Journal of Palaeogeography
2012, 1(1): 27–42
DOI: 10.3724/SP.J.1261.2012.00004

Biopalaeogeography and palaeoecology

The Carboniferous reefs in China

Gong Enpu*, Zhang Yongli, Guan Changqing, Chen Xiaohong

Department of Geology, Northeastern University, Shenyang 110819, China

Abstract The Carboniferous period was a unique period for reef developments during the Late Paleozoic; however, in past years, studies dealing with the Carboniferous reefs in China were very rare. In recent years, the Carboniferous reefs were studied in detail and diverse types of reefs have been discovered in different areas of China. In these areas, the Mississippian reefs were primarily built of bryozoans and rugose corals, which were associated with various kinds of calcareous algae. During the Pennsylvanian, in South China, the reef builders were composed of the rugose coral *Fomichevella* and phylloid algae, whereas in North China, the reef builders were composed of *Chaetetes*, bryozoans and corals. There are two main reef-building communities within Carboniferous reefs in China; an algal reef-building community and a reef-building community dominated by colonial coral. No evolutionary relationships between these two types of communities can be detected, thus indicating that two different linerages of reef-building communities evolved during the Carboniferous; the former community consists of cyanobacteria, bacteria and calcareous algae, while the latter one consists of various skeletal metazoan organisms. Through careful study of the developments of Chinese Carboniferous reefs, the evidence indicates that various communities of organisms played important reef-building functions during this period. The occurrence of these metazoan framework reefs also indicates that, during the Carboniferous, most areas in China would have been dominated by the environments with a tropical or subtropical climate.

Key words Carboniferous, reef, China, evolution, marine ecosystem

1 Introduction

The Carboniferous represents an important orogenic period with complicated tectonic movements in geologic history. Since the end of the Mississippian, the global structure had been a subject to the great change due to the formation of Pangaea. Significant continental collisions occurred, and resulting in extensive orogenic belts. The Carboniferous tectonic movements obviously influenced the formation and evolution of biocommunities, palaeobiogeographic differentiation, palaeogeography and palaeoclimate. The Carboniferous reefs of China were constructed based on this geological background (Gong, 1997). The Carboniferous could be regarded as a unique period for reef-building in the Late Paleozoic, during that period abundant rugose corals flourished, which were associated with other reef-building organisms such as stromatolites, sponges and bryozoans. In past years, the papers related to the Carboniferous reefs were very rare, which might be caused by the Frasnian/Famanian mass extinction events and also that there have been relatively few studies performed on these Carboniferous reefs (Gong and Guan, 1998). In recent years, these reefs were studied in detail; as the results, the diverse types of reef were discovered (Gong *et al*., 2004; Guan *et al*., 2004, 2007; Zhang *et al*., 2010).

2 Geological setting and stratigraphy of the Carboniferous reefs in China

In China the paleogeographic framework of the Mississippian age was inherited from the Late Devonian. On

* Corresponding author: Professor. Email: gongep@mail.neu.edu.cn.
Received: 2011-12-15 Accepted: 2012-02-29

the continent of China four marine sedimentary areas were divided by two uplifts, *i.e*., Tarim-Sino-Korean landmass and Upper Yangtze-Kangdian landmass (Wang *et al*., 1990). During the Mississippian, the area of South China was covered by a continental sea that gradually became shallow in the direction from the southwest to the north-northeast with many carbonate platforms of various sizes. During the Datangian stage of Visean age, some coral-bryozoan patch reefs were developed on the carbonate platforms, while stromatolitic algal reefs were built on the margins of carbonate platform (Fang and Hou, 1987; Zhou and Zhang, 1991). There are possibly some Carboniferous reefs within the late Mississippian and the early Pennsylvanian *Eostaffella* Zone and *Pseudostaffella* Zone respectirely. The existence of these reefs is presumed by comparing with the reef-developing factors of Akiyoshi reef in Japan. They were distributed in the following counties: the Lianyuan, the Lengshuijiang, the Xiangxiang, the Shuangfeng, the Xinshao, the Shaoyang and the Shaodong counties in the central part of the Hunan Province (Liu, 2002).

During the Pennsylvanian, widespread carbonate sediments were deposited as a result of expansion of the South China Sea, and various types of reefs were developed on the margin of carbonate platforms. Some red algae reefs occured in the Maping Formation of the Beibuwan sea area in Guangxi Autonomous Region. *Parachaetetes* and *Ungdarella* are the main reef-building organisms. Calcareous green algae are also associated with these reefs (Gong, 1997). In recent years, phylloid algal reefs, coral reefs and reefs built by an unnamed organism were discovered in the lower portion of the Maping Formation (Xiaoyaoian Stage) in southern Guizhou Province. All three types of reef were developed on the carbonate platform margin during the Pennsylvanian (Tan, 1991; Fan and Rigby, 1994; Gong *et al*., 2003, 2007a, 2007b, 2007c; Guan *et al*., 2004, 2007; Zhang *et al*., 2007; Gong *et al*., 2009; Zhang *et al*., 2010). *Fomichevella* coral reefs are the most common Pennsylvanian carbonate buildups in southern Guizhou Province. During the Huashibanian Stage (Moscovian), patch coral reefs from the bottom of the Jiadaogou Formation, Chifeng, and bryozoan-calcareous alga baffling mounds found in the Qijiagou Formation, the eastern Xinjiang occurred in the Tianshan-Xingan active ocean trough (Gong, 1997; Zhang and Liao, 1998). During the Pennsylvanian the North China Plate evolved into a series of hemipelagic coal-bearing basins alternating between marine and continental environments. During this period, the North China Sea was formed as a result of a large transgression containing abundant reef-building organisms, and *Chaetetes*-coral reefs occurred during the Benxian Stage (Moscovian) (Gong, 1994). In the southwest of the Tarim Basin, the patch reefs built by corals, sponges, bryozoans and cyanobacteria are found in the Pennsylvanian to Early Permian Kangkelin Formation (corresponding to the Xiaoyaoian and Zisongian). The reefs in this area were dominated by algal reefs during the Pennsylvanian (Wang *et al*., 2006).

A summary of the spatiotemporal distributions of Chinese Carboniferous reefs from the study is shown in Table 1 and Fig. 1. The reefs of the Mississippian were primarily built by bryozoans and rugose corals, but also included various types of algae. During the Pennsylvanian, in South China, the reef-builders mainly included the rugose coral *Fomichevella* and phylloid algae, whereas in North China, the reef-builders were *Chaetetes*, other corals, and bryozoans.

3 Types and models of development of the Carboniferous reefs in China

The Carboniferous reef building communities found in China are relatively monospecific, and few reefs are constructed by more than two different reef-building organisms. Comparing with the reefs of the Devonian and Permian, both the methods of reef-building and the Carboniferous reefs themselves are very simple.

3.1 The Mississippian reefs in China

3.1.1 *The bryozoan-coral reefs in Guangxi Autonomous Region*

The bryozoan-coral reefs discovered near the Langping ard the Tianlin County, Guangxi Autonomous Region are the only Mississippian framework reefs discovered in China to date. These reefs are almost 200 m long and up to 114 m thick, as compared to contemporary deposits elsewhere in the region, which are only 83 m thick. The reefs developed symmetrically and are composed of reef core facies and reef flank deposits without forereef and backreef deposits, therefore these are pinnacle reefs, developed in the interior of carbonate platform (Fang and Hou, 1987). The main reef-building organisms are *Thysanophyllum* and *Fistulipora*, with abundant *Syringopora* and *Lithostrotion*. The growth pattern of the coral colonies is fasciculate, and the bryozoan colonies have orbicular, hemispheric, orthogon-massive, and tuberose morphologies. The organisms associated with the reef are crinoids, brachiopods, solitary corals, forams, gastropods,

ostracodes, algae, and many others. Four growth cycles can be recognized in the reef, and they are, from bottom to top: 1) *Thysanophyllum* framework reef, 2) *Fistulipora* framework reef, 3) *Thysanophyllum* framework reef, and 4) *Thysanophyllum-Fistulipora* framework reef. Each growth cycle developed upon a biodetritus bank, and corresponds with an increase of shallow-water organisms. Based on the palaeogeography of South China, similar reef groups were probably developed on other carbonate platforms or carbonate platform margins of the Mississippian in the Napanjiang Basin.

3.1.2 *Stromatolitic reefs in the Laibin Area of Guangxi Autonomous Region*

Abundant algal boundstones and the Mississippian stromatolites are widely distributed in Laibin County of Guangxi Autonomous Region, and they are found mainly

Table 1 Spatiotemporal distributions of the Carboniferous reefs of China

International stratigraphy chart of Carboniferous		China		Distribution of reefs	Reef types
		South China	North China		
Pennsylvanian	Gzhelian	Xiaoyaoan Stage	Jincian Stage	Ziyun Area, Guizhou Beibuwan Area, Guangxi Tarim Basin	Coral reef, phylloid algal reef, algal bioherm Red algal reef Patch reefgroup (algal reefs)
	Kasimovian	Dalan Stage		Tianlin Area, Guangxi	Coral reef
	Moscovian	Huashi-banian Stage	Benxian Stage	Eastern Tianshan, Xinjiang	Coral pach reef, bryozoan-calcareous algae mound
				Benxi Area, Liaoning	Chaetetes – coral reef
Mississippian	Bashkirian	Luosuan Stage		Central Hunan	Possibly?
	Serpukhovian	Dewuan Stage			
	Visean	Datangian Stage		Tianlin Area, Guangxi	Coral-bryozoan reef
				Laibin Area, Guangxi	Stromatolitc reef
	Tournaisian	Yanguanian Stage			

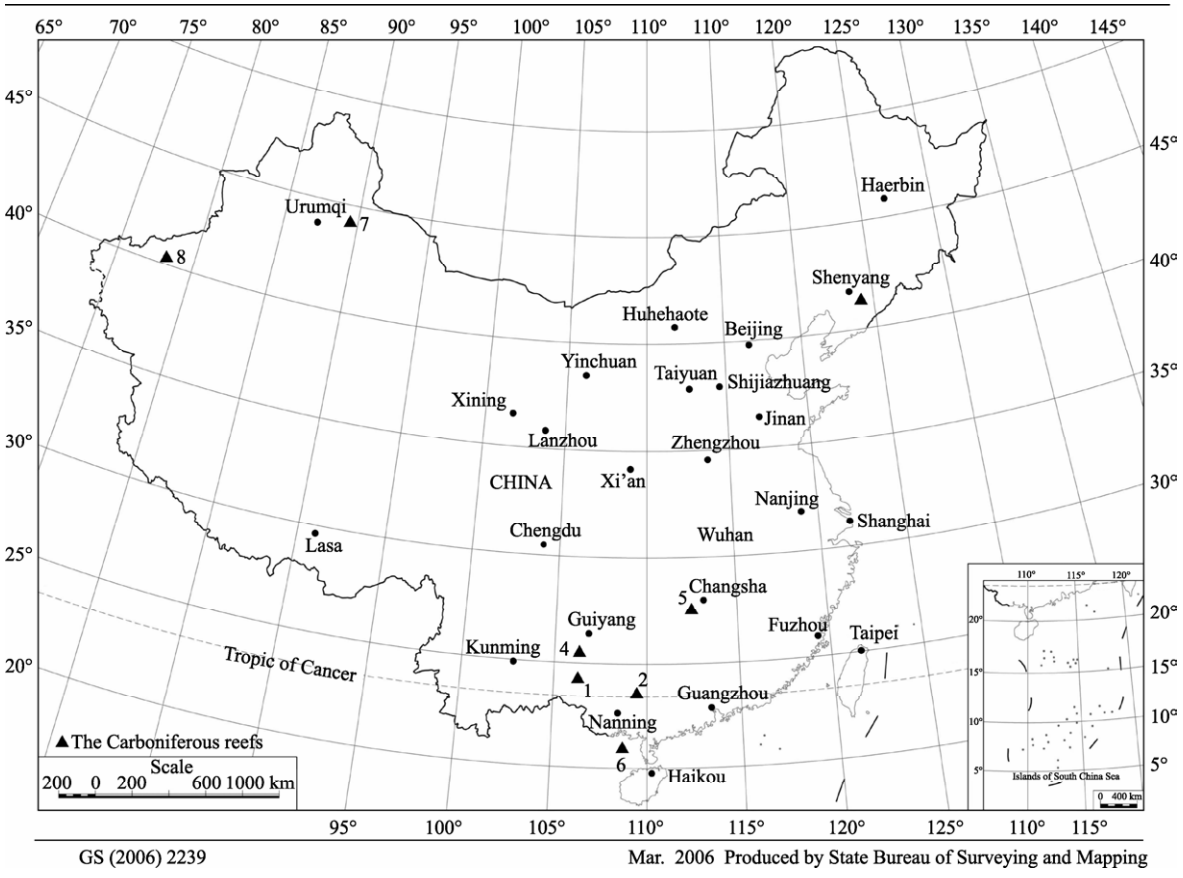

Fig. 1 The distribution of the Carbonifeorus reefs in China

1 – Tianlin Area, Guangxi; 2 – Laibin Area, Guangxi; 3 – Benxi Area, Liaoning; 4 – Ziyun Area, Guizhou; 5 – Central Hunan; 6 – Beibuwan Area, Guangxi; 7 – Eastern Tianshan, Xinjiang; 8 – Tarim Basin

in the upper part of Datangian Stage, overlying a dark gray micritic limestone bearing *Caniostrotion* sp. with siliceous banding. The reef limestone is composed almost entirely of stromatolites with diverse morphologies, five types of which can be recognized: laminar, wavy-laminar, hemispheric, bulbous, and flabellate. The Mengcun village reef in Laibin County of Guangxi Autonomous Region is a typical example of the Mississippian stromatoloitic reefs (Zhou and Zhang，1991). The stromatolitic reefs are the first described Mississippian stromatolitic buildups in South China (Shen and Qing, 2010). Stromatoloitic reefs occur multiple times in the section, and the reef complex itself is more than 100 m in thickness in stratigraphic succession. The reef rock is composed of laminated-columella or laminated stromatolitic limestone. The algal stromatolites have turbinate, hemispheric and fan pillar morphologies. The flabellate stromatolites measure up to 60 cm in height, and they form the framework of the reef. The stromatolitic reefs in this area developed on a carbonate platform margin. The stromatolites grew in a relatively low energy, deep-water setting (Shen and Qing, 2010). The diverse morphologies of the stromatolites are controlled by fluctuations of the sea-levels and water energy.

3.2 The Pennsylvanian reefs in China

3.2.1 *The Moscovian sponge-coral reefs in eastern Liaoning Province*

Only a few small-scale, Pennsylvanian reefs developed in North China, and they are distributed mainly in the Taizi River Basin, eastern Liaoning Province. At the beginning of the Pennsylvanian, a massive south-north transgression occurred in this region. The sedimentary environment changed from fan delta to fiord coast and then into a carbonate platform, and thus several reefs with a nearly east-west trend were built on the nearshore side of the platform. These reefs are relatively small, with thickness of 2–4 m. There are abundant benthic organisms found in these reefs, and the biotic content is up to 60% of the reef volume. *Arachnastraea manchurica* and *Chaetetes penchiensis* are the dominant building organisms in these reefs (Fig. 2). Their colonial skeletons are tabular in shape with varying thickness. *Multithecopora penchiensis* is the secondary building organism in the reefs of this region, and it mainly occur in the spaces between *Chaetetes* and *Arachnastraea*. There are also such binding organisms in the reef as *Archaeolithoporella* and *Girvanella*. The organisms associated with the *Chaetetes* coral reef are fusulinids, foraminiferans, brachiopods, ostracodas, bryozoans, gastropods and various genera of algae.

3.2.2 *The Pennsylvanian coral reefs in Guangxi Autonomous Region*

Carbonate platforms were widespread in South China during the Pennsylvanian, and several coral reefs were developed on the margin of these platforms. Coral reefs mainly occur in the Huanglong and Maping Formations of Tianlin County, Guangxi Autonomous Region. Reef outcrops are generally found about 3–4 km northwest of the town of Langping (Fig. 3). *Antheria*, *Paralithostrotion* and *Cystophorastraea* are the main reef-building organisms for these Pennsylvanian reefs.

(1) Spatiotemporal distributions of the Pennsylvanian reefs in Guangxi Autonomous Region

The Pennsylvanian reefs in the Tianlin County, Guangxi are discovered in different horizons and different sedimentary environments (Table 2). These reefs

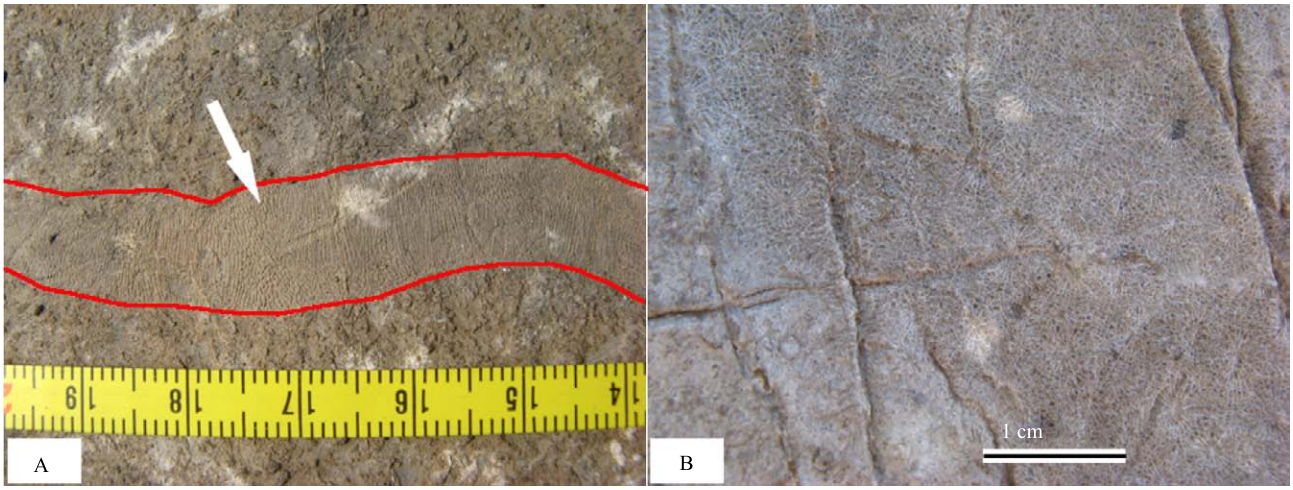

Fig. 2 Field view of the dominant reef-building organisms of the Moscovian reefs in eastern Liaoning Province
A–The thin, spreading sheet of *Chaetetes penchiensis* (arrow); B– Cross- sections of *Arachnastraea manchurica* on a weathered limestone surface

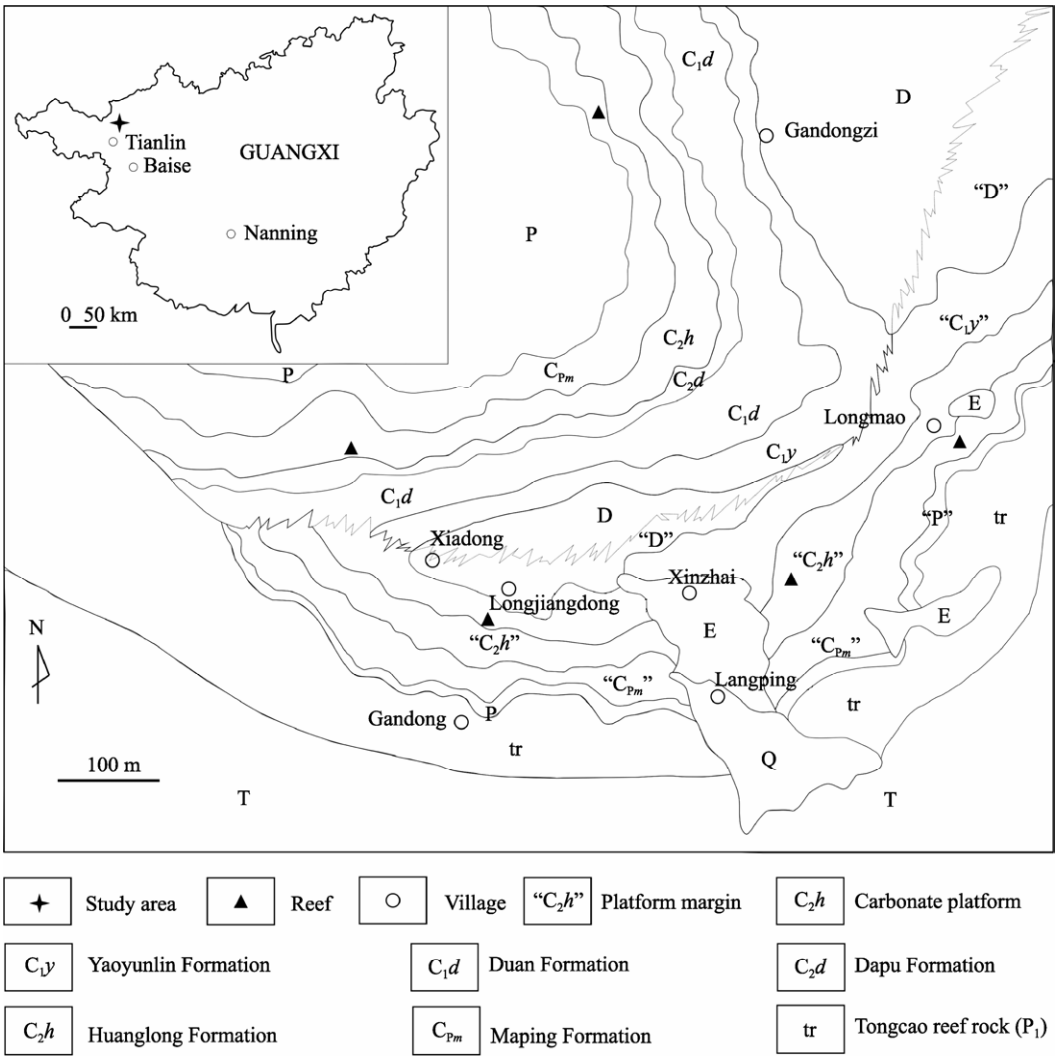

Fig. 3 The geological map and distribution of the Pennsylvanian reefs in Guangxi Autonomous Region
D – Devonian; C – Carboniferous; P – Permian; T – Triassic; E – Eocene; Q – Quaternary

Table 2 Spatiotemporal distributions of the Carboniferous reefs of Tianlin County, Guangxi Autonomous Region

Stratum	Location	Size and morphology	Reef-building organism	Sedimentary environment
Lower part of Maping Formation	Near Wangjiantuo Village, Langping Town	Patch reef ?	*Ivanovian* (coral), *Cystophorastraea*	Carbonate platform
Huanglong Formation	Near Longjiang Village, Langping Town	Large-scale reef	*Donophyllum*, *Antheria*	Carbonate platform margin
	Near Xiadong Village, Langping Town	A group of patch reefs	*Paralithostrotion*, *Syringophyllum*, *Donophyllum*, *Antheria*	Carbonate platform margin
	Near Xinzhai Village, Langping Town	Small-scale patch reef	*Antheria*	Carbonate platform margin
	West to Gandongzi Village, Langping Town	Small-scale patch reef	Bryozoan, *Antheria*	Carbonate platform
Upper part of Datangian Formation	Near Gandongzi Village, Langping Town	tower reef	*Thysanophyllum*, *Fistulipora*	Carbonate platform

were built up by different organisms, including *Donophyllum*, *Cystophorastraea*, *Ivanovian* (coral), *Antheria*, *Paralithostrotion* and so on.

(2) Basic features of coral reefs in the Langping County and the Tianlin County, Guangxi

The Pennsylvanian reefs in the Langping County, Guangxi Autonomous Region are relatively small, but they occur in several locations and they are mainly composed of groups of coral patch reefs. The location and brief description of some typical reefs near Langping are as follows: ① Bryozoan reef in the Huanglongian Formation, west of Gandongzi Village, Langping, with a length of

5–7 m and a thickness of 3–4 m; ② A group of coral reefs in the Huanglong Formation (Fig. 4), near Longjiangdong Village, Langping, composed of three platform margin patch reefs which are located not far from each other. They have the same developmental model and reef-building community. Thus, they likely belong to one large lamella coral reef divided into three sections (Fig. 5). The length of the entire reef could reach up to 400 m. The exposed length of the largest lamella coral reef is 300 m. The unnamed reef-building organisms found in this reef also occur in the Huanglong Formation of Longjiangdong Village, which is similar to that reported by Guan *et al*. (2007) in Ziyun County, Guizhou Province (Fig. 6); ③ Patch coral reefs in the Maping Formation, north of Wangjiatuo Village, Langping. The outcrops of coral reefs in the Maping Formation are not as abundant as those in the Huanglong Formation, and only one patch coral reef is found in outcrop, about 3 km west of Gandongzi Village. In general, coral reefs in the Maping Formation are relatively small and few in number in this region.

(3) The features of coral reef communities

In the course of this study, some significant characteristics of the coral reefs in the Huanglong and Maping Formations in the Langping region, Guangxi Autonomous Region have been discovered: the composition of the reef-building community is very monotonous; there are only one or two builders in each reef-building stage. The reef-building process is very simple; each part of the reef has been built separately by various reef-building mechanisms, and most of these parts was built using one building mechanism at a time. There have been only a few parts built by two coexisting building mechanisms. The process of reef building is often discontinuous and lacks transition between the reef-building communities. The main builders of the reefs in the Huanglong Forma

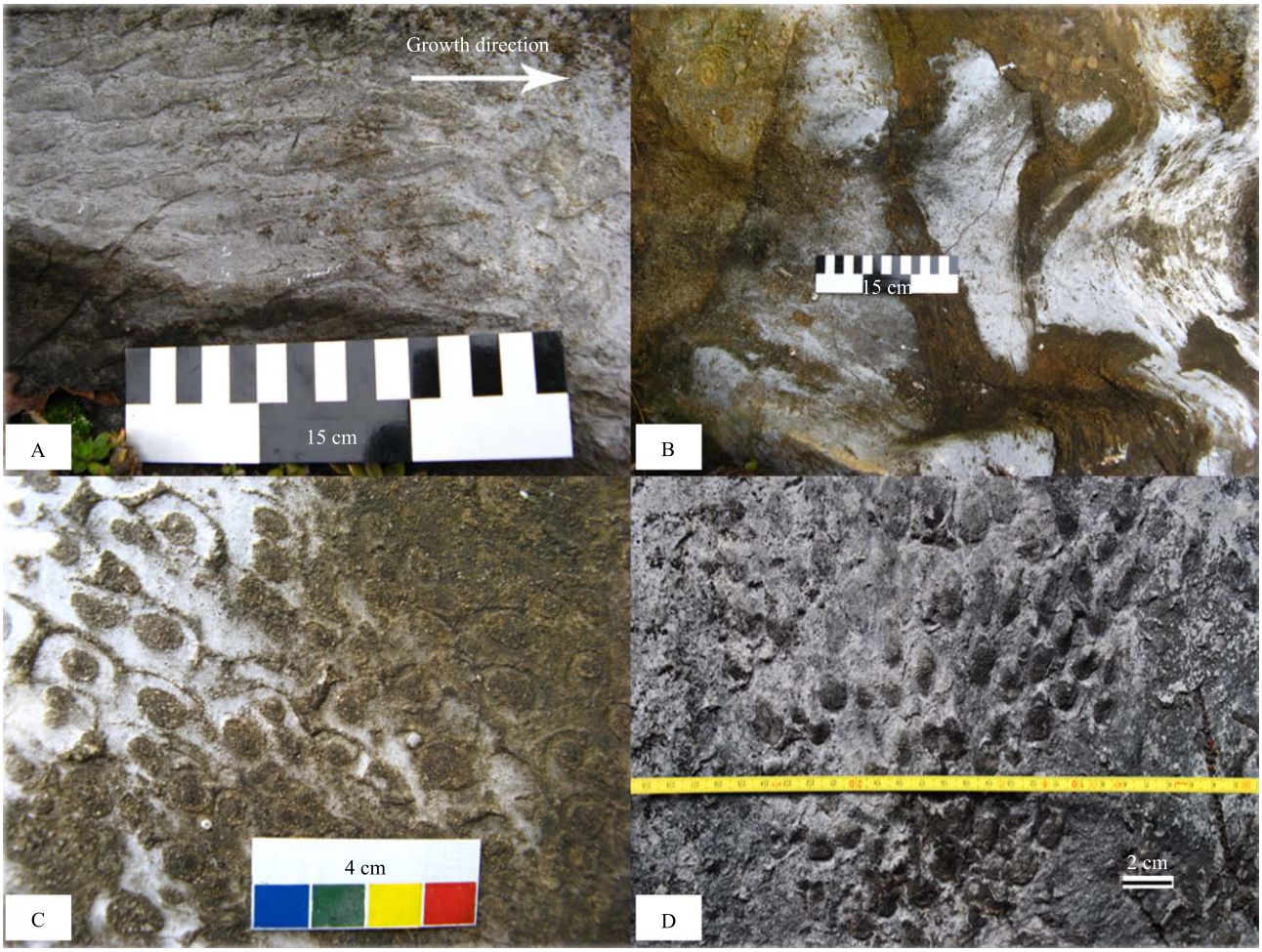

Fig. 4 *In situ* outcrops of the patch coral reefs in the Huanglong Formation of Longjiangdong Village
A – Photograph of fasciculate *Donophyllum* corallites; B– Field view of the core of the patch coral reef of Longjiangdong Village; C – Field view of relatively concentrated corallites of *Donophyllum*; D – Field view of relatively thick corallites of *Donophyllum* on the weathering surface of the limestone.

Fig. 5 Outcrop view of the coral reefs in the Huanglong Formation of Longjiangdong Village
The three exposures (R1, R2 and R3) are exposed in a nearly E-W orientation; they thus likely belong to one large lamella coral reef divided into three sections. The exposed length of the large lamella coral reef is 300 m. Reef 1 (R1) has a thickness of 15 m and an exposed length of 35 m; Reef 2 (R2) has a thickness of 20 m and an exposed length of 50 m; Reef 3 (R3) has a thickness of 8 m and an exposed length of 15 m. The direction indicated by the white arrow is west (W).

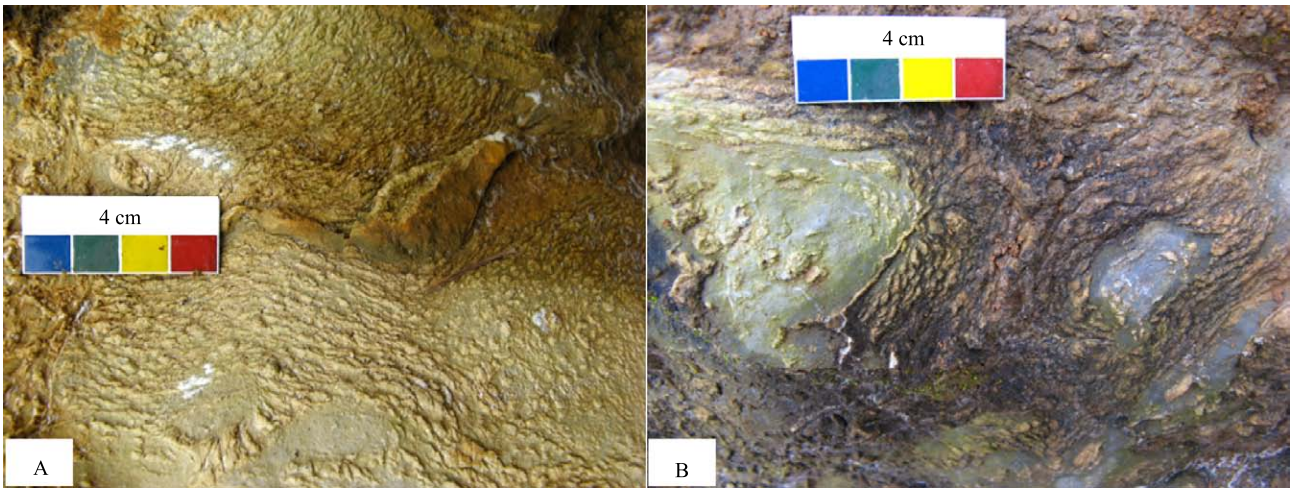

Fig. 6 Field view of *in situ* unnamed reef-building organisms in Huanglong Formation of Longjiangdong Village (A–B)

tion include *Paralithostrotion*, *Fistulipora*, *Syringopora*, *Chaetetid*, *Caninia*, *Antheria,* and an unnamed building organism. Massive colonies of the coral *Ivanovia*, the unnamed building organism and the coral *Cystophorastraea* were common reef builders in the Maping formation, but only *Cystophorastraea* built a small patch reef. These features of the reef communities in the Pennsylvanian of Guangxi Autonomous Region shows that reef-building organisms were widely distributed in the region and that no large-scale reefs were built due to the unstable sedimentary environment.

3.2.3 *The Pennsylvanian reefs in southern Guizhou Provine*

(1) Bianping Village, Ziyun County

A large Pennsylanian coral reef is found in the Bianping Village about 4 km west of Houchang Town in Ziyun County, southern Guizhou Province. The Bianping coral reef (Fig. 7) is exposed in a nearly N-S orientation, and occurs in the *Triticites* Zone of the Maping Formation (Gzhelian, uppermost Pennsylvanian). The reef, 80–100 m high and about 700 m long, may be one of the largest Pennsylvanian metazoan frameworks in the world. It developed on a carbonate platfrom margin, and the main builder of the reef was the rugose coral *Fomichevella* (Fig. 8). *Fomichevella* built a firm framework against waves with its thick, long, tightly-adhering corallites. Other reef-building organisms, such as phylloid algae, microbes, *Ivanovia* cf. *manchurica*, and *Antheria*, also took part in the construction of the coral reef (Fig. 9).

1) Lithology of the reef rock

The rocks comprising this coral reef have a simple

structure, which can be divided into basement, inter-reef deposition, reef core, backreef, reef cap, *etc*. according to the exposure of reef core and reef back. The main types of reef rocks are *Fomichevella* framestone (Fig. 10A), *Ivanovia* cf. *manchurica* skeletal coverstone (Fig. 10B), phylloid algae bafflestone (Fig. 10C), cyanobacteria

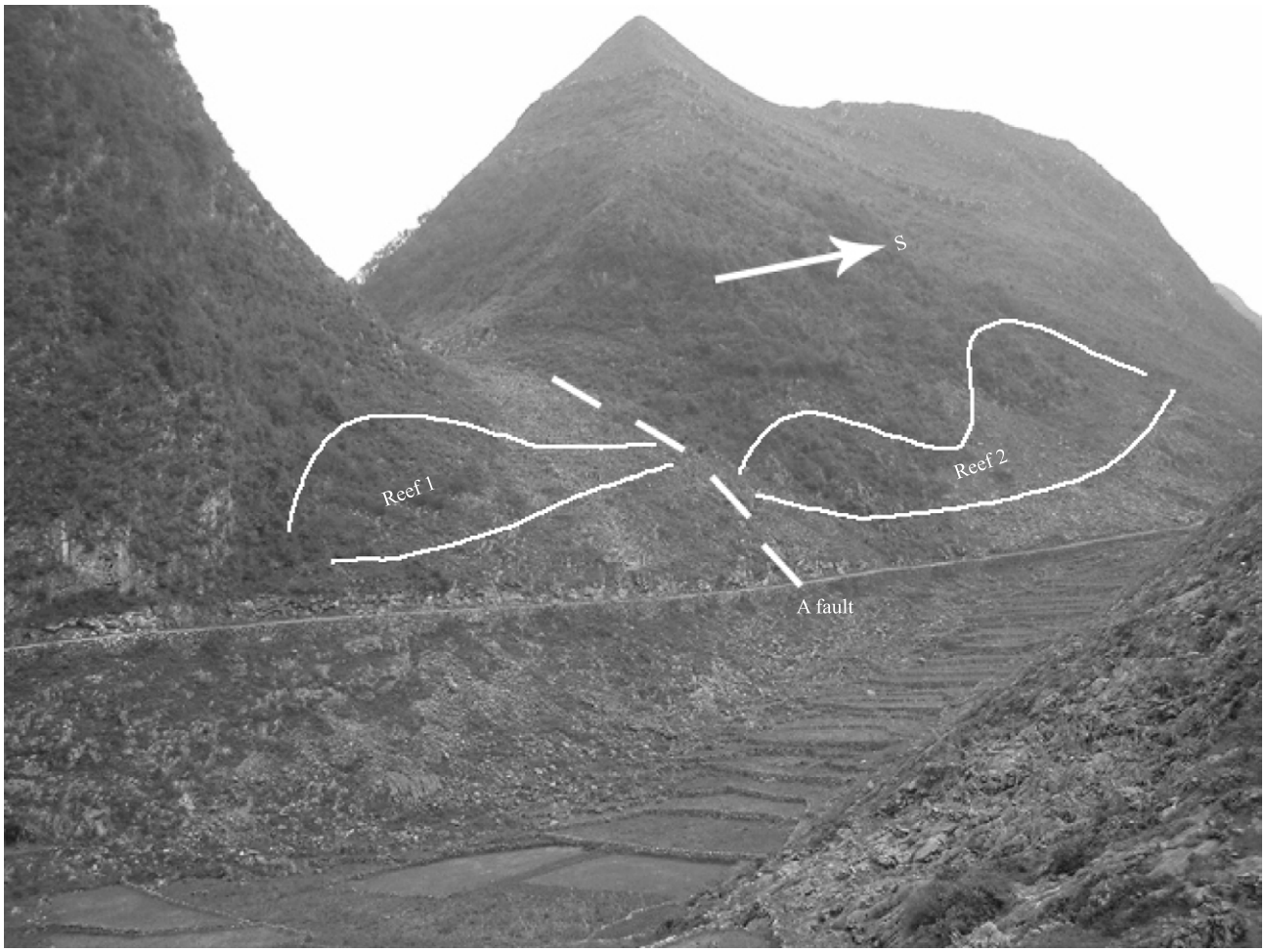

Fig. 7 Field view of the outcrops of the Bianping coral reef
The two exposures (Reef 1 and Reef 2) are separated by an apparent fault; they thus likely represent the same reef complex. The Bianping coral reef is approximately 700 m long. The direction indicated by the white arrow is south (S).

Fig. 8 Field view of *Fomichevella* framestone
The *Fomichevella* corallites appear as cross-sections on the bedding surface of the limestone (A–B).
The length of the pen is 15 cm.

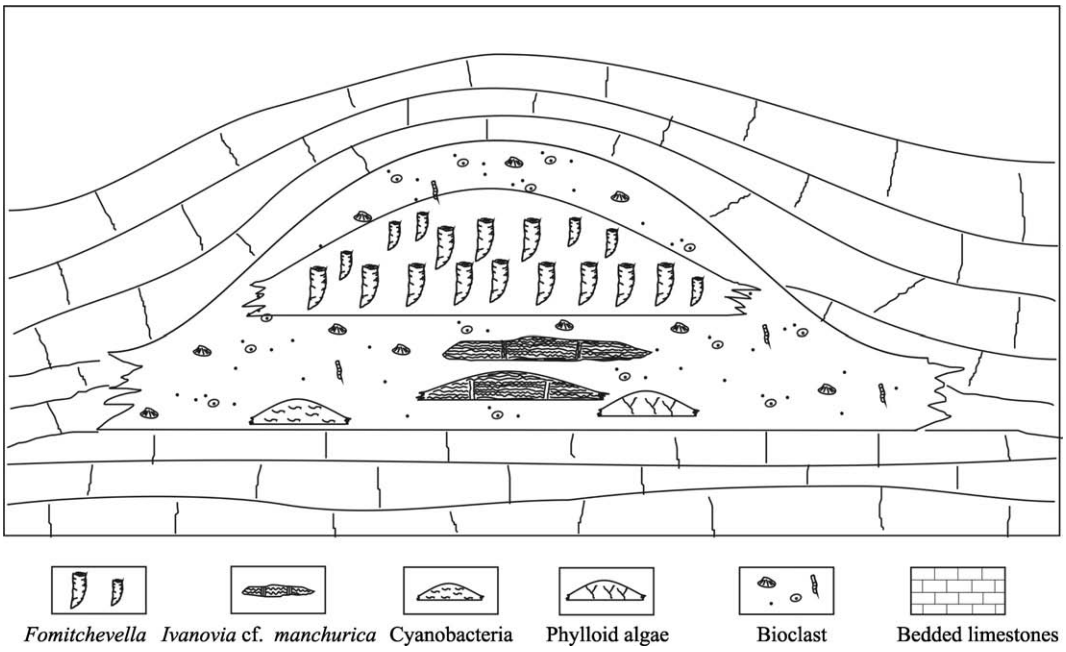

Fig. 9 The structure sketch diagram of the Bianping coral reef showing distribution of reef building components

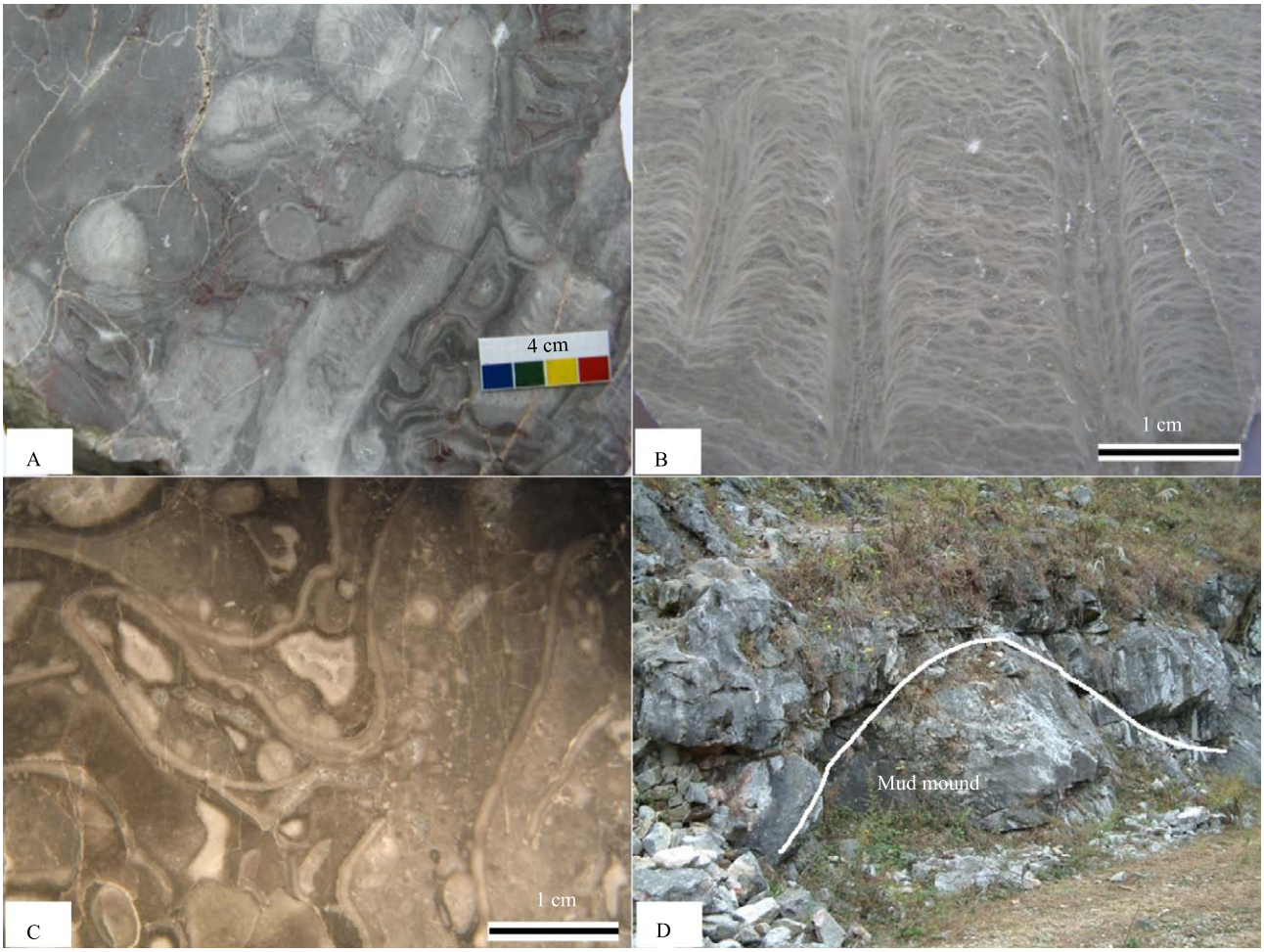

Fig. 10 Types of the Pennsylvanian coral reef limestone at Bianping Village, Ziyun County
A – *Fomichevella* framestone; B – *Ivanovia* cf. *manchurica* skeletal coverstone; C – Phylloid algae bafflestone; D – Field view of the mud mound built by cyanobacteria boundstone;
The mud mound has an exposed length of 2.5 m and a thickness of 1 m.

boundstone (Fig. 10D), and bioclastic limestone that contains *Fomichevella*.

2) Features of reef-building communities

This reef contains abundant organisms, and the principal reef-builders are *Fomichevella*, *Ivanovia* cf. *manchurica*, phylloid algae and cyanobacteria. In different stages of the building process and associated habitats, these reef builders constructed various types of reef as the key species in the community, and formed a special reef complex that is unique to southern Guizhou Province. Three main reef-building communities can be found in the Bianping reef. From bottom to top of the reef section, they are a cyanobacteria-*Ivanovia* cf. *manchurica*-phylloid algae community, a *Fomichevella*-brachiopods community and a *Fomichevella* community (Fig. 11).

(2) Phylloid algal reefs of the Pennsylvanian in southern Guizhou Province

The well-exposed phylloid algal reefs were widespread in Houchang Town, Ziyun County, southern Guizhou. Stratigraphically, the algal reefs belong to the Maping Formation (*Triticites* Zone, Gzhelian, uppermost Pennsylvanian). Phylloid algae are the only reef-building organism in these reefs (Fig. 12). Phylloid algae have different growth forms, which enable them to construct a framework as a barrier to the waterflow; then reefs are built around this framework. The associated organisms in the algal reefs mainly include brachiopods, foraminifera, fusulinids, corals, crinoids, bryozoans, gastropods and *Tubiphytes*. The sizes and morphologies of these reefs are diverse, and the following three forms are recognized: ① phylloid algae patch reef, with a thickness of 1.5 m and an exposed length of 4–5 m; ② superimposed phylloid algal reef complex of different sizes, and seven reefs can be seen in a profile with a maximum thickness of 8 m. Most of them are lenticular and pinch out on both sides, with an exposed length of 30 m or even more; and ③ large-scale phylloid algae reef, with an exposed length of 55 m and a thickness of 18 m (Fig. 12). The Pennsylvanian phylloid algal reefs were developed on a carbonate platform margin. Furthermore three growing stages with distinct parts are recognized: ① the reef base consisting of a bioclastic shoal, ② the reef core, when phylloid algae proliferated and contributed to reef growth, and ③ the reef cover indicating the termination of phylloid algal growth.

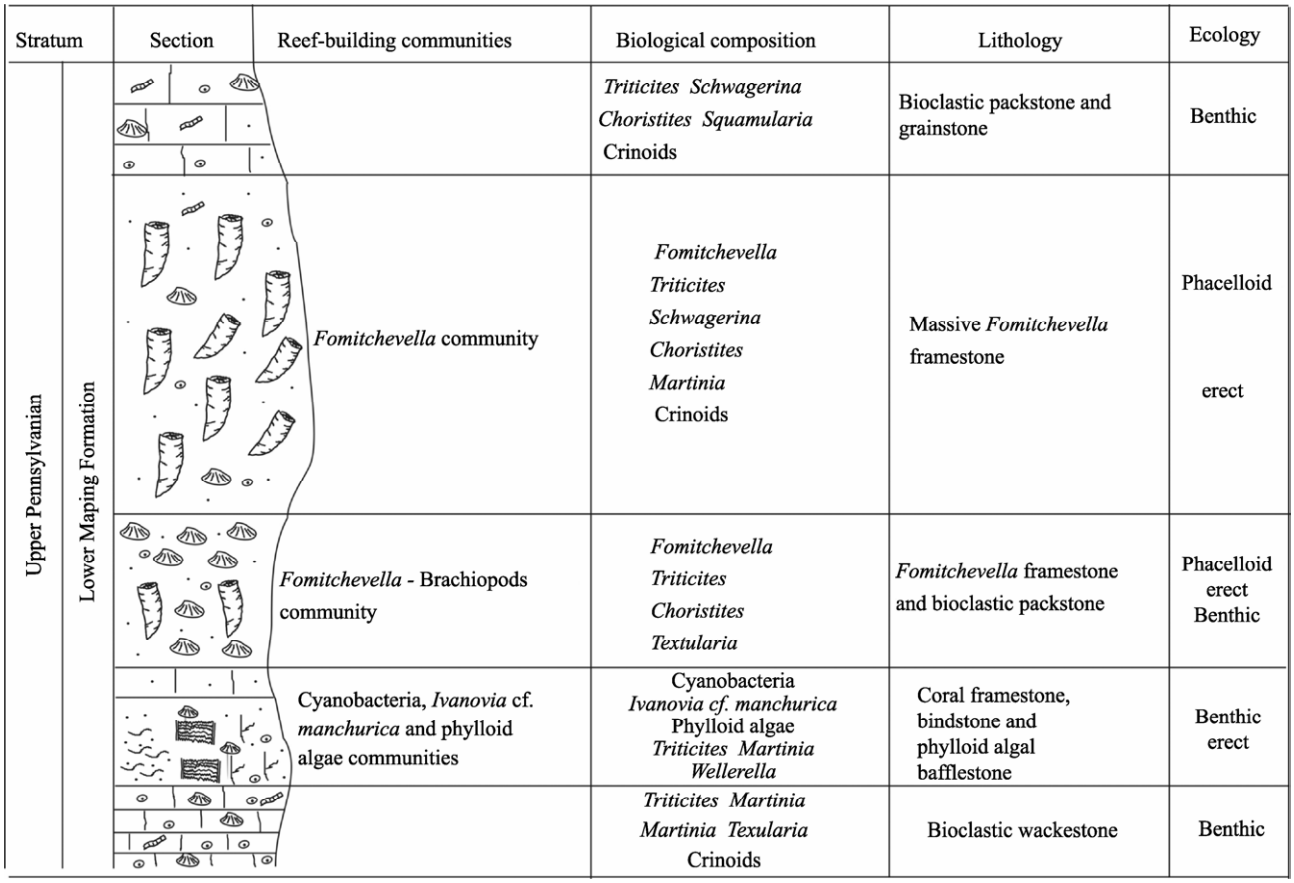

Fig. 11 Sketch diagram of the community succession of the large Bianping coral reef (after Gong *et al*., 2007a)

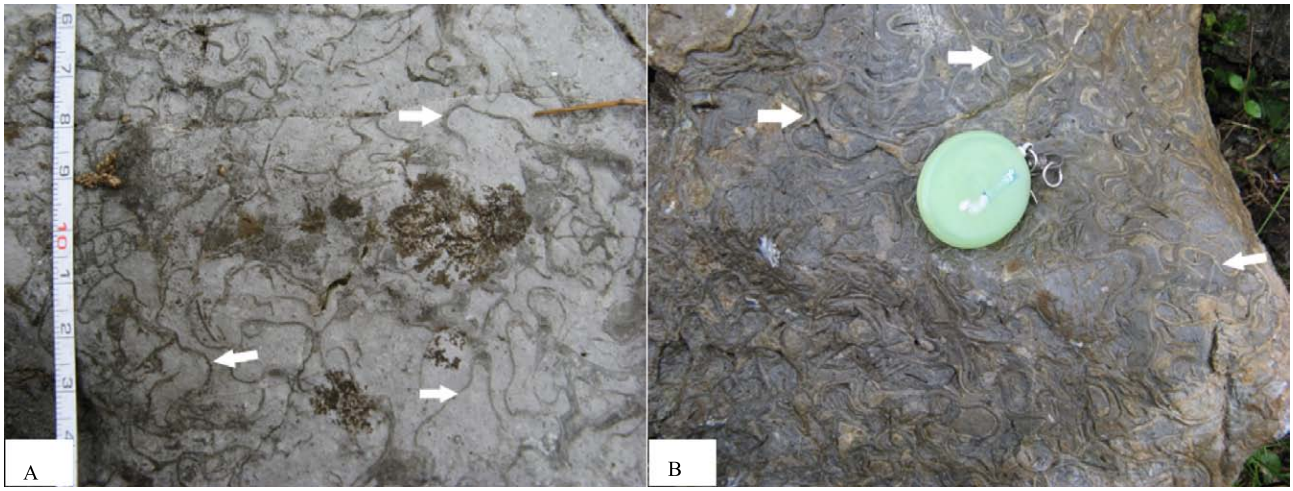

Fig. 12 Field view of the phylloid algal limestone of the Pennsylvanian in southern Guizhou Province
The complete and broken phylloid algal blades are well-preserved and unabraided, indicating that the phylloid algae is *in situ*. Phylloid algal thalli (arrows) appear as broad "v" or "u" shapes on the surface of the limestone.

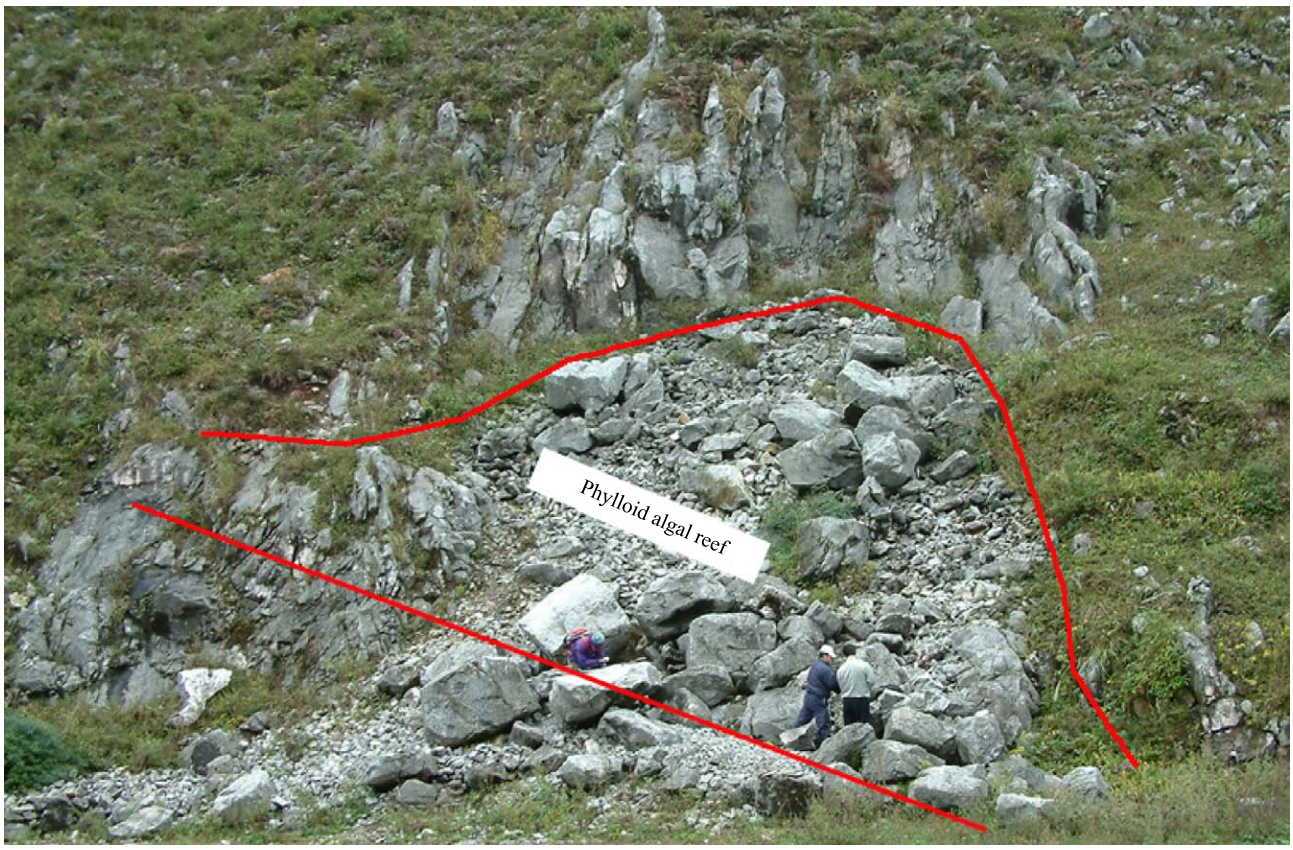

Fig. 13 Field view of the outcrop of the large phylloid algal reef in Houchang Town, Ziyun County
It occurs in the *Triticites* Zone of the Maping Formation (Gzhelian). It has since been destroyed by mining processes.

4 A comparison with global Carboniferous reefs

Many Carboniferous reefs have been well reported in Europe and North America (Flügel and Flügel, 1992; Wahlman, 2002; Webb, 2002). There are seven common types of Carboniferous reefs: (1) phylloid algal reefs, (2) stromatolic reefs, (3) coral reefs, (4) Waulsortian mounds, (5) *Chaetetes* reefs, (6) microbial-algal reef, and (7) algal reefs. The following is the comparison between the Carboniferous reefs in China and the ones from other regions around the world (Table 3):

Table 3 Comparison of the Carboniferous reefs in the worldwide

Characters of the reef	China	Japan	Europe	North America	Australia
The main reef-building organisms	Coral Phylloid algae Bryozoan Stromatolites Chaetetids Calcareous algae	Coral Bryozoan Stromatolites Chaetetids	Microbes Coral Alage Bryozoan	Coral Chaetetids Phylloid algae Bryozoan Microbes Calcareous algae	Microbes Coral Stromatolites Alage
Reef-building model	Framework reef Baffling reef Binding mounds	Framework reef Baffling reef	Binding mounds Framework reef Baffling reef	Framework reef Baffling reef	Binding mounds Baffling reef Framework reef
Scale and number of the reef	Large scale Moderate	Large scale A few	Large scale Many	Large scale Many	Small scale A few
The age range of the framework reefs	Visean Moscovian Kasimovian Gzhelian	Visean-Middle Permian	Visean	Moscovian	Visean
The age range of the Waulsortian mounds and stromatolitic	Visean		Tournaisian-Early Visean	Tournaisian-Early Visean	Tournaisian-Early Visean
The age range of the algal reefs	Kasimovian-Gzhelian		Kasimovian-Gzhelian	Kasimovian-Gzhelian	

Early Carboniferous (Mississippian): During this period, the reefs were distributed in eastern Australia, the western Newfoundland in Canada, Europe, North Africa, southwestern United States, the Urals of Russia, Japan, and China (Flügel and Flügel, 2002, 1992; Shen and Qing, 2010). The earliest known Mississippian reef occurred very near to the Devonian–Carboniferous boundary in Queensland, Australia (Webb, 1998, 2005); and it was constructed mainly by microbes, including stromatolites and thrombolites. Microbial activities were, at that time, the dominant factor controlling the reef development. During the Tournaisian to the Early Visean, reefs dominated by Waulsortian mounds or similar mounds with rich carbonate mud had a widespread distribution: Belgium, Ireland, Northern England and the southwestern United States(James, 1984; Lees *et al*., 1985; Lees and Miller, 1985, 1995; West, 1988; Brown and Dodd, 1990). Although the numbers of carbonate mud mounds were far greater than those of framework reefs, there are some framework reefs presented in the middlelate Visean (Webb, 2002). An organic reef system composed of barrier reef and reef-reef flat-lagoon was developed on the shelf margin in Derbyshire, England, in which reef-building organisms are mainly *Lithostrotion irregulare* and algaes, or bryozoans (Wolfenden, 1958; Adams, 1984). A middle Visean coral atoll was constructed mostly by dense clusters of branching rugose corals (*Nagatophyllum* and *Hiroshimaphyllum*), accompanied by associated organisms, which was found in southern Honshu, Japan. The associated organisms including stromatolitic algae, bryozoans and Chaetetids could baffle and bind sediments (Fagerstrom, 1987). The associated reef-building organisms is similar to which of the late Visean coral-algae reef in Australia (Webb, 1987; Shen and Webb, 2005). A Visean framework reef was also reported in Nova Scotia, Canada, which consists of algal boundstone and the tabulate coral *Clandochonus* comprise the framework of the reef (Schenk and Hatt, 1984). Furthermore, there is a Late Visean small-scale framework reef in Alabama, United States, and the framework is built by *in situ Caninia flaccida* (Kopaska-Merkel *et al*., 1998; Kopaska- Merkel and Haywick, 2001). In China, the reported Mississippian reefs mainly occurred in the Visean, including the stromatolite reef complex in the Laibin County of Guangxi Autonomous Region, and the bryozoan-coral reef in Guangxi Autonomous Region. The Waulsortian mounds or similar mud mounds of Tournaisian to Visean age have not been reported from China. In China during the Mississippian period, reef- building organisms that made framework reefs mainly include *Thysanophyllum* and *Fistulipora*, with some *Syringopora* and *Lithostrotion*. Consequently, the framework types of the Carboniferous reefs between China and the other regions of the world are similar; framework reefs dominated by corals occur mainly in the Visean.

Late Carboniferous (Pennsylvanian): During this period, the reefs were distributed in the southwestern United States, the Arctic Islands of Canada, western Europe and the Alps, North Africa, the Urals of Russia, Japan, and China (Flügel and Flügel, 1992; Samankassou and West, 2002; Gong *et al*., 2007c). There are some small-scale framework reefs in the Early Pennsylvanian (Bashkirian), such as the coral reef bioherms in Oklahoma, USA (Sutherland and Henry, 1977). During the Moscovian，the framework reefs were further developed further, and the main reef-building organisms were *Cha-*

etetes sponges (Fagerstrom, 1987). These reefs are dominated by sponges in Nevada, USA, and accompanied by fusulinids, algae (*Ivanovia*, *Donezella* and *Dvinella*), rugose corals (*Caninia*, *Amandophyllum*, *Caniniostrotion*, and *Tschussovskenia*), tabulate corals (*Syringopora* and *Multithecopora*), and bryozoans (Wilson, 1963; Nelson and Langenheim, 1980). The reefs dominated by *Chaetetes* degenerated at the end of the Moscovian, and phylloid algae reefs dominated the reef ecosystem from the Late Pennsylvanian to the Early Permian (West, 1988). From the Kasimonvian to the Gzelian, phylloid algal reefs had a worldwide distribution. These reefs were mainly constructed by red and green algae, such as *Ivanovia*, *Eugonophyllum*, *Anchicodium*, *Archaeolithophyllum*, and *Archaeolithoporella*. *Ivanovia* and *Eugonophyllum* are the most significant reef builders (Heckel, 1974; Wilson, 1975; Wahlman, 2002), especially in North America (West, 1988). During the Pennsylvanian, not only is the development of framework reefs relatively all over the world obviously, but also the diversity of reef-building organisms is more abundant (West, 1988; Wahlman, 2002). The large, massive reef-building organisms were nevertheless absent in the Pennsylvanian, and, outside of China, reefs were built mainly by huge quantities of relatively small colonial organisms (Wahlman, 2002). Thus, the developmental model of the Pennsylvanian reef was similar throughout the world. The most important difference was that, outside of China, the phylloid algal reefs dominated the reef ecosystem from the Kasimonvian to the Gzelian, whereas the typical metazoan framework reef occurred in China, especially large coral reef in the Ziyun.

5 The evolution of the Carboniferous reefs and marine ecosystem in China

The Frasnian-Famennian mass extinction event wiped out the coral-bryozoan reef-building communities of the Late Devonian (West, 1988; Webb, 2002). During the Carboniferous, new reef-building communities were established; however the organisms that constructed them were different from those that inhabited the Devonian reefs. Two types of reef communities in the Mississippian are recognized. One is an algae reef-building community, which shows features of junior reef-building communities. The presence of these minor communities may indicate the influences by the Late Devonian mass extinction event. The other is a reef-building community dominated by colonial coral, which was formed independent of the mass-extinction event by blooms of new coral communities during the Carboniferous. There is no evolutionary relationship between the two types of communities. They appeared at the same time (Datangian Stage) but developed separately. As a result, two distinct types of reefs existed in the Mississippian.

The Mississippian reefs in the South China mainly occurred in the Datangian Stage (Visean), and the reef-building communities of this time period included a microbial reef community and a coral-bryozoan community. The structures of microbial reef communities were simple, and they were composed almost entirely of stromatolites with laminated, sinuate, hemispheric, turbinate, and fan pillar morphologies. Because the reefs are mound-shaped in outcrop, therefore, they represent a group of reefs developed on a carbonate platform margin. In China the typical Mississippian framework reef was built by coral-bryozoan communities; their reef-building organisms are mainly *Thysanophyllum* and *Fistulipora*, followed by *Syringopora* and *Lithostrotion*. Associated organisms that have no relation to reef-building were abundant in these reefs. All of the facts indicate that the reef-building communities of the Mississippian in China were relatively mature.

Clearly, the Pennsylvanian reef-building communities were obvious more developed and advanced than the Mississippian communities; their characteristics expressed numerous significant changes. During the Early Pennsylvanian, *Chaetetes* dominated the reef-building communities. Coral reef-building and phylloid algal reef-building communities are more common in the Late Pennsylvanian in China, furthermore phylloid algal reef-building communities have a worldwide distribution during this period. The Pennsylvanian reefs that developed in North China mainly occurred during the Moscovian, and they were distributed mainly in the Taizi River Basin, eastern Liaoning Province. *Chaetetes* and *Arachnastraea* were the main reef-building organisms in these communities. *Multithecopora* was the secondary building organism in these communities, and it is usually found in the space between *Chaetetes* and *Arachnastraea*. *Chaetetes* was not only the typical reef-building organism of the Early Pennsylvanian in North China, but it was also an important reef-builder in other shallow-marine carbonate environments during this period.

The reefs of the Late Pennsylvanian mainly occurred in the Xiaoyaoian Stage (Gzhelian) of South China. Phylloid algae and rugose coral *Fomichevella* were the main builders of this period, and they dominated the de-

velopment of the reef-building communities. The structure of the Pennsylvanian phylloid algal communities is simple; the different growth forms of phylloid algae, built reefs as a baffling organism. The sizes and morphologies of the phylloid algal reefs are diversified which include the patch reefs complex superimposed reefs and the large-scale reefs. In China the largest Pennsylvanian framework reef was built by the rugose coral *Fomichevella*, which had a phacelloid growth form. This very large framework reef has a high biotic content, and the main reef-builders are *Fomichevella*, *Ivanovia* cf. *manchurica*, phylloid algae and cyanobacteria. In the different stages of the building process and in the reef habitats, these builders constructed various types of reef as the key species in the community, and they created different reef complexes. The development of the Pennsylvanian reef ecosystem has a close relationship with the marine ecosystem of this time period. The Yunan-Guizhou-Guangxi basin first formed during the Devonian, and after the further development during the Carboniferous into the Permian, subsidence was halted at the end of the Permian. During the Pennsylvanian, a small number of patch coral reefs were developed in the Moscovian and Kasimovian of Tianlin County, Guangxi Autonomous Region (east of this basin) and a large coral reef developed during the Gzhelian of Ziyun County, Guizhou Province (west of this basin). The Pennsylvanian reefs of Guangxi are mainly patch reefs and lamella reefs; however the coral reef of Guizhou is the largest Pennsylvanian framework reef in China that has been discovered to date. Therefore, the reefs of Guangxi are therefore, not well-developed if compared with the massive coral reef in Guizhou. This may indicate that the reef ecosystem of Guangxi developed in an earlier stage of the marine ecosystem evolution than the reef of Guizhou. The reefs of Guangxi are very different from the coral reefs of Guizhou in terms of reef builders, reef size, building mechanisms, biological components and reef-building environments, as well as in several other respects. These conditions indicate an ongoing gradual stabilization of reef building environment, increasing the reef size, increasing complexity of reef structure, and more mature reef-building communities in the marine ecosystem of the Yunan-Guizhou-Guangxi basin. The occurrence of the largest coral reef in Guizhou indicates that the marine ecosystem had entered a special period, in which the environment was stable enough to permit the production of large reef complex.

6 Conclusions

The Frasnian-Famennian mass extinction event wiped out the framework reef-building communities in the Late Devonian. During the Carboniferous, new reef-building communities were built up again and were different from those of the Devonian. In China, the Mississippian reefs were built mainly by bryozoans and rugose corals, followed by various types of algae. During the Pennsylvanian in South China, the dominant reef builders were the rugose coral *Fomichevella*, and phylloid algae, whereas in North China, the reef builders were *Chatates*, bryozoans, and corals. Algae reef-building communities and metazoan-colonial coral reef-building communities were the two main reef-building communities of the Carboniferous reefs in China. There is no evolutionary relationship between the two types of communities, indicating that two separate reef-building organisms evolved during the Carboniferous.

Coral-bryozoan communities built the typical Mississippian framework reef in China, which indicates that these Mississippian reef-building communities were relatively mature. The Pennsylvanian reef-building communities were more advanced, and the metazoan framework reef-building communities dominate the reef ecosystem of this period. The large coral reef built by *Fomichevella* is the archetypal Pennsylvanian framework reef in China. The diversity and development of the Carboniferous reefs shows that the reef communities of this period had recovered their reef-building functions after the Late Devonian mass extinction.

The metazoan framework reefs were strongly developed during the Carboniferous in China. The dominant building organisms of this particular reef ecosystem are all shallow marine benthic organisms. The builders and associated organisms of these Carboniferous reefs favored shallow, warm, and clear seawater, which indicate that most areas of China had a tropical to sub-tropical shallow marine paleoenvironment during this period.

Acknowledgements

Financial support for this research was provided by the National Natural Science Foundation of China (Project No. 40972004) and the Fundamental Research Funds for the Central Universities (N090401011). We express our gratitude to Ian D. Somerville, Zhong-Qiang Chen and Fan Jiasong for their suggestions and for helping to improve the early manuscript. We wish to thank Amanda R. Falk and Desui Miao for language corrections.

References

Adams, A. E., 1984. Development of algal-foraminiferal-coral reefs in the Lower Carboniferous of Furness, Northwest England. Lethaia, 17 (3): 233–249.

Brown, M. A., Dodd J. R., 1990. Carbonate mud bodies in Middle Mississippian strata of southern Indiana and northern Kentucky: End members of a Middle Mississippian mud mound spectrum? Palaios, 5: 236–243.

Fagerstrom, J. A., 1987. The evolution of reef communities. New York: John Wiley and Sons, 1–600.

Fan, J., Rigby, J. K., 1994. Upper Carboniferous phylloid algal mounds in Southern Guizhou, China. Bringham Young University Geology Studies, 40: 17–24.

Fang, S., Hou, F., 1987. Tatangian (Carboniferous) bryozoan-coral patch reef in Langping of Tianlin, Guangxi. In: 11th International Congress of the Stratigraphy and Geology of the Carboniferous Abstracts, 167–168.

Flügel, E., Flügel, K. E., 1992. Phanerozoic reef evolution: basic questions and data base (Carboniferous). Facies, 26: 203–212.

Gong Enpu, 1997. Carboniferous reefs of China. Liaoning Shenyang: Northeastern University Publishing House, 132 (in Chinese with English abstract).

Gong Enpu, Dong Xuming, Zhang Yongli, Guan Changqing, Sun Baoliang, 2009. Paleoecological characteristics of the Carboniferous phylloid algal buildups in Southern Guizhou. Geological Review, 55 (5): 731–735 (in Chinese with English abstract).

Gong Enpu, Samankassou E., Guan Changqing, Zhang Yongli, Sun Baoliang, 2007c. Paleoecology of Pennsylvanian phylloid algal buildups in south Guizhou, China. Facices, 53: 615–623.

Gong Enpu, Guan Guangyue, 1998. Carboniferous extinction and influence on evolution of reef communities. Journal of Northeastern University (Natural Science), 19 (2): 122–124 (in Chinese with English abstract).

Gong Enpu, Zhang Yongli, Guan Changqing, Samankassou E., Sun Baoliang, 2007b. Paleoecology of Late Carboniferous Phylloid Algae in Southern Guizhou, SW China. Acta Geologica Sinica, 81 (4): 566–572.

Gong Enpu, Zhang Yongli, Guan Changqing, Sun Baoliang, 2007a. Primary features of reef-building communities of Carboniferous reef in South Guizhou Province. Acta Geologica Sinica, 81 (9): 1183–1194 (in Chinese with English abstract).

Gong Enpu, 1994. The discovery and study on some middle Carboniferous reefs in Taizi River Basin, Eastern Liaoning. Acta Sedimentologica Sinica, 12 (1): 23–31 (in Chinese with English abstract).

Gong Enpu, Yang Hongying, Guan Changqing, Sun Baoliang, Yao Yuzeng, 2004. Unique recovery stage of reef communities after F/F event in a huge coral reef of Carboniferous, Southern Guizhou, China. Science in China (Ser. D) ,47 (5): 412–418.

Guan Changqing, Gong Enpu, Zhang Yongli, Sun Baoliang, Chen He, Guo Jianhua, Li Qun, 2007. A new type reef of the Late Carboniferous in the South of Guizhou Province. Geological Review, 53 (4): 433–439 (in Chinese with English abstract).

Guan Changqing, Gong Enpu, Yao Yuzeng, Sun Baoliang, 2004. Biocoenose community analysis of Bianping reefs of the Late Carboniferous in southern Guizhou Province. Journal of Palaeogeography, 6 (3): 339–346 (in Chinese with English abstract).

Heckel, P. H., 1974. Carbonate buidups in the geologic record: a review. In: Laporte, L. F. (ed). Reefs in Time and Space, SEPM (Soc. Sediment. Geol.) Special Publication, Tulsa, 18: 90–155.

James, N. P. 1984., Reefs. In: Walker, R. G., (ed). Facies Models. Geoscience Canada Reprint, Ser. 1, 229–244.

Kopaska-Merkel, D. C., Haywick, D. W., Robinson, J., 1998. A baffling Chesterian mud mound in north Alabama. Geological Society of America Abstracts with Programs, 30 (7): 315–316.

Kopaska-Merkel, D. C., Haywick, D. W., 2001. A lone biodetrital mound in the Chesterian (Carboniferous) of Alabama?. Sedimentary Geology, 145: 253–268.

Lees, A., Hallet, V., Hibo, D., 1985. Facies variations in Waulsortian buildups: part 1. A model from Belgium. Geological Journal, 20: 133–158.

Lees, A., Miller, J., 1985. Facies variations in Waulsortian buildups: part 2. Mid-Dinantian buildups from Europe and North America. Geological Journal, 20: 159–180.

Lees, A., Miller, J., 1995. Waulsortian banks. In: Monty, C. L. V., Bosence, D. W. J., Bridges, P. H., Pratt B R., (eds). Carbonate mud mounds: Their origin and evolution. International Association of Sedimentologists, Special Publication, 23: 191–271.

Liu Zuhan, 2002. On factors of Carboniferous reef developing in Hunan: a comparing study with Akiyoshi reef in Japan. Chinese Journal of Geology, 37 (1): 38–46 (in Chinese with English abstract).

Nelson, W. J., Langenheim, R. L., 1980. Ecological observations on *chaetetes* in Southern Nevada. Pacific Geology, 14: 1–22.

Samankassou, E., West, R. R., 2002. Construction versus accumulation in phylloid algal mounds: an example of a small constructed mound in the Pennsylvanian of Kansas, USA. Palaeogeography, Palaeoclimatology, Palaeoecology, 185: 379–389.

Schenk, P. E., Hatt, B. L., 1984. Depositional environment of the Gays River reef, Nova Scotia, Canada. In: Geldsetzer, H. H. J. (ed). Part: 1 Atlantic Coast Basins: Compte Rendu, Ninth International Congress on Carboniferous Stratigraphy and Geology, Southern Illinois University Press, Carbondale, Illinois, 3: 117–130.

Shen Jianwei, Webb, G. E., 2005. Metazoan-microbial framework fabrics in a Mississippian (Carboniferous) coral-sponge-microbial reef, Monto, Queensland, Australia. Sedimentary Geology, 178: 113–133.

Shen Jianwei, Qing Hairuo, 2010. Mississippian (Early Carboniferous) stromatolite mounds in a fore-reef slope setting, Laibin, Guangxi, South China. International Journal of Earth Sciences, 99: 443–458.

Sutherland, P. K., Henry, T. W., 1977. Carbonate platform facies and new stratigraphic nomendature of the Morrowan Series (Lower and Middle Pennsylvanian), northeastern Oklahoma. Geological Society of America Bulletin, 88: 425–440.

Tan Daiyou. 1991. The characteristics of Wengdaowan red algal reef in Ziyun ,Guizhou. Exploration and Exploitation of Gas ,14 (3): 78–84 (in Chinese with English abstract).

Wahlman, G. P., 2002. Upper Carboniferous-Lower Permian (Bashkirian-Kungurian) mounds and reefs. In: Kiessling, W., Flügel, E., Golonka, J. (eds). Phanerozoic Reef Patterns. SEPM Special Publication, 72: 271–338.

Wang Lidong, Yu Bingsong, Zhang Yongwang, Miao Jijun. 2006. Characteristics of reef and beach facies in the Kangkelin Age from Western Tarim Basin – a case study from the Subashi outcrop section in the Keping Area. Geoscience, 20(2): 291–298 (in Chinese with English abstract).

Wang Zengji, Hou Hongfei, 1990. Carboniferous system in China. Beijing: Geological Publishing House, 1–419(in Chinese with English abstract).

Webb, G. E., 1987. Late Visean coral-algal bioherms from the lion Greek Formation of Queensland, Australia. 11th International Congress on the Stratigraphy and Geology of the Carboniferous Abstracts, I: 100.

Webb, G. E., 1998. Earliest known Carboniferous shallow-water reefs, Gudman Formation (Tn1b), Queensland, Australia: Implications for Late Devonian reef collapse and recovery. Geology, 26 (10): 951–954.

Webb, G. E., 2005. Quantitative analysis and paleoecology of Earliest Mississippian microbial reefs, Gudman Formation, Queensland, Australia: Not just post-disaster phenomena. Journal of Sedimentary Research, 75: 877–896.

Webb, G. E., 2002. Latest Devonian and Early Carboniferous reefs: Depressed reef building after the middle Paleozic collapse. In: Flügel, E., Kiessling, W., Golonaka, J., (eds). Phanerozoic Reef Patterns. SEPM Special Publication, 72: 239–269.

West, R. R., 1988. Temporal changes in Carboniferous reef mound communities. Palaios, 3: 152–169.

Wilson, E. C., 1963. The tabulate coral *Multithecopora* Yoh from the *Chaetetes-Profusulinella* faunizone in eastern Nevada. Journal of Paleontology, 37 (1): 157–163.

Wilson, J. L., 1975. Carbonate Facies in Geologic History. New York: Springer Verlag, 1–471.

Wolfenden, E. B., 1958. Paleoecology of the Carboniferous reef complex and shelf lime-stones in northwest Derbyshire, England. Geological Society of America Bulletin, 69: 871–898.

Zhang Wei, Liao Zhouting, 1998. Petrology and diagenesis of Late Carboniferous Carbonate buildups in eastern Tianshan Mountains, China. Acta Petrologica Sinica, 14 (4): 559–567 (in Chinese with English abstract).

Zhang Yongli, Gong Enpu, Wilson, M. A., Guan Changqing, Sun Baoliang, 2010. A large coral reef in the Pennsylvanian of Ziyun County, Guizhou (South China): The substrate and initial colonization environment of reef-building corals. Journal of Asian Earth Sciences, 37: 335–349.

Zhang Yongli, Gong Enpu, Guan Changqing, Samankassou, E., Sun Baoliang, 2007. Carboniferous phylloid algal reefs in Ziyun County, Guizhou (South China): Evidence of algal blooms. Acta Sedimentologica Sinica, 25 (2): 177–182 (in Chinese with English abstract).

Zhou Huailing, Zhang Zhenxian, 1991. The Early Carboniferous stromatolitic algal reef in Laibin County, Guangxi. Geology of Guangxi, 4 (4): 1–5 (in Chinese with English abstract).

(**Edited by Wang Yuan, Liu Min**)