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Research paper

# Benthic foraminifera distribution and sedimentary environmental evolution of a carbonate platform: A case study of the Guadalupian (middle Permian) in eastern Sichuan Basin

Yifeng Peng [a], Hong Li [a,*], Marcelle BouDagher-Fadel [b,*], Liangjun Wang [c], Dongdong Zhang [a], Tianyu Zheng [a], Kang Yang [a]

[a] Department of Geology, Northwest University, Xi'an 710069, China
[b] Office of the Vice-Provost (Research), University College London, Taviton Street, London WC1H 0BT, UK
[c] Sinopec Exploration Company, Chengdu 610041, China

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ABSTRACT

Benthic foraminifera are significant indicators of habitat changes and are useful for paleoenvironmental reconstruction. During the Permian period, the variation in species, individual sizes, and morphological characteristics of the different assemblages, such as the fusulinids, is a clue to paleoecological and paleoenvironmental interpretations. The eastern part of the Sichuan Basin, located near the equator in the middle Permian, Guadalupian period, was precipitated by thick beds of marine carbonate rocks with numerous benthic foraminifera. In this study, we record the species and calculate the frequency of benthic foraminifera from 445 thin sections of Guadalupian (Maokou Formation) marine carbonate rocks. Seven types of benthic foraminiferal biofacies are recognized and associated with five sedimentary microfacies in the Erya and Huilongchang sections, eastern Sichuan area. During the early Guadalupian period, small uniserial nodosariids and Endothyrida dominated the benthic foraminiferal assemblages; in the middle Guadalupian period, species of Miliolida, Ammodiscidae, and uniserial nodosariids were common; however, the species of Fusulinida, such as *Schwagerina* sp. and *Verbeekina* sp., were abundant in the late Guadalupian period. The associated sedimentary microfacies indicates a shallow open platform to marginal platform. In our study area, the early Guadalupian was deposited in an open platform to grain shoals. This was followed by gradual shallowing as the sedimentary environment shifted to marginal shallow shoals from the middle to late Guadalupian period until the paleoweathering abruptly terminated the deposition at the end of the Guadalupian period.

## 1. Introduction

Permian benthic foraminifera are of great importance to carbonate microfacies analysis and can be used to rebuild the paleosedimentary sequence (Flügel, 2004; BouDagher-Fadel, 2018). They include non-fusulinid benthic foraminifera and Fusulinida. Fusulinida have a complex construction with a volume over 3 mm$^3$ (Ross, 1974) and are associated with microscopic symbiotic algae (Hallock, 1985; Hohenegger and Yordanova, 2001; BouDagher-Fadel, 2018). These fusulinids exhibit a typical fusiform shape shown by some Holocene benthic foraminifera, such as the miliolides (e.g., *Alveolinella*), that today appear to be confined to normal shallow marine (at depths of 80 m), well-oxygenated, nutrient-rich, tropical, and subtropical water (BouDagher-Fadel, 2018). Fossil benthic foraminifera, such as the fusulinids, are inferred to be widespread in shallow and tropical carbonate sedimentary environments (Afzal et al., 2011; Sarkar, 2017; BouDagher-Fadel, 2018).

Due to different environmental preferences, benthic foraminifera species are distributed in various ecological environments (from salt marsh to warm water). Since larger benthic foraminifera genera, with various lifestyles, such as attached (e.g., *Triticites*), and infaunal (e.g., *Pachyphloia*) lifestyles, have different levels of environmental sensitivities, their preferential accumulation reflects the environmental features, such as paleobathymetry and paleo-water energy. Moreover, benthic foraminifera distribution is influenced by nutrients, temperature, salinity and oxygen condition. This is reflected by the variation in

* Corresponding authors.
*E-mail addresses:* lihong2008@nwu.edu.cn (H. Li), m.fadel@ucl.ac.uk (M. BouDagher-Fadel).

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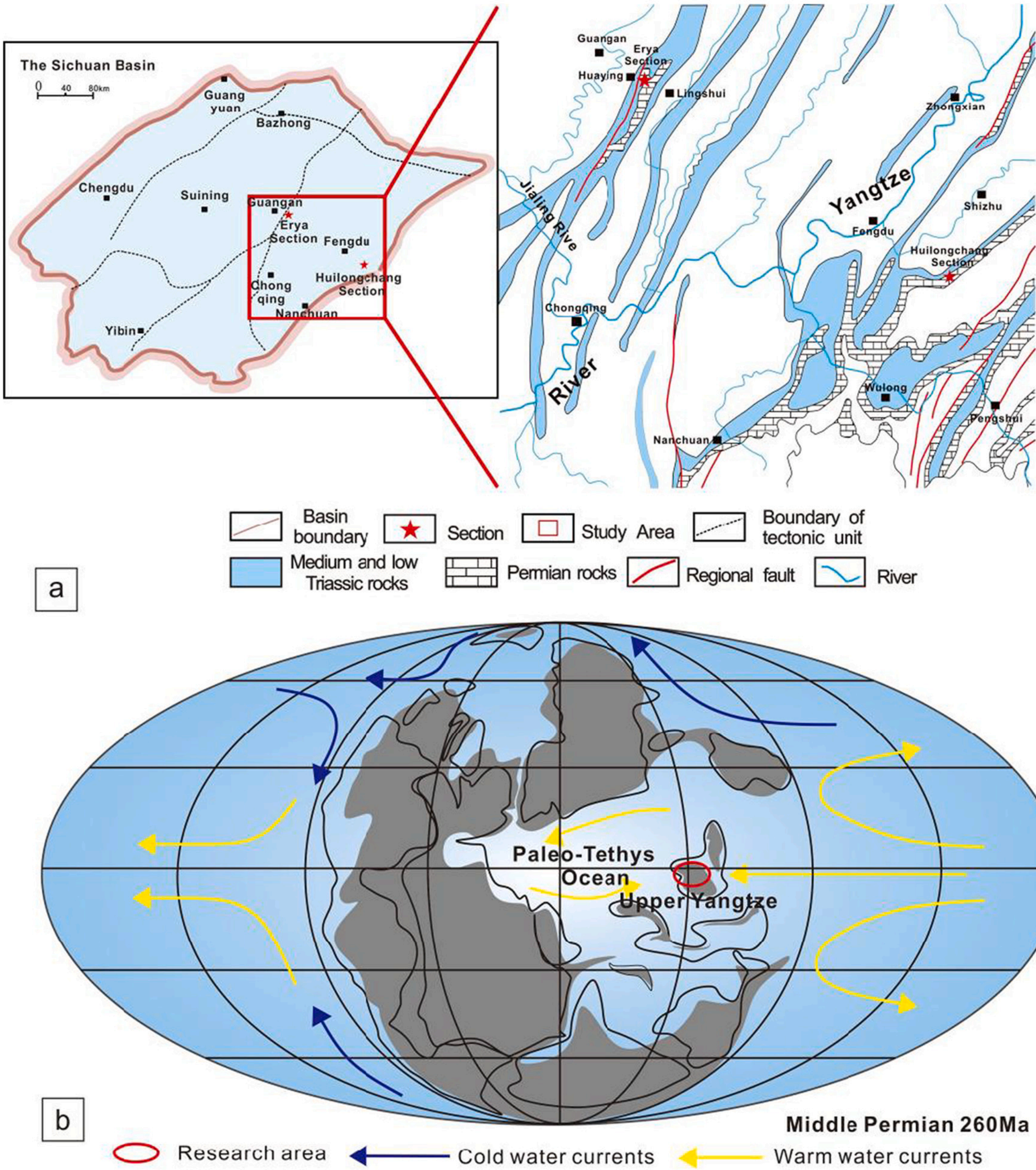


**Fig. 1.** Simple map of the study area.
(a) Location of the study area. (b) Middle Permian global paleocurrent reconstruction (modified from Yan and Zhao, 2002).

their sizes, morphology, and wall thickness, as well as the composition of foraminiferal shells, which are indicators of paleoenvironmental changes.

The eastern part of the Sichuan Basin, located near the equator in the middle Permian (Li et al., 2015; Fig. 1) was deposited as thick beds of warm carbonate rocks in shallow water, containing numerous small benthic foraminifera, fusulinids, and corals. Many previous studies on the eastern Sichuan area were used by carbonate microfacies analysis to rebuild the paleogeography, but only few papers use benthic foraminifera as the main research object to interpret the paleoenvironment (Li, 1988; Bai and Zhou, 1990; Xue et al., 2018). By analyzing the features of benthic foraminifera groups, such as the individual morphological trends and the community variation rules, we recognized seven types of biofacies and five types of microfacies in Guadalupian (Maokou Formation) carbonate rocks. In this paper, we aim to evaluate the paleoecological significance of benthic foraminifera, and to reconstruct the sedimentary paleoenvironment in the Guadalupian period.

## 2. Geological setting

The research area is located in the eastern Sichuan Basin and is restricted by the boundaries of Huayingshan in the north, Dianjiang in the west, Nanchuan in the south, and Shizhu in the east (Fig. 1). In the Permian period, the Sichuan Basin belonged to a part of the Upper Yangtze platform, floating in the east of the Paleozoic Tethys Ocean as a small plate (Yan and Zhao, 2002). According to the regional stratigraphic investigation, concentrations of radioelements in rocks, index fossils (fusulinids: *Verbeekina* and corals: *Hayasakaia*), the Guadalupian period (Maokou Formation) is divided into the Roadian, Wordian, and Capitanian Stages from the bottom up in this paper (Fig. 2a; Lucas and Shen, 2018; Shen et al., 2019).

The Guadalupian (Fig. 2b, c, d, e, f) is mainly composed of limestones, dolostones, siliceous rocks and mudstones in the study area. The Roadian and Wordian Stages are dominated by grayish black, dark gray thin to middle layers of wackestones and packstones. The Capitanian

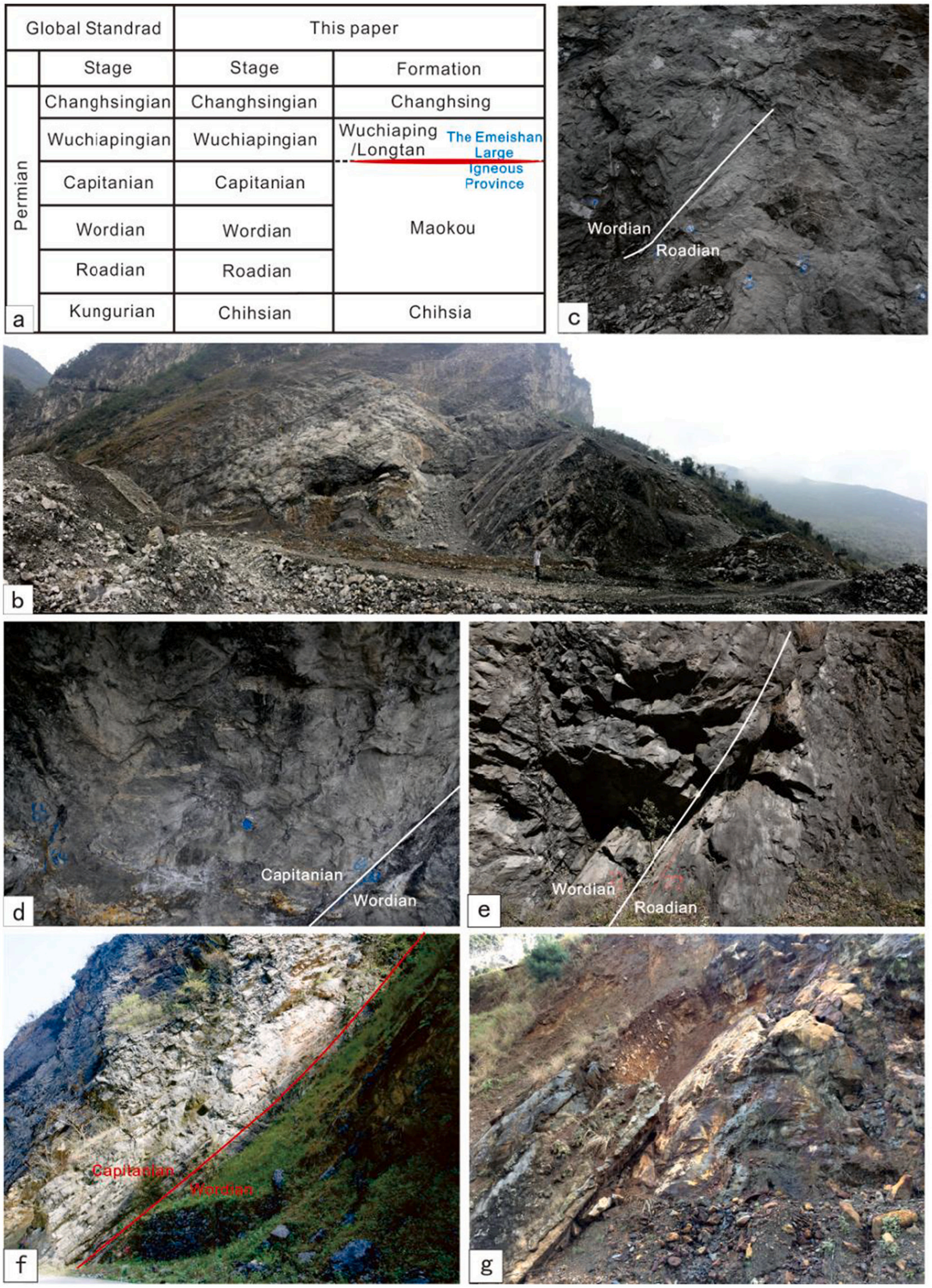


**Fig. 2.** Stratigraphic framework of the Guadalupian period (Maokou Formation).
(a) A simple stratigraphy and timescale of the Guadalupian period (Lucas and Shen, 2018; Shen et al., 2019). (b) The Roadian Stage in the Erya Section. (c) The boundary between the Roadian and Wordian Stages in the Erya Section. (d) The boundary between the Wordian and Capitanian Stages in the Erya Section. (e) The boundary between the Roadian and Wordian Stages in the Huilongchang section. (f) The boundary between the Wordian and Capitanian Stages in the Huilongchang section. (g) The paleoweathering crust on top of Guadalupian carbonate rocks in the Huilongchang section.

Stage is characterized as light gray and off-white thick layers of bioclastic grainstones, packstones, interbedded by thin cherty layers or nodules, dark gray to light gray dolostones and dolomitic limestones. Moreover, the Guadalupian contains various fossils, such as fusulinids, non-fusulinid benthic foraminifera, gastropods, brachiopods, corals, ammonoids, and echinoderms (Fig. 3 and Fig. 4a–e), indicating a tropical marine- and shallow-water environment.

## 3. Material and methods

All the work was conducted on the two bases of profile measurement of two lithological sections, the Erya section (northwest) and

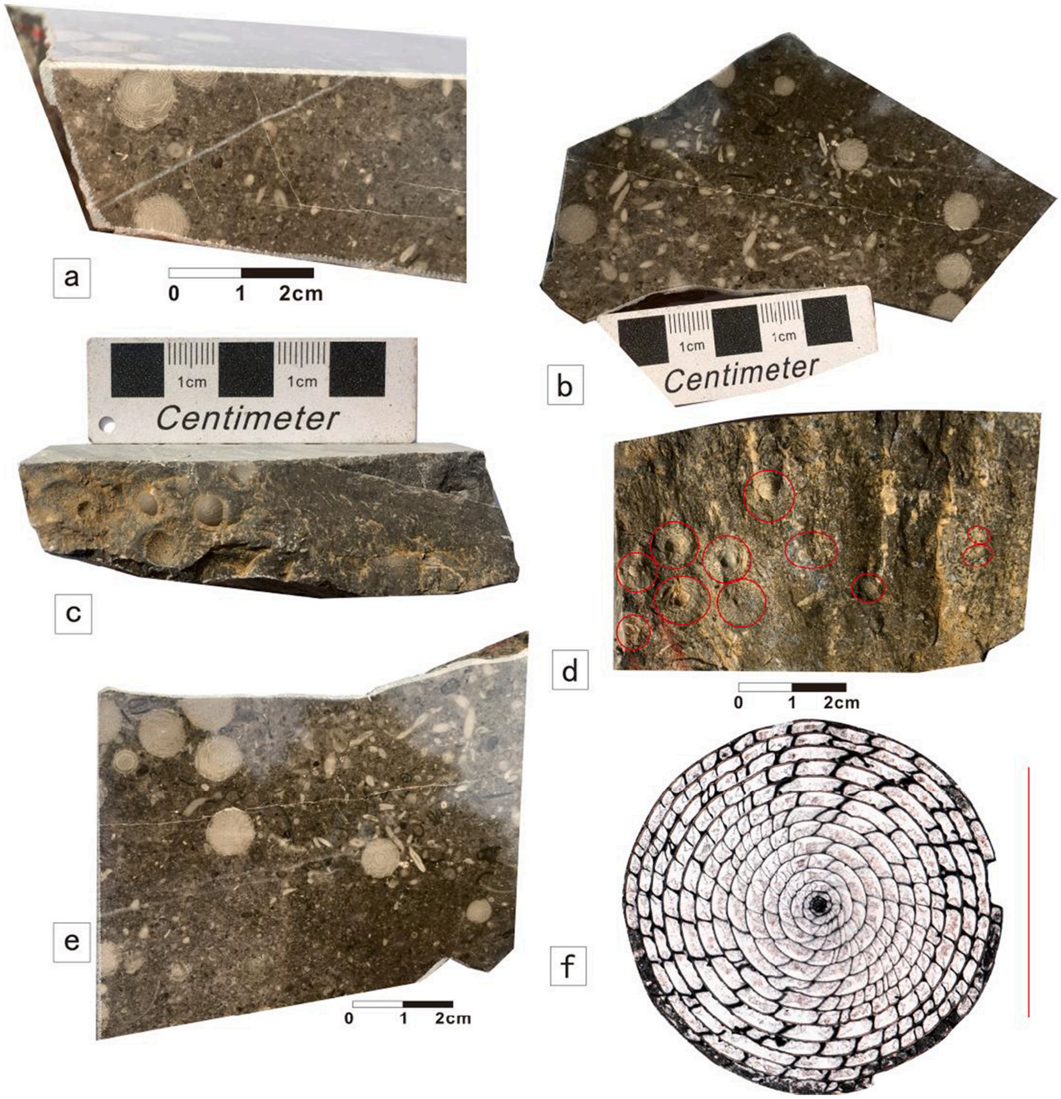


**Fig. 3.** The benthic foraminifera and fusulinid fossils in the Huilongchang section.
(a)–(e) Various cross-sections of fusulinids and non-fusulinid benthic foraminifera in the polished specimens in the Capitanian Stage in the Huilongchang section. Scale bar = 1 cm. (f): *Verbeekina heimi* Thompson and Foster. An axial section taken by microscope from the same specimen. Scale bar = 500 μm.

Huilongchang section (southeast). These two sections are successive and complete in the Guadalupian period. 445 thin sections were taken from these two sections for microfacies analyses, 279 of them from the Erya section, and 166 from the Huilongchang section. All the samples were sectioned into 35 × 20 × 0.03-mm$^3$ thin slices. A few slices prepared from both the sections were half stained with alizarin-S for dolomitization observing. According to the dominant species, group characteristics, abundance, and cluster analysis, we divided all benthic foraminifera into seven types of benthic foraminiferal biofacies.. Then, we correlated the biofacies to five sedimentary microfacies.

The typical benthic foraminifera in the study area are shown in Table 1 (the species classifications are based on Vachard et al., 2010; Gaillot and Vachard, 2007; Pawlowski et al., 2013; Vachard, 2018; BouDagher-Fadel, 2018).

## 4. Results

### 4.1. Identification of several typical benthic foraminifera

#### 4.1.1. Tetrataxis and Climacammina

*Tetrataxis* and *Climacammina* both have double-shell structures, with an inner layer of fiber-layer structures and an outer layer of cryptocrystalline structures (Fig. 5a). Yu (1989) found that the foraminifera with this structure appeared in both high-energy and low-energy environments in the shallow sea. Their lenticular shape helps maintain stability in a turbulent environment (Ferguson, 1962; Henbest, 1963; Gallagher, 1998). Most of them, however, appeared in the transition zone from high to low energy environment, or in a high-energy environment. Cossey and Mundy (1990) and Vachard et al. (2010) suggested that *Tetrataxis* were easily attached to substrates, such as corals or algae. They change their position flexibly, so they can be found in algal forests with crinoids and bryozoans in open subtidal zones or under below-normal wave conditions, repeatedly washed by currents and storms (Flügel, 2004). In the study area, *Tetrataxis* and *Climacammina* were found in Roadian and Capitanian Stages, respectively, indicating a shallow and high-energy environment.

#### 4.1.2. Tubothalamea

According to molecular phylogenetics (Pawlowski et al., 2013), Miliolida, Spirillinida, and Ammodiscidae of the Textulariida are believed to have the same feature of tubular chambers during early development and should be categorized as Tubothalamea. Based on the

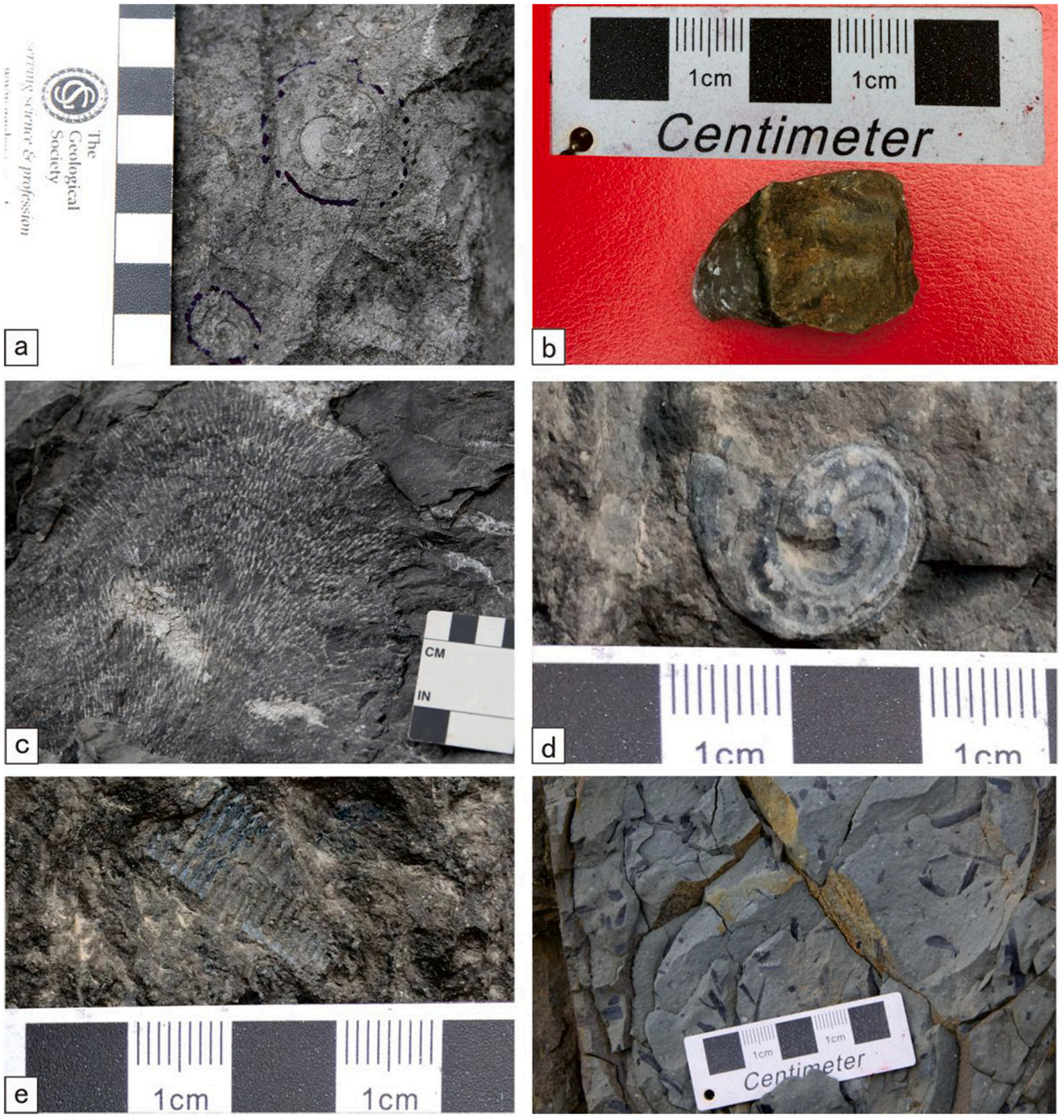


**Fig. 4.** The fossils in the Guadalupian period in the eastern Sichuan Basin.
(a): Gastropods. (b): Bivalve *Hemiptychina* sp. (c): Coral *Hayasakaia* sp. (d): Ammonoid. (e): A fragment of crinoids. (f): Plant fragments in Longtan Formation interbeded between Guadalupian paleoweathering curst and Wuchiapiangian carbonate rocks.

**Table 1**
The typical benthic foraminifera in the Guadalupian period, eastern Sichuan Basin.

| Order | Superfamily | Species |
|---|---|---|
| Endothyrida | Palaeotextularioidea | *Climacammina*, *Deckerella*, *Cribrogenerina* |
| | Tetrataxoidea | *Tetrataxis* |
| | Globivalvnlinoidea | *Globivalvalina* |
| Fusulinida | Ozawainelloidea | *Ozawainella* |
| | Schwagerinoidea | *Triticites* |
| | Neoschwagerinoidea | *Neoschwagerina*, *Yabeina kaizensis* |
| | Verbeekinidea | *Verbeekina* |
| Nodosariida | Nodosariodea | *Geinitzina*, *Nodosaria*, *Pachyphloia*, *Padangia* |
| Pseudoammodiscida | Tuberitinoidea | *Eotuberitina*, *Neotubertina* |
| Class | Order | Species |
| | Miliolida | *Hemigordius* |
| Tubothalamea | Superfamily | Species |
| | Ammodiscidae | *Ammodiscus*, *Glomospira* |

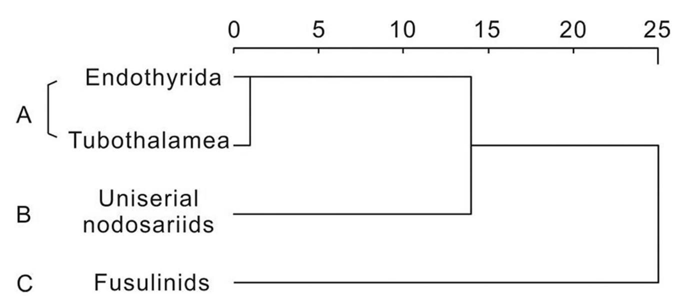


**Fig. 5.** Dendrogram showing benthic foraminiferal groups recognized by cluster analysis.

morphogroup, the calcareous genera, *Hemigordius* and *Spirillina* with planispiral tests or irregular coiling, have trophic strategies and epifaunal lifestyle similar to those of the agglutinated foraminifera *Ammodiscus* and *Glomospira* (Nagy et al., 2009; Reolid et al., 2008). Therefore, *Hemigordius*, *Ammodiscus*, and *Glomospira* are attributed to epifaunal habitat and herbivore feeding. Nagy (1992) proposed that

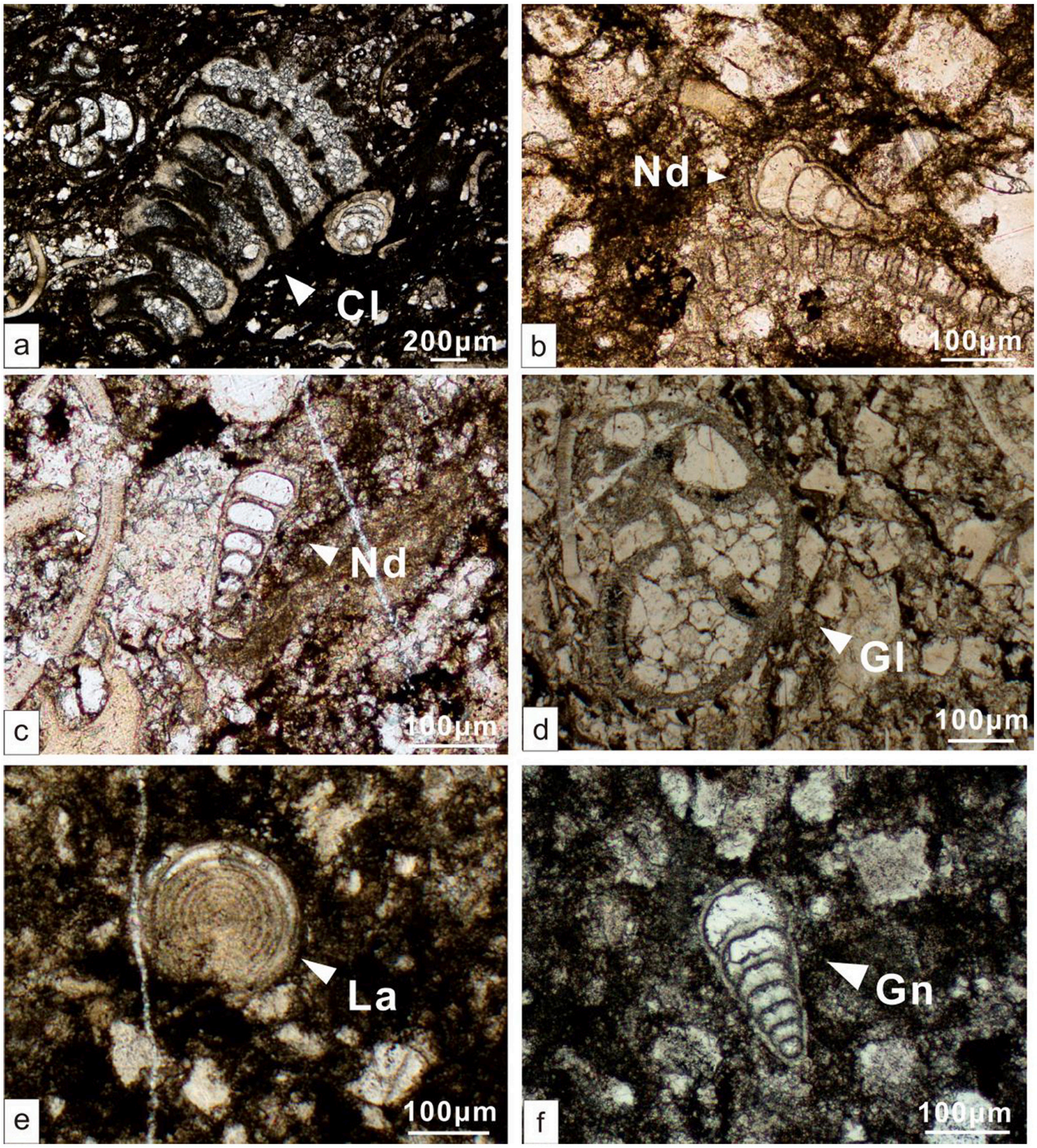


**Fig. 6.** (a)–(b):BF1 Endothyrida + uniserial nodosariids, (c)–(f): BF2 Uniserial nodosariids + Tubothalamea/Endothyrida.
(a) *Climacammina* sp. (Cl). (b) *Nodosaria* sp. (Nd) (c) *Nodosaria* sp. (Nd). (d) *Globivalvalina* sp. (Gl). (e) Lasiodiscids (La). (f) *Genitzina* sp. (Nd).

*Ammodiscus* lives on the flocculent bottom surface layer or on macroscopic algae. These genera may represent an oxygenated condition.

In the study area, *Hemigordius, Ammodiscus* and *Glomospira* were found together during the whole Guadalupian period (Fig. 6c, d). In the Wordian Stage, however, their proportion was higher than that in the Roadian and Capitanian Stages.

### 4.1.3. Tuberitinoidea (Diplosphaerina)

Owing to the different shapes of the sections, there are quite a few synonyms of *Eotuberitina*, such as *Tuberitina* and *Diplosphaerina* (Zheng, 1989). BouDagher-Fadel (2018) suggests that the small resilient foraminifera ("disaster forms") survived the end Devonian event. Some species disappeared during the early Carboniferous period, with only the Tuberitinidae surviving into the Permian period (BouDagher-Fadel, 2018). Song (2012) believes that *Diplosphaerina inaequalis* (*Eotuberitina*) is a disaster species that survived from Permian/Triassic Extinction and remained in early and middle Triassic periods.

In this study area, *Eotuberitina* and *Neoeotubertina* were often found in wackestones and packstones during the whole Guadalupian period (Fig. 12h–j). They were speculated to be opportunistic species with small, round shapes, prosperous in shallow water under medium-water-energy and low- to -high aerobic conditions.

### 4.1.4. Fusulinids

Most fusulinids live in tropical and subtropical shallow water (Vachard and Kabanov, 2007), and they are widely distributed in the ocean. *Sphaeroschwagerina /Pseudoschwagerina* can be found from 45°S to 45°N (Vachard and Kabanov, 2007). Their ecological distribution varies from the platform to the marginal slope. Some species of Schubertelloidea in the late Permian period are adapted to a high-salinity-evaporation environment (Vachard et al., 2010). The tests shape indicates a shallow-water environment with different depths and different energy. The fusiform and elongated-spindle shapes indicate high-water-energy conditions, and the spherical shape indicates a low-water-energy condition (Ross, 1982; Wang et al., 1982; Beavington-Penney and Racey, 2004).

Small fusulinids mainly appeared in the Wordian Stage in the Huilongchang and Erya sections, and few were found in the Roadian Stage.

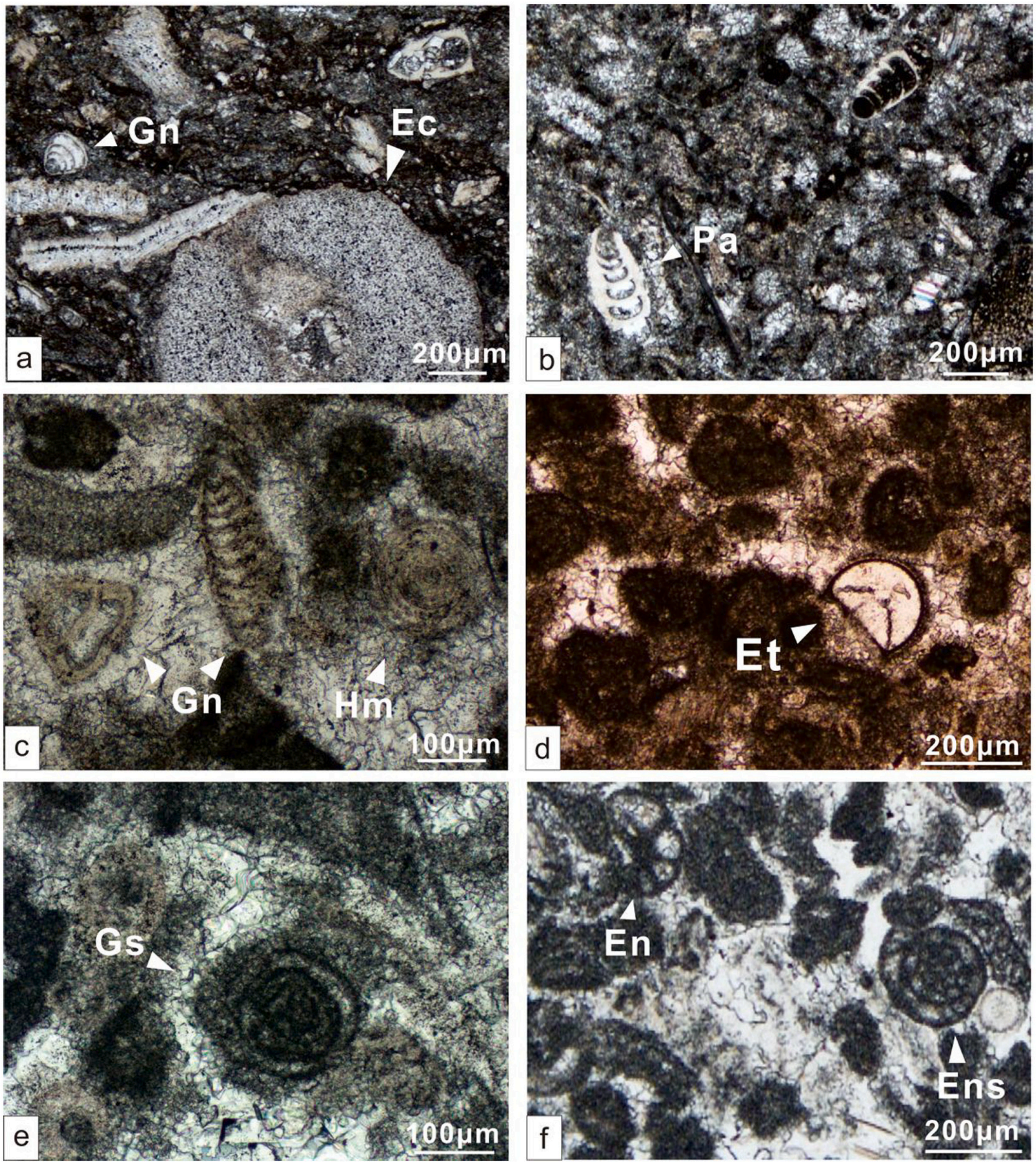


**Fig. 7.** (a)–(b): BF3 Uniserial nodosariids, (c)–(f): BF4 Fusulinids + Tubothalamea + uniserial nodosariids.
(a): *Geinitzina* sp. (Gn) and echinodermata (Ec). (b): *Pachyphloia* sp. (Pa). (c): *Hemigordius* sp. (Hm) and *Geinitzina* sp. (Gn). (d): *Eotuberitina* sp. (Et) (e): *Glomospira* sp. (Gs). (f): *Endothyra* sp. (En) and *Endothyranopsis* sp. (Ens).

Their sub-spherical globular shape indicates a preference to a still-water environment. The elongate fusiforms, e.g., *Schwagerina* and *Sumatrina*, are common in high-water-energy regions in marginal shallow shoals.

### 4.2. Cluster analysis

In this paper, the frequency of different benthic foraminifera in each lithologic slices of two sections was counted, and 264 valid data were obtained. Using SPSS software, square Euclidean distance was selected to perform Q-type clustering of data. Cluster analysis results are usually expressed in dendrograms. According to the principle of cluster analysis, the closer the sample positions are in a dendrogram, the more similar they are, and vice versa.

According to Fig. 5, Endothyrida and Tubothalamea have a great correlation when the distance coefficient is within the range of 5 and show a good clustering effect. When the distance is within the range of 15, they can be divided into three categories: Endothyrida and Tubothalamea, uniserial nodosariids, and Fusulinid.

The first category mainly includes *Climacammina*, *Deckerella*, *Cribrogenerina*, *Tetrataxis*, *Globivalvalina*, *Globivalvalina*, *Hemigordius*, *Ammodiscus*, and *Glomospira*, which mainly represent medium- to high-water energy conditions. The second category includes *Geinitzina*, *Nodosaria*, *Pachyphloia*, and *Padangia*, which represent low-to-medium-water- energy conditions. The third type contains *Yabeina*, *Schwagerina*, *Sumatrina* and *Verbeekina*, which shows a good ecological shallow environment. Combined, the three categories can be roughly divided into seven biofacies according to different combination types.

### 4.3. Seven types of benthic foraminifera biofacies (BF1–7)

Seven types of benthic foraminifera biofacies were recognized.

#### 4.3.1. BF1 Endothyrida + uniserial nodosariids (Fig. 6a–6b)

*BF1-1 Palaeotextularioidea + uniserial nodosariids + Globivalvalina*

*BF1-2 Globivalvalina + uniserial nodosariids*

*Description*: Textural compositions include micrite, microspar calcite,

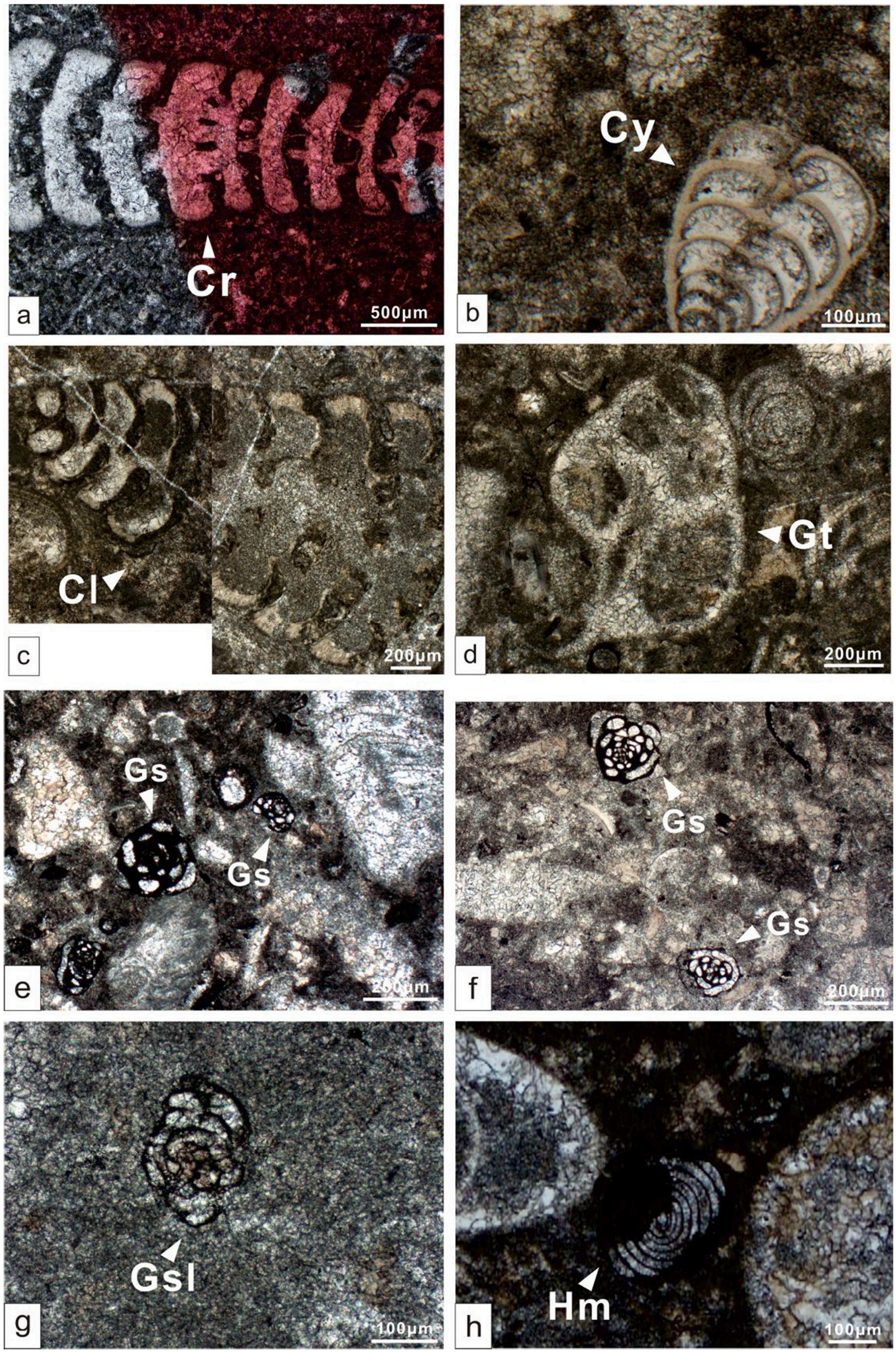


**Fig. 8.** (a)–(d): BF5 Endothyrida+ Fusulinids+ uniserial nodosariids, (e)–(h): BF6 Tubothalamea + uniserial nodosariids.
(a): *Cribrogenerina* sp. (Cr). (b): *Cryptoseptida* sp. (Cy). (c): *Climacammina* sp. (Cl). (d): Gastropod (Gt). (e) (f): *Glomospira* sp. (Gs). (g): *Glomospirella* sp. (Gsl). (h): *Hemigordius* sp. (Hm).

terrestrial clay, and fossils. In a high-clay-content environment, taper-shaped benthic foraminiferal walls become thicker, the morphologies become more complex, and the sizes are larger than those in a low-clay-content environment. Palaeotextularioidea (*Climacammina*, *Cribrogenerina*) are elongate and tapered in form. Uniserial nodosariids have considerable diversity, including *Geinitzina*, *Nodosaria*, *Pachyphloia*, and *Padangia*. *Tetrataxis* occurs occasionally. Sometimes the tests are broken and were arranged in elongate orientation. Additionally,

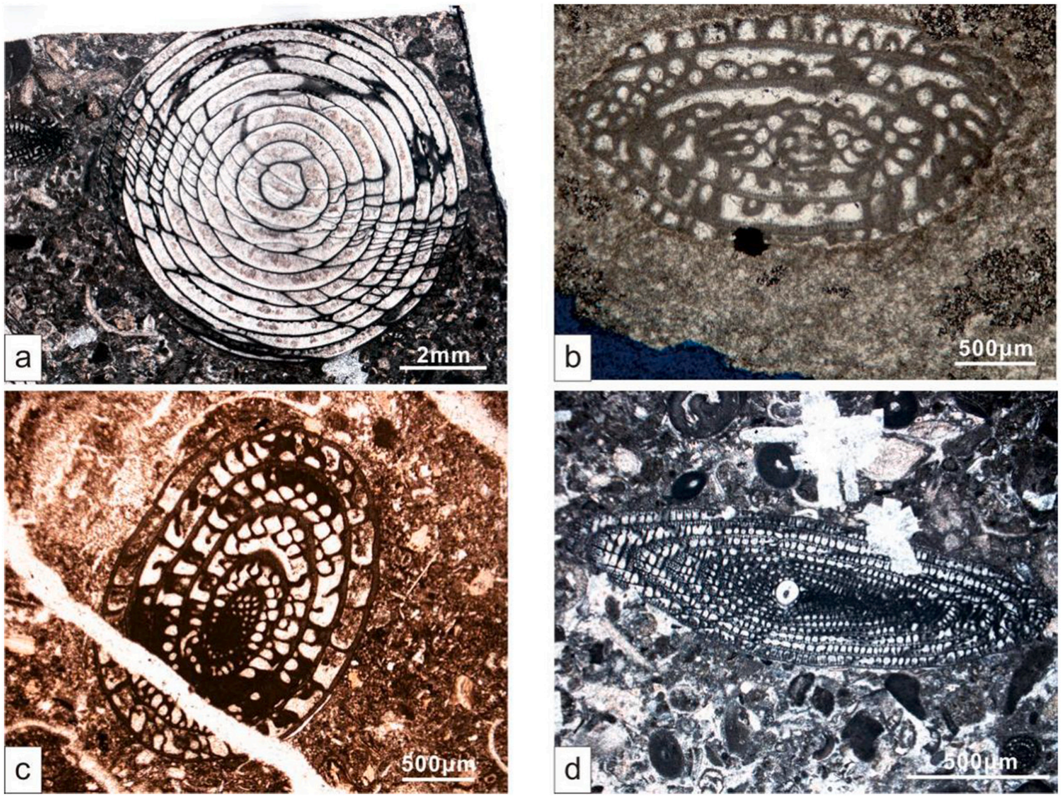


**Fig. 9.** BF7 Fusulinids. (a): *Verbeekina* sp. (b)–(c): *Schwagerina* sp. (d): *Sumatrina* sp.

**Table 2**
Classification of sedimentary facies in the Guadalupian period, eastern Sichuan Basin.

| Sedimentary facies | | Microfacies | Benthic foraminiferal biofacies types |
|---|---|---|---|
| Marginal platform | Marginal shoal | Marginal shallow shoal | BF1, BF6, BF7 |
| | | Dolomitized shoal | BF2 |
| | Grain shoal | Grain shoal | BF1, BF3, BF5, BF6 |
| Open platform | Open marine | Open marine | BF2, BF3 |
| | | Bioclastic shoal | BF3, BF4, BF7 |

other fossils of bivalves, ostracods, brachiopods, brachiopod spines, and bryozoans are included along with a small number of corals and algae.

*Interpretation*: The thicker walls of Palaeotextularioidea and uniserial nodosariids may contribute to wave resistance. High diversities and complex individual structures indicate a good nutritional environment. *Tetrataxis* and *Climacammina* are attached foraminifera (Vachard et al., 2010), possibly attached to algae or corals at a water depth of about 10 m. These microfacies reflect a high-water-energy environment, possibly a marginal shallow shoal or grain shoal.

*4.3.2. BF2 Uniserial nodosariids + Tubothalamea /Endothyrida (Fig. 6c–6f)*

*BF2-1 Uniserial nodosariids + Globivalvalina*

*BF2-2 Uniserial nodosariids + Hemigordius/ Lasiodiscids*

*Description*: This microfacies is characterized by dolomitization, containing silt-sized subhedral to euhedral dolomite with planar crystal boundaries, sometimes only outlines remain of the original fossil fragments. The dominant genera belong to the small uniserial nodosariids with simple, elongated, or short-tapered forms, other genera are thin-walled *Globivalvalina* with near-spherical shapes and planispiral-coiled *Hemigordius* and Lasiodiscids, sometimes accompanied by crinoids, brachiopods, and ostracods.

*Interpretation*: According to Gaillot and Piuz (2002), behind the bioclastic shoals, yielded numerous *Hemigordius* and small Miliolida in the late Permian period. On the other hand, open marine environments are characterized by uniserial nodosariids (Vachard et al. (2010). These biofacies may represent an inner open platform environment.

*4.3.3. BF3 Uniserial nodosariids (Fig. 7a, 7b)*

*Description*: This microfacies has high lime mud content and is dominated by small uniserial nodosariids (<600 μm) with simple structures and elongated or short-tapered forms, accompanied by a large number of echinoderms, brachiopods, gastropods, algae and a few shell fragments.

*Interpretation*: Nodosariids often appear under low and moderate degree of oxygen depletion conditions in the bottom water (Koutsoukos et al., 1990). Uniserial nodosariids and occasional brachiopod fragments may represent grain shoal or an open marine environment, which have low and moderate oxygen concentrations.

*4.3.4. BF4 Fusulinids + Tubothalamea + uniserial nodosariids (Fig. 7c–7f)*

*Description*: This biofacies is mainly composed of grainstones with abundant bioclasts and pellets. The fossils are generally less than 200 μm. Dominant species are small fusulinids, simple and thin-walled uniserial nodosariids (*Geinitzina* and *Nodosaria*), spherical or near-spherical shapes of carbonate microgranular foraminifera with glomospire coiling, and few *Hemigordius*, Lasiodiscids, *Eotuberitina, Globivalvalina*, and echinoderms.

*Interpretation*: Globular and enrolled forms, well preserved (wear-free) suggest low-water-energy conditions. Fossils are preserved possibly in their original places. This microfacies represents very shallow-water conditions, such as bioclastic shoals, similar to SMF 17 (Flügel, 2004).

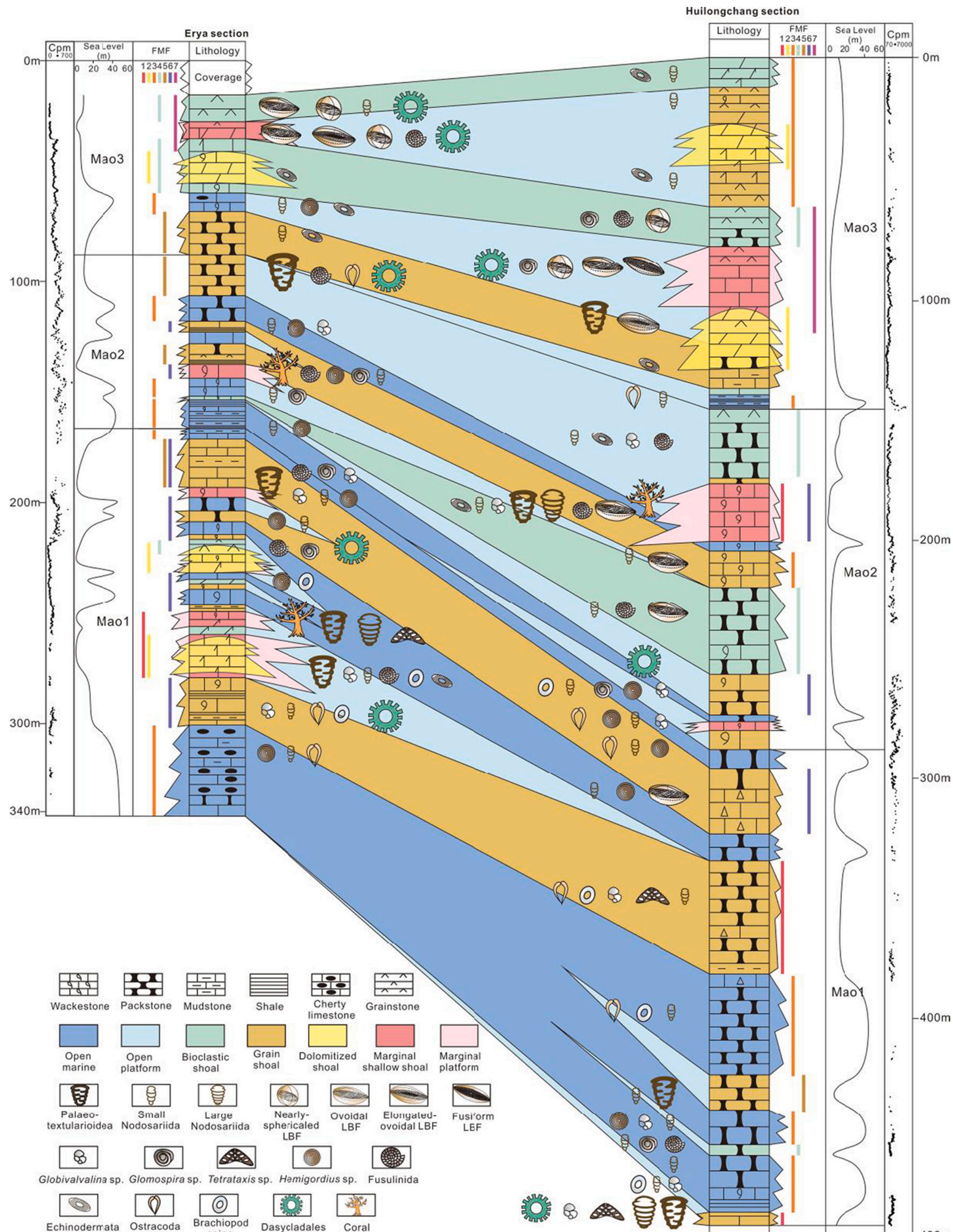


**Fig. 10.** Lithological profiles and sedimentary microfacies of the Guadalupian period in the Erya and Huilongchang sections.

#### 4.3.5. BF5 Endothyrida+ Fusulinids+ uniserial nodosariids (Fig. 8a–8d)

*Description*: This microfacies includes various kinds of fossils, often formed as packstones, and shells are usually broken. Endothyrida specimens are large, usually over 600 μm. Fusulinids are less than 600 μm. Uniserial nodosariids are small and have a complex structure. This microfacies comprised other organisms, such as echinoderms, ostracods, dasyclads, and gastropods.

*Interpretation*: Fossil fragments are rounded and incomplete, indicating high-water-energy conditions, which is confirmed by the presence of dasyclads. The thick walls of benthic foraminifera show the abilities of wave resistance. These features possibly represent grain shoals.

#### 4.3.6. BF6 Tubothalamea + uniserial nodosariids (Fig. 8e–8h)

*Description*: There are mainly packstones or wackestones in this microfacies, sometimes containing a small amount of intraclasts.

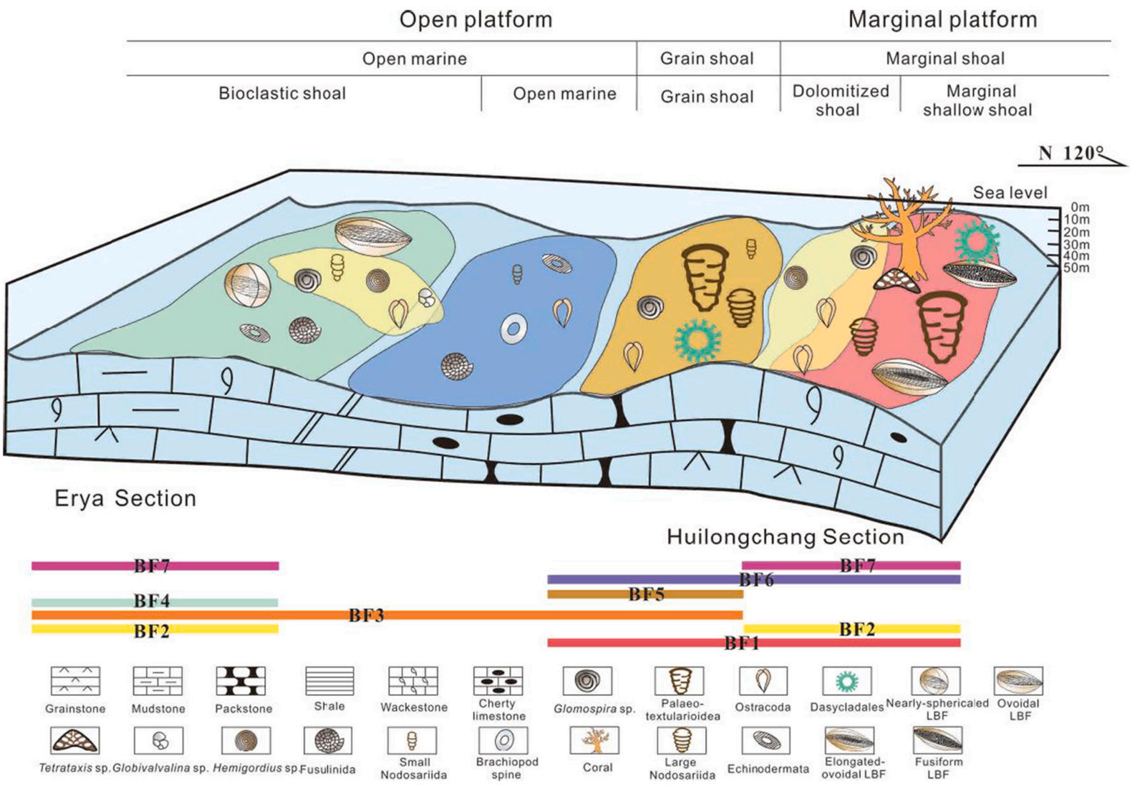


**Fig. 11.** Sedimentary model of the Permian Guadalupian period in eastern Sichuan Basin.

*Glomospira* and *Glomospirella* with russet margin are the dominant species, including other taxa such as *Hemigordius*, uniserial nodosariids, and *Globivalvalina*. Fragments of gastropods, brachiopods, fusulinids, bryozoans, and ostracods are also found scattered randomly in the micritic matrix.

*Interpretation*: The biotic assemblage indicates a relatively deep-water depth, and medium-to-high-water-energy conditions, corresponding to the environment of grain shoal or marginal shallow shoal.

#### 4.3.7. BF7 Fusulinids (Fig. 9)

*Description*: The fusulinids are always accompanied by dasyclad algae, small uniserial nodosariids (about 200 μm), and echinoderms were found in this microfacies as well. Grainstone and packstone are the main rock types with the textural compositions of fusulinids, pellets, sparry to microspar calcite cement. This microfacies is similar to BF4, the only difference is that the fusulinids in BF4 are usually smaller than those in BF7.

*Interpretation*: We can use the morphological information of fusulinids and their assemblages to reconstruct the paleoenvironment. By measuring and calculating the axial ratio of fusulinids and considering the shape and morphology of the test, we can roughly estimate the water-power environment (Wang et al., 1982; Beavington-Penney and Racey, 2004; BouDagher-Fadel, 2018). The subspherical globular shape is mainly found in a bioclastic shoal with medium-low water energy whereas elongate fusiform tests occupy mainly a marginal shoal with high-water-energy.

### 4.4. Sedimentary facies and microfacies

The seven types of biofacies enable us to reconstruct the sedimentary environment (Table 2) and possibly understand the sedimentary evolution during the Guadalupian period.

#### 4.4.1. Marginal platform facies

Marginal platforms lying between an open platform and a slope are shallow platforms with high-water-energy where the euryhaline species live. They are built by reef or skeletal grain shoals. In this study area, grainstones with peloids, bioclastics, sparry calcite cement, and dolomitized grainstones were identified in this environment. Two microfacies, marginal shallow shoal and dolomitized shoal, are included in the marginal platform (Table 2).

Marginal shallow shoal consists of grainstones, reflecting high-water-energy (Jin et al., 2013), water depth within 10 m. According to the statistical analysis performed on 52 slices of thin sections, a total number of 1122 foraminifera were found in bioclastic and pelleted grainstones in the Maokou Formation. They are identified as *Glomospira*, *Nodosaria*, *Geinitzina*, *Pachyphloia*, *Padangia*, *Cribrogenerina*, and *Climacammina*. Additionally, other fossils of fusulinids, corals, algae, bivalves, ostracods, brachiopods, brachiopod spines, and bryozoans are found along with them. The various biotas living together indicate sufficient supplies of nutrients, dissolved oxygen, and good ecological conditions in the water. Benthic foraminifera in marginal shallow shoals usually have thicker walls to resist sea waves. They tend to become elongate-ovoid and elongate-spindle shapes in current and wave conditions. Dasyclads and corals sometimes occur in this environment as well. In this study, the benthic foraminiferal microfacies, BF1, BF6, and BF7 are categorized into the sedimentary microfacies of marginal shallow shoals (Fig. 10, Fig. 11).

The dolomitized shoal is composed of fine-grained dolostones (sucrosic dolostones) and dolomitic grainstones that usually appeared in the Capitanian Stage. The dolostones consist of euhedral dolomite with a "cloudy center and clear rim" and a high proportion of intergranular pores. BF2 corresponds to this sedimentary microfacies (Fig. 10, Fig. 11).

#### 4.4.2. Open platform facies

An open platform is characterized by shallow-water algae, foraminifera, bivalves, gastropods, and brachiopods, at a few dozen meters of water depth. The typical lithology includes medium-to-thick layers of lime mudstones, wackestones, packstones and grainstones (Mou et al.,

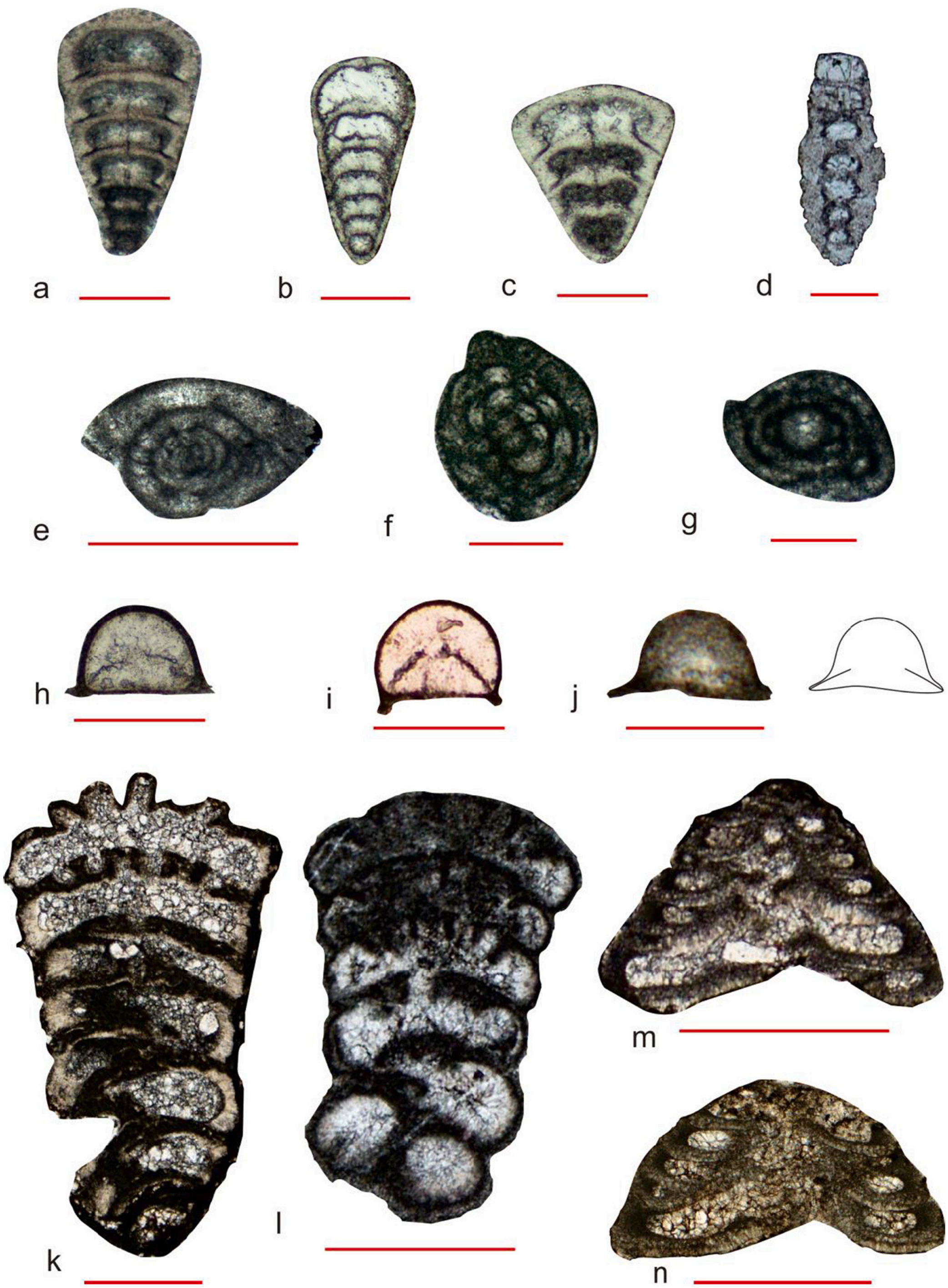


**Fig. 12.** (a)–(b): *Geinitzina* sp. in the Erya section. (c): *Cryptoseptida* sp. in the Erya section. (d): *Pachyphloia* sp. in the Huilongchang section. (e): *Schubertella* sp. in the Erya section. (f): *Endothyra* sp. in the Erya section. (g): *Glomospira* sp. in the Erya section. (h)–(j): *Eotuberitina* sp., (h), (j) in the Erya section, (i) in the Huilongchang section. (k)–(l): *Climacammina* sp., (k) in the Huilongchang section, (l) in the Erya section. (m)–(n): *Tetrataxis* sp., (m) in the Huilongchang section, (n) in the Erya section. (a)–(d), (f)–(j) = 100 μm, (e), (k)–(n) = 500 μm.

2009; Chen et al., 2002). In this study, it can be divided into three sedimentary microfacies, namely, grain shoal, open marine, and bioclastic shoal (Table 2).

Grain shoal has good water circulation with a medium-to-low intermittent cycle of water energy and abundant species. Skeletal grains include tapered benthic foraminifera, brachiopods, gastropods, bivalves, and ostracods. The common rock types are gray, grayish-brown, dark gray packstones and grainstones. The benthic foraminiferal microfacies of BF1, BF3, BF5, BF6 are classified into this sedimentary microfacies (Fig. 10, Fig. 11).

Open marine has low water energy and water depth less than 100 m. Dark gray lime mudstone and wackestone are the typical rocks in this environment, rich in organic matter, sometimes with nodular chert. The fossils are mostly in situ, and mainly composed of simple and small benthic foraminifera, ostracods, echinoderms, brachiopods, and gastropods. The foraminifera microfacies of BF2 and BF3 are specific to open marine (Fig. 10, Fig. 11).

A bioclastic shoal is characterized by all kinds of small-sized species, such as small fusulinids, benthic foraminifera, and echinoderms; sometimes, a micrite envelope is visible around the fossil fragments. Foraminifera microfacies of BF3, BF4, and BF7 are included in this sedimentary microfacies (Fig. 10, Fig. 11).

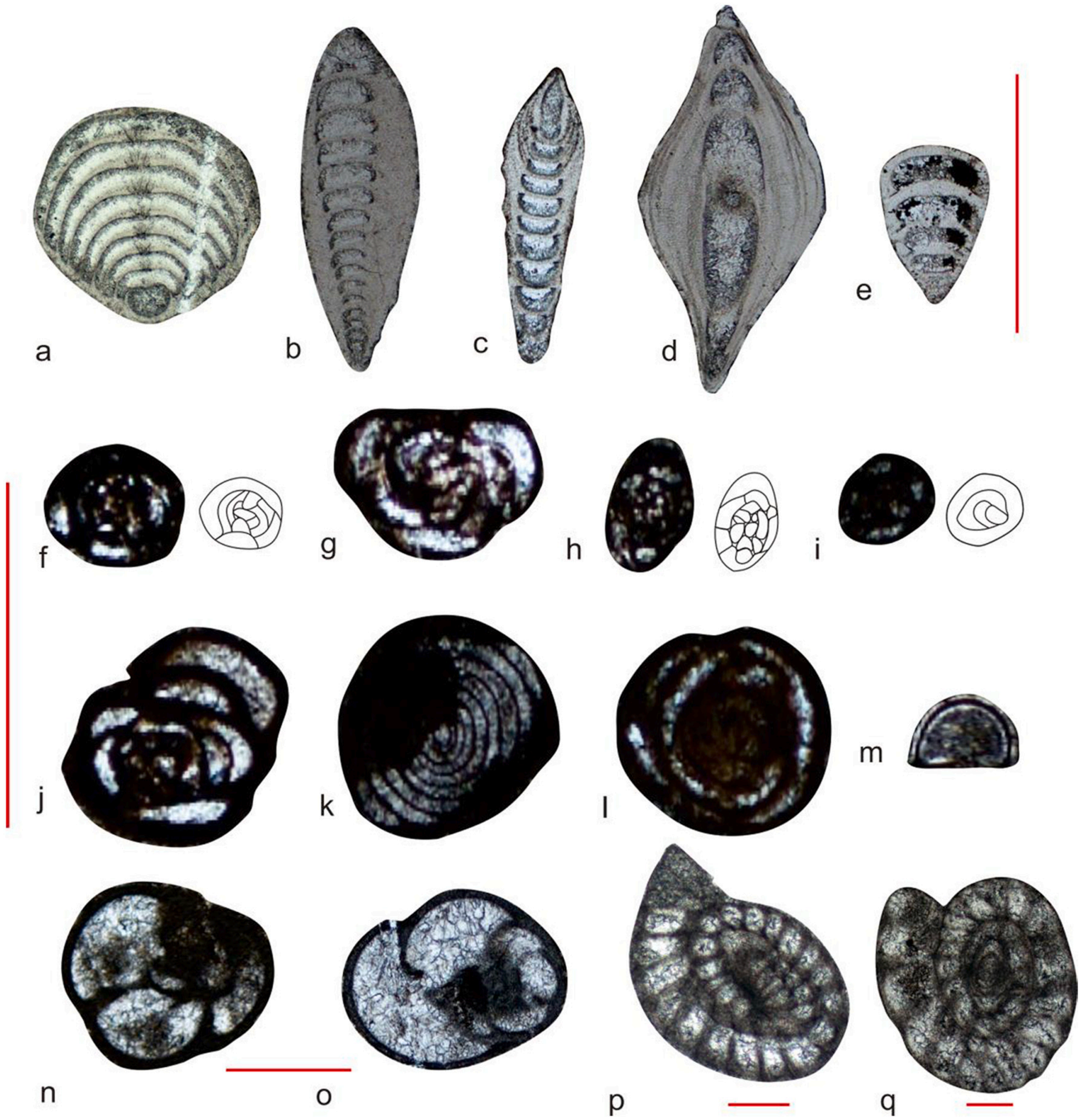


**Fig. 13.** (a)–(d): *Pachyphloia* sp., (a) in the Erya section, (b)–(d) in the Huilongchang section. (e): *Nodosaria* sp. in the Huilongchang section. (f)–(i): *Glomospira* sp. in the Huilongchang section. (j): *Glomospirella* sp. in the Huilongchang section. (k)–(l): *Hemigordius* sp., in the Huilongchang section. (m): *Eotuberitina* sp. in the Huilongchang section. (n)–(o): *Globivalvalina* sp. in the Huilongchang section. (p)–(q): *Codonofusiella* sp. in the Erya section. (a)–(o) scale bar = 500 μm; (p)–(q): scale bars =100 μm.

## 5. Discussion

### 5.1. The changes of benthic foraminifera taxa in the Guadalupian period

#### 5.1.1. The Roadian Stage

In the eastern Sichuan area, the water depth was relatively deep in the early Guadalupian age (the Roadian Stage), but no more than dozens of meters. The dominant benthic foraminifera are uniserial nodosariids, carbonate microgranular foraminifera with glomospire coiling (*Glomospira*, *Glomospirella*), and Globivalvalinoidea. Other benthic foraminifera taxa are Palaeotextularioidea and Fusulinida.

Uniserial nodosariids are generally a simple form of *Nodosaria* (Fig. 12a–d). The marginal shoal facies with high-water-energy is reflected by the common occurrence of *Nodosaria* with the slightly thicker test walls (Fig. 12a, b). Additionally, some small uniserial nodosariids are found in open marine facies (Fig. 12c, d). Small- and medium-sized Fusulinida are occasionally seen in the Roadian Stage (Fig. 12e, f), possibly because of hypoxia and insufficient nutrients under deeper water conditions. Tuberitinoidea (Fig. 12h–j) can be frequently seen in bioclastic shoals, representing relatively good nutrition conditions. *Climacammina* (Fig. 12k, l) and *Triticites* (Fig. 12m, n) appear in both Erya and Huilongchang sections, reflecting high-water- energy and a better ecological environment.

#### 5.1.2. The Wordian Stage

The water depth in the middle Guadalupian age (the Wordian Stage) became gradually shallower than that in Roadian Stage. Grain shoals with about 10 m water depth are very common during this time. Dominant foraminifera taxa include uniserial nodosariids (e.g., *Pachyphloia* and *Nodosaria*; Fig. 13a–e), carbonate microgranular foraminifera with glomospire coilin (*Glomospira* and *Glomospirella*; Fig. 13f–j), *Hemigordius* (Fig. 13k, l), Tuberitinoidea (*Eotuberitina*; Fig. 13m), and Globivalvalinoidea (Fig. 14n, o). Other benthic foraminifera taxa are fusulinids (*Codonofusiella*; Fig. 13p, q) and Palaeotextularioidea.

The most common assemblages, carbonate microgranular foraminifera with glomospire coiling (*Glomospira, Glomospirella*), streptospiral

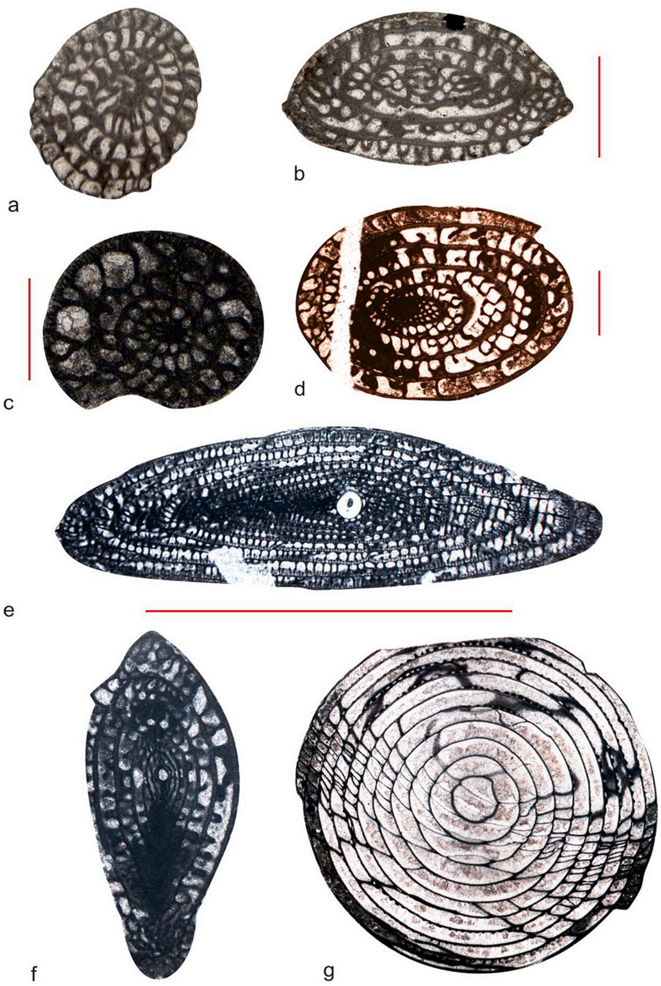


**Fig. 14.** (a): *Misellina* sp. in the Erya section. (b): *Schwagerina* sp. in the Erya section. (c)–(d): *Schwagerina* sp. in the Huilongchang section. (e): *Sumatrina* sp. in the Huilongchang section. (f): *Pseudofusulina* sp. in the Huilongchang section. (g): *Verbeekina* sp. in the Huilongchang section. (a)–(b), (c), (d) scale bar = 500 μm; (e) and (g) scal bar = 5 mm; (f) scale bar = 1 mm.

to planispiral (*Hemigordius*) and conical (Lasiodiscids), often coexisted in Guadalupian grainstones and packstones in microfacies of grain shoal and bioclastic shoal. Sometimes *Eotuberitina* makes up to 27% of the whole assemblage, pointing to suitable ecological conditions. The sizes and diversity of the fusulinids increase gradually in each section, indicating the favorable water depth, energy, temperature, and nutrients for their growth.

#### 5.1.3. The Capitanian Stage

In the late Guadalupian age (the Capitanian Stage), the dominant taxa in both Huilongchang and Erya sections were giant-size fusulinids, such as *Misellina* (Fig. 14a), *Schwagerina* (Fig. 14b–d), *Pseudodoliolina* (Fig. 14f), and *Verbeekina* (Fig. 14g). *Schwagerina* and *Verbeekina* are preferential biostratigraphic markers of the Guadalupian period. Other common benthic foraminifera include Palaeotextularioidea, carbonate microgranular foraminifera with glomospire coiling (*Glomospira* and *Glomospirella*), and uniserial nodosariids. Opportunistic taxa, such as *Eotuberitina* were rare, because they could not compete with the fusulinids under the nutrient conditions at that time. The length of some taxa, such as *Verbeekina*, reached almost 1 cm in diameter (Fig. 3a, e). The thriving of giant-size fusulinids in grainstones indicates a warm, shallow, well-oxygenated, and nutrient-rich environment that was suitable for their growth and reproduction (BouDagher-Fadel, 2018).

### 5.2. Evolution of the sedimentary environment

The sea level in the eastern Sichuan Basin that was a part of the Yangtze platform changed several times during the Guadalupian period (Liu and Li, 1988; Xiang et al., 2011; Hu et al., 2012; Tian et al., 2012; Zhong et al., 2014; Hou et al., 2017). Biotas of fusulinids, indicate that the eastern Sichuan area was deposited in an open shallow carbonate platform, such as open marine and marginal shoals (Fig. 10). Our observation indicates that the sea-levels changed several times in both the Huilongchang and Erya sections during the Guadalupian period (Fig. 10) and continued to decrease in an overall trend. Among the changes, three sea-level drops and two sea-level rises are particularly remarkable. The first significant sea-level drop and rise occurred in the early Guadalupian age (Roadian Stage). The second sea-level drop and rise occurred in the middle Guadalupian age (Wordian Stage) with several fluctuations. The most significant and continuous drop was found in the late Guadalupian age (Capitanian Stage) (Fig. 10). In every cycle of sea-level drop and rise, the marine water depth gradually decreased from several tens of meters of open marine to less than tens of meters marginal shoals or dolomitized shoals, which further increased to several tens of meters of open marine (Fig. 10, Fig. 15). Overall, the water depth became shallower from the early to late Guadalupian age. Particularly in the late Guadalupian age, the abundance of fusulinids confirms the warm, very shallow, nutrient-rich ecological environment in the study area.

The reasons for the sea-level changes in the Guadalupian period have been rarely discussed for the Sichuan Basin. The decrease of water depth might have lasted until the end of the Guadalupian period because there was a weathering of paleocrusts found on top of the Guadalupian period in both sections (Fig. 2g). Xiang et al. (2011) believed that the Sichuan Basin experienced one large-scale and three small-scale transgressive-regressive cyclic depositions in the Guadalupian period. Terrestrial mudstones and sandstones with fragments of plants in the lowermost Lopingian Longtan Formation next to Maokou paleoweathering crusts are presented in the Erya section (Fig. 4f). Similar paleokarst capped over Guadalupian carbonate rocks were also found in Western Hubei province by Niu et al. (2000), and in the south Sichuan Basin by He et al. (2010) and Shi et al. (2014). These palaeokarsts indicate a regional crustal uplift and paleoweathering shortly after the sedimentation of the Guadalupian period. He et al. (2010) evaluated the distribution and the extent of paleoerosion and suggested that the pre-volcanic short-term domal uplift before the Emieshan mantle plume eruption was responsible for the crustal uplift.

Moreover, similar sea-level changes during the Guadalupian period in adjacent regions have also been reported by some researchers (Haq and Schutter, 2008; Isozaki et al., 2008; Chen et al., 2009; Wignall et al., 2009; Wei et al., 2012). They showed that several sea-level drops and rises occurred in a shallower global sea–level environment. Qiu et al. (2014) identified transgressive–regressive sequences from the Guadalupian to Lopingian period in the Laibin area in Guangxi, south China. They found that a drop in sea-level in the Laibin area started gradually from Roadian until the end of the Capitanian Stages. Additionally, Chen et al. (2009) found that several sea-level drops and rises happened at the Tieqiao section in the Laibin area during the whole Guadalupian. Such research results are generally consistent with our observation of sea-level drops in the Guadalupian period, particularly the most significant drop in the Capitanian Stage that crossed the late Guadalupian-early Lopingian boundary (G–LB) in the eastern Sichuan Basin. Saitoh et al. (2010) examined the lithostratigraphy in detail and lithofacies of Guadalupian and Lopingian at the Chaotian area of northern Sichuan. The main parts of the Upper Guadalupian and the lowermost Upper Permian Wuchiapingian were probably deposited in the euphotic zone on a continental shelf, the uppermost Guadalupian was probably deposited in the dysphotic zone on a continental slope/basin. They believed that the change in stratigraphic lithofacies at Chaotian reflected the sea-level rise during the late Guadalupian period, but then

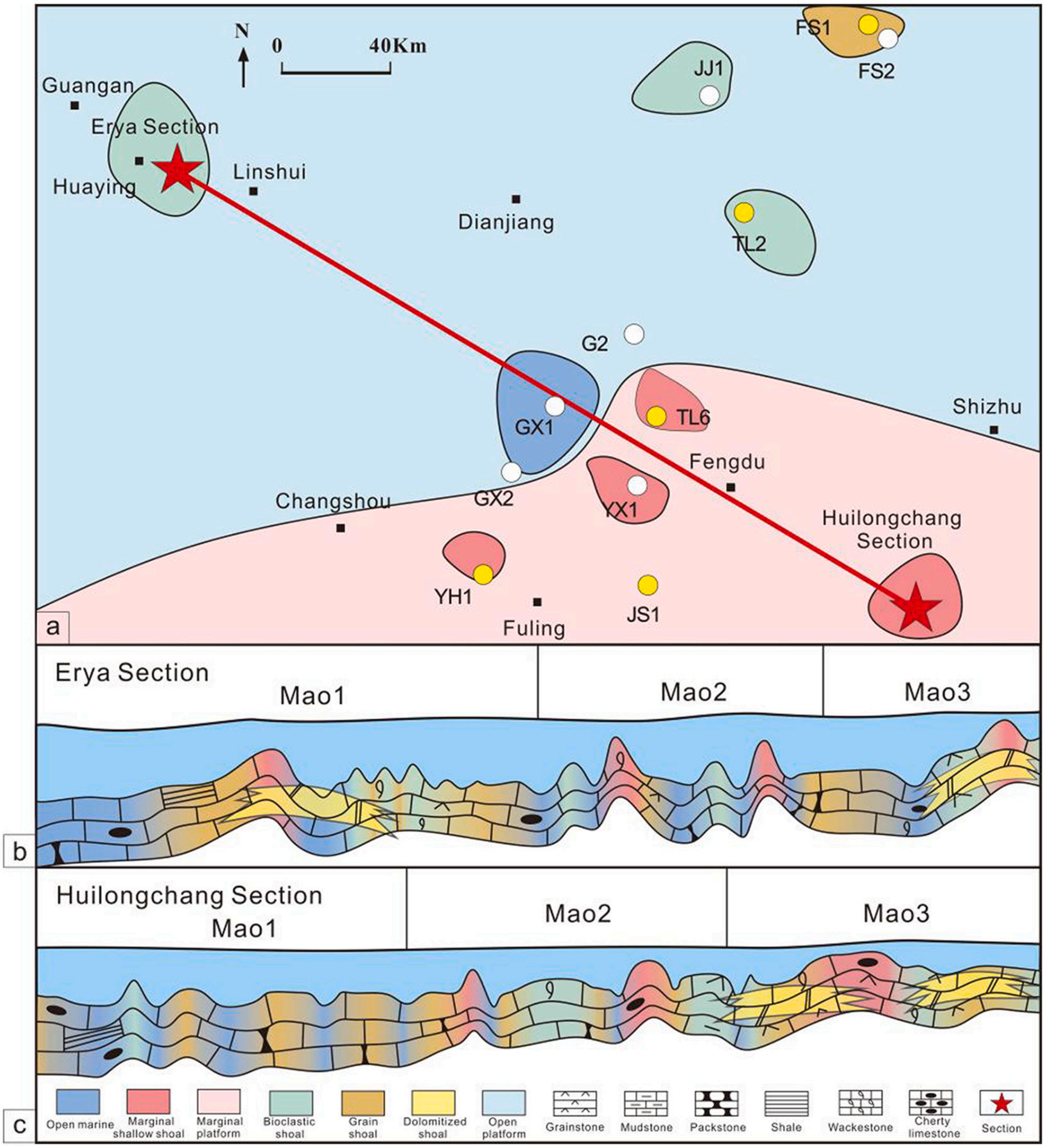


**Fig. 15.** The evolution of sedimentary environment in the Permian Guadalupian period.
(a): The evolution of sedimentary environment of the Guadalupian period in the Huilongchang section. (b): The evolution of sedimentary environment of the Guadalupian period in the Huilongchang section. (c): Sedimentary environment of the Capitanian Formation in the eastern Sichuan area. FS1, FS2, JJ1, TL2, TL6, G2, GX1, GX2, YH1, YX1, JS1 are the names of wells.

fell rapidly across the G–LB. Similarly, Kofukuda et al. (2014) reported a remarkable sea-level drop across G–LB in Akasaka and Ishiyama in Japan but attributed it to global cooling instead of a tectonic uplift. Additionally, they also mentioned a depositional site shift from subtidal to intertidal zone in the latest Capitanian Stage and subaerially exposed immediately before the G–LB and consequently entering into the intertidal setting across the G–LB before reaching the Wuchiapingian.

Generally, more studies are needed to explore the reasons for sea-level changes in the Guadalupian period, particularly at the G–LB. For example, whether the short-term tectonic uplift led to the sea-level decline and the extinction of fusulinids in the Capitanian Stage, which seemed to be continued during the entire period of the Capitanian Stage; or the global climate alteration was the essential reason to end the middle Permian regression. Further work, therefore, should objectively evaluate the sedimentary and biological evolution in the middle Permian period.

## 6. Conclusions

(1) Seven types of benthic foraminiferal biofacies were recognized by analyzing 445 lithological thin slices in middle Permian Guadalupian carbonate rocks in the eastern Sichuan Basin. They are as follows: Endothyrida + uniserial nodosariids (BF1), Uniserial nodosariids + Tubothalamea/ Endothyrida (BF2), Uniserial nodosariids (BF3), Fusulinids + Tubothalamea + uniserial nodosariids (BF4), Endothyrida + Fusulinids + uniserial nodosariids (BF5); Tubothalamea + uniserial nodosariids (BF6), and the Fusulinids (BF7).

(2) A sedimentary model of the eastern Sichuan area was built using the benthic foraminiferal microfacies. It consists of a shallow carbonate open platform with open marine and marginal shoals from the Guadalupian period.

(3) From the early to late Guadalupian age, the marine water depth tended to decrease gradually from several tens of meters to less than ten meters. The numerous giant fusulinids in the Capitanian Stage indicate a warm, shallow, well-oxygenated, and nutrient-rich environment

prevailing in the late Guadalupian period which continued until the abrupt weathering at the end of the Guadalupian period.

## Author statement

Benthic foraminifera distribution and sedimentary environmental evolution of a carbonate platform: a case study of the Guadalupian (middle Permian) in eastern Sichuan Basin:

I have made substantial contributions to the conception or design of the work, acquisition, analysis, or the acquisition, analysis, or interpretation of data for the work. And I have drafted the work or revised it critically for important intellectual content. I have approved the revised manuscript. And I agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

All persons who have made substantial contributions to the work reported in the manuscript, including those who provided editing and writing assistance but who not authors, are named in the Acknowledgments section of the manuscript and have given their written permission to be named. If the manuscript does not include Acknowledgments, it is because the authors have not received substantial contributions from non authors.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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