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The Permian Reefs of South China and Comparisons with the Permian Reef Complex of the Guadalupe Mountains, West Texas and New Mexico

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ABSTRACT

Permian reefs have been recognized in western Hubei, eastern Sichuan, northwestern Guangxi, and in eastern Yunnan Provinces in China. In these areas, three different kinds of Permian reefs have been recognized in the Middle and Upper Permian rocks, generally in the Maokou and Changxing Formations.

Permian reefs in eastern Sichuan and western Hubei Provinces generally occur in the uppermost part of the latest Permian Changxing Formation and are particularly well exposed in the Lichuan district near Jiantianba, Huangnitang, and Jiannan on the southwestern flank of Yupize anticline. The reefs overlie basin facies of dark gray to black micrite and siliceous shales. Fore-reef and slope facies grade upward from basin facies rocks into the massive reef core, composed in large part of sphinctozoans, inozoans, and hydrozoans as frame builders, and blue-green algae, *Tubiphytes*, and bryozoans as binders. Coarsely crystalline, light gray massive dolomite overlies the reef-core facies and records submergence of the reef tract. Diagenesis of the reef masses generally involve several generations of cement, dolomitization, and dissolution.

Reefs of eastern Sichuan are best represented by mounds at Laolongdong. These mounds may be up to 50 m high, in the center, and are composed mainly of sponge bafflestones and skeletal wackestones. The mounds began as echinoderm banks or shoals and grew upward as sponge bafflestone mounds. They developed into bryozoan-echinoderm banks and finally were buried by skeletal wackestones over the mound crests.

Middle and Upper Permian reefs are widely distributed and well developed in eastern Yunnan, southwestern Guizhou, and in northwestern Guangxi Provinces. A barrier reef belt rims a carbonate platform on the northwest, west, and southwest of the major deep-water basin. Reef-building organisms have produced a characteristic carbonate platform marginal reef. Such marginal reefs are well represented by those at Xiangbo, in Longlin County, northwestern Guangxi. The Xiangbo reef shows distinct cycles that consist of alternations of reef framework facies and reef-flat facies. Two cycles developed during Middle Permian Maokou time, two cycles during late Permian Wujiaping time, and two cycles during the latest Permian Changxing time.

The reefs generally show diverse assemblages of frame-building organisms, such as inozoan and sphinctozoan sponges, that are bound into a solid carbonate mass by algae, such as *Archaeolithoporella* and *Tubiphytes*, tabulozoans, and fistuliporid bryozoans. Reef-flat rocks are generally rudstones or floatstones, with various clast sizes, that contain abundant gymnocodiacean and dasycladacean algae, as well as foraminifers, echinoderms, and brachiopods. Skeletal intraclastic grainstones play a major role in some of the reef-flat units. Like the reefs at Jiantianba, those of southern China also show dolomitization, dissolu-

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tion, and introduction of coarse crystalline calcite cement with minor development of authigenic minerals such as quartz.

Reefs of southern China show remarkable similarity to the Capitan reef complex of the Guadalupe Mountains of west Texas and New Mexico. Back-reef beds in most of the Chinese reefs document drowning and submergence of the reef tracts rather than emergence, as documented by the Carlsbad Group rocks of the Guadalupe Mountains.

INTRODUCTION

Marine Permian deposits are widely distributed in South China. Following exploration for and exploitation of oil and gas in reef and nonreef carbonate rocks in South China, several Permian reef complexes have been discovered in recent years. As a result, three kinds of Permian reefs have been recognized in different areas of China. These areas include (1) eastern Sichuan, (2) western Hubei, (3) northwestern Guangxi, and (4) eastern Yunnan (fig. 1).

CLASSIFICATION OF MARINE PERMIAN FORMATIONS OF SOUTH CHINA

In former years Permian strata were divided into the Lower and Upper Permian. Recently, however, we have recognized that Permian strata can be clearly divided into three parts and separate the rocks into Lower, Middle, and Upper Permian (table 1). Lower Permian rocks are included in two fusulinid zones: the *Triticites* zone, below, and the *Pseudoschwagerina* zone, above, which can be correlated with the Wolfcampian.

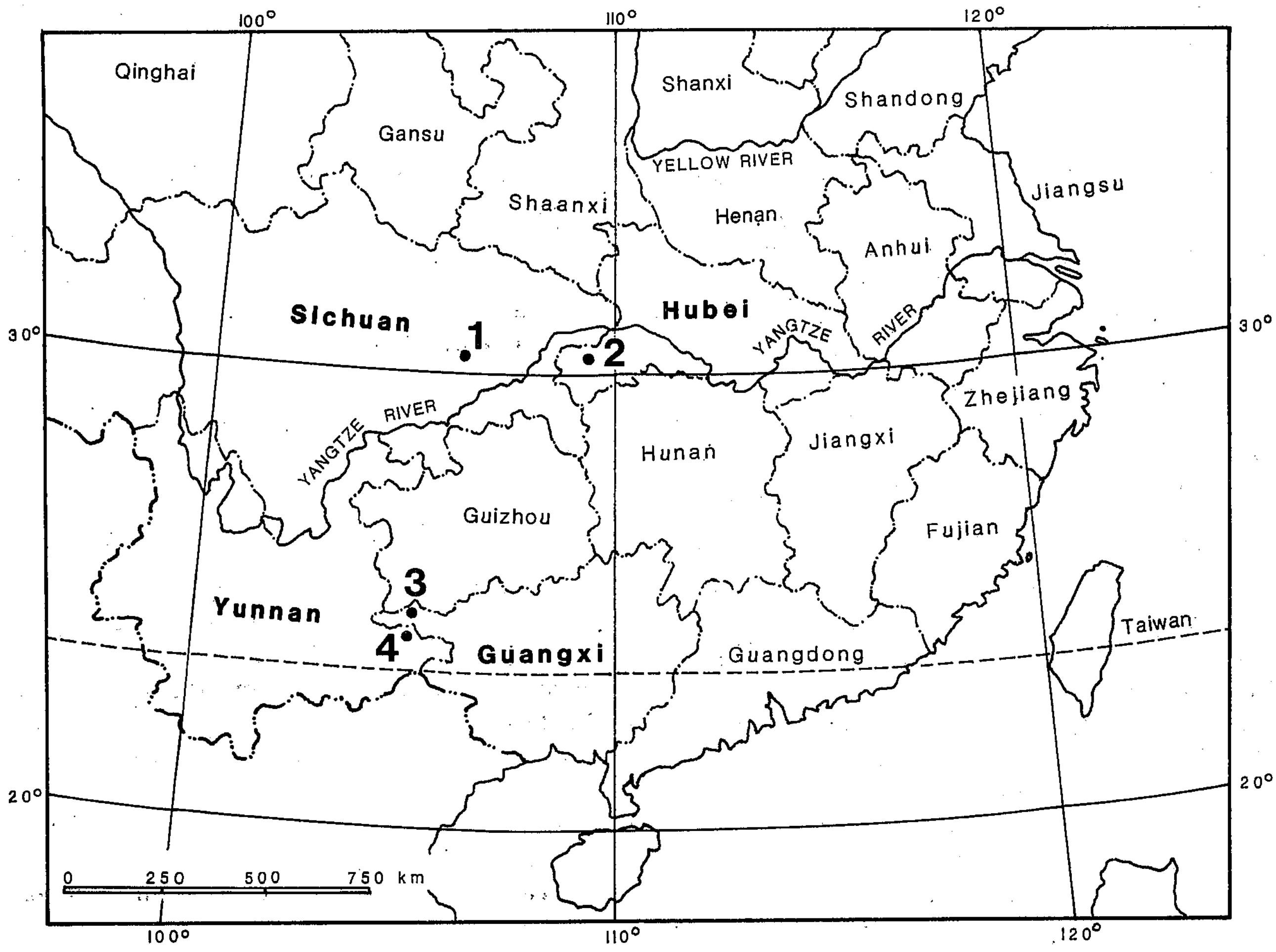


FIGURE 1.—*Index map to four major Permian sponge-reef localities in southern China. Locality 1, in eastern Sichuan, is at Laolongdong, and Locality 2, in western Hubei, is near Jiantianba in the upper part of the Late Permian Changxing Formation. Locality 3, in western Guangxi, is at Xiangbo in Longlin County where Middle and Late Permian reefs are well developed. Locality 4, near Guangnan in eastern Yunnan, is along part of the barrier-reef trend for Late and Middle Permian reefs.*

Table 1. Stratigraphic nomenclature of Permian rocks of South China and correlation to Russian and North American series (Sheng and others 1985; Zhao and others 1981).

SYSTEM	SERIES		FORMATION	FUSULINID ZONE	RUSSIAN	NORTH AMERICA
PERMIAN	UPPER PERMIAN	LOPING SERIES	**Changxing Formation**	*Palaeofusulina* zone	Tatarian Kazanian Ufimian	Ochoan
			Wujiaping Formation	*Codonofusiella* zone		Guadalupian
	MIDDLE PERMIAN	YANGXIN SERIES	Maokou Formation	*Yabeina* zone *Neoschwagerina* zone *Cancellina* zone	Kungurian	
			Qixia Formation	*Misellina ovalis* zone *Brevaxina otakiensis* zone	Artinskian	Leonardian
	LOWER PERMIAN		Baomoshan Formation	*Psuedoschwagerina* zone	Sakmarian Asselian	Wolfcampian
			Longyin Formation	*Triticites* zone		

Middle Permian rocks in South China are divided into the Maokou Formation and Qixia Formation. Sheng and others (1985) concluded that the Qixia Formation may be further subdivided into three parts. The lower Qixia Formation is composed of light gray to gray wackestone, packstone, and sometimes lime mudstone that contain a diverse benthonic fauna. Common in collections are the fusulinaceans *Misellina changmoensis, Robustoschwagerina, Parafusulina, Schwagerina,* and *Pseudofusulina.* Brachiopods include *Choristites* and *Linoproductus,* and corals include *Wentzellophyllum,* and *Szechuanophyllum.* Middle and upper parts of the Qixia Formation are composed of medium gray to dark gray packstone and wackestone, intercalated with light gray grainstone. Middle and upper Qixia beds contain the fusulinaceans *Misellina claudiae, Cancellina, Parafusulina,* and *Nankinella.* The corals *Wentzellophyllum* and *Hayasakaia* and the brachiopods *Chaoina* and *Orthotichia* also occur.

Sheng and others (1985) suggested that the Maokou Formation also may be divided into two parts. The lower part is made up of gray packstone intercalated with light gray grainstone and dark gray wackestone. Lower Maokou beds contain the fusulinaceans *Neoschwagerina, Verbeekina, Sumatrina,* and *Afghanella,* along with the corals *Ipciphyllum* and *Iranophyllum.* The upper Maokou beds consist of light gray, thick-bedded to massive packstone and grainstone intercalated with wackestone. Fossils found in upper Maokou beds include the fusulinaceans *Lepidolina, Yabeina, Neomisellina, Sumatrina, Polydiexodina, Kahlerina,* and *Schwagerina* and the corals *Ipciphyllum* and *Allotropiophyllum.*

The discovery of *Polydiexodina,* reported here, in the upper part of the Maokou Formation, suggests correlation of the Maokou Formation with the Guadalupian Series.

Polydiexodina occurs in the Seven Rivers Formation and up to the middle part of the Yates Formation (Unit B) in back-reef beds in the Guadalupe Mountains of Texas and New Mexico, and also extends through the basin-facies Bell Canyon Formation up the top of the McCombs Member (table 2). This characteristic fusulinid has not been recognized in the Lamar Member, the upper limestone of the Bell Canyon Formation. Because of the mutual occurrence of *Polydiexodina,* the Maokou Formation may be correlated with the Guadalupian.

The Upper Permian series in China includes the Wujiaping Formation and the overlying Changxing Formation. The Wujiaping Formation is composed mainly of dark gray to black wackestone and packstone. It contains the following fusulinaceans: *Codonofusiella, Nankinella, Sphaerulina,* and *Reichelina;* the corals *Liangshanophyllum* and *Heshanophyllum;* and the brachiopods *Araxathyris* and *Streptorhynchus.* The Wujiaping Formation may be correlated with the Ochoan of North America.

Table 2. Stratigraphic nomenclature of formations in the Guadalupe Mountain reef complex of west Texas.

BASIN					REEF	BACKREEF
SERIES			FORMATION	MEMBER	FORMATION	
OCHOAN			Castile	Gypsum		
				Basal limestone		?
GUADALUPIAN	Delaware Mountain Group	Upper	Bell Canyon	Lamar	Capitan	Tansill
				McCombs	Capitan	C
				Rader		B Yates
						A
				Pinery		Seven Rivers
				U. Hegler		
				Lower Hegler		
		Middle	Cherry Canyon	Manzanita		Shattuck Member
				South Wells	Goat Seep	Queen
				Getaway Upper		Dog Canyon
				Getaway Lower	?	San Andres
				Cherry Canyon Sandstone Tongue		
		Lower	Brushy Canyon			

The uppermost Permian Changxing Formation is composed mainly of light gray packstone and grainstone. The formation contains the fusulinids: *Palaeofusulina, Nanlingella, Reichelina, Sphaerulina,* and *Nankinella;* the small foraminifer *Colaniella;* the brachiopods: *Peltichia zigzag* and *Spinomarginifera alpha;* and the coral *Waageno-phyllum.* The Changxing Formation is conformably overlain by Lower Triassic rocks and probably includes the youngest Permian deposits in the world.

THE HISTORY OF RESEARCH ON PERMIAN REEFS IN SOUTH CHINA

Research on Permian reefs in South China began somewhat earlier than the 1970s but began in earnest approximately 15 years ago. Several groups of geologists have contributed to the study of Permian reefs in China. In Guizhou Province, for example, Liu Bingwen and Wang Zhihua, in an informal report, discussed preliminary investigations of Permian reefs that are well exposed in Ziyun, Ceheng, Wangmo, and Houchang. They recognized that these Permian reefs are composed mainly of sponges that are usually encrusted by blue-green algae. Lu Zuyu, Wang Jiongzhang, and others have carried out extensive investigations in East Yunnan, southwestern Guizhou, and northwestern Guangxi Provinces. Although their work was limited to a general geological survey, it was the base for further study on Permian reefs in southwestern China.

In western Hubei (fig. 1), preliminary investigations were carried out during the early 1960s. By the beginning of the 1970s, however, detailed research was underway on the reefs exposed at Jiantianba and Huangnitang. These exposures have been studied subsequently by many people, resulting in the documentation of details of these reefs. Most prominent early workers include Chen Jingren, Liu Lingshan, and Liu Huaibo.

With the exploration for oil and gas in carbonate rocks of South China, beginning in the early 1980s, a great many people have studied these Permian reefs. Their work covers various aspects of reef research including reef fossils and systematic paleontology, analysis of related fossil communities, reef rock petrology and diagenesis, stratigraphic development and growth of reefs, geographic distribution of reefs, and the probability for production of oil and gas from these reefs. For example, Li Shushun, Liu Dacheng, and Gu Shunhua (1985) surveyed the Honghua reefs exposed in Kaixian County, in northeastern Sichuan. Qiang Zhitong and others (1985) made a detailed study of the Laolongdong mounds, northwest of Chongqing in eastern Sichuan. Fang Shaoxian (1983) studied diagenesis of the Jiantianba reef, especially silicification; Chen Jigao, Zhao Xianwen, and Zhang Yinben (1985) made a careful study of cores of reef rocks that were collected by drilling in eastern Sichuan. Zeng Hui (personal communication) has discussed the distribution and structural features of reefs exposed at Tingliang, Ningming County in western Guangxi.

Recently, Zeng and Liu (1984) and Zeng, Liu, and Huang (1984) contributed comprehensive syntheses of work on Paleozoic and Triassic reefs in South China.

All of the works cited above have provided important bases for further study of the Permian reefs.

THE DISTRIBUTION AND DURATION OF THE PERMIAN REEFS IN SOUTH CHINA

Permian reefs in eastern Sichuan and western Hubei generally occur in the uppermost part of the latest Permian Changxing Formation, in beds equivalent to the *Palaeofusulina sinensis* zone. Middle Permian barrier reefs have not been discovered yet in these regions.

Except for the Laolongdong patch reefs and scattered and isolated mounds, which are baffled mounds, all of the reefs in East Sichuan have typical reef texture and abundant frame-building organisms.

Upper Permian reefs exposed in Yunnan, Guizhou, and Guangxi Provinces were formerly regarded as occurring only in the Upper Permian Changxing Formation. More recent research on biostratigraphy of the Xiangbo reefs, however, indicate that reefs may extend also down into the underlying Wujiaping Formation. Middle Permian reefs in the same regions generally occur in the Maokou Formation, in rocks of the *Neoschwagerina* zone (fig. 2).

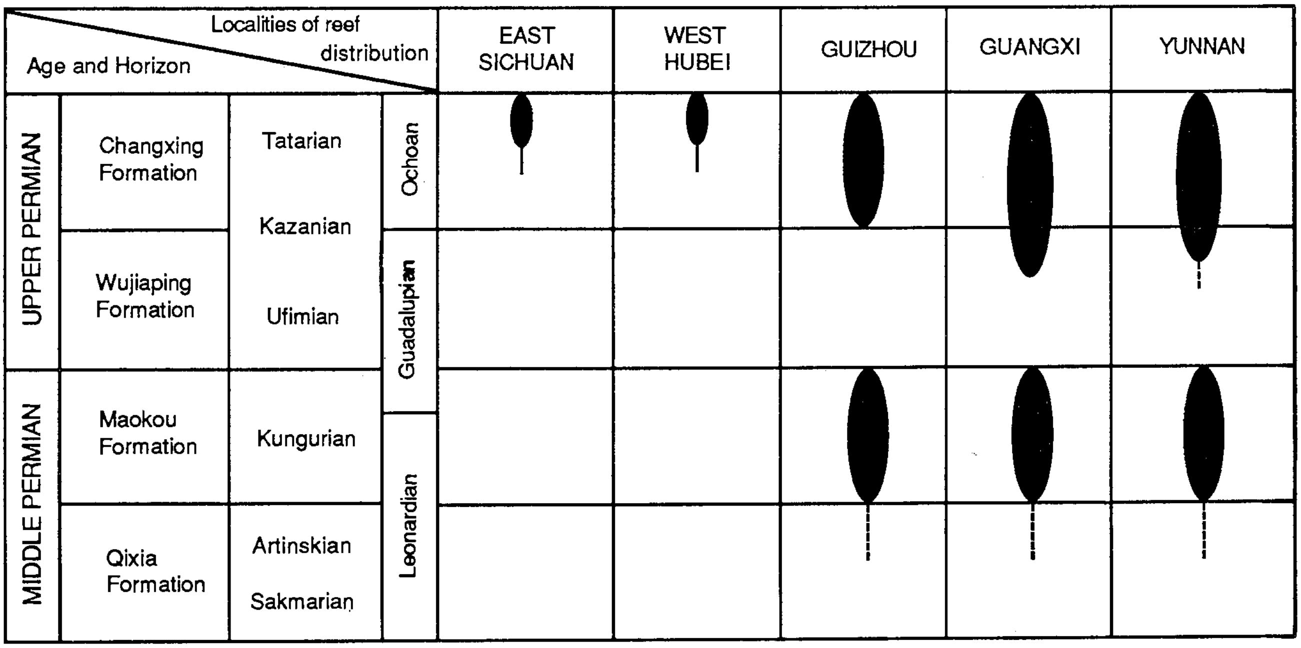


FIGURE 2.—*Times of extensive development of Permian reefs in South China. Middle and Late Permian reefs are well developed in Guizhou, Guangxi, and Yunnan Provinces. Late Permian reefs, in addition, are also developed in eastern Sichuan and western Hubei. Solid lines indicate limited development before major reef expansion in rocks of the latest Changxing Formation. Dashed lines indicate probable development during the earlier part of the Middle Permian and Late Permian in southern China. Sizes of ellipses indicate relative development.*

WESTERN HUBEI REEFS

GENERAL INTRODUCTION AND STRATIGRAPHY OF UPPER PERMIAN DEPOSITS IN THE LICHUAN DISTRICT, WESTERN HUBEI

Upper Permian reefs are widely distributed in the Lichuan district of western Hubei (fig. 3). Sphinctozoans, inozoans, and hydrozoans constitute the frame-building organisms of typical reefs there (Fan and others 1982; Fan and Zhang 1985, 1987). Reefs are well exposed at Jiantianba, Huangnitang, and Jiannan in Lichuan County, and are particularly well exposed on the southwestern flank of the large Yupize anticline. The Jiantianba section is one of the best sequences of basin to reef and back-reef beds exposed on the anticline. Reef outcrops there usually form an escarpment that extends from Jiantianba to Gongshan Pass along the southwestern flank of the fold (fig. 3).

Upper Permian rocks of the Lichuan district are generally divided into two formations: the lower Wujiaping Formation and upper Changxing Formation (table 1). The Wujiaping Formation is composed mainly of interbedded, thin-bedded, cherty limestone, brown and black chert, spiculite, and carbonaceous shale. These rocks contain *Codonofusiella, Waagenophyllum, Lophophyllidium, Tylopecten,* and other fossils. The overlying Changxing Formation generally consists of dark gray, thick-bedded bioclastic limestones that contain *Palaeofusulina, Lophocarinophyllum,* and *Pseudotirolites.* The Dalong Formation is regarded as a lateral facies of the Changxing Formation and represents deep-water basin deposits.

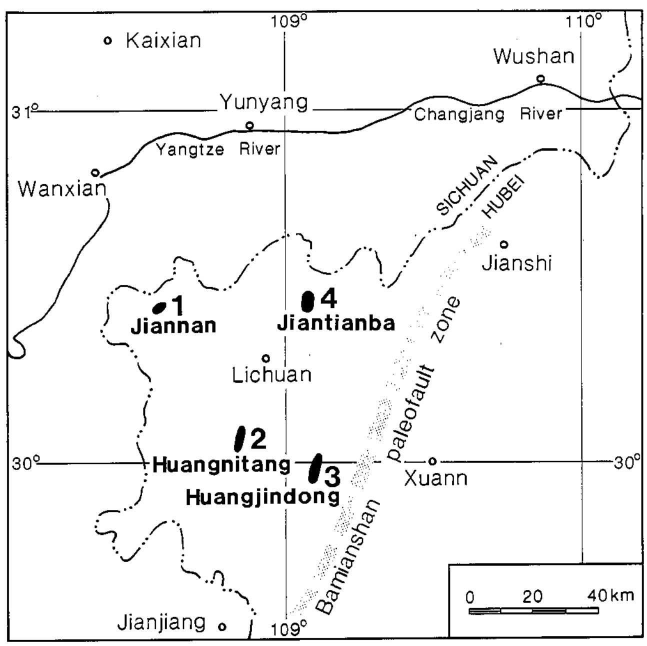


FIGURE 3.—*Index map to currently documented extensive reef developments in western Hubei, in the Lichuan area.*

The Dalong Formation is composed of thin-bedded siliceous rocks and cherty limestones, which yield abundant ammonites such as *Pseudotirolites* and *Pseudogastrioceras*.

FACIES AND DEPOSITIONAL HISTORY OF THE JIANTIANBA REEF

Careful study of the reef sections allows establishment of facies patterns and understanding of the depositional history of the Jiantianba reef (fig. 4).

Basin facies rocks underlie the reef complex (fig. 4) and are typical deeper-water euxinic beds. They consist of dark gray and black, thin- to medium-bedded micrites that contain well-preserved radiolarians, calcispheres, and sponge spicules. The limestone units are intercalated with dark gray to black cherty layers and spiculitic siliceous rocks.

Fore-reef and slope facies grade upward from basin facies rocks and represent the initial stages of reef growth.

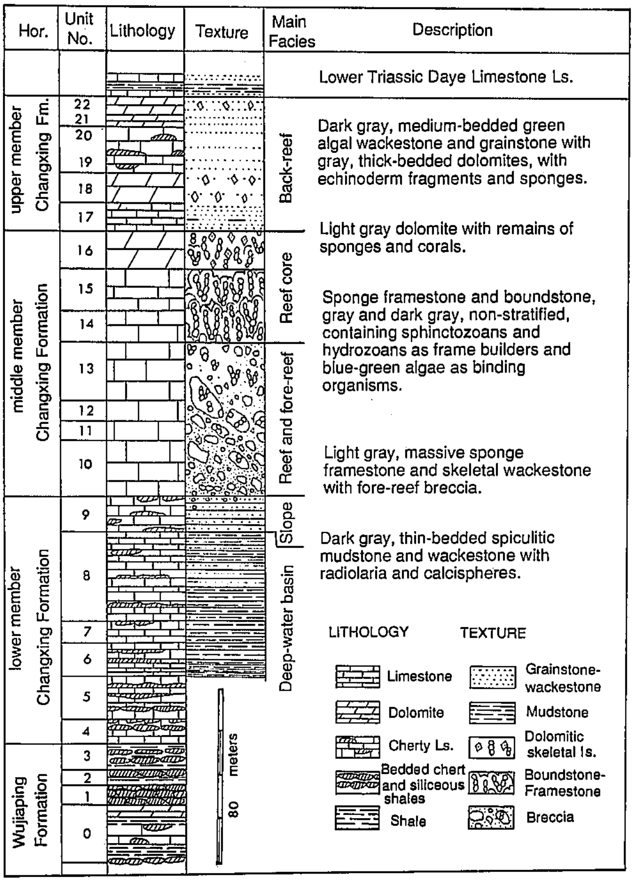


FIGURE 4.—*Vertical section through the Jiantianba reef showing distribution of organisms and major rock types. Reef and fore-reef–slope facies transgress over thin bedded limestone and siliceous rocks of basin facies and, in turn, are overlain by lagoonal or shelf limestone and dolomite.*

These reef-related rocks consist of light gray, thick-bedded to massive sponge-skeletal limestones. Some thinner-bedded and wedge-shaped masses of fore-reef slump breccias interfinger with both the reef limestones and basin beds.

Reef-core facies overlie the fore-reef and slope facies. Reef-core rocks are composed of gray to dark gray, nonbedded sponge framestones in which sphinctozoans, inozoans, and hydrozoans are the frame-builders and blue-green algae and *Tubiphytes* are the binders (fig. 5), much as in the Guadalupe Mountains of Texas (Yurewicz 1977, Babcock, 1977) and in Permian-Triassic reefs of the Alps (Brander and Resch 1981; Flügel 1977, 1979, 1981a, 1981b; Piller 1981) or Triassic reefs in Canada (Reid and Tempelman-Kluit 1987; Stanley 1980, 1982). Accessory organisms include echinoderms, brachiopods, gastropods, bryozoans, and abundant foraminifers. Frame-building organisms make up much of the rock volume and are well preserved, often in upright growth position. Binding organisms encrusted the frame builders and bound individual elements of the reef into a solid structure. Their encrusting habits provided strength to the frame-building elements.

Framework and binding organisms, such as laminar blue-green algae, are usually coated by a marine cement of fibrous calcite, which in turn is coated by a thin layer of euhedral dolomite crystals. The remaining reef cavities were later filled by bladed to blocky sparry calcite.

Much of the clastic interstitial material is composed of micrite, probably formed by breakdown of skeletal elements or produced by activity of the blue-green algae.

Main frame-building organisms include the sphinctozoan calcisponges: *Amblysiphonella*, *Girtycoelia*, *Waagenella*, *Colospongia*, *Sollasia*, *Intrasporeocoelia*, *Cystothalamia*, *Uvanella*, *Rhabdactinia*, *Lichuanospongia*, *Polycystocoelia*, *Sinocoelia*, and *Stromatocoelia*, described and figured by Fan and Zhang (1985). Inozoans also play a major role and include *Peronidella* and *Stellispongia* (Fan and Zhang 1987). Tabulozoans, tentatively included within the sclerosponges, are also important, as is the hydrozoan *Disjectopora*.

The coarsely crystalline, light gray, massive dolomites that overlie the reef-core facies contain remains of echinoderm fragments and other bioclasts. During late stages of reef growth, the area may have been uplifted and tops of the reefs subaerially exposed. Local dolomitization and intense leaching followed. Intercrystalline porosity, combined with solution porosity, is well developed. Equivalent dolomite beds are productive reservoir rocks for oil and gas in other structures in central and southern China.

Late in the Permian, the reef tracts were drowned and then covered by carbonate platform deposits that consist of intercalated dark gray, medium- to thick-bedded packstone and wackestone. These rocks contain abundant

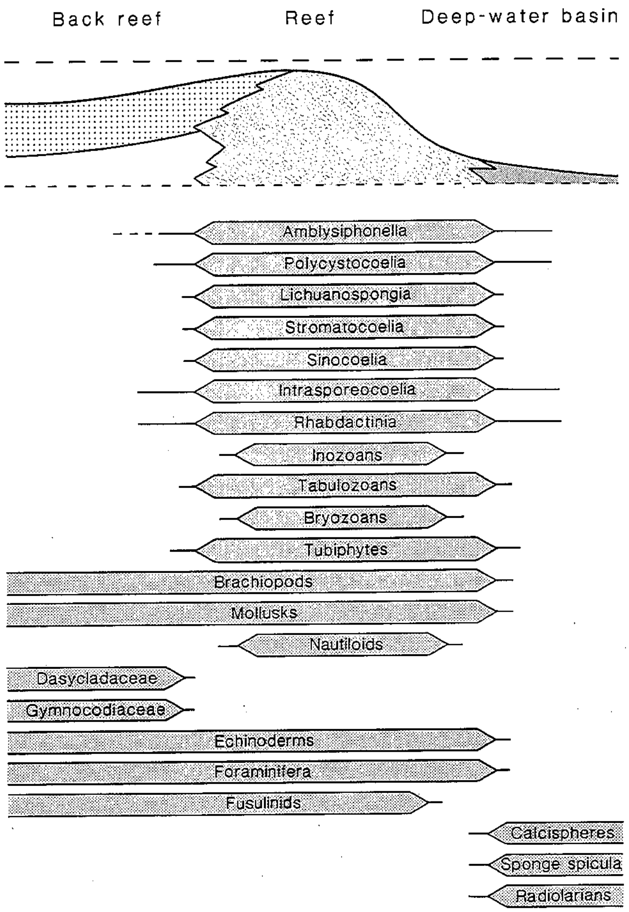


FIGURE 5.—*Distributions of various organisms associated with the reef at Jiantianba. Dasycladacean and gymnocodiacean algae are concentrated in back-reef or lagoon rocks and sponges and encrusting binders in the reef facies. Calcispheres, sponge spicules, and radiolarians characterize the deeper-water basin facies. Echinoderms, small foraminifera, fusulinids, brachiopods, and mollusks are widely developed as accessory forms in the reef and lagoonal beds but are present in the marginal basin-facies rocks largely as transported elements.*

echinoderm fragments, foraminifers, brachiopods, and gymnocodiacean algae. *Colaniella* and *Palaeofusulina* are common elements in these deposits. These carbonate platform deposits record cessation of reef growth, presumably because the sea became too deep for active upward growth of the reefs.

DISTRIBUTION OF THE BIOTA AND THEIR COMMUNITIES WITHIN THE UPPER PERMIAN REEF COMPLEX

Rocks of different facies also reflect different faunal assemblages. The reef core has a characteristic assemblage of sphinctozoans, inozoans, tabulozoans, hydrozoans, bryozoans, *Tubiphytes*, and nautiloids. The latter might have swum into areas of reef growth and became trapped within cavities of the reefs. Principal organisms of the back-reef facies are foraminifers, including fusulinids, brachiopods, molluscs, and gymnocodiacean and dasycladacean algae. The assemblage indicates an origin in restricted marine carbonate platform environments. Organisms characteristic of deep-water basin facies are calcispheres, siliceous sponges, and radiolarians.

Five communities have been recognized within the reef complex. Their distributions and distributions of various groups of organisms are shown in figures 5 and 6.

1. Sphinctozoan—blue-green algal community: This community is characterized by sphinctozoan sponges and bryozoans, which are generally encrusted by spongiostromate algae and *Tubiphytes*. The community represents the colonization stage (initial community) of the reef. Voids in the framework were filled with lime mud and fine-grained skeletal debris. Accessory organisms include various brachiopods, gastropods, and echinoderms.

2. Tabulozoan-sphinctozoan community: This community is characterized by the predominance of tabulozoans with sphinctozoans playing a lesser role. Interstitial spaces between organisms are filled with lime mud, fine-grained skeletal debris, and, in places, with fibrous and drusy sparry calcite. This community seems to have lived in relatively protected parts of the reef core.

3. Sphinctozoan-inozoan community: The community is characterized by an assemblage of abundant and highly diverse sphinctozoans. The percentage of open spaces within the organic framework is high and filled with several generations of fibrous to bladed calcite cement. This community is believed to have flourished within reef-core environments that faced the open, relatively deep-water basin.

4. Green algae-echinoderm-foraminifer community: Typical organisms of this community include dasycladacean and gymnocodiacean algae, echinoderms, smaller foraminifers, and fusulinids. This community is regarded as having occupied platform or lagoonal environments.

5. Sponge spicule-radiolarian community: The community is characterized by planktonic organisms, such as radiolarians, calcispheres, and by disassociated sponge spicules. This assemblage is regarded as typical of sediments deposited within or on the margin of a relatively deep, commonly anoxic basin.

DIAGENESIS

Diagenetic modification of the reefs includes cementation, dolomitization, and dissolution (fig. 7).

1. Cementation: Three generations of cement have been distinguished including early fibrous calcite, later euhedral dolomite rims and, finally, void-filling bladed to

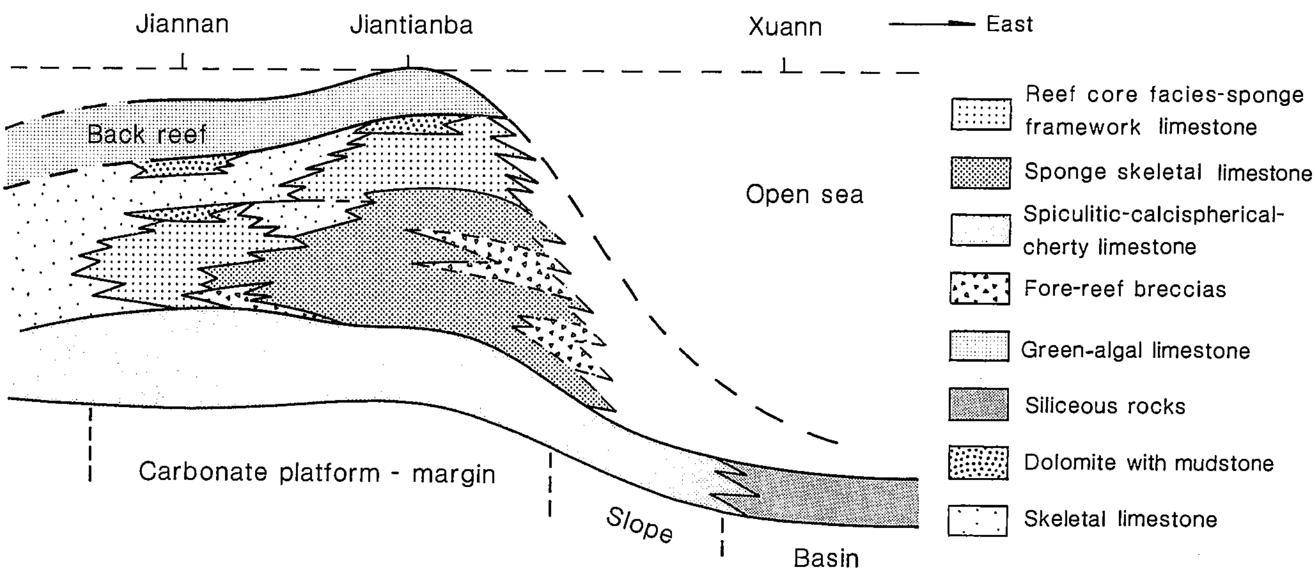


FIGURE 6.—*Generalized cross section through the Jiantianba carbonate platform marginal reef shows relationships of various lithologies. Well-developed back-reef rocks at Jiannan contrast to the thick reef-related rocks at Jiantianba and the thin basin-facies rocks at Xuann. Rocks equivalent to the reef facies at Jiantianba have been removed by erosion where the Xuann sections were measured. In general, the reef-core facies transgresses over shelf margin skeletal limestones that, in turn, are transgressive eastward over basin-facies rocks. Vertical section at Jiantianba approximately 300 m. Jiannan and Jiantianba are approximately 50 km apart.*

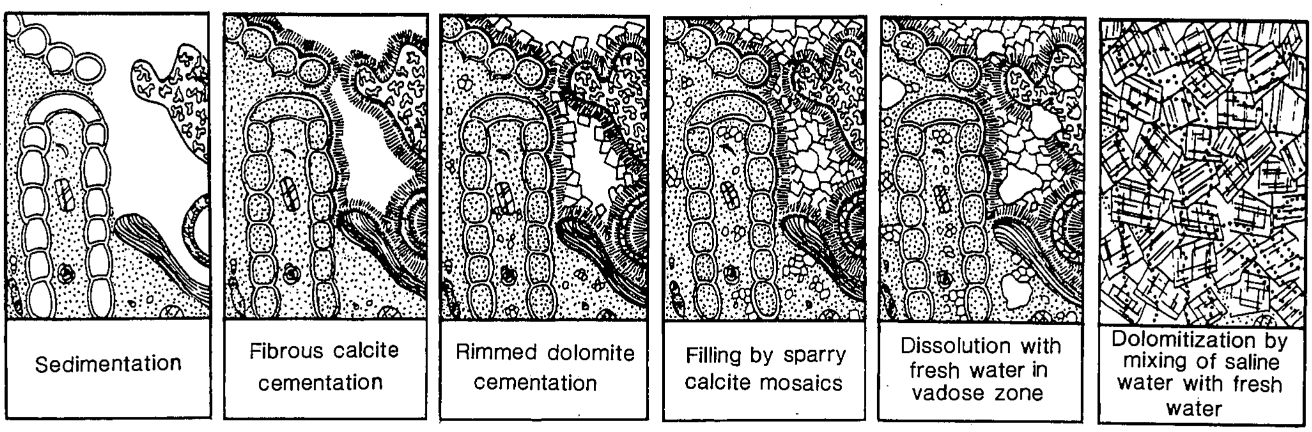


FIGURE 7.—*Generalized model showing diagenetic modification of characteristic reef fabric in the Jiantianba area. (A) Early growths of sponges were bound by encrusting* Archaeolithoporella *during initial stages of sedimentation when calcareous debris filled in the spaces around the growing reef frame. (B) That structure was later encrusted by fibrous calcite marine cement, which locally produced voids where reef-frame organisms were separated and interspaces unfilled. (C) At Jiantianba, the cement was rimmed by a thin layer of rhomboidal dolomite and then (D) void spaces were filled by sparry calcite mosaics. (E) These mosaics and cement, as well as some organic structures, were then modified by dissolution in the vadose zone where the reefs were exposed. (F) Subsequent dolomitization locally destroyed the general reef fabric during the latest major diagenetic event (modified from Fan and others 1982).*

blocky cement. The fibrous calcite represents early marine cementation during initial filling of openings between organisms within the reefs, like that seen in Late Paleozoic occurrences in North America (Mazzulo and Cys 1977, 1979). These fibrous layers might have been originally aragonite, which was later converted into low-Mg calcite. The thin crust of euhedral dolomite might have developed in a shallow burial stage when hyper-saline water from the lagoonal area seeped into the permeable reef to promote dolomitization. The remaining reef cavities were later filled by sparry calcite.

2. Dolomitization: The thin dolomite layer and other

areas of dolomite in the upper reef were possibly produced when saline water mixed with fresh water during subaerial exposure of the reef, but the coarse blocky "saddle dolomite" probably resulted from deeper burial or exposure to elevated temperatures. These thin dolomite layers are characterized by rather large (300–500 μm) euhedral crystals. In addition to this layered dolomite, some clear euhedral dolomite crystals are scattered irregularly in the reef rocks. Crystals of both these characteristic dolomite accumulations show undulose extinction and curved crystal faces, indicating formation by replacement.

3. Dissolution: Irregularly distributed secondary porosity within the reef rocks is interpreted to be a result of freshwater dissolution in the vadose zone during subaerial exposure.

A more detailed investigation of diagenesis of the Jiantianba reef is underway by Liu Huaibo and J. K. Rigby.

DISTRIBUTION OF UPPER PERMIAN REEFS IN WESTERN HUBEI

Sedimentation nearly filled the basin in the Jiantianba area during Late Permian Changxing time so that the sea gradually became shallower, following deep-water basin sedimentation during Wujiaping time. As a result, the Jiantianba area was probably transformed from a stagnant basin into a shallow-water carbonate platform. Such a model can be postulated from facies patterns evident in Upper Permian exposures in western Hubei and eastern Sichuan and also from correlation of reef outcrops with subsurface data.

Two major depositional regions (figs. 3, 6) were differentiated by Bamianshan paleofaulting. Uplift was predominant on the northwestern side of the faults and helped to block out a carbonate platform in eastern Sichuan and western Hubei. A discontinuous barrier reef, oriented in a north–northeast direction, developed along the eastern margin of the carbonate platform (fig. 3). The reef-core facies occurs at the margin and tends to rise southeastward in time, with the shallowing of the sea. These facies shifts indicate a gradual progradation of the carbonate platform basinward. In the deep-water basin, on the southeastern side of the faults, rocks equivalent to the reef complex are thinner. They are mainly black, thin-bedded siliceous rocks, micrite, and shale and contain ammonites, radiolarians, and sponge spicules.

PATCH REEFS IN EASTERN SICHUAN

INTRODUCTION

Numerous patch reefs are widely distributed within the carbonate platform of eastern Sichuan and western Hubei. The structure of this area is characterized by a series of long, parallel, narrow folds, aligned approximately NE–SW (fig. 8). Reefs are exposed in flanks of the structures.

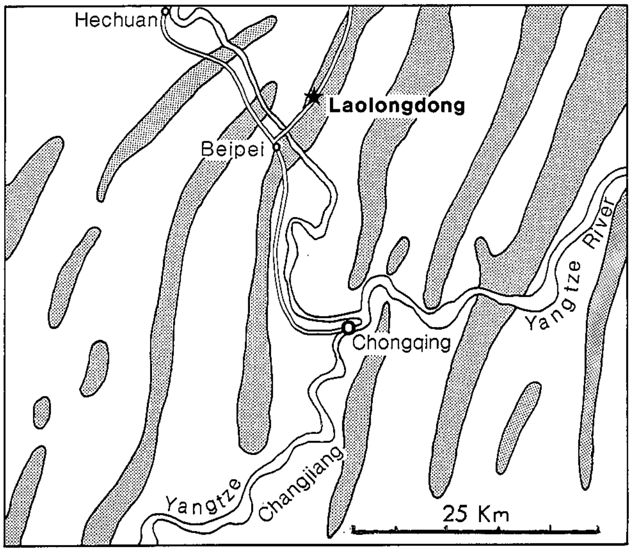


FIGURE 8.—*Index map to the Laolongdong reef locality in eastern Sichuan shows the locality on the flank of one of the long north–northeast-trending folds of the region. Anticlinal areas have been patterned.*

The Laolongdong reefs are typical examples of such relationships and are exposed on the northwestern flank of the Guangyinxia anticline, the core of which exposes Middle Permian Maokou Formation. Both flanks of the anticline expose the Upper Permian coal-bearing Longtan Formation, which is overlain by the Changxing Formation. Permian beds are overlain, in turn, by Lower and Middle Triassic deposits. Jurassic red continental deposits are preserved in troughs of the bordering synclines. The typical shape of the Laolongdong reefs is moundlike (figs. 9, 10). The width of a characteristic mound, at its base, is about 40 m, while the height at the center is about 50 m.

The mounds are characterized by massive nonbedded limestones and have greater thicknesses than off-mound equivalent rocks. The mounds occur in beds equivalent to the uppermost part of the Changxing Formation, in the *Palaeofusulina sinensis* zone. The mounds are overlain by Lower Triassic limestones and mudstones of the Feixiangguan Formation.

Three stratigraphic sections were measured through the Laolongdong mound (fig. 9) to aid in understanding its development. These detailed sections and analysis of thin section document that the mounds are composed mainly of sponge bafflestones and skeletal wackestones. Both kinds of limestone contain a high percentage of lime mud and fine bioclastic debris as interstitial material.

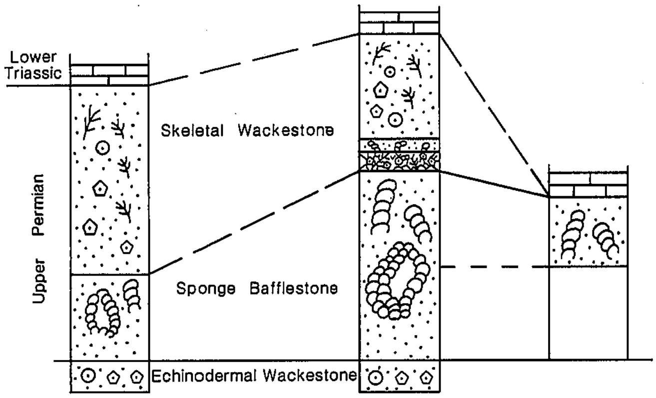


FIGURE 9.—*Generalized stratigraphic sections of three measured sections through a Laolongdong reef-mound complex show distribution of the mound-core sponge bafflestones with a base of echinoderm wackestones. Skeletal wackestones overlie the mounded carbonate and are, in turn, overlain by Lower Triassic limestones. Fossil organisms are not abundant in outcrops of the mounds, but* Amblysiphonella *may make up to 20% of the rock volume and was apparently the principal baffling form. Encrusting* Archaeolithoporella *and fistuliporid bryozoans are locally common but do not produce a well-developed boundstone reef core. The middle section represents approximately 50 m of rocks.*

TYPES AND TEXTURE OF CARBONATE ROCKS DEVELOPED IN THE LAOLONGDONG MOUNDS

Before discussion of the various carbonate rocks of the Laolongdong mounds, it is necessary to differentiate types of skeletal grains, coarse nonskeletal grains, matrix, and cement.

Skeletal grains are considered to include organisms and their skeletal debris. Sphinctozoan and inozoan calcisponges are predominant as in situ organisms, but vari-

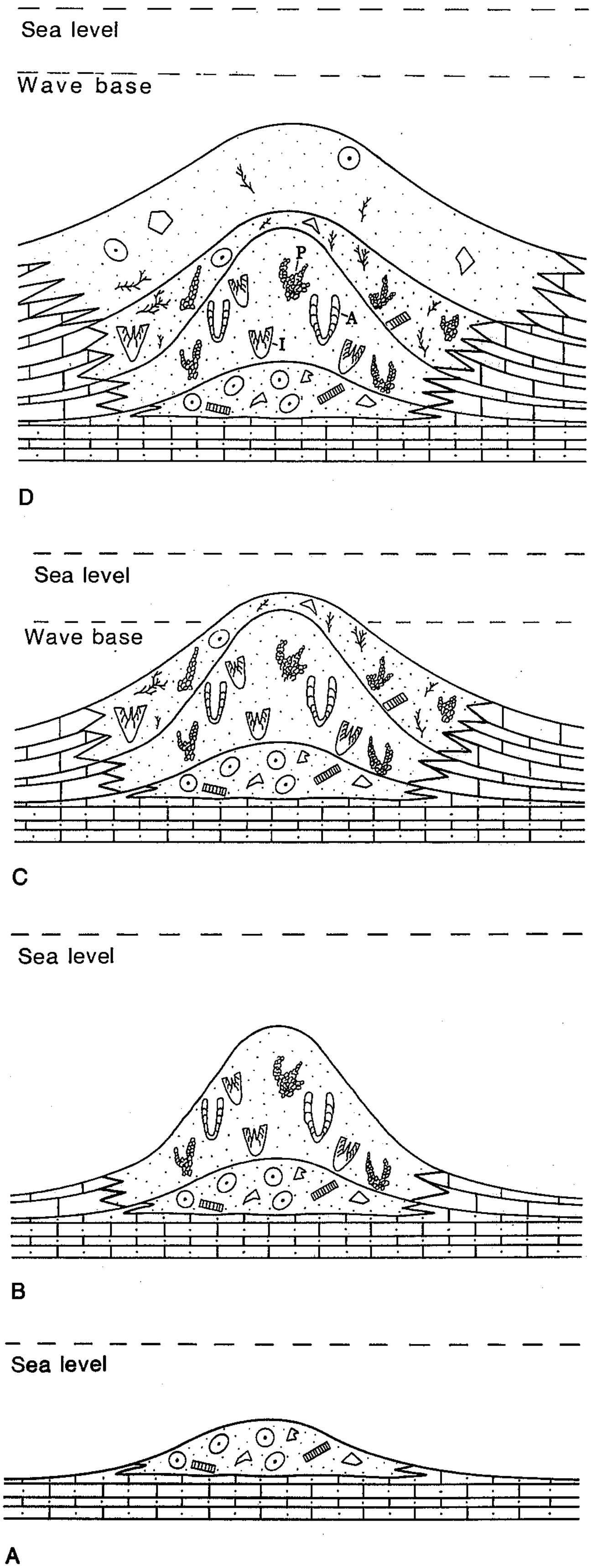


FIGURE 10.—*Generalized developmental model of a characteristic reef mound at Laolongdong, in the Upper Permian Changxing Formation. (A) Early bank or shoal stage where heaps of echinoderm debris apparently acted as a substrate for later mound development. Basal lenses now are largely echinoderm wackestones. (B) Sponge bafflestone mound stage produced the major features of relief. Rocks are mainly sponge or bryozoan-sponge bafflestones, all with a high percentage of lime-mud matrix. (C) Third stage resulted in bryozoan-echinoderm grainstones draped over the mound core, and the sediment-water interface reached above wave base. (D) Fourth-stage rocks record rapid drowning of the mound when the area subsided. Skeletal wackestones accumulated over the mound crest. These latter rocks record the transition from high-energy to low-energy environments. Individual mounds may be approximately 50 m high and have average widths of approximately 40 m.*

ously sized inozoan fragments also occur as debris. Tabulozoans play a significant role as main frame-building or baffling organisms, and also as binding organisms. They commonly encrust the exteriors of various sphinctozoans and inozoans.

Colonies of the hydrozoan *Disjectopora* are abundant in the mounds, but these fossils usually occur as clasts of various sizes, both in the mounds and in the flanking rocks.

Bryozoans also occur in the mounds. They are locally abundant and include representatives of the Rhabdomesidae, Fenestellidae, Acanthocladiidae, Goniocladiidae, and Fistuliporidae, as well as the less common Dyscritellidae. Fenestellids are sporadically scattered within the mound rocks and are important baffling components. The Fistuliporidae usually encrust other organisms and are also important binders. The following genera have been identified in samples of the mounds: *Acanthocladia, Fenestella, Fustulipora, Sulcoretepora, Dybowskiella, Clausotrypa*, and *Polypora*.

Brachiopods are evident as spine fragments and pieces of punctate shells. Bivalve shells usually occur as isolated and scattered fragments in the mound rocks, but gastropods usually are complete, at least as seen in thin sections.

The following genera and species of smaller foraminifers were identified in samples of the mound rocks: *Colaniella parva, Pachyphloia lameolata, Neoendothyra, Nodosaria, Pararobuloides, Geinitzina*, and *Cribrogenerina*. Of these, *Colaniella* is abundant and the most common element. Among the larger foraminifera of the mounds, the fusulinid *Palaeofusulina* is also very abundant and is associated with *Nankinella* and *Reichelina*.

Calcareous algae recognized in the mounds include *Pseudovermiporella, Tubiphytes*, and *Archaeolithoporella*, and gymnocodiacean elements. *Tubiphytes* is moderately abundant. It and *Archaeolithoporella* usually encrust other organisms and are characteristic binders.

Echinoderms are represented mainly by fragments of crinoids that are variable in size and shape. Echinoid plates also occur but are more rare.

Ostracode shells are found as common elements within the lime-mud matrix but make up only a small part of the total volume. Similarly, monaxial sponge spicules play a minor role.

Nonskeletal grains in the mounds include intraclast fragments and larger breccias clasts. These grains range from sand- to pebble-size. Breccia fragments are composed of lime muds that contain fine skeletal debris. These clasts appear to have formed by breakage of reef rocks.

Matrix in mound rocks is mainly lime muds, but includes fine skeletal debris. Sparry cement is absent, except in a thin bed of bryozoan-echinoderm grainstone in the middle part of the mounds.

Table 3. Types of carbonate rocks in the Laolongdong mounds of eastern Sichuan.

Wackestone	Bafflestone	Breccia	Grainstone
1. Echinoderm wackestone 2. Bryozoan-echinoderm wackestone 3. Echinoderm-bryozoan wackestone 4. Skeletal debris wackestone 5. Sponge-bryozoan wackestone	1. Sponge-bafflestone 2. Bryozoan-sponge bafflestone 3. Hydrozoan bafflestone		1. Bryozoan-echinoderm grainstone

TYPES OF CARBONATE ROCKS IN THE LAOLONGDONG MOUNDS

The scheme of classification of carbonate rocks proposed by Dunham (1962) is used here. Main rock terms are preceded by principal grain types, as modifiers, then subordinate grain types are also added before the principal modifier, if necessary, thus allowing a series of functional rock terms to be formed (see table 3).

1. Wackestones are those carbonate rocks in which bioclastic debris amounts to more than 10% of the volume, with the remainder largely lime-mud matrix. Several types of wackestones occur in the Laolongdong mounds and associated beds.

Echinoderm wackestones contain crinoid debris, which is locally the predominant skeletal component and may make up to about 20% of the total of skeletal fragments (pl. 1, fig. 2). Associated skeletal debris includes brachiopod spines, fragments of fenestrate and fistuliporid bryozoans, smaller foraminifers, larger fusulinids, and dasycladacean algae. Micrite is the dominant matrix material, but locally a few areas of microspar may occur. Euhedral dolomite crystals also occur locally and represent products of later alteration. Dolomite mosaics may have coarse crystals up to 75 um in diameter. Syntaxial overgrowths are evident around outer borders of some crinoid grains.

Bryozoan-echinoderm wackestones are rocks in which skeletal grains are predominantly echinoderm debris, but bryozoans are also important (pl. 1, fig. 5). Echinoderm debris amounts to 15% to 20% of the total grains. Some echinoderm fragments have been silicified. Fenestrate bryozoans and *Clausotrypa* (Rhabdomesidae) make up about 10% of total debris. Other organisms in these rocks include smaller foraminifers, fusulinids, fragments of brachiopods, and *Tubiphytes*.

Micrite is the major matrix component. Minor amounts of original micrite have been recrystallized into microspar. Dolomite patches of coarse euhedral crystals, 75 μm in average size, occur locally.

Echinoderm-bryozoan wackestones are rocks in which the major constituents are bryozoan fragments, including both fistuliporid and fenestrate forms (pl. 1, fig. 6). Subordinate skeletal debris includes echinoid and brachiopod spines and the smaller foraminifer *Colaniella*. Syntaxial overgrowth occurs along borders of echinoid spines. The matrix is mainly micrite and, less commonly, microspar. The latter was formed by neomorphism of micritic calcite.

Skeletal debris wackestones consist of a mixture of organisms and include clasts of echinoderms, fistuliporoid and fenestrate bryozoans, dasycladacean and gymnocodiacean algae, *Tubiphytes*, and the foraminifers *Reichelina* and *Palaeofusulina* (pl. 1, fig. 4). Matrix is mainly micrite and microspar. Local dolomitization was observed.

Sponge-bryozoan wackestones are those rocks in which fistuliporid bryozoans make up about 20% of the total debris and are the predominant component (pl. 1, fig. 3). Secondary contributors of debris are inozoan sponges, which make up about 10% of the total clasts within the rocks. Matrix is mainly micrite and microspar.

2. Bafflestones in the mounds were separated because of differences in importance of various baffling organisms. Sponge bafflestones, bryozoan-sponge bafflestones, and hydrozoan bafflestones have been recognized.

In sponge bafflestones the main baffling organisms are *Amblysiphonella* and various genera of inozoans and tabulozoans. These organisms contribute about 20% to the total rock volume (pl. 2, fig. 1; pl. 2, fig. 5). Subordinate organisms include fenestrate and fistuliporid bryozoans and the foraminifers *Pseudoglandulina* and *Colaniella*. *Archaeolithoporella* and fistuliporid bryozoans usually encrust the baffling sponges. Matrix is micrite and microspar. Some of the micrite has been dolomitized locally.

In bryozoan-sponge bafflestones (pl. 2, fig. 6) the principal baffling organisms are sphinctozoan and inozoan sponges and tabulozoans. These organisms may compose about 30% of the rock volume. Fistuliporid bryozoans are next in importance and usually encrust the sponge fossils. Interstitial spaces between sponges are filled with micrite and microspar. Associated secondary organisms include echinoderms, foraminifers, gastropods, ostracodes, and *Tubiphytes*.

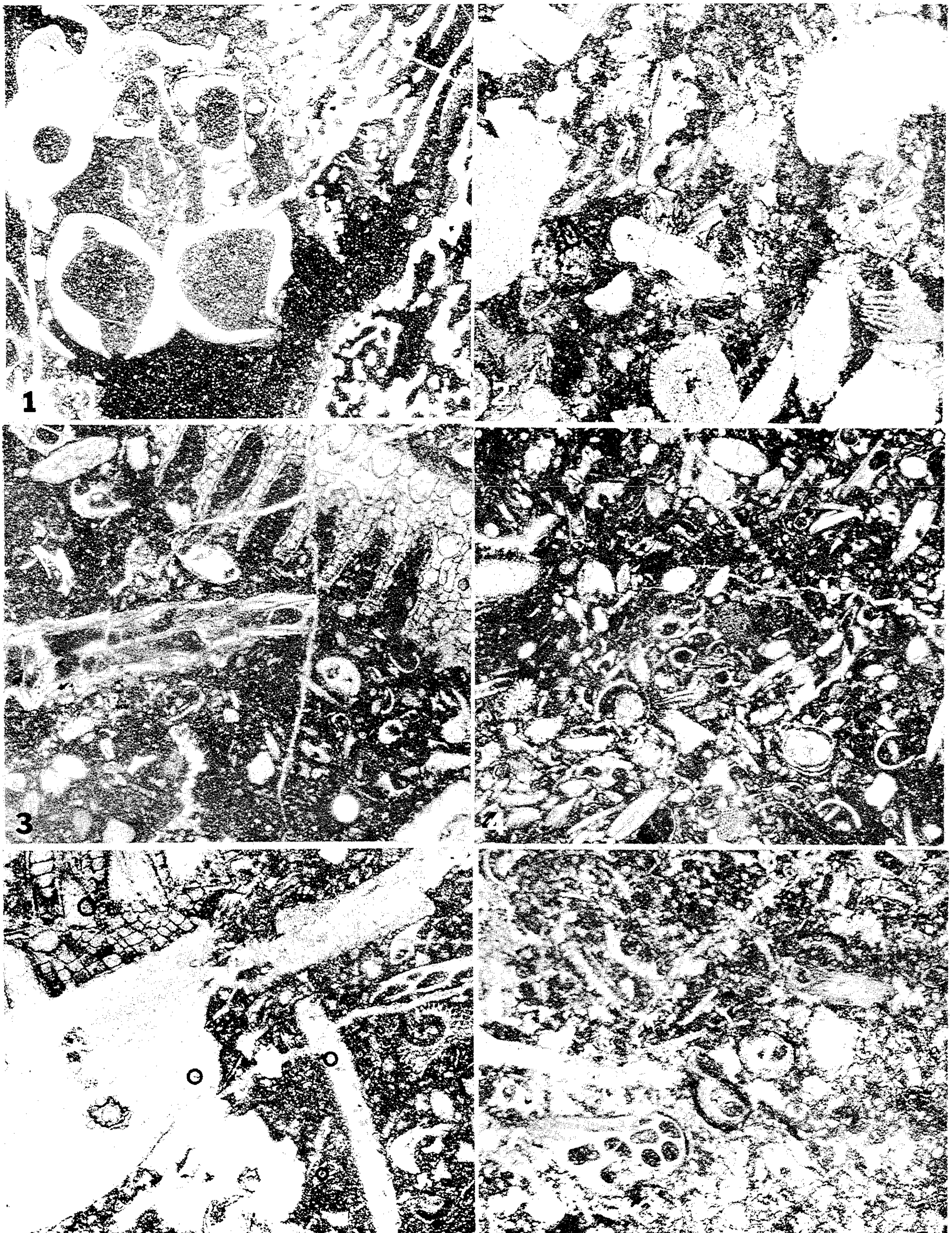
Hydrozoan bafflestones are rocks in which the main baffling organism is *Disjectopora*, which makes up to 15% or 35% of the total volume produced by recognizable organisms (pl. 1, fig. 1; pl. 2, fig. 3). Inozoan sponges and fistuliporid bryozoans are associated with the hydrozoans. Byrozoans usually encrust the sponges. Algal fragments and echinoderm debris, and other accessory organisms, occur but are rare. The matrix is lime mud that was baffled by the hydrozoans.

EXPLANATION OF PLATE 1

All of the rocks figured here were collected from the Upper Permian Changxing Formation, from the Laolongdong patch reefs, Beipei, northwest of Chongqing, eastern Sichuan.

All figures X25 except figure 1, which is X10.

Fig. 1—*Hydrozoan bafflestone.* On the right is the hydrozoan *Disjectopora*, the main baffling organism in the Laolongdong patch reefs. Sphinctozoan sponges (*Sollasia*) on the left are commonly associated with the hydrozoans. The matrix is lime mud, which was baffled by the hydrozoans and associated sphinctozoan sponges. LRI-20-3. Fig. 2—*Echinoderm wackestone.* Crinoid debris is the predominant skeletal component and locally may make up more than 20% of the total skeletal fragments. Associated skeletal debris includes fenestrate bryozoans near the middle right margin and the upper middle part of the figure. A distinctive echinoid spine occurs near the base. Micrite and fine skeletal debris are the dominant matrix materials. LRII-21-3. Fig. 3—*Sponge-bryozoan wackestone.* Fistuliporoid bryozoans are in the upper right corner. Fragments of fenestrate bryozoans are scattered in the middle. Associated debris includes fragments of echinoderms, ostracodes, and dasycladacean algae. Matrix is mainly lime mud. LRI-24-1. Fig. 4—*Skeletal debris wackestone.* Skeletal debris consists of fragments of echinoderms, brachiopods, foraminifers, bryozoans, and ostracodes. Matrix is mainly micrite. LRI-21-5. Fig. 5—*Bryozoan-echinoderm wackestone.* The large clasts in the left of the figure include echinoderm and fistuliporoid bryozoan fragments. On the right occurs fenestrate bryozoan and dasycladacean algae debris. Micrite and fine skeletal debris are the dominant matrix. In the upper right, a patch of sparry calcite infills or replaces skeletal fragments. LRI-19-2. Fig. 6—*Echinoderm bryozoan wackestone.* Fenestrate bryozoans, like in the middle of the figure, constitute the major skeletal components. Subordinate skeletal debris includes echinoderm, brachiopod, and other skeletal fragments. The matrix is lime mud and fine skeletal debris. LRI-20-5a.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3. Breccias in the mounds are composed of clasts of various size that usually consist of lime mud and fine skeletal microlaminated debris (pl. 2, fig. 2). Some inozoan fragments were found within such clasts. Because of strong recrystallization, only relict fibres of the sponge skeletons were preserved. Total clasts of various sizes may make up to 70% of the whole rock volume. Interstitial spaces between clasts are filled with lime mud and skeletal debris of sphinctozoan and inozoan sponges, bryozoans, brachiopods, echinoderms, and ostracodes. Some euhedral dolomite may be distributed along fractures, as well as along margins of some clasts. These breccias apparently resulted from in situ breakage of mound rocks.

4. Grainstones make up only a small percentage of total mound rocks. Bryozoan-echinoderm grainstones are characteristic examples. Echinoderm debris is the major organic component, amounting up to 30% of the total skeletal debris. Bryozoan debris is subordinate but may make up to 12% of the total skeletal debris (pl. 2, fig. 4). Other skeletal debris includes foraminifers, fusulinids, *Tubiphytes*, and brachiopods. Cement consists of sparry calcite.

BAFFLING AND BINDING ORGANISMS IN THE LAOLONGDONG MOUNDS

Fossil organisms are not abundant in outcrops of the mounds. The most evident frame-building or baffling organisms are sphinctozoans, usually *Amblysiphonella*. These sponges are commonly weathered into relief on outcrop surfaces. They amount to only about 15% to 20% of the rock volume, but appear to be in place.

In thin sections, additional sphinctozoans and inozoans, hydrozoans, tabulozoans, and bryozoans were discovered. All may have functioned as baffling organisms.

Several genera and species of sphinctozoans have been described from the Laolongdong mounds. These include *Polycystocoelia huajiaopingensis* Zhang, *Amblysiphonella* sp., *Amblysiphonella vesicula minima* Zhang, *Amblysiphonella obliquisepta* Zhang, and *Glomocystospongia beipeiensis* Rigby, Fan, and Zhang. *Glomocystospongia beipeiensis* is a widespread form in the mounds and is an abundant fossil. Other species are less common.

Calcareous inozoan sponges generally occur as scattered fragments within various kinds of bafflestones. Their fibrous skeletons are usually well preserved and distinct. *Peronidella* was recognized in the mound samples.

The typical hydrozoan of the mounds is *Disjectopora*. Its coenosteum is made of distinct, straight trabeculae that usually tend to parallel each other, and thin numerous transverse tabula. The characteristic canal-like vertical tubes are irregularly distributed within the netlike skeleton. *Disjectopora* was originally described by Waagen and Wentzel (1887) from the Permian of the Salt Range, Pakistan. These and related hydrozoans were later discussed by Flügel and Sy (1959) and Flügel (1975, 1981b).

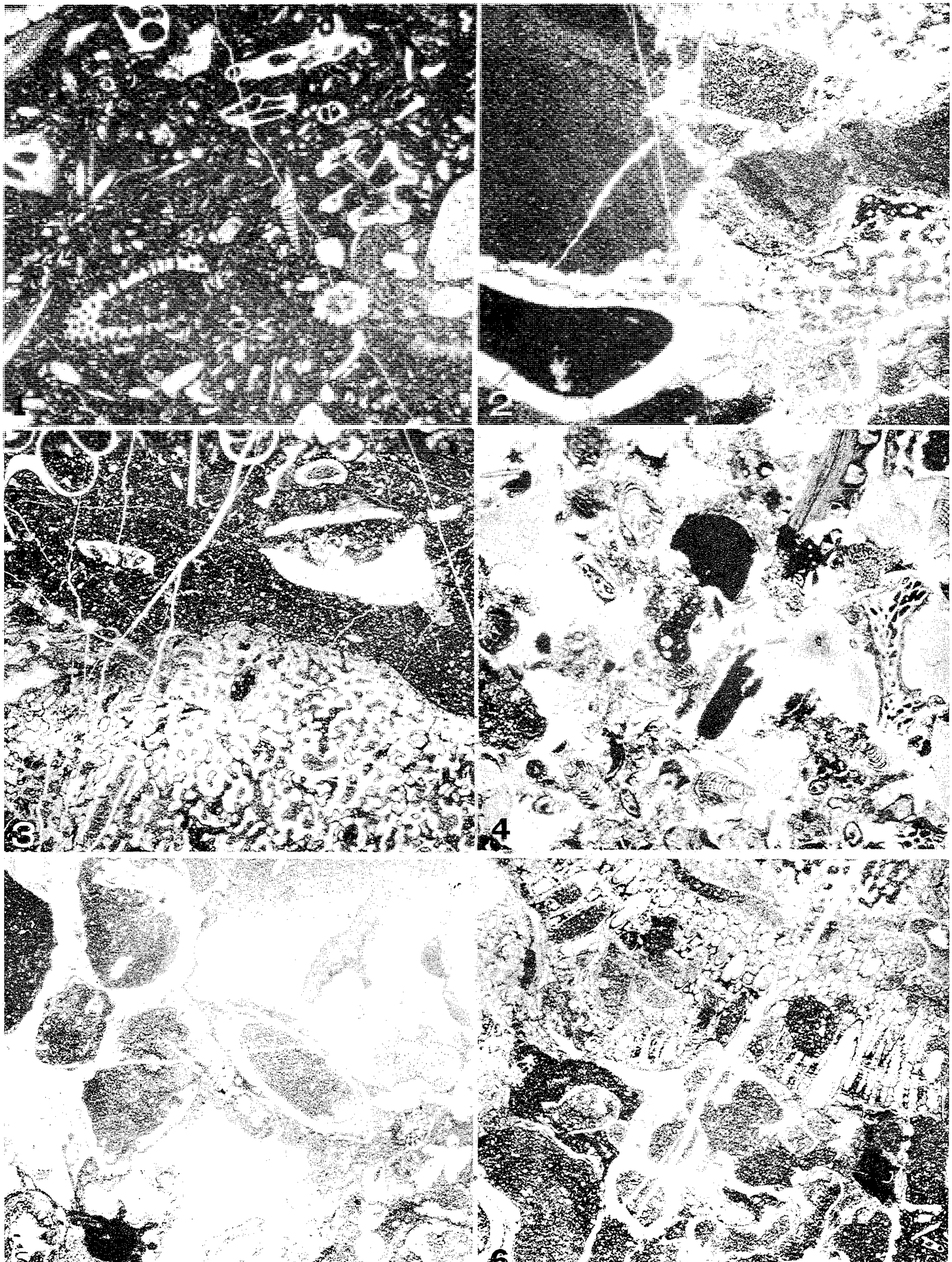
Tabulozoans present in the mound are characterized by densely spaced, longitudinal, parallel tubes in structures

EXPLANATION OF PLATE 2

All of the rocks figured here were collected from the Upper Permian Changxing Formation, from Laolongdong patch reefs, Beipei, northwest of Chongqing, eastern Sichuan.

All figures X10.

Fig. 1—*Skeletal debris in a bafflestone.* This figure shows lime muds that contain fenestrate bryozoans and *Gymnocodium* fragments, smaller foraminifera, and larger fusulinid fragments on the middle right side. All were trapped or baffled by sponge or hydrozoan frame builders. LRI-20-4. Fig. 2—*Breccia in the patch reefs or mounds.* Lime-mud clasts with distinctive angular edges are of various sizes. In the lower left corner a sphinctozoan chamber, with a few pores, is filled with dark lime mud. In the lower right occurs a coarsely fibrous inozoan fragment. Microlaminae are visible in the interior of the lime-mud clasts. These breccias occur only locally within the bafflestone and may result from in situ breakage of mound rocks. LRI-20-2b. Fig. 3—*Hydrozoan bafflestone.* The lower half of the figure is the hydrozoan *Disjectopora* with distinctive zooidal tubes in the lower left, now filled with lime mud. Lime mud in the upper half contains gastropods, brachiopods, and echinoderm fragments that were all baffled by the associated hydrozoans. LRI-21-7. Fig. 4—*Bryozoan-echinoderm grainstone.* Echinoderm fragments constitute the major skeletal components and generally have syntaxial border cements. Subordinate skeletal debris includes fenestrate bryozoans and the foraminifer *Colaniella*, as well as a few intraclasts. Scattered lime-mud pockets are also present. The rock represents lateral bank deposits that accumulated during mound growth. LRI-23-1. Fig. 5—*Sponge bafflestone.* Sphinctozoan sponges are distinctive in the middle of the figure. In the lower right, fenestrate bryozoan and echinoid spine debris are visible. Sparry calcite patches are also present between patches of lime muds. LRI-20-5. Fig. 6—*Bryozoan-sponge bafflestone.* A fistuliporid bryozoan colony encrusts an inozoan sponge in the upper part of the figure. The lower half of this figure is mainly lime mud in which occur fragments of sphinctozoan sponges, bryozoans, and gastropods. LRI-20-8.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reminiscent of fine-textured *Favosites* colonies. Kuhn (1942) proposed that tabulozoans may be related to anthozoans, hydrozoans, and scyphozoans, but the systematic position of tabulozoans is still not resolved. Some researchers (Flügel 1981a, 1981b) have suggested tabulozoans may be included in the sclerosponges, but tabulozoans lack siliceous spicules within their skeleton. Such a lack makes uncertain their inclusion within the sponges.

Fistuliporid bryozoans and the alga *Archaeolithoporella* are well developed in the mound. Both generally play important roles as encrusting organisms. *Archaeolithoporella* encrusts other organisms but not as extensively as do the fistuliporid bryozoans.

DEVELOPMENT AND GROWTH OF THE LAOLONGDONG MOUNDS

Development and growth of the Laolongdong mounds can be divided into four stages (pl. 3). They began as echinoderm banks, grew vertically to form mounds, and were then drowned immediately prior to the Triassic.

First Stage: Echinoderm Bank or Shoal (Fig. 10A)

These early banks are composed of transported echinoderm debris of various sizes and appear to have acted as the substrate for later reeflike growth. Rocks of the early banks are echinoderm wackestones and bryozoan-echinoderm wackestones. In addition to the echinoderms, bryozoans, brachiopods, and foraminifers contributed to the bank accumulation.

Second Stage: Sponge-Bafflestone Mound (Fig. 10B)

A sponge-bafflestone mound was developed by upward growth, and this facies was first differentiated when the mounds became distinct features of relief. Rocks that accumulated at this stage of mound growth are mainly sponge bafflestones, bryozoan-sponge bafflestones, hydrozoan bafflestones, and hydrozoan-sponge bafflestones. All of these rocks contain high percentages of lime mud. Bryozoan wackestones, echinoderm wackestones, skeletal wackestones, and sponge wackestones are associated with these bafflestones.

In some sponge bafflestones, the sphinctozoan frameworks are locally encrusted by fistuliporoid bryozoans and *Archaeolithoporella*. Some breccias accompany the sponge bafflestone and represent in-place breakage of parts of the mounds during growth.

Third Stage: Bryozoan-Echinoderm Bank (Fig. 10C)

After the mound was formed, the sedimentation surface of the mound crest gradually grew upward and approached wave base or low tide level. As a result, the mound crest was eventually transformed into an area where only high-energy bank deposits accumulated. These bank deposits are mainly bryozoan-echinoderm grainstones. However, thickness of these bank deposits is not great, indicating only a short duration for the third stage of mound growth.

Fourth Stage (Fig. 10D)

After growing up into a high-energy environment, the mounds were rapidly drowned when the area subsided and the mounds were dropped to below wave base. Thereafter, only skeletal wackestones accumulated on the mound crest. Deposits of this stage consist of bryozoan-echinoderm wackestone, skeletal wackestone, echinoderm wackestone, and sponge wackestone. Only thin local deposits of sponge bafflestones occur in early deposits of stage four, between the grainstones and overlying wackestones. These sponge bafflestones may be regarded as transitional deposits recording the shift from high-energy to lower-energy environments.

Fortunately, numerous additional small sponge-baffled mounds have been found in the subsurface in eastern Sichuan in recent years. In the subsurface, these mounds have been subjected to strong dolomitization. Locally, they have been totally transformed into coarsely crystalline dolomite with high porosity. Consequently, such mounds have become important targets for exploration and exploitation of oil and gas in eastern Sichuan.

THE MIDDLE AND UPPER PERMIAN XIANGBO REEFS, LONGLIN COUNTY, NORTHWESTERN GUANGXI

INTRODUCTION

Middle and Upper Permian reefs are widely distributed and well developed in eastern Yunnan, southwestern Guizhou, and northwestern Guangxi (fig. 1). Two types of Permian reef occurrences are recognized. The first is a barrier reef belt that rims a carbonate platform on the northwest, west, and southwest of a major deeper-water basin (fig. 11). It is a typical carbonate platform margin reef. Within this belt, reefs have been discovered at Ziyun, Ceheng, the Anran structure near Longlin, and at Guangnan. The Xiangbo reefs in Longlin County may be regarded as one of the most typical reef outcrops of this region. The second type is characterized by smaller reefs that rim isolated carbonate platforms. These reefs occur irregularly within the widespread basin-facies deposits. Isolated carbonate platforms have been mapped and identified as the Wenliu, Longlin, Wangmo, Leye, Lingyun, and Tiane-Pingguo isolated carbonate platforms. Carbonates of these platforms are surrounded by the Permian basin-facies deposits (figs. 11, 12).

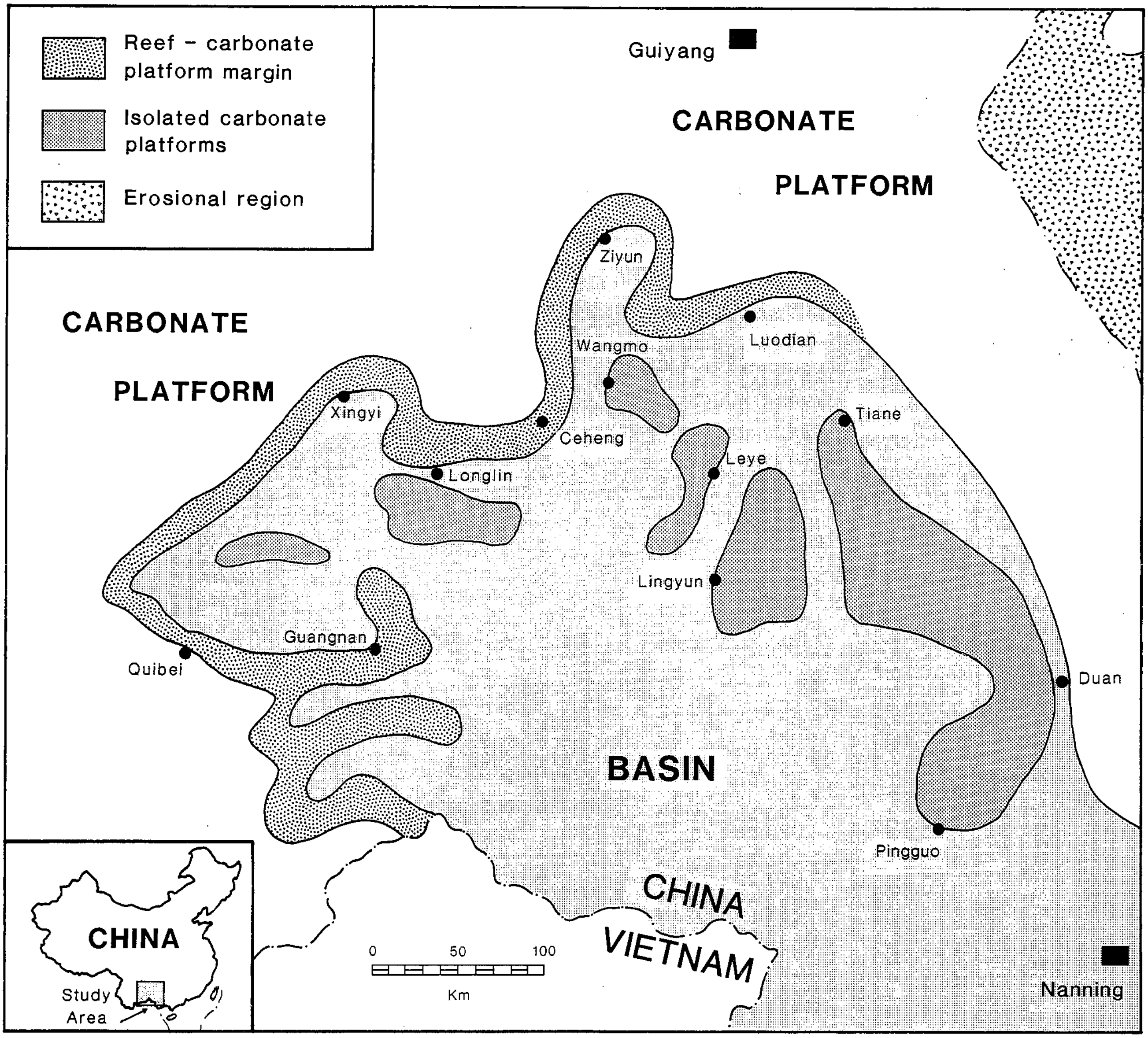


FIGURE 11.—*Paleogeographic and reef-facies map of Middle Permian rocks of South China shows a general reef margin to the carbonate platform that rimmed a deeper-water basin. Isolated carbonate platforms rose as distinct elements within the basin facies. Reefs on the Anran structure at Xiangbo occur near Longlin, near the northern margin of the basin.*

The reefs exposed on Anran anticline in northwestern Guangxi are part of carbonate platform-margin reef. The Anran structure (fig. 13) is a typical anticline with its longitudinal axis oriented approximately east–west. It is cored by exposed Upper Carboniferous rocks. Lower, Middle, and Upper Permian carbonate rocks and Middle Triassic clastic rocks are exposed successively outward. Permian reefs are well exposed on the western outer margin of the Anran anticline and appear as a horseshoe-shaped atoll. The reefs crop out on the northwestern flank of the anticline as well as on the western nose and southwestern flank of the structure. The Xiangbo reef stratigraphic section (fig. 14) can be regarded as typical of the reef outcrops on the southwestern flank of the fold and as typical of the carbonate margin barrier reefs.

MAIN FEATURES AND EVOLUTION OF THE XIANGBO REEFS DURING PERMIAN TIME

Careful study of reef rocks and fossils collected from the Xiangbo reefs documents facies in the Permian sequence and evolution of the reefs. Microfacies analyses of thin sections of reef rocks following on the general pattern of Flügel (1983) or Wilson (1975) were particularly helpful.

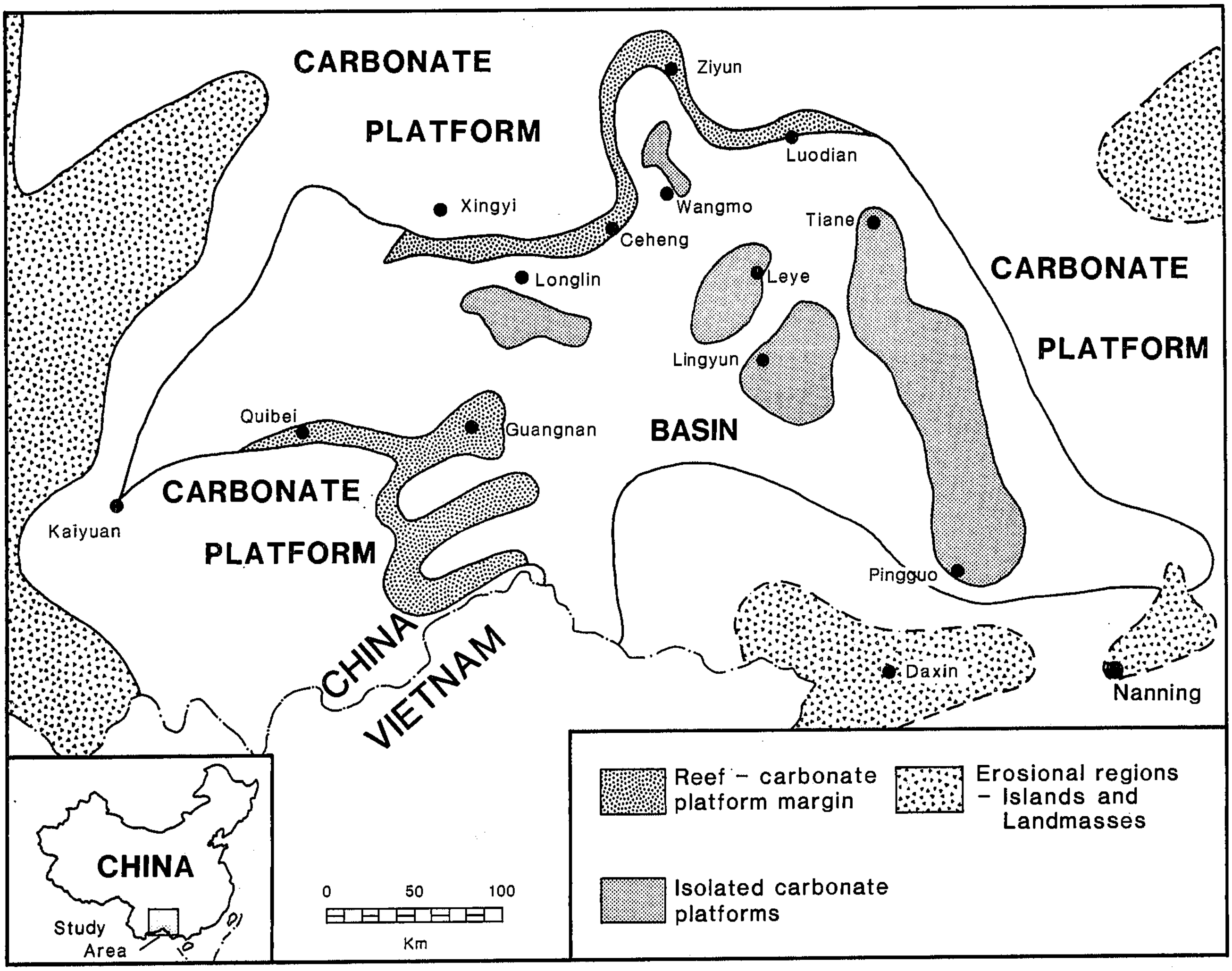


FIGURE 12.—*Paleogeographic and reef-facies map of Upper Permian rocks of South China shows barrier reefs at the carbonate platform margin and the continued development of isolated carbonate platforms within the basin. Late Permian reefs at Xiangbo are part of those represented north of Longlin, in the north central part of the map.*

The Xiangbo reefs clearly exhibit distinct cycles (fig. 14). Each cycle consists of a member of reef framework facies and a member of reef-flat facies. Two such cycles developed during Middle Permian Maokou time; two cycles during the Late Permian Wujiaping time, and two cycles during the Late Permian Changxing time.

Skeletal and Intraclastic Bank or Shoal

The substrate for the Xiangbo reef during the Middle Permian time was a bank or shoal made up of a variety of grainstones including skeletal and intraclastic grainstones, phylloid grainstones, *Tubiphytes*, lump grainstones, and fusulinid grainstones. Common organisms in these well-washed rocks include smaller foraminifers, gastropods, echinoderms, *Tubiphytes*, dasycladacean algae, and other minor forms. Phylloid algae with curved, slender, leaflike plates are often associated with other organisms. Interiors of most phylloid algae plates are made of granular calcite mosaics, but some are made of micrite. The outer margins of some phylloid algae plates show strong micritization. Local lime muds and fine skeletal debris have been sheltered by these phylloid algal plates. During the late stage of bank development, carbonate lumps and *Tubiphytes* increase in abundance in the grainstones.

Interstitial spaces between grains and skeletal debris are largely filled with sparry calcite cement. Micrite and micritic peloidal matrix occur only locally. Many skeletal fragments and fusulinid tests show dissolution. These grains have wavy to distinctly irregular margins. The thickness of these rocks in the lower part of the Xiangbo measured section is at least 50 m. The entire bank or shoal sequence may be thicker than that.

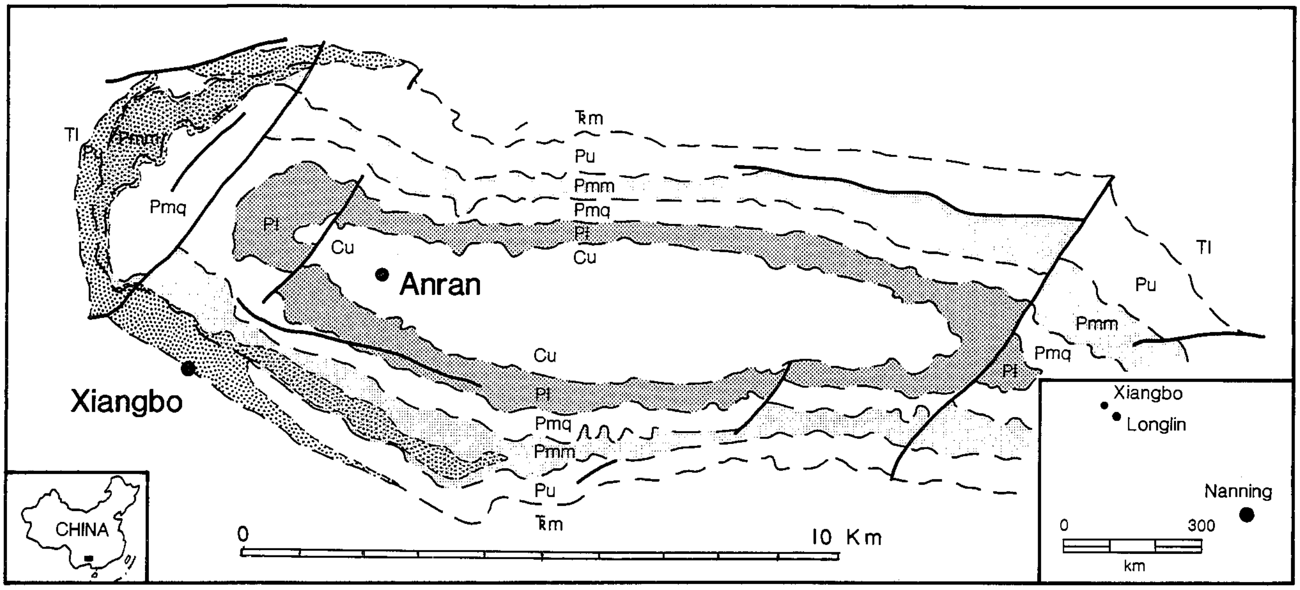


FIGURE 13.—*Generalized geologic map of the Anran anticline shows distribution of Carboniferous, Permian, and Triassic rocks on the flanks and nose of the fold. Distribution of Middle and Late Permian reef rocks is shown by the coarse dotted pattern around the western nose of the anticline. Upper Carboniferous rocks are exposed in the core of the anticline, and Middle Triassic rocks rest unconformably on Upper Permian rocks around the doubly plunging structure. The stratigraphic section of reefs shown in figure 14 was measured at Xiangbo.*

First Cycle of Reef Development During Middle Permian Time

The first cycle of reef development began when frame-building organisms started to flourish and stabilized the substrate of the bank so that it became an area of in situ accumulation rather than one blanketed by transported debris.

The reef of the first cycle is made of a diverse assemblage including abundant frame-building organisms such as inozoan (pl. 5, fig. 2) and sphinctozoan sponges. Most such sponges have upright growth habits, and all play important roles in constructing the reef framework. Frame-building organisms are generally encrusted and bound by *Archaeolithoporella* (pl. 4, fig. 4), *Tubiphytes* (pl. 5, figs. 4, 6), tabulozoans, and fistuliporid bryozoans. Interstitial areas between the framework fossils are filled with micritic pellets and intraclasts of sand-size. Locally, the remaining void spaces were filled with blocky calcite cement. Reef-dwelling or accessory organisms include echinoderms, foraminifers, brachiopods (pl. 4, fig. 1) (*Prorichthofenia*), gastropods, fenestrate bryozoan (pl. 4, fig. 2) (*Acanthocladia*), fistuliporid bryozoans, and the problematic alga *Donezella*. These fossils may be abundant locally.

Near the top of the reef layer, a great amount of reef breccia was formed. This occurrence is interpreted to indicate that the upward rate of reef growth was more rapid than subsidence. Tops of the reefs became shallower and shallower and eventually were transformed into reef flats, as indicated by the upward decrease in frame-built structures and the presence of extensive reef breccias and skeletal grainstones.

The thickness of reef framework within the first cycle in the Xiangbo section is about 25.5 m. (fig. 14), and the overlying skeletal grainstones are only 5.7 m. thick. The total thickness of deposits of the first cycle is about 32 m.

Second Cycle of Reef Development During Middle Permian Maokou Time

Two subcycles are recognized in the second cycle of reef growth (fig. 14). Reef growth was interrupted by relatively minor pulses of packstone and wackestone deposition.

In the lower subcycle, sponge framestones are the principal rocks, for they make up most of the subcycle sequence. Considerable reef breccia is associated with these sponge framestones. Binding organisms, like those of the first cycle, are still abundant. Several generations of sparry calcite cement are evident and usually show many interruptions in accumulation. Rocks of the upper part of this subcycle are mainly skeletal packstones and wackestones, indicating a shallowing of the sea and transformation of the reef into reef-flat environments. The total thickness of this subcycle is 23 m in the Xiangbo section.

The upper subcycle begins with a return of accumulation of sponge framestones. As in the lower cycle, these

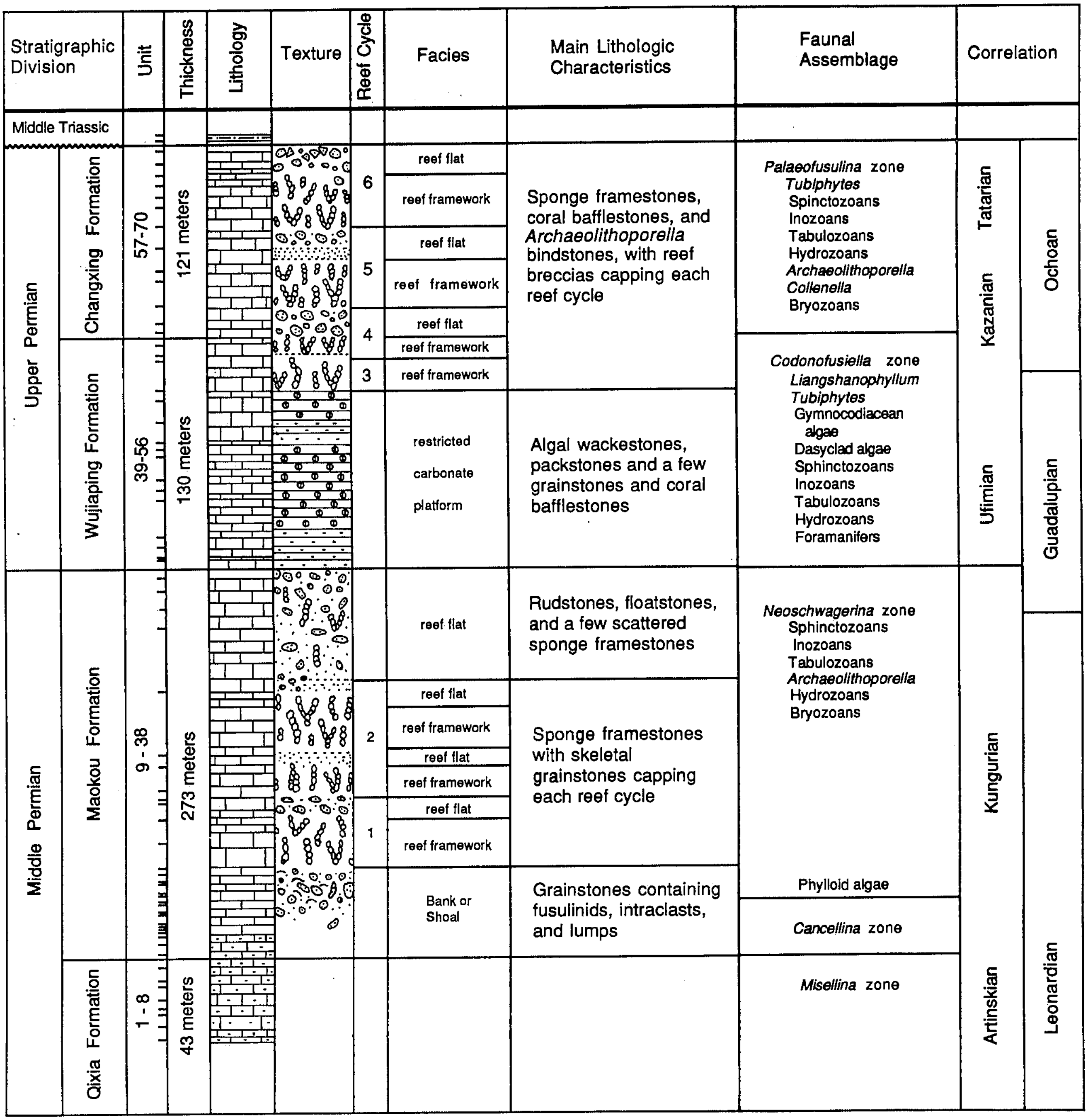


FIGURE 14.—Stratigraphic section of middle and upper Permian rocks at Xiangbo and facies interpretation of the section. Figure shows lithology, texture, and cycles of the reef and reef-flat rocks, as well as principal lithologic characteristics and distributions of main fossil forms. Reefs are well developed in the Middle Permian Maokou Formation and uppermost Wujiaping Formation, as well as in the younger, later Permian Changxing Formation. Reef-flat and lagoonal rocks separate sections of Middle and Late Permian reef developments.

framestones were succeeded by reef-flat skeletal wackestones and packstones. The total thickness of this subcycle is about 30 m.

Reef Crest and Reef-Flat Facies

Near the end of Maokou time (fig. 14), shallow-water environments were widespread and reef environments were converted into reef-crest and reef-flat environments. These shallow-water environments were also widespread behind that of the reef framework facies and resulted in accumulation of a moderately thick sequence on top of the cyclic reef-flat section. These Maokou reef-flat rocks in the measured section are characterized by the accumulation of rudstone and floatstones of various clast size that also contain much skeletal debris of sand-size. In addition, fossils of some isolated fiame-building organisms also may be present. For example, sphinctozoan and inozoan sponges appear to have been irregularly scattered on the reef flat and may have formed small patch reefs. An unusual hexactinellid sponge root tuft was discovered in a single outcrop of this facies. The tuft appears as an "anchor rope" on a sponge that may have floated off the bottom (Rigby and Fan 1988). Total thickness of this reef-flat section is about 80 m.

Restricted Carbonate Platform Facies and Reefs of the Wujiaping Formation

The Middle Permian Maokou Formation is overlain by carbonate platform deposits of the Wujiaping Formation in the Xiangbo measured section (pl. 6; fig. 14). These platform rocks are light gray, medium-bedded limestones that contain cherty nodules that usually occur along bedding planes. Silty-peloidal-skeletal wackestones and packstones are the predominant rocks of the lower part of the Wujiaping Formation. Abundant foraminifers, echinoderms, brachiopods, dasycladacean and gymnocodiacean algae, and rugose corals all occur. These fossils, combined with the lithology, indicate that the rocks accumulated in restricted carbonate platform environments. Gymnocodiacean and dasycladacean algae (pl. 5, figs. 1, 5) increase upward and form algal packstones. Some lenses of skeletal and intraclastic grainstones occur in the carbonate platform section. These somewhat cleaner, higher-energy deposits are interpreted as tidal channel fills or as carbonate sand-bar deposits.

Small rugose coral bafflestone buildups also occur within the carbonate platform section. Here, rugose corals, mainly *Liangshanophyllum*, appear to have trapped a large amount of lime mud to form the buildups.

Near the top of the Wujiaping Formation, reefs are again developed in two new cycles. Reef framework of the lower cycle of these upper Wujiaping beds consists of inozoans, tabulozoans, and other accessory organisms. Frame builders are usually encrusted by *Archaeolithoporella* (pl. 4, fig. 4). Interstitial spaces between the builders are filled with well-developed fibrous calcite cement. Micrites that contain characteristic and well-preserved rivulariacean algae (pl. 5, fig. 3) occur at the end of the lower cycle and mark the beginning of the upper cycle. These unusual algae are included in the blue-green algae.

Reef rocks of the upper of the two late Wujiaping cycles are magnificently exposed on the lower slope of the mountains at Xiangbo. There the various sponge reef builders are well developed and well preserved. They are encrusted by distinct white rinds of *Archaeolithoporella* as seen in the field. However, rocks of the main interval of the cycle vary greatly, and, laterally, the reef is replaced by reef breccias to the northwest. Such facies shifts indicate that reef growth was not uniform along the reef trend.

Late Permian Changxing Formation Alternating Reef and Reef-Flat Facies

Reef development of the late Permian Changxing Formation is also characterized by two cycles (fig. 14). Within the reefs, the main frame-building organisms are sphinctozoan and inozoan sponges and the alga *Tubiphytes*. The sphinctozoans are commonly encrusted by *Tubiphytes*, and inozoans are encrusted by tabulozoans and *Archaeolithoporella*. *Tubiphytes* also acts as a frame builder locally. Some algal bindstones also occur in the reef facies. Rugose corals also functioned locally as builders and baffled lime muds and skeletal debris. Interstitial spaces between various reef builders are generally filled with lime mud, peloids, and skeletal debris. The latter includes fragments of echinoderms, brachiopods, *Tubiphytes*, bryozoans, and gymnocodiacean and solenoporacean algae (pl. 4, fig. 3). However, spaces between individual algae-encrusted masses may be filled with sparry calcite cement. Total thickness of the late Permian Changxing Formation in the Xiangbo area is about 120 m.

MICROFACIES TYPES OF THE PERMIAN XIANGBO REEF COMPLEX, GUANGXI PROVINCE

Four major sedimentary facies were differentiated in the Permian Xiangbo reefs through careful study and analysis of reef rocks and their fossil distribution. These are (a) carbonate platform margin bank facies, (b) carbonate platform margin reef facies, (c) reef-flat facies, and (d) restricted carbonate platform facies. Each facies zone consists of a number of microfacies types.

Within the Carbonate platform margin-bank facies, the skeletal-intraclastic grainstone microfacies (pl. 7, figs. 4, 6) plays a major role. Principal grains are fusulinid and smaller foraminifer tests, echinoderm and gastropod fragments, and micritic intraclasts of sand- and pebble-size. Fusulinid tests have been subjected to strong dissolution or breakage, thus causing their outer margins to be wavy or irregular. Spaces between grains are filled by a sparry calcite mosaic.

Phylloid algae wackestone (pl. 7, fig. 1) and phylloid algae grainstone microfacies contain phylloid algae as principal bioclasts. These plates may float in mudstone matrix or be surrounded by sparry cement. Generally the interior of the phylloid plates is composed of a sparry calcite mosaic, a result of diagenesis from dissolution—precipitation or recrystallization. Some plates, however, are composed of micrite. Interstitial filling material in these grainstones is a sparry calcite cement mosaic, but in the wackestones the matrix is micrite and skeletal debris. Locally a few patches of lime mud and fine skeletal debris have been sheltered by the phylloid algal plates in some grainstones. These algae have formed small phylloid algal mounds.

The fusulinid grainstone microfacies (pl. 7, fig. 5) is made up of rocks in which fusulinid tests are the predominant bioclastic component. Skeletal debris of other organisms may be associated with the fusulinids, but such debris plays a relatively minor role. Spaces between the fusulinid tests and skeletal debris are filled with sparry calcite cement.

The *Tubiphytes*-lump grainstone microfacies (pl. 7, fig. 3) is characterized by an abundance of lumps of limestone that usually have irregular outlines. Such lumps may be moderately large, some range to several cm long—they may have been formed by algal cohesion of fine debris. Fragments of dasycladacean algae have also been found in these rocks. Cements are sparry calcite.

Carbonate platform margin reefs are composed of rocks of several microfacies.

Sponge framestone microfacies (pl. 8, figs. 1, 3) rocks are the most common. Sphinctozoans, inozoans, hydrozoans, and tabulozoans are the main building organisms in the microfacies. They are usually encrusted by well-developed *Archaeolithoporella, Tubiphytes,* and tabulozoans. Locally, these frame builders are encrusted by fistuliporid bryozoans. A variety of accessory organisms are associated with these fossils and include, in decreasing abundance, fenestrate bryozoans (*Acanthocladia, Polypora*), brachiopods (for example, *Prorichthofenia*), echinoderms (especially crinoids), gastropods, foraminifers, solenoporacean algae, ostracodes, and even dissociated sponge spicules. Locally, interstitial spaces between organism frameworks are filled with matrix of lime muds, peloids, and skeletal debris (pl. 8, fig. 4), but original voids may also have been filled by sparry calcite cement, or by both cement and matrix.

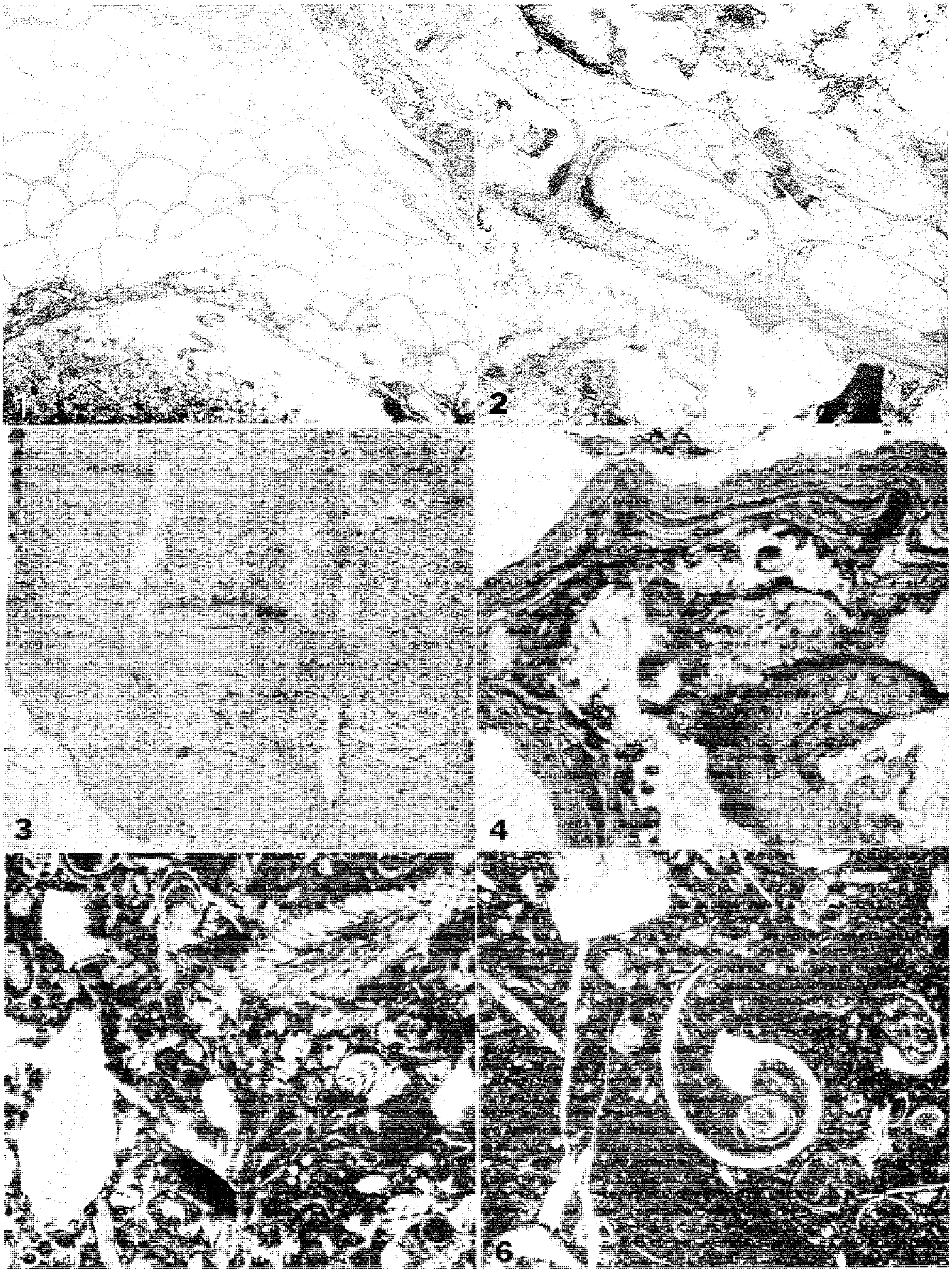
Rocks of reef breccia (pl. 9, fig. 2) or rudstone microfacies are usually associated with the sponge framestone microfacies. Clasts usually have angular, irregular shapes and are composed of broken inozoans, hydrozoans, tabulozoans, bryozoans, echinoderms, and other less common organisms. A few clasts are made of lime mud, peloids,

EXPLANATION OF PLATE 4

All of the rocks, except those shown in figures 5 and 6, were collected from Middle and Upper Permian Maokou and Changxing Formations, from Xiangbo, Longlin County, northwestern Guangxi. Those shown in figures 5 and 6 are from the Changxing Formation, Laolongdong patch reefs, Beipei, northwest of Chongqing, eastern Sichuan.

All figures X25 except figure 6, which is X10.

Fig. 1—*Prorichthofenia.* The interior of the coral-like productid brachiopod contains bubblelike fillings. *Prorichthofenia* is usually associated with sphinctozoan and inozoan sponges and acts as an accessory organism in the reef framework. Xiangbo, B33-6. Fig. 2—*Fenestrate bryozoans.* Fenestrate bryozoans are common organisms that may be accessory or frame building. Zooecia and fenestrules are filled with sparry calcite mosaics. Small fragments of fenestrate bryozoans are common in filling materials within the reefs. Xiangbo, B31-5. Fig. 3—*Solenopora.* The alga *Solenopora* consists of masses of subparallel longitudinal tubes. *Solenopora* may encrust other organisms but most commonly occurs as isolated fragments within the reef framework or as filling material. Xiangbo, B36-3. Fig. 4—*Archaeolithoporella.* The laminar alga, *Archaeolithoporella,* encrusts *Tubiphytes* and sphinctozoan sponges as a frame builder or binding organism. *Tubiphytes* usually also encrusts other organisms as a typical binding organism. However, here *Tubiphytes* obviously acted as a frame builder. The figure also represents a characteristic reef framestone in the Xiangbo section, Longlin County. The cement forms sparry calcite mosaics. IB58-1. Fig. 5—*Colaniella* and *Gymnocodium.* Smaller foraminifers, *Colaniella,* and the red alga, *Gymnocodium,* are accessory organisms here within matrix of the Laolongdong mounds. These fossils are very common and may locally make up great parts of the rocks. LRII-24-4. Fig. 6—*Gastropoda.* Gastropoda are common fossils within the matrix that was baffled by reef- or mound-forming organisms. LRII-22-4.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and fine skeletal debris, and were a result of breakup of interstitial filling materials. In some clasts, the *Archaeolithoporella*-encrusting rim around larger organisms has been broken. Clast size varies greatly, some larger fragments are 1.5–3.0 cm in diameter. Clasts in this microfacies usually appear to be in contact with each other to form grain-supported rocks, but voids between grains are filled with a sparry calcite mosaic.

The skeletal-*Tubiphytes* grainstone microfacies (pl. 8, fig. 2) is generally associated with reef breccias or rudstones. Skeletal debris in the microfacies consists of pieces of inozoans, bryozoans, brachiopods, *Tubiphytes*, crinoids, and dasycladacean and solenoporacean algae. Average grains are about 1.5–2.0 mm in diameter. Some larger clasts are up to 2–3 cm in longitudinal direction. Abundant *Tubiphytes* and its debris are widespread. These fossils commonly have irregular outlines and consist of dark, sometimes fibrous-appearing micrite where internal structure is visible. Interstitial spaces between skeletal grains are filled with sparry calcite mosaics.

The rugose coral bafflestone microfacies (pl. 8, fig. 5; pl. 10, fig. 2) is characterized by abundant rugose corals, which often are in situ. These corals have baffled lime mud and fine skeletal debris that was trapped between the corallites. This microfacies occurs only in the Wujiaping carbonate platform deposits and appears as isolated baffled mounds within the carbonate platform.

The algal bindstone microfacies (pl. 8, fig. 6) is characterized by well-developed encrusting *Archaeolithoporella* that may form masses up to 2.5 cm in diameter. These masses may be called oncolites, if loose and spheroidal, or rhodolites, if attached (Flügel 1981a). Cores of these algal-encrusted masses may be composed of inozoan sponges. Diameters of the sponge cores may be up to about half the diameter of the whole mass. Interstitial spaces are totally filled with fibrous calcite cement and a blocky, somewhat later, calcite mosaic.

Reef-flat facies rocks include several microfacies. The sponge root tuft framestone microfacies is the most limited, stratigraphically and geographically, and is characterized by an abundance of very coarse root tuft spicules. The spicules have a slender cylindrical form, and most appear to be approximately 0.30–0.35 mm in diameter. These root tuft spicules are overgrown by thin concentric layers of *Archaeolithoporella* and a variety of secondary encrusting forms. Areas between individual spicules were filled first by radial fibrous calcite cements and locally, and secondarily, by blocky cement.

The reef-flat breccia microfacies (pl. 9, figs. 1, 2; pl. 9, fig. 5) is composed of limestones made of reef fragments and various other clasts. These clasts commonly have irregular shapes, some may be elongate and others flattened disklike. They show a great range in size. Some larger clasts are up to 6 cm or more in diameter, while smaller ones are less than 0.5 cm in diameter. It was surprising to discover that many of these clasts were derived from underlying or associated bank deposits, with distinctive fusulinid fossils, rather than from immediately older reef-flat and reef-framework rocks. Spaces between the clasts are commonly only partly filled with lime muds and fine skeletal debris. The remaining original voids were then filled with sparry bladed and blocky calcite cement.

Restricted carbonate platform facies rocks also are made of several microfacies. The silty-peloidal-skeletal wackestone microfacies (pl. 9, fig. 4) is characterized by

EXPLANATION OF PLATE 5

All of the rocks figured here are from the Upper Permian Wujiaping and Changxing Formations, from Xiangbo reefs, Longlin County, northwestern Guangxi.

All figures X25.

Fig. 1—*Dasycladacean algae. Mizzia,* shown here, is a common component within rocks of the restricted carbonate platform facies. The algae are commonly associated with smaller foraminifera and echinoderm and other debris. B44-3. Fig. 2—*Inozoan sponge.* A new inozoan, with top to right, is typical of forms that are important in the reef framework. This genus is characterized by a series of subparallel exhalant tubes within the sponge body. Lateral inhalant canals are also distinctive. Fig. 3—*Rivulariacean algae.* These fossils are common in the reef structure and appear with a peculiar texture in sections. B55. Fig. 4—*Tubiphytes.* The fine fibrous skeleton of the alga *Tubiphytes* shows episodic growth. Original skeletal openings are filled with crystalline calcite cement. IB62-1. Fig. 5—*Gymnocodium. Gymnocodium* is a common fossil in the restricted carbonate platform facies. It is usually associated with foraminifers but here is associated with debris of frame-building organisms in reef framework. B56-4. Fig. 6—*Tubiphytes. Tubiphytes* is a common alga in reefs at Xiangbo and in organic debris in the shelf section IB70-3.

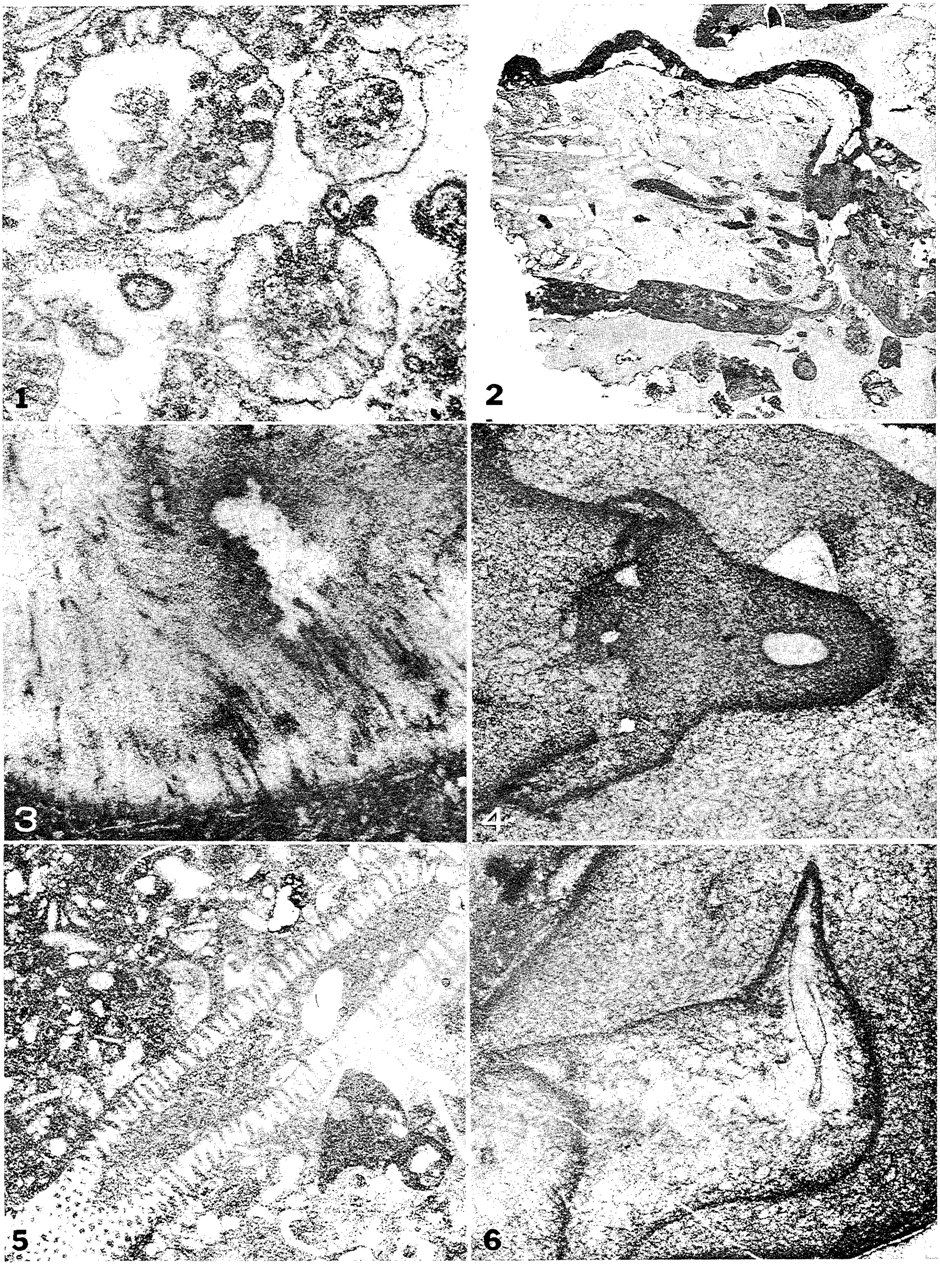
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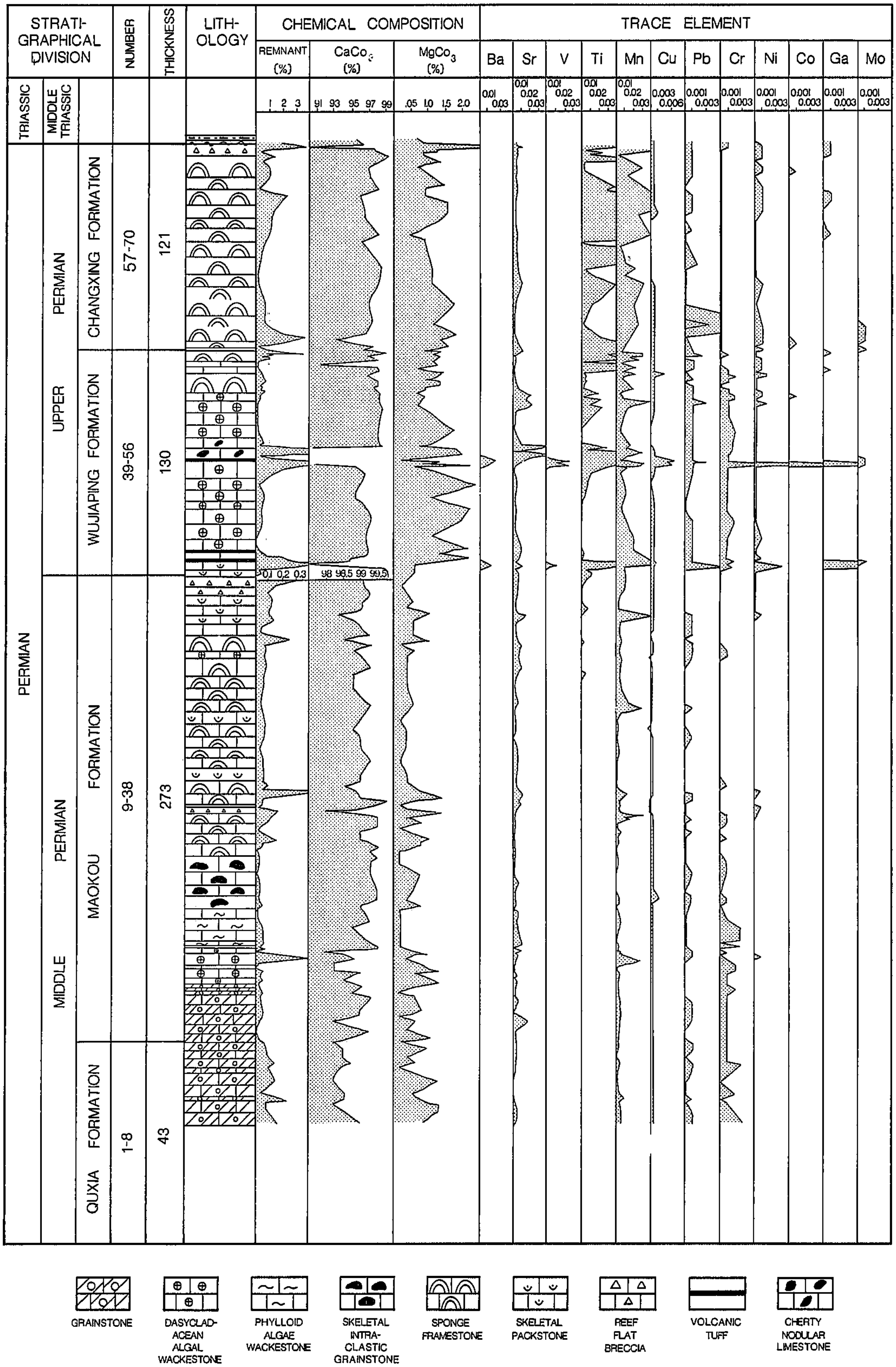
PLATE 6

Distribution of Carbonate Chemical Composition and Trace Element in the Permian Reefs of Xiangbo, Longlin County, Northwestern Guangxi



rocks in which peloidal grains are the predominant components and make up about 40% of the total grains. Only a few skeletal fragments, including bits of echinoderms, bivalves, and foraminifers, are associated with these peloidal grains. Main cements are microspars, which were formed by recrystallization of lime-mud matrix. Remnants of the lime mud, however, still occur in small areas.

The algal-foraminiferal wackestone (pl. 9, fig. 6) and packstone microfacies is characterized by bioclasts that are predominantly dasycladacean and gymnocodiacean algae and various kinds of foraminifers. Some echinoderm debris and gastropod shells may also occur. Matrix is mainly micrite with only minor areas of microspar.

The gymnocodiacean algae-foraminferal wackestone microfacies (pl. 9, fig. 3) is made of rocks in which the major organic components are gymnocodiacean algae, but minor constituents may also include foraminifers, echinoderm debris, and ostracode shells. The matrix is mainly micritic lime mud.

The intraclastic-skeletal grainstone microfacies (pl. 10, fig. 1) is characterized by rocks composed mainly of micritic intraclastic grains of sand-size. Only a few bits of identifiable skeletal debris are evident, including codiacean algae, brachiopods, and echinoderms. Interstitial spaces are totally filled by sparry calcite. Rocks of this facies may represent carbonate sand bars or tidal channel-fill deposits that accumulated on the carbonate platform.

DIAGENESIS OF THE PERMIAN XIANGBO REEFS

Because of a succession of diagenetic features, two broad periods of diagenesis of the Xiangbo reefs can be differentiated. Early diagenesis took place under marine conditions, but late diagenesis may have taken place where marine and nonmarine waters mixed or in deep-burial environments.

Early diagenesis occurred while sediments were still in moderately deep to shallow marine environments and when sediments were only shallowly buried (pl. 10, fig. 3). Various modifications took place at or close to the sediment-water or sediment-air interface.

Evidence of algal boring and micritization is widespread in deposits of shoal and bank environments. Margins of phylloid algal plates and other skeletal debris, for example, are bored by endolithic algae and filled by micrite.

Algal cohension-produced masses are widespread in deposits of shoal and bank environments. These algal lumps exhibit various irregular shapes.

Evidence of early lithification of lime muds is common in most interstitial lime-mud fillings between framework organisms. For example, fibrous marine cements were directly precipitated onto these crusts of lime mudstone (pl. 10, fig. 6), indicating the crusts were solidified early in reef history.

Fibrous calcite cement occurs as crusts and isopachous fringes lining interparticle and framework voids in many facies and may have had several generations of precipitation (pl. 10, fig. 4; pl. 11, figs. 1, 2). In most cases, such cement completely filled the primary cavities and pores. There is strong evidence for a submarine origin of such cement because it was deposited in the fluid-filled primary pore system and it locally occurs alternating with marine internal sediments.

Later diagenesis includes modifications of dolomitization, dissolution, and coarse cement introductions. For example, deposition of fibrous calcite was generally followed by precipitation of blocky sparry calcite, which is clean, bright, and has large crystal size. Blocky calcite is the final filling of many voids left open between fibrous crusts.

Selective dissolution (pl. 11, fig. 4) occurred at irregular times within the reef rocks. Early solution, for example, took place associated with encrusting growth of *Archaeolithoporella*. Solution cavities usually are filled with bright and clean crystalline calcite, and it is assumed that such filling may have taken place during later filling of voids by blocky sparry calcite cement.

Euhedral authigenic quartz crystals (pl. 11, fig. 3) are irregularly distributed within the reef rocks, especially in the late Permian Changxing Formation. These crystals usually replace not only parts of various grains, but also micritic matrix. They represent later products of diagenesis.

Dolomitization occurred irregularly and sporadically during and subsequent to later stages of reef growth and usually produced euhedral dolomite crystals (pl. 10, fig. 5; pl. 11, figs. 5, 6). The euhedral form indicates products of later replacement. Dolomitization, though extensive elsewhere, is not well developed in the Permian Xiangbo reefs. Euhedral crystals of dolomite have replaced parts of *Tubiphytes* and internal lime-mud fillings within chambers of some sphinctozoans locally in the Xiangbo carbonate rocks.

MODEL OF PERMIAN REEF DEVELOPMENT IN LONGLIN COUNTY, NORTHWESTERN GUANGXI, SOUTH CHINA (FIG. 15A, B)

Models of reef deposition and distribution may be constructed now from the wealth of detail on Permian geology accumulated during the past ten years in eastern Yunnan, southwestern Guizhou, and northwestern Guangxi. Extensive surveys on the Permian reefs exposed there and careful study of reef rocks and fossils from the typical Xiangbo reef section and related reef sections document the general features of the Middle and Late Permian Xiangbo reefs in particular.

The Xiangbo reefs belong to a larger body of carbonate platform margin-barrier reefs. To the south of Xiangbo, contemporaneous deep-water basin deposits are widespread. These are mainly dark gray, thin-bedded micritic limestones intercalated with black, thin-bedded siliceous rocks. The reefs grew upward from a substrate of typical bank deposits that surrounded the basin. Such bank deposits formed the substrate for reefs not only at Xiangbo, but also in eastern Yunnan at Guangnan, in reefs of the same age (Fan and others 1987).

Well-developed reef crest and reef flats developed behind the reefs and are characterized by a vast area of shallow-water deposits with scattered and isolated patch reefs. Shoreward-restricted carbonate platform deposits accumulated. There dasycladacean and gymnocodiacean algae and foraminifers flourished. Typical restricted carbonate platform deposits are well exposed at Hongshiyan, a small village northeast of Anran (fig. 13).

The model of late Permian reef development is similar to that of the Middle Permian, except no bank deposits are known to immediately underlie the Upper Permian reefs. The Upper Permian Xiangbo reefs, for example, grew directly on the carbonate platform on its southern margin.

SUMMARY AND COMPARISON OF THREE KINDS OF REEFS IN SOUTH CHINA

The main features of the three kinds of reefs known from exposures in South China can be summarized as follows:

1. The reefs exposed in western Hubei belong to a discontinuous barrier reef and show distinct basinward-prograding facies. Frame-building organisms include sphinctozoans, inozoans, tabulozoans, and hydrozoans, all of which are abundant and diverse.

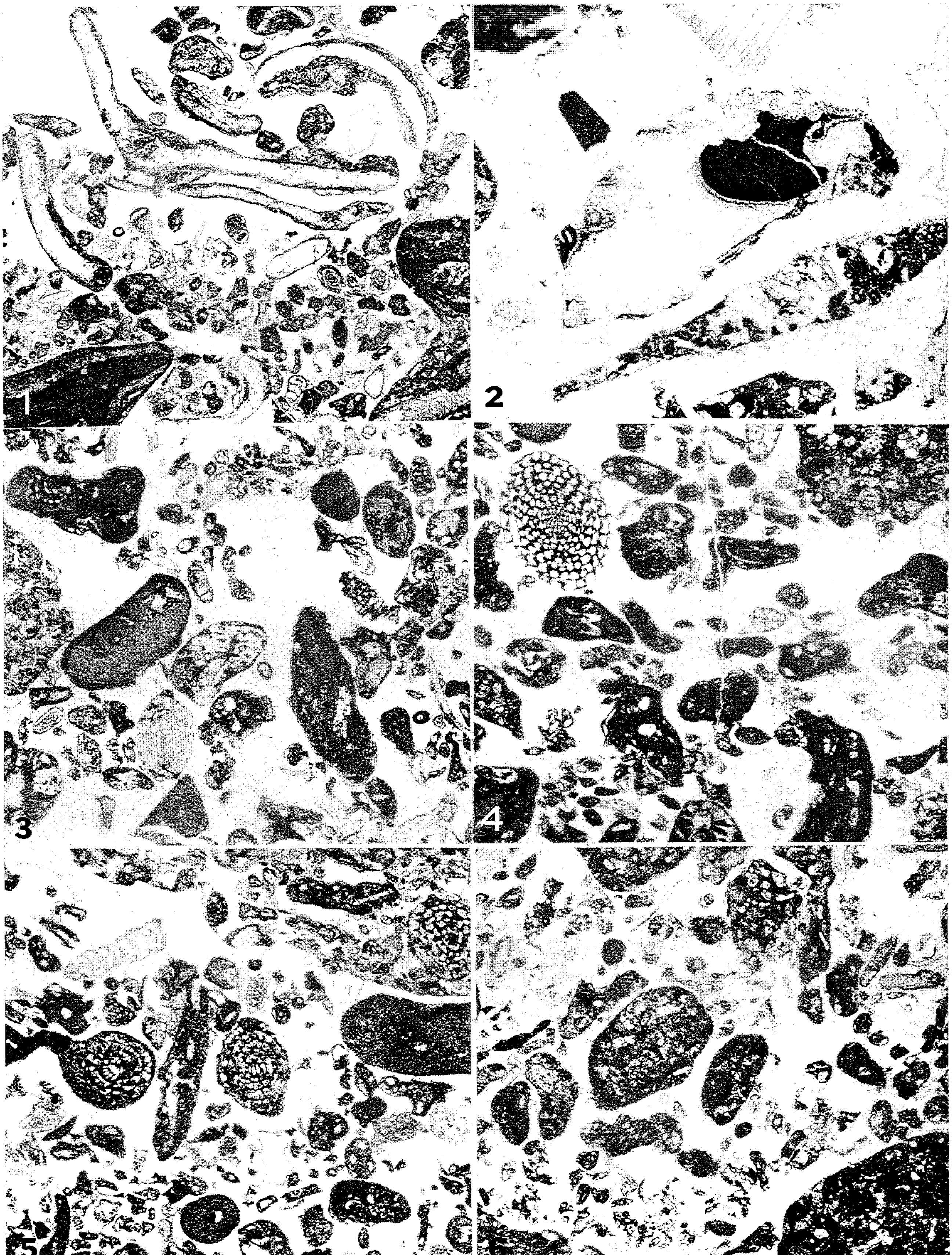
The frame builders are usually preserved in upright growth position. Reef textures are distinct, with several generations of encrusting fibrous calcite cement. The reef grew upward and prograded basinward over deposits of a marginal deep-water basin. During a late stage the area of reef growth may have been uplifted so that tops of the reefs were possibly subaerially exposed and subjected to dolomitization and dissolution and later to deeper burial and dolomitization. Such dolomite beds became locally effective reservoir rocks for oil and gas. Near the end of the Permian the reefs were drowned, and in the latest

EXPLANATION OF PLATE 7

All of the rocks figured here were collected from the Middle Permian Maokou Formation, from Xiangbo, Longlin County, northwestern Guangxi.

All figures X10.

Fig. 1—*Phylloid algae wackestone and grainstone microfacies.* Thin phylloid algal plates in the upper half of the figure now consist of sparry calcite mosaics. Large intraclasts show in both the lower left and right. Smaller foraminifers, gastropods, and intraclasts are abundant in the lower half. Micritic envelopes coat the outer margin of the phylloid algal plates. Lime mud and fine skeletal debris were sheltered by the phylloid algal plates. Cement is mainly sparry calcite. Micrite is rare. B26-3. Fig. 2—*Reef breccia microfacies.* These rocks include coarse carbonates that contain reef-derived clasts. These usually have angular edges and are of various shapes. A slender clast with pointed ends is shown here in the lower right. The cement is crystalline calcite. B28-1. Fig. 3—*Tubiphytes*-lump grainstone microfacies. Micritic lumps are abundant. They usually have irregular rounded outlines. These lumps usually appear dark and may have been formed by algal cohesion. Skeletal debris and intraclasts are also shown. *Tubiphytes* fragments are shown in the lower right and left center. Cement is sparry calcite. B26-1. Fig. 4—*Skeletal intraclastic grainstone microfacies.* Principal grains have irregular outlines and some show internal textures. Skeletal grains are fusulinids, smaller foraminifers, and fenestrate bryozoan debris. The fusulinid test in the upper left has been subjected to strong dissolution or breakage because its outer margin is wavy or irregular. Spaces between grains are filled by a sparry calcite cement mosaics. B26-4. Fig. 5—*Fusulinid grainstone microfacies.* Fusulinid tests are distinctive of the facies. Lumps and intraclasts also occur. Abundant *Tubiphytes* fragments are shown on the left. Spaces between various grains are filled with sparry calcite cement. B26-0. Fig. 6—*Skeletal intraclastic grainstone microfacies.* Intraclasts shown are of various sizes and outlines. They usually show some internal texture and their margins are usually irregular. A pebble-size interclast shows in the lower right. Spaces between grains are filled with sparry calcite cement. B22-2.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Permian somewhat deeper-water deposits accumulated over these reef tracts. Lower Triassic rocks were deposited conformably over latest Permian ones.

2. Permian reef mounds exposed in eastern Sichuan and western Hubei are isolated patch reefs and are irregularly distributed across carbonate platforms. These mounds are characterized by their small size, relative rarity of frame-building organisms, and abundance of lime-mud matrix. In fact, these reeflike structures may be more accurately called sponge-baffled mounds. The substrates upon which these mounds grew were echinoderm banks. In the subsurface, some of these mounds have been totally dolomitized and have become important targets for exploration for oil and gas.

3. Reefs exposed in northwestern Guangxi can be divided into two types: (a) a barrier reef that rimmed a carbonate platform margin, and (b) reefs that rimmed isolated carbonate platforms within a deep-water basin. Both types are characterized by distinct stratigraphic sections that show cycles of alternating reef framestone and reef-flat deposits. Frame-building organisms in the reefs include sphinctozoans, inozoans, tabulozoans, hydrozoans, and the alga *Tubiphytes*. All play important roles in constructing the basic framework. Binding organisms, such as the algae *Archaeolithoporella* and *Tubiphytes* and fistuliporid bryozoans, usually encrust the various frame-building organisms and greatly strengthened the reef to form a rigid, wave-resistant structure. Locally, *Archaeolithoporella* is particularly well developed and formed typical *Archaeolithoporella*-encrusting bindstones. The well-knit reef texture is distinct. Fibrous calcite cement commonly shows several generations of encrusting relationships.

Reef-dwelling accessory organisms were abundant and diverse. Fusulinids, brachiopods, foraminifers, bryozoans, bivalves, gastropods, echinoderms, and ostracodes and dasycladacean and solenoporacean algae have been collected from the reefs and related rocks of the complexes.

Substrates upon which the reefs grew during Middle Permian time were banks or shoals, but Late Permian reefs grew directly upon the carbonate platform margin.

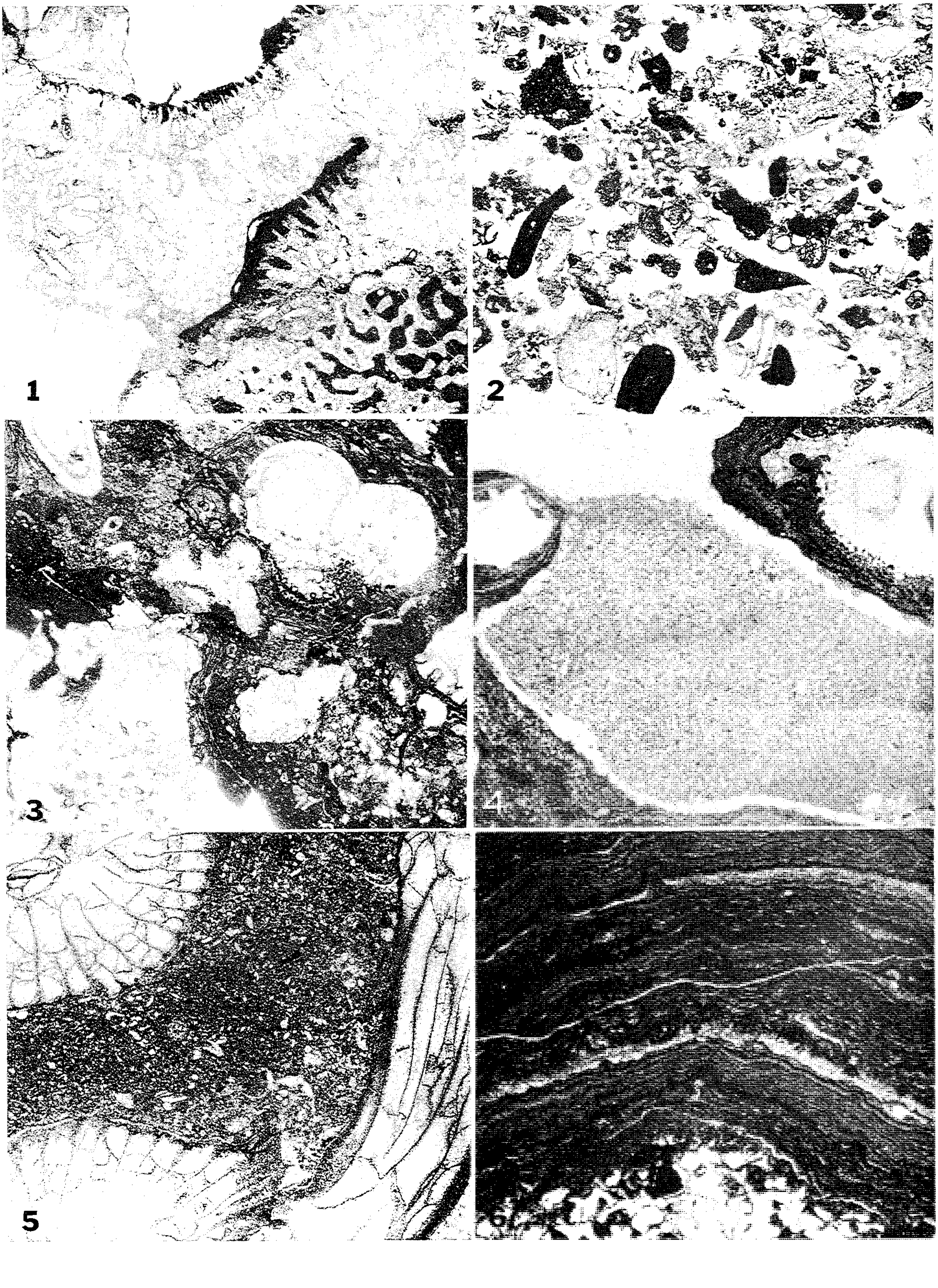
Dolomitization was not extensive in these Guangxi-Yunnan Late Permian reefs, for only limited layers of euhedral dolomite crystals were found. These represent products of later diagenetic replacement.

EXPLANATION OF PLATE 8

All of the rocks shown here are from the Middle and Upper Permian Maokou, Wujiaping and Changxing Formations, from Xiangbo, Longlin County, northwestern Guangxi.

All figures X10.

Fig. 1—*Sponge framestone microfacies.* The inozoan sponge in the lower right was encrusted by a common binding tabulozoan, which is characterized by thin subparallel tubes. Walls of these tubes are composed of sparry calcite mosaics. *Tubiphytes* and *Archaeolithoporella* occur between the inozoan and encrusting tabulozoan. *Archaeolithoporella* also occurs on the exterior of the tabulozoan. Spaces between the various framework organisms were filled with sparry calcite mosaics. In the lower left, a possible inozoan has been extensively recrystallized and is difficult to identify. B27-2. Fig. 2—*Tubiphytes* skeletal grainstone. These rocks represent intermittent deposits between reef cycles. They are characterized by a variety of skeletal debris, *Tubiphytes*, and micritic intraclasts. Near the middle right margin is a distinct crinoid fragment. Variously shaped masses of *Tubiphytes* are widespread within the rocks. Micritic intraclasts in the middle part of the figure have pointed ends. Cement is sparry calcite. B29-2. Fig. 3—*Sponge framestone microfacies.* Sphinctozoan sponges are encrusted by *Archaeolithoporella* in the upper half of the figure. In the lower left, an obscure fossil fragment may be an inozoan fragment, but because of strong recrystallization it is difficult to identify. B56-a. Fig. 4—*Lime-mud matrix trapped in sponge framestone.* Frame builders, shown here, are sphinctozoan sponges that are encrusted by dark *Archaeolithoporella.* The trapped lime muds seem to have accumulated on early fibrous calcite and represent original filling of openings within the reefs. Other areas are filled with sparry calcite cement mosaics. B27-3. Fig. 5—*Rugose coral bafflestone microfacies.* Lime mud and fine skeletal debris make up much of the sediments shown in the figure and were baffled by the rugose corals, all within the reef at Xiangbo. B50-2. Fig. 6—*Algal bindstone microfacies.* The rock is characterized by well-developed, irregularly laminated *Archaeolithoporella*, which here encrusts an inozoan sponge. Some fine skeletal debris was included in thick bands of *Archaeolithoporella.* These rocks constitute a subfacies within the Permian Xiangbo reefs. IB60-3.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COMPARISONS OF THE PERMIAN REEFS OF SOUTH CHINA WITH THE PERMIAN REEF COMPLEX OF THE GUADALUPE MOUNTAINS, WEST TEXAS AND NEW MEXICO

The Permian reef complexes of western Texas and southeastern New Mexico have long functioned as models for reef, back-reef, and basin facies in carbonate deposition and paleoecology (Bain 1967; Cys 1985; Cys and others 1977; James 1978a, 1978b; Newell 1972; Newell and others 1953; Pray and Esteban 1977; Wilson 1975; and Yurewicz 1977). No other reef has influenced thinking about carbonate models equal to that of the Guadalupe (fig. 16) and the Glass Mountains of Texas and New Mexico. Both of these areas show, in spectacular exposures, the shelf-to-basin transition, and their biologic and lithologic facies have been intensely studied and compared.

Permian reefs in western Hubei, South China, also show the shelf-to-basin transition, and the main facies features are very similar to the Permian reefs so well exposed in western Texas and southeastern New Mexico. Basin facies deposits of China are dark gray and black, thin- to medium-bedded micrites intercalated with cherty layers and spiculitic siliceous rocks. Marginal basin rocks usually contain reef breccias and bioclastic debris flows that were eroded from the carbonate platform margin reefs and accumulated near the toe of reef slope. The transition from distal basin-facies micrite and spiculite deposits are very similar to the transition from dark mudstones to wackestones and coarse rudstones seen in classic exposures of Lamar and Pinery members of the Bell Canyon Formation (fig. 16). In west Texas, spectacular submarine landslide deposits of the basin margin Rader member actually produced extensive turbidite deposits that spread far into the deep-water Delaware basin (Newell and others 1953). Coarse breccia beds and turbidite deposits were also laid down in similar fashion in the reef complex near Jiantianba and near Huangnitang.

The reef-core facies in West Hubei is characterized by abundant sphinctozoan and inozoan sponges as frame-building organisms in the Permian carbonate buildups. These frame and associated binding organisms are usually coated by fibrous calcite marine cement of several generations. These relationships are strikingly similar to those of the typical Capitan Formation massive boundstones (Babcock 1974, 1977; Toomey and Babcock 1983) where calcareous sponges are encrusted by *Tubiphytes* and *Archaeolithoporella*, which are in turn bound or coated by radial fibrous calcites. Bryozoans and *Tubiphytes* also locally serve as nuclei for multiple crusts of *Archaeolithoporella* and syndepositional submarine cement in the Capitan reef. Phylloid algae also were found in Capitan limestone massive rocks, but none were found in reef-core facies of West Hubei.

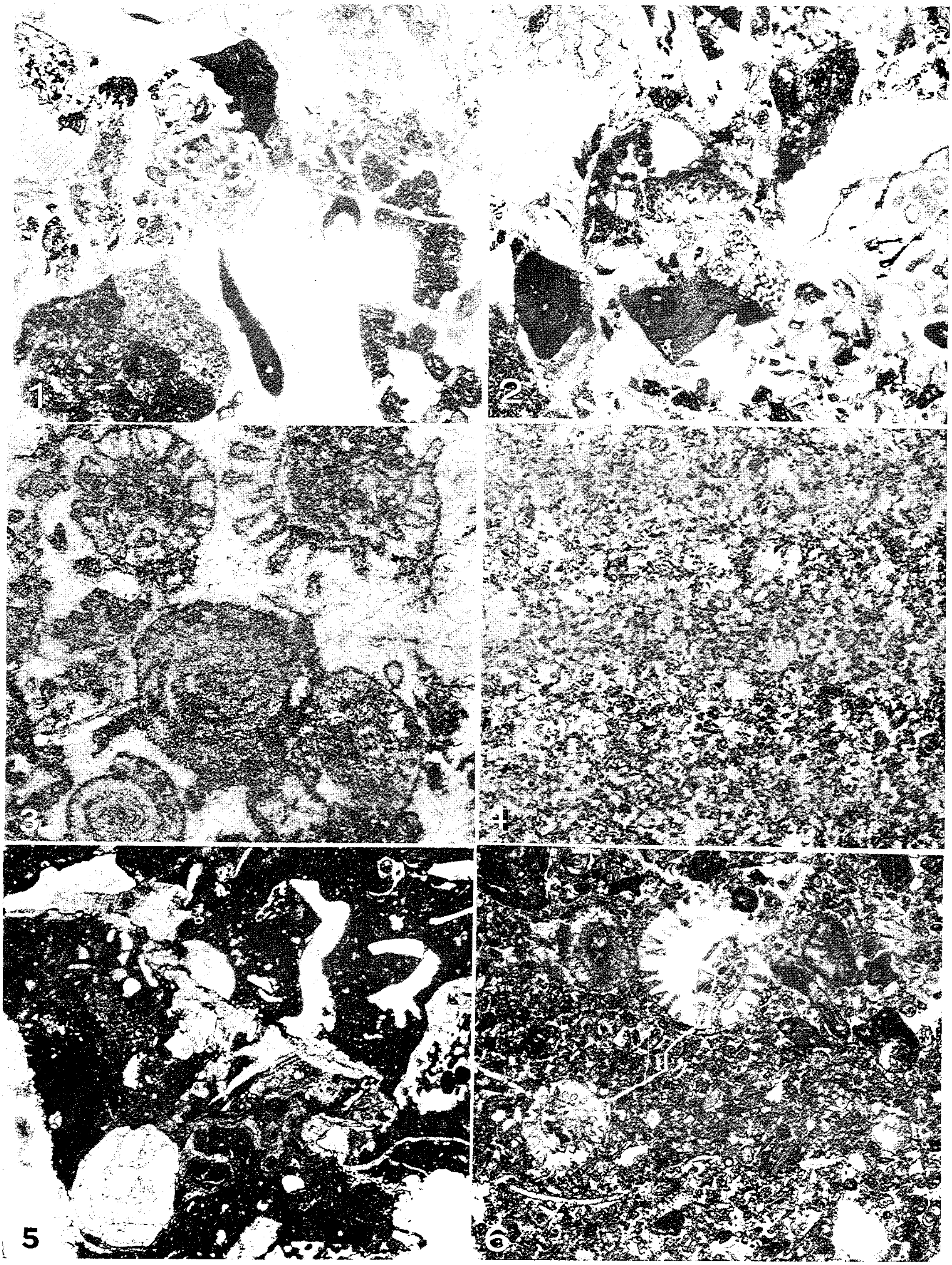
Back-reef facies deposits in West Hubei are comparable to those near the reef deposits in the Guadalupe Mountains (fig. 16). Dasycladacean algae, such as *Mizzia* and *Gymnocodium*, and gastropods and fusulinids are well exposed immediately west of reef rocks of youngest

EXPLANATION OF PLATE 9

Rocks figured here were all collected from the Middle and Upper Permian Maokou, Wujiaping and Changxing Formations, from Xiangbo, Longlin County, northwestern Guangxi.

All figures X10.

Fig. 1—*Reef-flat breccia microfacies.* The rock consists of reef fragments of irregular shapes and various sizes, usually with angular edges. Some of these clasts were derived from the immediately underlying reef rocks, but some clasts also came from underlying bank rocks. B35-4. Fig. 2—*Reef-flat breccia microfacies.* The rock is similar to that shown in figure 1. B37-4. Fig. 3—*Gymnocodium-foraminiferal packstone and wackestone microfacies.* The major organic components shown here are gymnocodiacean algae, *Mizzia,* and foraminifers. The matrix is mainly lime mud, but also included is a sparry calcite cement. B51-2. Fig. 4—*Silty-peloidal-skeletal wackestone microfacies.* Peloidal grains are the predominant component, with only a few skeletal fragments. Principal cement is a microspar, which was probably formed by recrystallization of lime-mud matrix. B39-1. Fig. 5—*Floatstone microfacies.* In this figure, various skeletal fragments, such as the sphinctozoan in the lower left, and lithic reef fragments are imbedded within a lime-mud matrix. IB59-1. Fig. 6—*Algal-foraminiferal wackestone microfacies.* This microfacies is characterized by skeletal debris made mainly of dasycladacean and gymnocodiacean algae and various kinds of foraminifers. The matrix is mainly micrite, with only minor areas of microspar. B47-2.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Capitan age in the mouth of Dark Canyon, near Carlsbad, New Mexico. Similar rocks in similar stratigraphic positions occur in these Chinese reefs, indicating they formed in the same environments of deposition. However, in Dark Canyon, *Collenella* heads also occur, and these types of algal boundstones are absent in back-reef deposits in the western Hubei complexes. More pronounced is the lack of back-reef evaporites, and caliche-produced vadose pisolites and tepee structures in the reef-related Chinese deposits.

The reef facies in the Permian rocks at Xiangbo, Longlin County, in northwestern Guangxi (fig. 14), is characterized by diverse and abundant frame-building organisms and well-developed *Archaeolithoporella*. Somewhat later fibrous calcite cement is also well developed. All of these features are similar to those in the massive upper Capitan Limestone of the Guadalupe Mountains. However, more diverse and abundant frame-building organisms occurred in the Xiangbo reefs and can be easily distinguished, in contrast to the similar but less apparent occurrences in the Capitan Limestone. Back-reef facies of the Xiangbo reefs are comparable to those of the near-reef Carlsbad Group rocks, for both contain characteristic assemblages of smaller foraminifers and dasycladacean and gymnocodiacean algae.

The similarities and dissimilarities between Chinese Permian reefs and the Permian reef complex of the Guadalupe mountains, west Texas and New Mexico, are summarized in table 4.

ACKNOWLEDGMENTS

The present paper is a result of an extensive project on the Permian reefs in South China that was financially supported by the National Natural Science Foundation of China. The research project consisted of two parts, a study of the Laolongdong patch reefs and a study of the Xiangbo reefs.

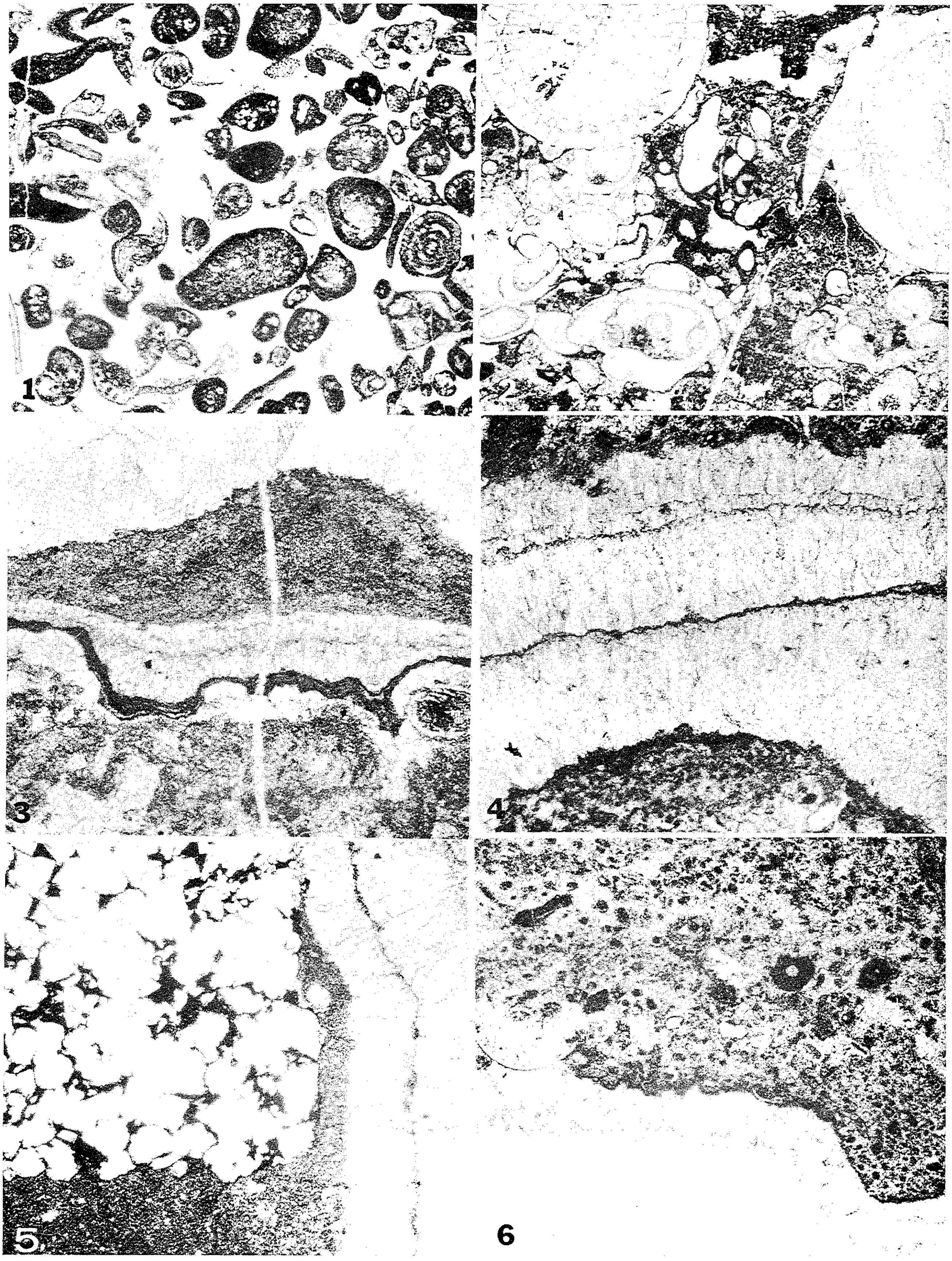
During the investigation of the Laolongdong patch reefs, Yang Wanrong, Wen Zhuanfen, Sun Xiaoxing, Wang Jianming, Wu Yasheng, Rui Lin, and Wang Jiogzhang took part in fieldwork and helped to collect rock and fossil samples and measure reef stratigraphic sections. Thin sections of reef rocks were all analyzed by Wen Zhuanfen and Sun Xiaoxing. Bryozoan fossils in the Laolongdong reefs were identified by Lu Linhuang, smaller foraminifers by Wang Keliang, calcareous algae by Mu Xinan, fusulinids by Rui Lin, and calcareous sponges by Zhang Wei. Spectrographic analyses were made by the chemical analysis laboratory in the Institute

EXPLANATION OF PLATE 10

All of the rocks figured here were collected from the Upper Permian Wujiaping and Changxing Formations, from Xiangbo reefs, Longlin County, northwestern Guangxi.

All figures X25 except figures 1 and 2, which are X10.

Fig. 1—*Intraclastic skeletal grainstone microfacies.* Main grains in the rocks are micritic intraclasts of sand-size, algal fragments, and brachiopod and echinoderm debris. In the lower left, dasycladacean algal fragments (*Mizzia*) show as clasts. In the upper middle, as well as near the right margin, foraminiferal tests also occur as clasts. Interstitial spaces are totally filled by sparry calcite. B44-1. Fig. 2—*Rugose coral bafflestone.* Rugose corals are shown in the upper part, and sections of sphinctozoan sponge chambers occur in the lower left. Lime mud and fine skeletal debris were baffled by the rugose corals and sponges. IB64. Fig. 3—*Vadose silt.* The lower half shows a frame builder that was encrusted by the binding *Archaeolithoporella,* over which was deposited fibrous sparry calcite. Darker vadose silt was deposited on the regular and even surface of that fibrous sparry calcite. Such relationships indicate early exposure of reef rocks. B55. Fig. 4—*Several generations of calcareous cement.* Three generations of sparry calcite overlie the frame-building organisms. Each generation of calcite has a dark line, possibly produced by a layer of blue-green algae, that indicates that sparry calcite cement was added intermittently. IB66-1. Fig. 5—*Sparry calcite cement and dolomite.* Two generations of sparry calcite are shown on the right. On the left, lime-mud matrix has been replaced by coarse euhedral dolomite crystals. IB66-1. Fig. 6—*Lime mud as a substrate for cement.* Peloids and lime mud are well shown in the upper half of the figure and represent primary filling within the reef framework. Sparry calcite cement in the lower part has grown on a substrate of the lime mud, which indicates that the lime muds were quickly lithified, at least firm enough to function as a substrate for later cement. B35-5.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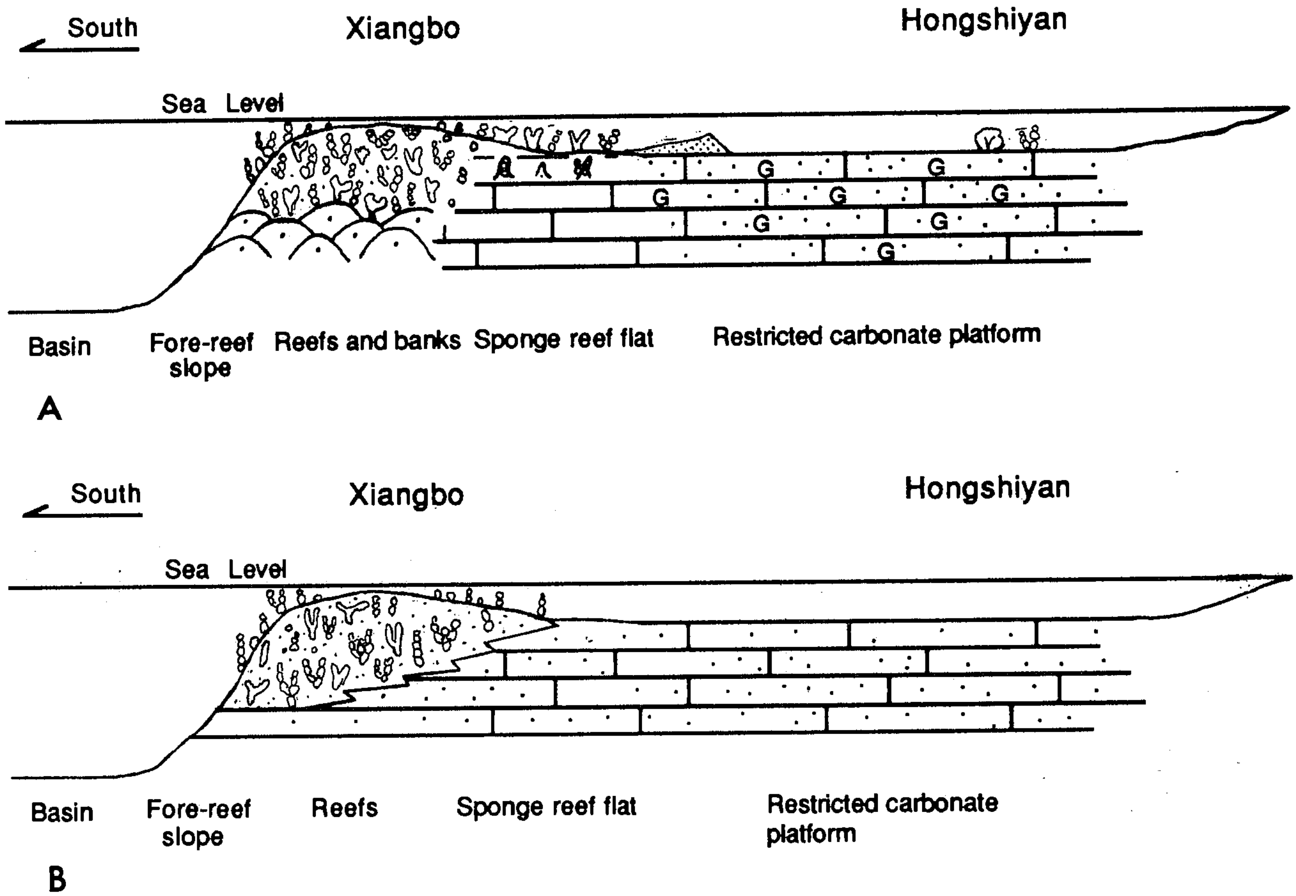


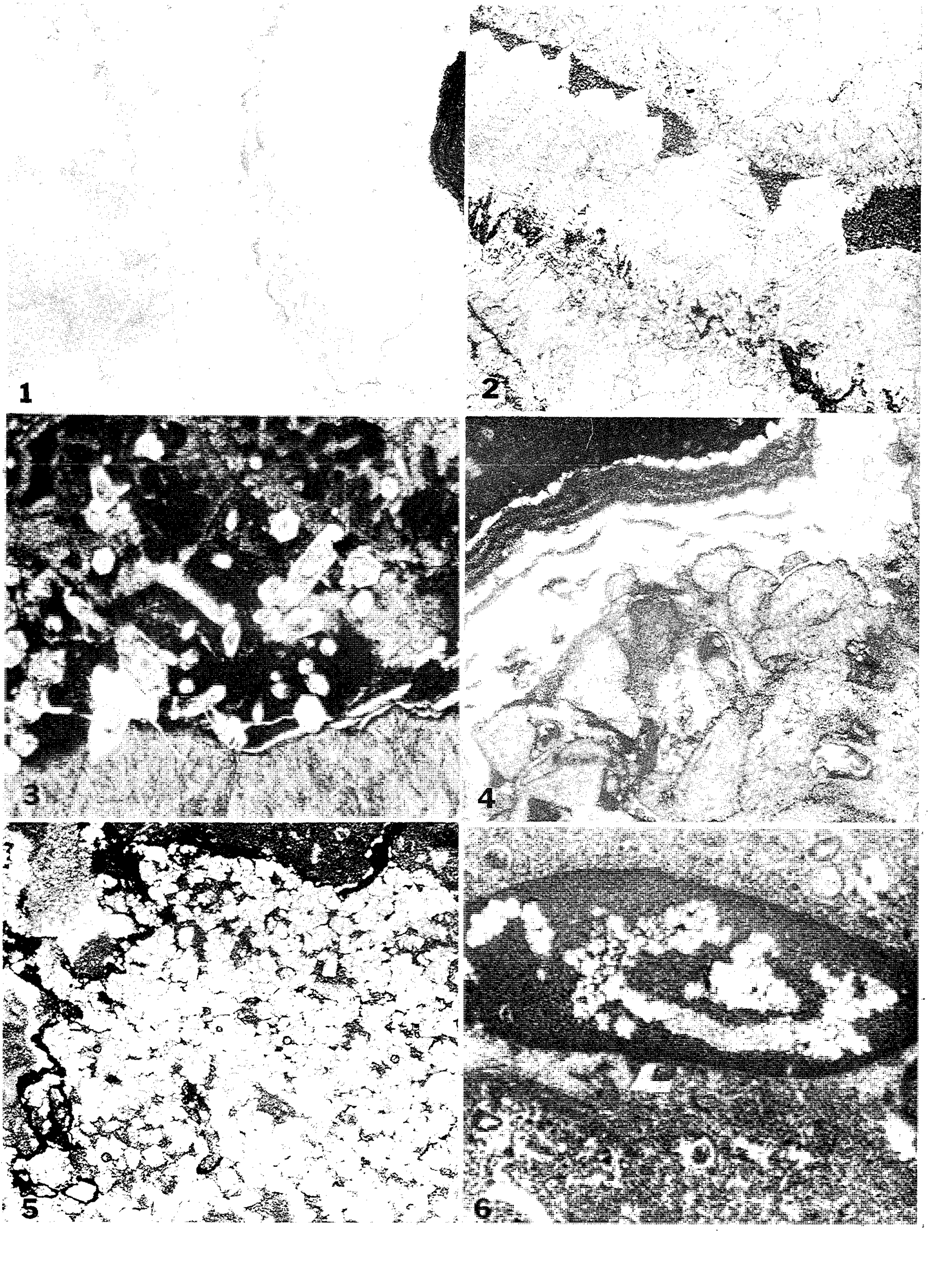
FIGURE 15.—*Models of reef development at Xiangbo, Longlin County, northwestern Guangxi, southern China. (A) Middle Permian Maokou Formation. (B) Upper Permian Wujiaping and Changxing Formations.*

EXPLANATION OF PLATE 11

All of the rocks figured here were collected from the Middle Permian Maokou Formation and the Upper Permian Wujiaping and Changxing Formations, from Xiangbo reefs, Longlin County, northwestern Guangxi.

All figures X25 except figure 1, which is X10.

Fig. 1—*Generations of cement and lime-mud deposition.* Several generations of sparry calcite cement are visible. A medial bright band of calcite may represent a product of dissolution-precipitation. Near the left margin the patch of lime mud represents late filling of a void within the reef framework. B29-3. Fig. 2—*Generations of cement and silt.* Calcite cement of at least three generations forms coarse crystals. Silt accumulated on the angular surface and was followed by an additional cement layer. B31-3. Fig. 3—*Authigenic quartz.* Lime-mud matrix has been replaced by euhedral authigenic quartz crystals, which represent replacement products of late diagenesis. B54-a. Fig. 4—*Generations of cement and silt.* Light sparry calcite forms a distinctive diagonal band across the upper parts of the figure, above the overgrown sponge. Lenses of silt accumulated intermittently on the undulating surface, followed by sparry calcite cement. More continuous layers of silt followed and are overlain by a thin bright layer of dolomite and then more silt. Bright layers may also represent solution-precipitation layers. IB70-2. Fig. 5—*Dolomite.* Coarse euhedral dolomite crystals are well developed in lime-mud matrix and represent replacement products of late diagenesis. B56-4. Fig. 6—*Dolomite within Tubiphytes.* Euhedral dolomite crystals within the high-magnesium calcite skeleton of the alga *Tubiphytes* are obvious replacement products, probably of late diagenesis. B57-7.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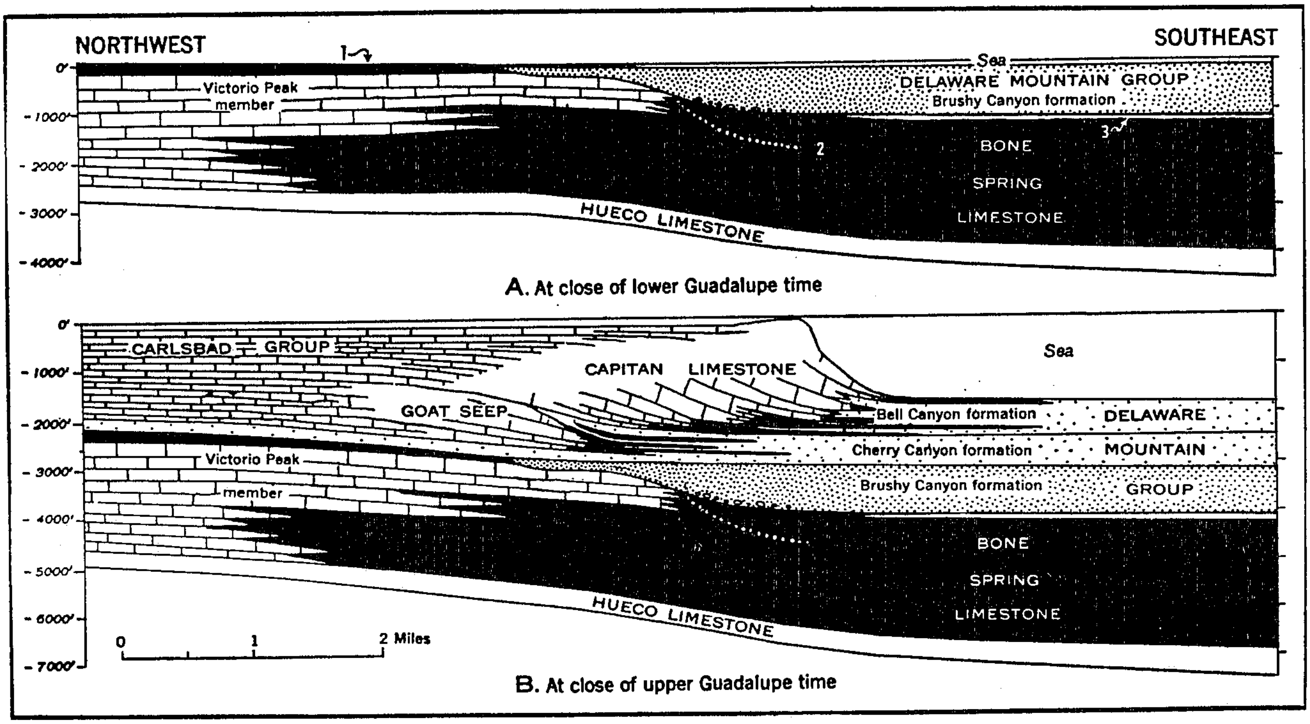

FIGURE 16.—*Generalized cross section through the Guadalupe Mountain reefs of Guadalupian age shows the generally regressive relationships of facies where the reef and fore-reef facies grew basinward over the dark fine-grained limestones and interbedded sandstones of the Delaware Basin. The reefs of China are strikingly similar in general characteristics, but most show cycles of moderate transgression and regression whereas the reef of the Guadalupe Mountains records principally regressive development, at least during Capitan time (modified from Newell and others 1953).*

of Geology, Academia Sinica. Thin sections were cut by Shao Guohua of the Institute of Geology.

During investigation of the Xiangbo reef, Qi Jingwen, Wang Jiogzhang, Zhou Tieming, Liu Junru, Zhang Xiaolin, Wang Jianming, Xie Gangping, and Li Hua, from the staff of the Yunnan-Guizhou-Guangxi Institute of Petroleum Geology, with Zhang Wei, Sun Xiaoxing, and Wu Yasheng from the Institute of Geology, Academia Sinica, made joint studies. Together they measured the reef sections of the Xiangbo locality and collected a great many samples. Thin sections of carbonate rocks were cut in both institutes and were examined separately in Beijing and Kunming; thus, a great amount of information was gained. All of the thin sections were analyzed by Wen Zhuanfen, Sun Xiaoxing, Li Anhua, Sheng Qinxing, and the authors.

When the authors worked on this manuscript in Beijing, Sun Xiaoxing made drafts of many of the illustrations. Some have been modified by Richard T. Brandley and Dru R. Nielson at Brigham Young University. Joyce Pritchard prepared the several drafts of the manuscript. To all the staffs mentioned above, the authors extend their sincere thanks. We also appreciate assistance from the Department of Geology, Brigham Young University, for providing working space and for other assistance to the joint research of the team from China and the USA. Partial financial support for the USA-part of our joint study came from a Brigham Young University Alumni Foundation Maeser Research Award to J. Keith Rigby.

REFERENCES CITED

Babcock, J. A., 1974, The role of algae in the formation of the Capitan Limestone (Permian, Guadalupian), Guadalupe Mountains, West Texas and New Mexico: Unpublished Ph.D. dissertation, University of Wisconsin, Madison, 241p.

__________, 1977, Calcareous algae, organic boundstones, and the genesis of the upper Capitan Limestone (Permian, Guadalupian), Guadalupe Mountains, West Texas—New Mexico, p. 3–44: In Hileman, M. E., and Mazzullo, S. J. (eds.), Upper Guadalupian Facies, Permian reef complex, Guadalupe Mountains, New Mexico and West Texas, v. 1, Permian Basin Section: Society of Economic Paleontologists and Mineralogists, Publication 77-16.

Bain, R. J., 1967, Paleoecology of some Leonardian patch reefs in the Glass Mountains, Texas: Brigham Young University Geology Studies, v. 14, p. 195–236.

Brander, R., and Resch, W., 1981, Reef development in the Middle Triassic (Ladinian and Cordevolian) of the northern limestone Alps near Innsbruck, Austria, p. 203–232: In Toomey, D. F. (ed.), European fossil reef models: Society of Economic Paleontologists and Mineralogists, Special Publication 30.

Table 4. Comparisons of the Capitan reef in west Texas and New Mexico with Chinese reefs at Jiantianba, Xiangbo, and Laolongdong in South China.

Reef Localitites / Characteristics	Capitan Reef in West Texas and New Mexico	Jiantianba Reef in West Hubei	Xiangbo Reef in Northwestern Guangxi	Laolongdong Patch Reefs in East Sichuan
Configuration of Reefs	Barrier Reef	Barrier Reef	Barrier reefs and small reefs rim isolated carbonate platforms in basin	Irregularly distributed patch-reefs or mounds on a carbonate platform
Geological Age or Horizon	Guadalupian Capitan Formation	Uppermost Permian Changxing Formation	Uppermost Permian Changxing and Wujiaping Formation, Middle Permian Maokou Formation	Uppermost Permian Changxing Formation
Pattern of Reef Formation	Progradation	Progradation	Unknown	Unknown
Reef Cycle	None	None	Distinct reef cycles	None
Substrate for Reef Growth	Goat Seep Reef and deep-water basin deposits	Deep-water basin deposits	Bank or shoal	Echinoderm bank
Frame-building Organisms	Sphinctozoans, bryozoans, rare inozoans, phylloid algae	Sphinctozoans, inozoans, tabulozoans, hydrozoans	Sphinctozoans, inozoans, tabulozoan, hydrozoan, *Tubiphytes*	Sphinctozoans, inozoans, hydrozoans
Binding Organisms	*Archaeolithoporella*, *Tubiphytes*, solenoporacean algae	*Archaeolithoporella*, tabulozoans, blue-green algae, and *Tubiphytes*	*Archaeolithoporella*, *Tubiphytes*, tabulozoans, fistuliporid bryozoans	rare *Archaeolithoporella*, fistuliporid bryozoans
Cement in Reef Core Facies	Radial fibrous cement	Fibrous cement of several generations, euhedral dolomite rim and blocky calcite	Radial fibrous calcite of several generations and blocky calcite	Mudstone matrix
Fore-reef Slope and Breccias	Well-developed turbidites and debris falls	Well-developed turbidites and bioclastic debris flows	Unknown	No flank deposits
Back Reef Rocks	Well-bedded wackestone and packstone with *Mizzia*, *Gymnocodium*, *Collenella*, and fusulinids, caliche layers with evaporites and vadose pisolites	Well-bedded wackestone and packstone with *Gymnocodium*, *Palaeofusulina*, and smaller foraminifers, no evaporites nor vadose pisolites	Well-bedded wackestone and packstone with dacycladacean and gymnocodiacean algae and foraminifers	No back reef rocks
Basin Rocks	Thin-bedded micritic cherty limestones intercalated with fine to medium grained sandstone	Thin to medium-bedded micrites intercalated with cherty layers and spiculitic siliceous rocks	Thin-bedded micritic limestones intercalated with siliceous rocks	None

Chen Jigao, Zhao Xianwen, and Zhang Yinben, 1985, Distribution of the reefs in Changxing Formation of Upper Permian in Sichuan Basin and its relation to oil and gas: Natural Gas Industry, v. 5, no. 2, p. 10–18.

Cys, J. M., 1985, Lower Permian phylloid algal mounds, southern Tatum basin, southeastern New Mexico, USA: p. 179–87: In Toomey, D. F., and Nitecki, M. H. (eds.), Paleoalgology: Contemporary research and applications, Springer-Verlag, Berlin-Heidelberg-New York-Tokyo.

Cys, J. M., Toomey, D. F., Brezina, J. L., Greenwood, E., Groves, D. B., Klement, K. W., Kullman, J. D., McMillan, T. L., Schmidt, V., Sneed, E. D., and Wagner, L. H., 1977, Capitan reef—Evolution of a concept, p. 201–322: In Hileman, M. E., and Mazzullo, S. J. (eds.), Upper Guadalupian Facies, Permian reef complex, Guadalupe Mountains, New Mexico and West Texas, v. 1, Permian Basin Section: Society of Economic Paleontologists and Mineralogists, Publication 77-16.

Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture, p. 108–121: In Ham, W. E. (ed.), Classification of carbonate rocks: American Association of Petroleum Geologists, Memoir 1.

Fan Jiasong, Ma Xing, Zhang Yinben, and Zhang Wei, 1982, The Upper Permian reefs in West Hubei, China: FACIES, v. 6, p. 1–14.

Fan Jiasong and Zhang Wei, 1985, Sphinctozoans from Late Permian reefs of Lichuan, West Hubei, China: FACIES, v. 13, p. 1–44.

________, 1987, On some inozoan Pharetronida (Calcisponges) and tabulozoans (Sclerospongiae) from Upper Permian reefs, Lichuan County, West Hubei, China: Scientia Geologica Sinica, 1987, no. 4, p. 326–32.

Fan Jiasong, Zhang Wei, Qi Jingwen, and Wang Jiongzhang, 1987, On the main feature of Lower Permian reefs in Guangnan County, southeastern Yunnan and their frame-building organisms—sphinctozoans: Scientia Geologica Sinica, 1987, no. 1, p. 50–60.

Fang Shaoxian, 1983, Silicification of sponge reefs of Upper Permian Jiantianba, Lichuan County, Hubei Province: Acta Sedimentologica Sinica, v. 1, no. 4, p. 29–36.

Flügel, E., 1975, Fossil Hydrozoan—Kenntnisstand und probleme, Paläontologische Zeitschrift, v. 49, no. 4, p. 369–406.

________, 1977, Environment models for upper Paleozoic benthic calcareous algal communities, p. 314–43: In Flügel, E. (ed.), Fossil algae, recent results and development: Springer Verlag, Berlin, Heidelberg, New York.

________, 1979, Paleoecology and microfacies of Permian, Triassic, and Jurassic communities of platform and reef carbonates from the Alps: Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine, v. 3, no. 2, p. 569–87.

________, 1981a, Lower Permian *Tubiphytes/Archaeolithoporella* buildups in the southern Alps (Austria and Italy), p. 143–60: In Toomey, D. F. (ed.), European fossil reef models: Society of Economic Paleontologists and Mineralogists, Special Publication 30.

________, 1981b, Paleoecology and facies of Upper Triassic reefs in the northern Calcareous Alps, p. 291–360: In Toomey, D. F. (ed.), European fossil reef models: Society of Economic Paleontologists and Mineralogists, Special Publication 30.

________, 1982, Evolution of Triassic reefs: Current concepts and problems: FACIES, v. 6, p. 297–328.

________, 1983, Microfacies analysis of limestone: Springer-Verlag, Berlin-Heidelberg-New York-Tokyo, 633p.

Flügel, E. and Sy, E., 1959, Die Hydrozoan der Trias: Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, v. 109, no. 1, p. 1–108.

James, N. P., 1978a, Facies models II, Reefs, p. 121–132: In Walker, R. G. (ed.), Facies models: Geological Association of Canada.

________, 1978b, Facies models, 10: Reefs: Geoscience Canada, v. 5, p. 16–26.

Kuhn, O., 1942, Zur Kenntnis des Rhät von Vorarlberg: Mitteilungendes Alpenlanden Geologischen Vereines, v. 33, p. 111–57.

Li Shushun, Liu Dacheng, and Gu Shunhua, 1985, Characteristics of the Honghua reef in Kai County of Sichuan and its significance in finding the new type hydrocarbon reservoir: Natural Gas Industry, v. 5, no. 2, p. 24–28.

Mazzullo, S. J., and Cys, J. M., 1977, Submarine cements in Permian boundstones and reef-associated rocks, Guadalupe Mountains, West Texas and southeastern New Mexico, p. 151–200: In Hileman, M. E., and Mazzullo, S. J. (eds.), Upper Guadalupian facies, Permian reef complex, Guadalupe Mountains, New Mexico and West Texas, v. 1, Permian Basin Section: Society of Economic Paleontologists and Mineralogists, Publication 77-16.

________, 1979, Marine aragonite sea-floor growth and cements in Permian phylloid algal mounds, Sacramento Mountains, New Mexico: Journal Sedimentary Petrology, v. 49, p. 917–36.

Newell, N. D., 1957, Paleoecology of Permian reefs in the Guadalupe Mountains area: Treatise on Marine Ecology and Paleoecology, v. 2: Geological Society of America, Memoir 67, p. 407–36.

________, 1972, The evolution of reefs: Scientific American, v. 226, no. 6, p. 54–65.

Newell, N. D., Rigby, J. K., Fischer, A. G., Whiteman, A. J., Hickox, J. E., and Bradley, J. S., 1953, The Permian reef complex of the Guadalupe Mountain region, Texas and New Mexico: W. H. Freeman and Co., 236p.

Piller, W. E., 1981, The Steinplatte reef complex, part of an Upper Triassic carbonate platform near Salzburg, Austria: In Toomey, D. F. (ed.), European fossil reef models: Society of Economic Paleontologists and Mineralogists, Special Publication 30, p. 261–90.

Pray, L. C., and Esteban, M. (eds.), 1977, Upper Guadalupian facies, Permian reef complex, Guadalupe Mountain, New Mexico and West Texas, v. 2, road logs and locality guides, Permian Basin Section: Society of Economic Paleontologists and Mineralogists, Publication 77-16, 194p.

Qiang Zhitong, Guo Yihua, Zhang Fan, Yan Chuantai, and Zheng Jiafeng, 1985, The Upper Permian reef and its diagenesis in Sichuan basin: Oil and Gas Geology, v. 6, no. 1, p. 82–90.

Reid, R. P., and Tempelman-Kluit, D. J., 1987, Upper Triassic Tethyan-type reefs in the Yukon: Bulletin of Canadian Petroleum Geology, v. 35, no. 3, p. 316–32.

Rigby, J. K., and Fan Jiasong, 1988, An unusual root tuft from the Middle Permian Maokou Formation, Guangxi Province, South China: Journal of Paleontology, v. 62, no. 5, p. 822–26.

Sheng Jinzhang, Rui Lin, and Chen Chuzhen, 1985, Permian and Triassic sedimentary facies and paleogeography of South China, p. 59–81: In Nakazawa, K., and Dickins, J. M. (eds.), The Tethys: Her paleogeography and paleobiogeography from Paleozoic to Mesozoic: Tokai University Press.

Stanley, G. D., Jr., 1980, Triassic carbonate buildups of western North America: comparisons with the Alpine Triassic of Europe: Rivista Italiana di Paleontologia e Stratigraphia, v. 85, p. 877–94.

________, 1982, Triassic carbonate development and reef building in western North America: Geologische Rundschau, v. 77, no. 3, p. 1057–75.

Toomey, D. F., and Babcock, J. A., 1983, Precambrian and Paleozoic algal carbonates, West Texas-southern New Mexico: Colorado School of Mines, Professional Contributions, no. 11, 345p.

Tyrrell, W. W., Jr., 1969, Criteria useful in interpreting environments of unlike but time-equivalent carbonate units (Tansill-Capitan-Lamar), Capitan reef complex, West Texas and New Mexico, p. 80–97: In Friedman, G. M. (ed.), Depositional environments in carbonate rocks: Society of Economic Paleontologists and Mineralogists, Special Publication 14.

Waagen, W., and Wentzel, J., 1887, Salt-Range fossils, pt. 1, Productus Limestone fossils, Coelenterata, Amorphozoa, Protozoa: Memoirs of the Geological Survey of India, p. 925–96.

Wilson, J. L., 1975, Carbonate facies in geologic history: Springer-Verlag, Berlin-Heidelberg-New York-Tokyo, 471p.

Yurewicz, D. A., 1977, The origin of the massive facies of the lower and middle Capitan Limestone (Permian), Guadalupe Mountains, New Mexico, and West Texas, p. 45–92: In Hileman, M. E., and Mazzullo, S. J. (eds.), Upper Guadalupian facies Permian reef complex, Guadalupe Mountains, New Mexico and West Texas, v. 1, Permian Basin Section: Society of Economic Paleontologists and Mineralogists, Publication 77-16.

Zheng Dingqian and Liu Bingwen, 1984, Permian reefs in southwestern China: Natural Gas Industry, v. 4, no. 2, p. 1–2.

Zeng Dingqian, Liu Bingwen, and Huang Yunming, 1984, Reefs through geologic ages in China: Institute of Exploration and Development, Nanhai (South China Sea) West Oil Corporation, 111p.

Zhao Jinke, Sheng Jinzhang, Yao Zhaoqi, Liang Xiluo, Chen Chuzhen, Rui Lin, and Liao Zhuoting, 1981, The Changxingian and Permian-Triassic boundary of South China: Bulletin of Nanjing Institute of Geology and Paleontology, Academia Sinica, 2:1–112.