplift

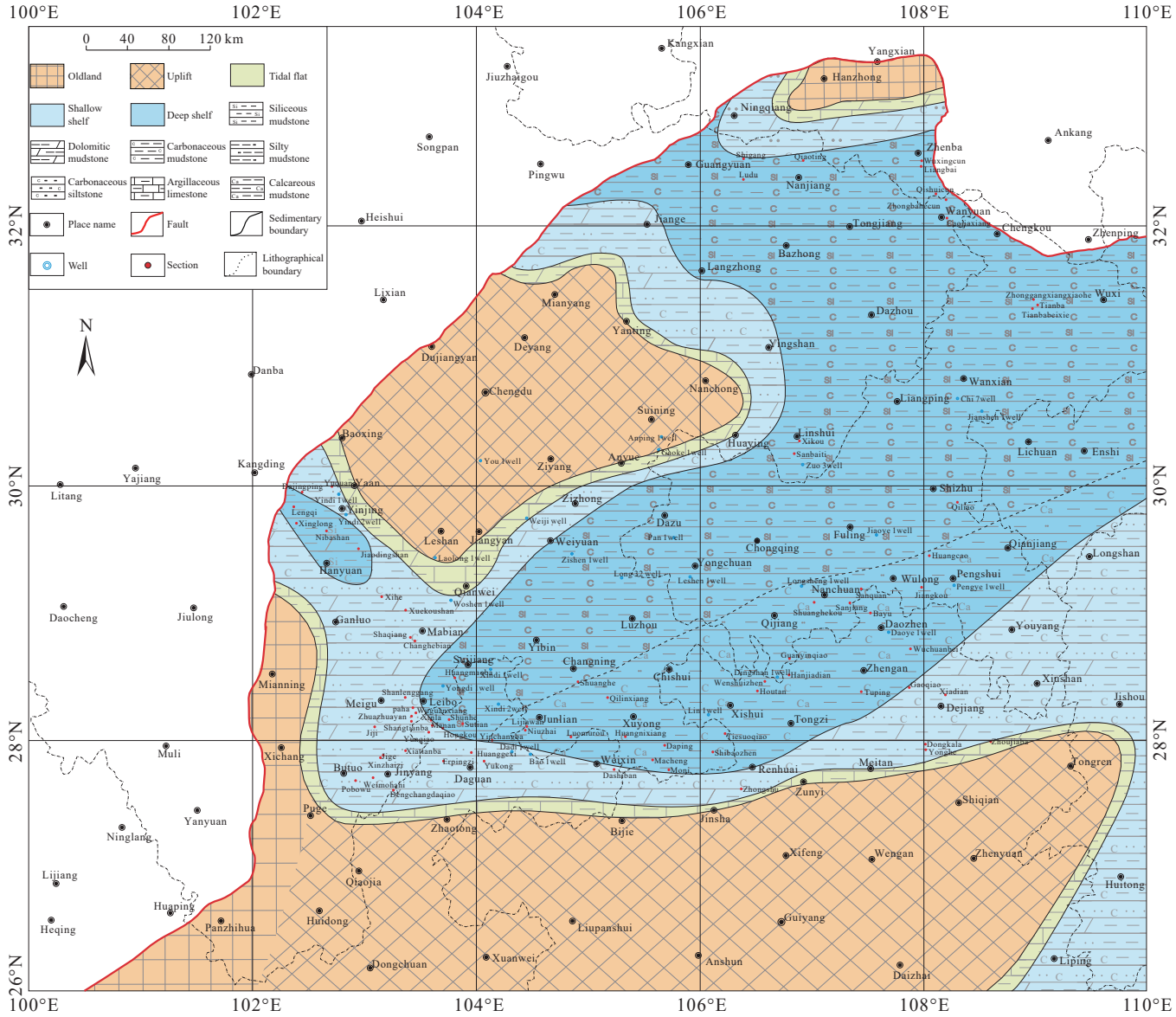

Fig. 15. Lithofacies paleogeography map of Wufeng formation in Sichuan Basin and its surrounding areas.

and Xuefeng Uplift are connected to form a large uplift. The northern uplift is roughly bounded by the Xichang - Puge - Zhaotong - Bijie - Jinsha - Zunyi - Tongren line, and the periphery of the uplift area is tidal flat facies which is composed of mainly mud-containing silty and sand clastic limestone and carbon-containing silty limestone. The shallow shelf facies is deposited on the outer edge of the tidal flat facies. The shallow shelf facies is bounded by the Hanyuan - Ganluo - Butuo - Jinyang - Junlian - Xuyong - Xishui - Zheng'an - Xiushan line and composed of carbon-containing argillaceous limestone and calcareous mudstone with horizontal bedding.

The deep water shelf facies occupies a large part of the east and south Sichuan Basin. The sedimentary facies roughly follows the Yingjing - Jingyan- Anyue - Nanchong - Yanting - Mianyang line to the southeast, Hanyuan - Ganluo - Butuo - Jinyang - Junlian - Xuyong - Xishui - Zheng'an - Xiushan line to the north to Zhenba - Wanyuan - Chengkou - Wuxi area. The area is divided into two lithologic associations roughly bounded by the Weiyuan - Yongchuan - Chongqing - Wulong - Pengshui line: In the south of this line, due to its proximity to Central Guizhou and Xuefeng Uplifts, the calcareous composition is obviously higher, and the lithofacies association is dominated by carbonaceous calcareous mudstone, silicon-containing carbonaceous silty mudstone and calcium-containing carbonaceous silty mudstone. In the north of this line, the lithologic association is dominated by carbonaceous mudstone and siliceous mudstone with small amount of carbonate composition.

5.4. Lithofacies paleogeography of the upper part of Longmaxi Formation

In the late sedimentary period of Longmaxi Formation, the tectonic compressions from the southeast were intensified, the uplifts moved to the northwest continuously, and the sea level decreased. Central Guizhou, Xuefeng and Central Sichuan Uplifts expanded, the upper part of Longmaxi Formation

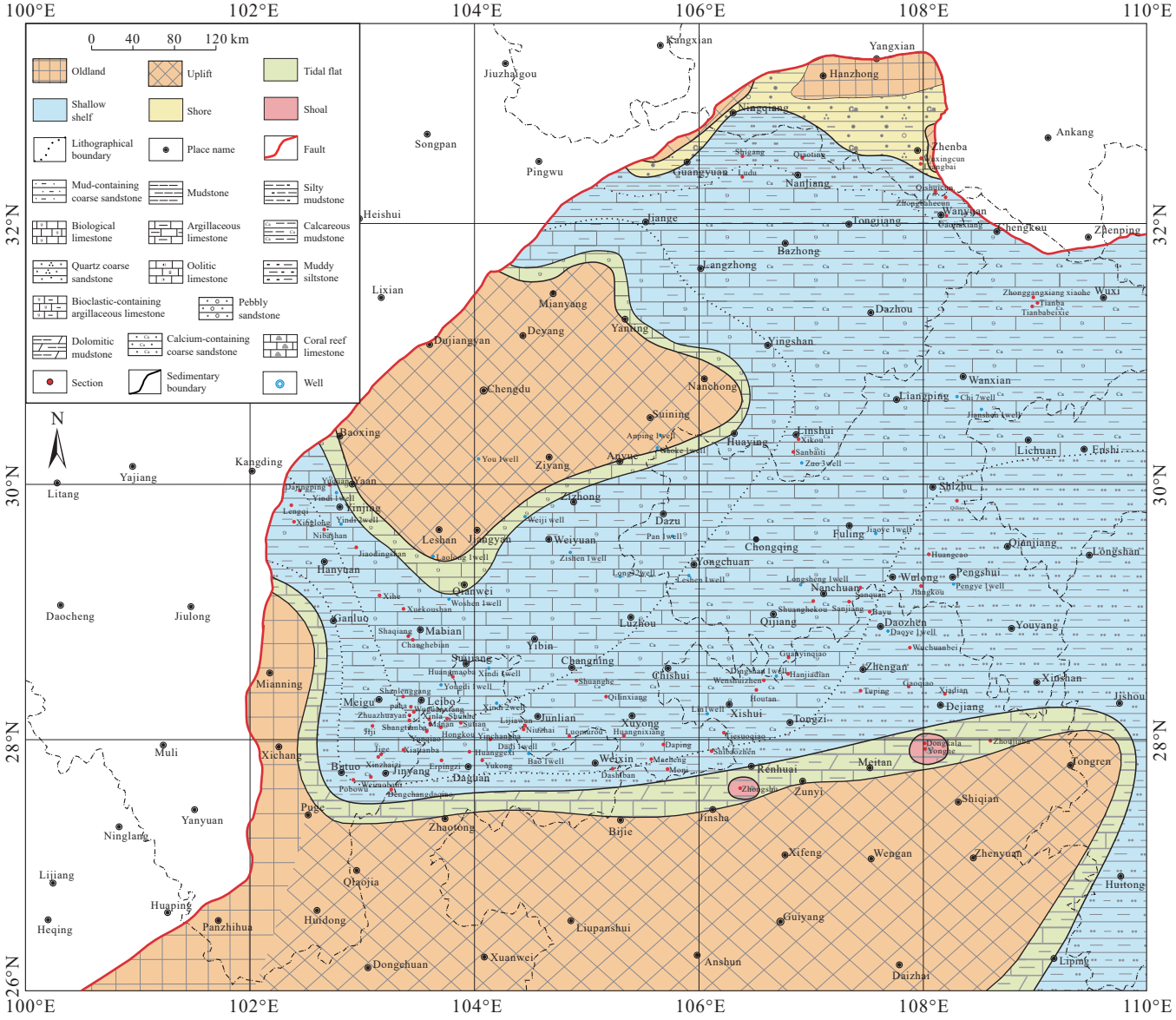

Fig. 16. Lithofacies paleogeography map of Guanyinqiao Formation in Sichuan Basin and its surrounding areas.

deposited gray-green, gray-yellow sandy shale and siltstones instead of black shales. Apart from the tidal flat facies developed in the periphery of these oldlands and uplift, the middle and upper part of Longmaxi Formation was basically in a shallow water shelf environment which occupied the majority of the study area (Fig. 18).

Compared with the early Longmaxi stage, the tidal flat facies near Kangdian Oldland, Central Guizhou and Xuefeng Uplifts extends to the Ganluo - Butuo - Danguan - Weixin - Tongzi - Dejiang - Xiushan area. This facies mainly deposits interbeds of gray, gray-green calcareous siltstone and argillaceous limestone in different thickness. The lithology color was shallower than that of the lower part, and the calcium composition increased, the terrigenous clastic grain size became coarse-grained, and the sedimentary sequence of Longmaxi Formation is shallower from bottom to top. shallow water shelf located in the periphery of tidal flat facies and occupied most areas of southeast Sichuan and Chongqing and western Hubei. The Weiyuan - Yongchuan - Chongqing - Wulong - Longshan line was divided into two lithofacies assemblages. In the south of the line, gray and dark gray carbon-containing calcareous mudstone and argillaceous limestone were mainly deposited, and the carbonate composition is significantly increased compared with the lower part of Longmaxi Formation, while the north of the line is still dominated by terrigenous fine clastic rocks with little carbonate composition, and composed of gray thin-medium carbon-containing silty mudstone and siltstone.

6. Sedimentary model of the black shales in Wufeng and Longmaxi Formations

Although Wufeng and Longmaxi Formations developed the same black shales, the formation mechanisms were different. There was a very short glacial event between the two sets of black shales, and the changes in sea level in the Ordovician-Silurian transitions were also quite frequent and influenced by multiple factors such as tectonic activity,

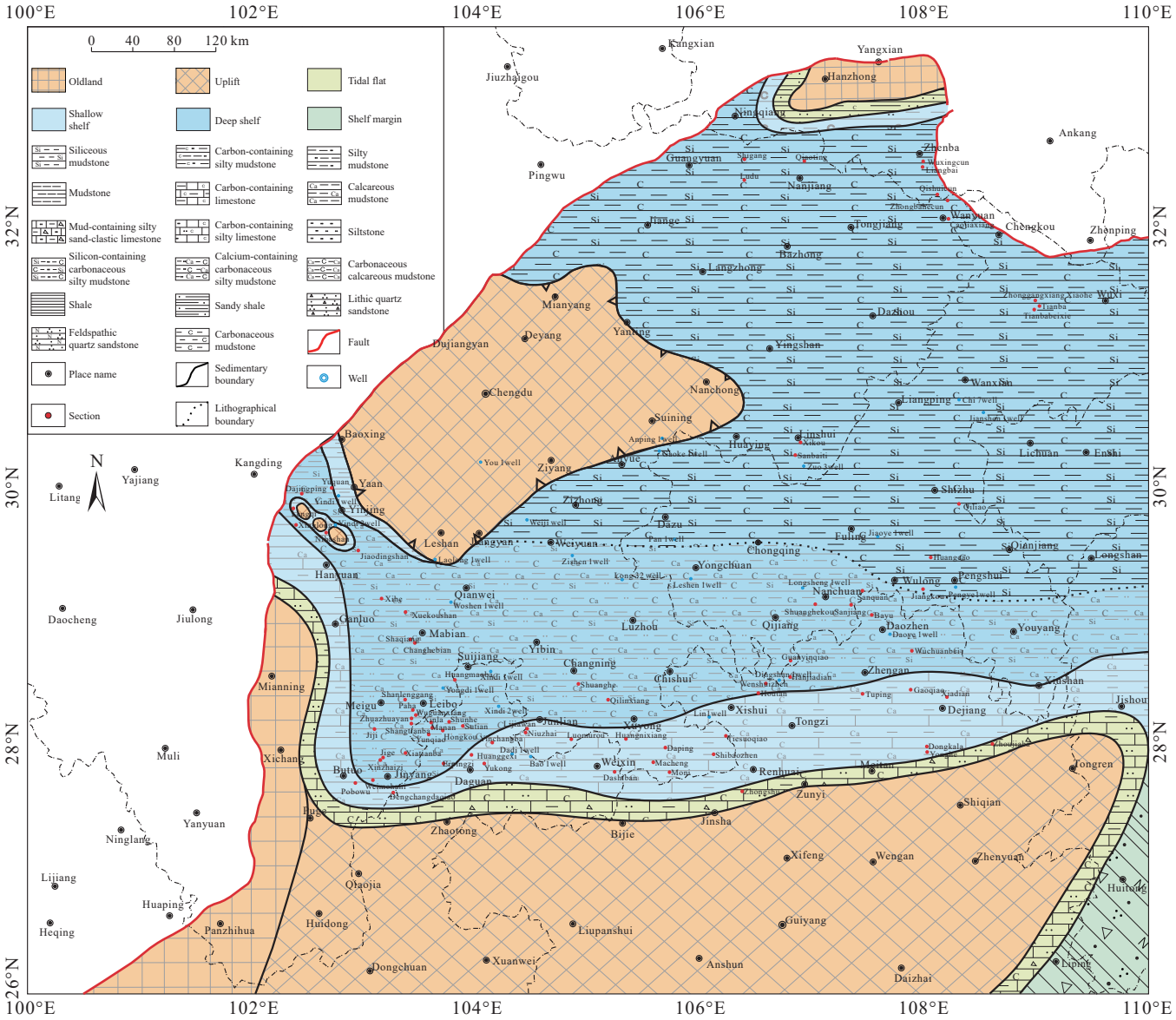

Fig. 17. Lithofacies paleogeography map of the organic rich shales from Longmaxi Formation in Sichuan Basin and its surrounding areas.

paleoclimate, global sea level change and terrigenous supply. In the Late Ordovician-Early Silurian, the Cathaysia and Yangtze Blocks collided due to Caledonian movement, uplifts (e.g., Central Guizhou, Central Sichuan, Western Sichuan and Central Yunan uplifts) constantly expanded and rose, the Yangtze area evolved into a semiclosed basin. As the marginal uplifts expanded, the basin base descended, and sea level rose relatively, coupled with frequent volcanic eruption events caused volcanic ash to fall to the surface of the sea and provide a lot of nutrients for the flourishing of organisms. Under these multiple factors, the lower part black shales of Wufeng formation were deposited in the Yangtze area instead of carbonate rocks. In the early Hirnantian, because of the sustained collision, the basin base continued to decline. However, the Gondwana glaciation started and the global sea level dropped. Since the falling rate of the basin base is ⩾ the descent of the sea level caused by the glaciation, black shales were still deposited in the Yangtze area in the upper part of the Wufeng formation with comparatively low TOC. In the middle Hirnantian, because of the sustained collision, the basin base continued to decline. The falling rate of the basin base was ⩽ the descent of the sea level caused by the glaciation, and the relative sea level went down, depositing the siltstones of the Guanyinqiao Formation. In the late Hirnantian, the change trend of the sea level corresponded with that of the early Hirnantian, and the sea level increased, the bottom black shale of Longmaxi Formation were deposited. In the Rhuddanian (Early Silurian), the ice melted, global sea level went up, and a new round of frequent volcanic eruption events restarted, which provided more food supplies for marine surface organisms and algae, resulting in the continuous deposition of black shale in the lower part of Longmaxi Formation (Fig. 19). To sum up, although there is no difference between the two sets of black shales in appearance and morphology, the genetic mechanism of their formation is not the same. When studying the main controlling factors of their organic matter enrichment and preservation, in addition to the factors of black shales and

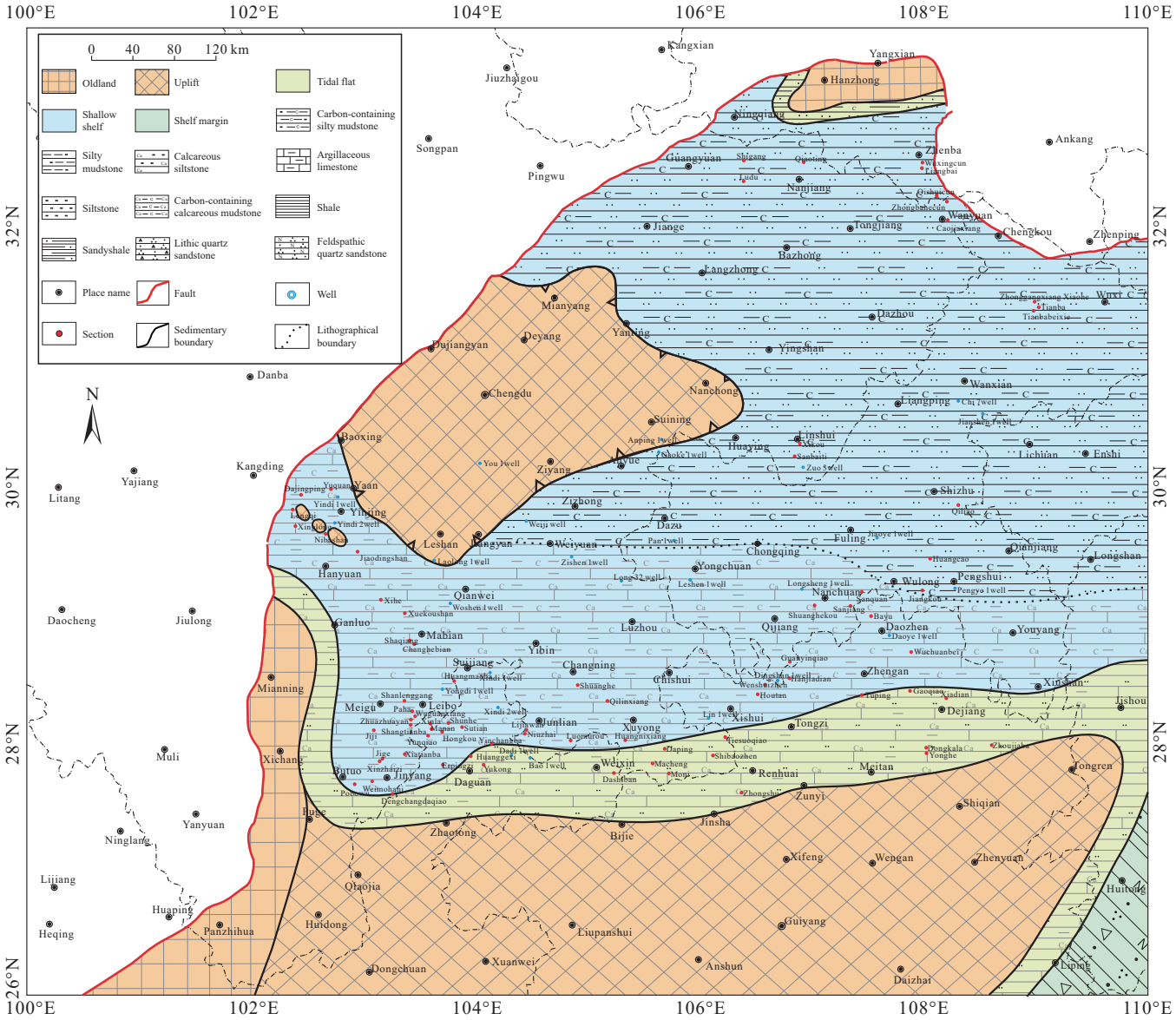

Fig. 18. Lithofacies paleogeography map of the upper part of Longmaxi Formation in Sichuan Basin and its surrounding areas.

ancient seawater environment, the influence of volcanic activity and glaciation should not be ignored. During the sedimentary period of the Wufeng Formation, only tectonic compression caused the depositional basement to decline, and the anoxic environment resulted in the deposition of the black shales. However, the black shales of Longmaxi Formation were deposited after the melting of glaciers. The melting and tectonic compression both led to the rise of sea level and intensified the anoxic environment, thus promoting the burial and preservation of black organic matter.

7. Shale gas potential evaluation

At present, the recoverable geological resources of the shale gas in China are 2.508×10^{12} m^3, of which 1.45×10^{12} m^3 is recoverable in South China, accounting for 58%, mainly distributed in the Sichuan Basin and its surrounding areas (Nie HK et al., 2019). The yearly shale gas production in China exceeded 220×10^{8} m^3 in 2021,and shale gas has become an important part of the exploration of unconventional oil in China (Zhang JC et al., 2021, 2022).

At present, for the Wufeng-Longmaxi Formations black shale, a key formation for marine shale gas exploration in South China, the authors have established a series of shallow national shale gas exploration demonstration zones with a buried depth of less than 3500 m in Fuling, Changning-Weiyuan and Zhaotong, and are about to break through the deep shale gas zone of 3500–4500 m in Luzhou. By the end of 2020, the shale gas geological reserves of Wufeng-Longmaxi Formations in Sichuan Basin are 2.0×10^{12} m^3, and the recoverable reserves are about 4700×10^{8} m^3. With the enhancement of shale gas exploration degree and technology in middle-shallow and complex structural areas in South China, the exploration in deep and ultra-deep shale gas fields has been promoted. Deep shale gas (buried more than 3500 m) has become an important strategic replacement area for subsequent shale gas exploration and development. At present, a number of wells in the Wufeng Longmaxi

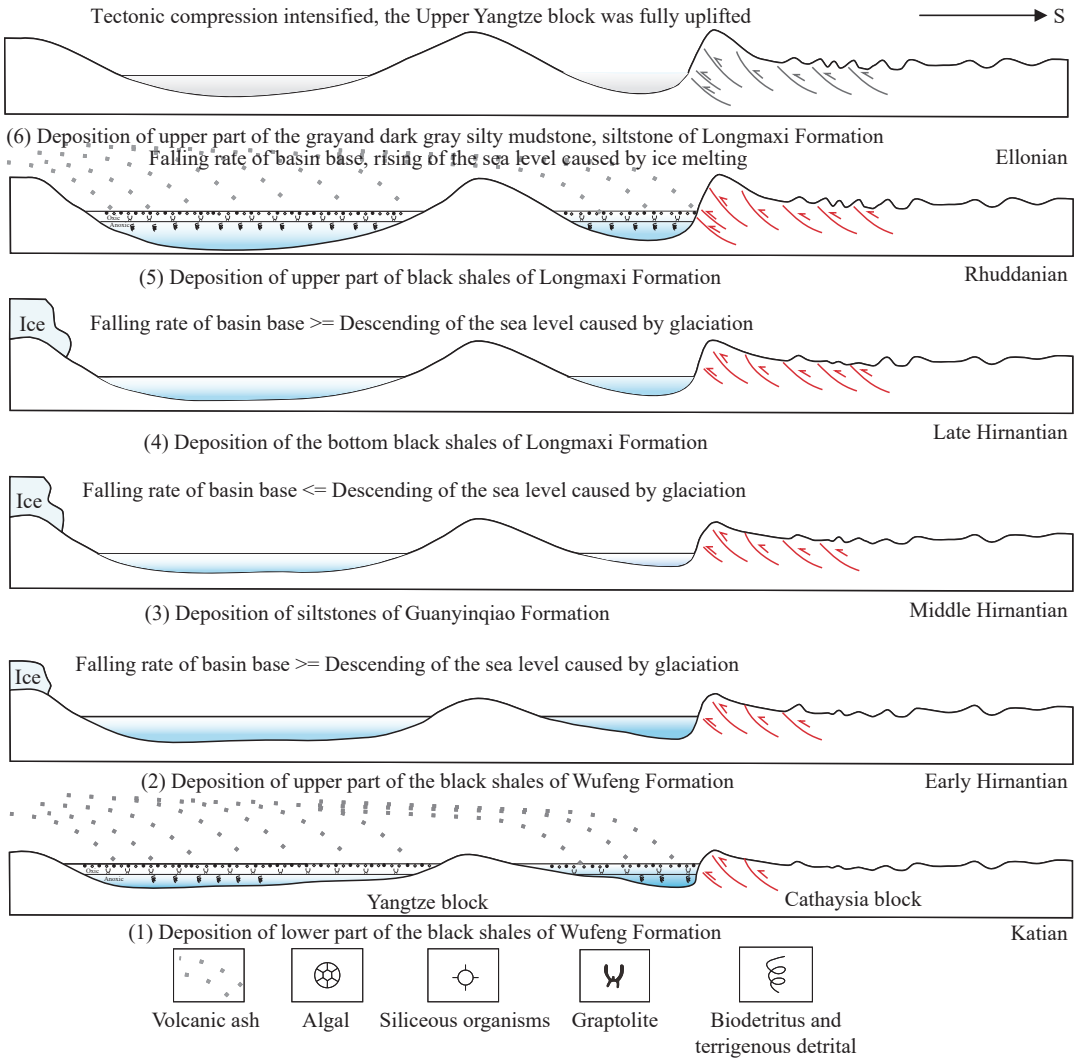

Fig. 19. Depositional model of black shales of Wufeng and Longmaxi Formations in Sichuan Basin.

Formation in Dingshan-Dongxi, Weiyuan-Yongchuan, Changning-Luzhou and other areas in the Sichuan Basin have obtained high-production shale gas, which further confirms the huge resource potential of the -deep-ultra deep shale gas field in the Sichuan Basin and its surrounding areas, and is a strategic replacement field for increasing shale gas storage and production in China in the future (Guo XS et al., 2022).

For the complicated structural belts in South-west edge of Yangtze, the influences of the complex faults, frequent tectonics and magmatic activities on the preservation of the shale gas is a key factor for shale gas accumulation and high production. In the previous work of public welfare shale gas basic survey conducted by China Geological Survey, Chengdu Center of China Geological Survey has successively deployed several shale gas survey wells in southwestern Sichuan and northeastern Yunnan. The thickness of the organic-rich shales in Xindi 2 well is 32 m, and the average field analytical gas volume is 2.01 m^3/t; the thickness of organic-rich shale in Yundadi 3 well is 40 m, and the average field analytical gas volume is 0.80–2.23 m^3/t. The thickness of organic-rich shale in well Yundaye 1 well is 38 m, and the field analytical gas volume is 2.90–9.68 m^3 /t (Yang YM et al., 2021). All the three wells with favorable gas logging shows are all in deep water shelf environment. The geological characteristics of the shale gas show that the shale gas resources of the Suijiang-Leibo-Daguan complicated structural area in southwestern Sichuan Basin have a bright prospect, and if the tectonics, magmatic activities or fault system do not damage the shale gas preservation in this area, the shale gas resource potential can be further enhanced.

The Luzhou-Zigong area, Weirong-Yongchuan area and Nanchuan-Dingshan area are geographically close to Changning-Weiyuan and Fuling shale gas fields. The sedimentary facies is deep water shelf facies which is consistent with that of the two gas exploration demonstration areas. The thickness, mineral composition and pore characteristics of the black shale of Wufeng-Longmaxi Formation are similar to those of Changning-Weiyuan and Fuling blocks. In addition, during the exploration of deep shale gas by CNPC (China National Petroleum Corporation) and Sinopec, multiple wells (WY1, YY1, DY2, DY4, DYS1, L203, Z201-H1) all showed industrial gas flow. In YY1 well region of Yongchuan area, 6 wells were tested with a daily gas rate of (8— 14) $\times 10^4$ m^3 with 234×10^8 m^3 proven reserves; 3 deep Wells in Dingshan area were tested with a daily gas rate of (5–15) $\times 10^4$ m^3, DYS1 well in Dongxi area

was 31.18×10^4 m^3, L203 well in Luzhou area was138×10^4 m^3, and Z201-H1 well in Dazhu area was 46×10^4 m^3 (He ZL et al., 2021). With further understanding of enrichment regularity of the deep shale gas resources, the continuous improvement of geological selection and sweet spot prediction methods and technologies, and the continuous improvement of drilling and fracturing technology and equipment system, Luzhou-Zigong area, Weirong-Yongchuan area, and Nanchuan-Dingshan area will become the key blocks of shale gas exploration in the next stage.

8. Conclusions

(i) Based on petrological characteristics, fossils, sedimentary sequences and structures, and laboratory analyses, the Wufeng, Guanyinqiao, and Longmaxi Formations can be classified into shore facies, tidal flat, shoal, shallow water shelf, and deep water shelf facies. This classification confirms the presence of shallow water deposition between the two sets of black shales in the Wufeng and Longmaxi Formations.

(ii) Although Wufeng and Longmaxi Formations developed the same black shales, their formation mechanisms were different. The Upper Yangtze area transitioned from a cratonic marine basin to a basin enclosed by uplifts. Frequent volcanic eruptions deposited volcanic ash on the sea surface, providing abundant nutrients that supported the flourishing of marine organisms. Under these combined influences, the black shales of the Wufeng Formation were deposited. Subsequently, tectonic compression between the Yangtze and Cathaysia landmasses intensified, causing the basin's basement to subside further. Melting glaciers led to rising sea levels, and a new phase of frequent volcanic eruptions began, supplying additional nutrients to marine organisms and algae. This resulted in the continuous deposition of black shale in the lower part of the Longmaxi Formation.

(iii) From the perspective of basic sedimentary geology and shale gas geological characteristics, the Suijiang-Leibo-Daguan area, Luzhou-Zigong area, Weirong-Yongchuan area, and Nanchuan-Dingshan area, located on the southwest margin of the Sichuan Basin, may be key regions for shale gas exploration of the Wufeng-Longmaxi Formations in the next stage.

CRediT authorship contribution statement

Xiang-ying Ge, Chuan-long Mou and Xin Men conceived of the presented idea. Qian Hou, Bin-song Zheng and Wei Liang carried out the experiment. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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