BRIGHAM YOUNG UNIVERSITY

GEOLOGY STUDIES

VOLUME 40 • 1994

BRIGHAM YOUNG UNIVERSITY
GEOLOGY STUDIES

Volume 40, 1994

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A Publication of the
Department of Geology
Brigham Young University
Provo, Utah 84602

Brigham Young University Geology Studies is published by the Department of Geology. This publication consists of graduate student and faculty research within the department as well as papers submitted by outside contributors. Each article submitted is externally reviewed by at least two qualified persons.

ISSN 0068-1016
6-94 550 10461/11134

The Permian Reefs in Ziyun County, Southern Guizhou, China[1]

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ABSTRACT

The Permian reefs in Ziyun County, southern Guizhou, are among the best developed and exposed Permian reefs in South China. Two horizons of reefs have been recognized: the lower is the Middle Permian Maokouan barrier reef in the Maokou Formation, and the upper is the Upper Permian Changxingian barrier and patch reefs in the Mobo Formation. Upper Permian Wujiapingian coral biostromes occur in the Jiyaopo Formation. These three units of reefs and biostromes developed along the margin of a carbonate platform adjacent to a deepwater trough during Permian time. Changxingian reefs are among the youngest Paleozoic reefs known. Their demise is essentially contemporaneous with the major extinction event near the Permian-Triassic boundary.

Principal frame-building organisms of the Middle Permian and the uppermost Permian barrier and patch reefs include sphinctozoans, inozoans, and hydrozoans. *Tubiphytes* and bryozoans are minor frame-builders. *Archaeolithoporella* plays a cardinal role in binding the frame-builders to form wave-resistant frameworks. The reef-dwelling biota is a very diverse one. Reef-building organisms in the Wujiapingian coral biostromes are mainly densely packed thickets of the rugose coral *Pseudohuangia* and the massive coral *Ipciphyllum.*

Calcite cements are very abundant in the framestones. At least five types of cement have been recognized: (1) peloidal micritic cement (may have been originally Mg-calcite); (2) acicular calcite, which was originally aragonite; (3) radiaxial fibrous calcite, which was originally Mg-calcite; (4) botryoidal calcite, which originally was aragonite; and (5) blocky calcite.

Vadose silt, solution cavities, and Permian weathering crusts in the reefs indicate that the reefs were periodically exposed during their development. Paleokarst surfaces have been observed at the tops of the Maokouan and Changxingian reef complexes, and long periods of exposure have been proposed for development of those surfaces. Typical tidal flat deposits accumulated on top of the Changxingian reef complex and coincide with the barrier paleotopography.

Facies differentiation within the barrier reef complexes is clear, and a member/facies stratigraphic nomenclature is proposed. Over a distance of less than six kilometers, basin facies, fore-reef facies, reef-core facies, back-reef bioclastic sand shoal facies, and restricted carbonate platform facies of the Changxingian stage can be observed. A contemporaneous platform lagoonal patch reef has been found near the village of Monan. A comprehensive model of the Permian reefs in Ziyun County has been constructed, based on mapping and examination of the stratigraphy and paleontology of the study area.

[1]Supported by the National Natural Science Foundation of China and Director of the Institute of Geology, Academia Sinica.

INTRODUCTION

Permian reefs are widely distributed in South China, especially in the Nanpanjiang area, including southern Guizhou and northwestern Guangxi Provinces, where numerous Permian reefs occur and are well exposed (figs. 1, 2).

The Permian reefs in Ziyun County in southern Guizhou are among the best exposed and expressed reefs in the area. Three types of reefs have been identified there in Middle and Upper Permian rocks: (1) barrier reefs, (2) patch reefs, and (3) biostromes. The present paper deals with the organic and inorganic components of the reefs and development of these features.

GEOLOGICAL SETTING

Southern Guizhou Province is situated in the southern part of the Upper Yangtze Platform where Upper Paleozoic strata are moderately thick and well exposed. Luo Zhili and others (1990) observed that this region was located in a back-island arc basin or marginal sea during the Late Paleozoic. During an early episode of the Emei Taphrogenesis, extensional movements created a set of fault-controlled blocks and troughs within the platform (Luo and others 1990). It was this tectonic framework that helped control Permian paleogeographic and sedimentary environments of the Ziyun region.

Regional geological surveys note that two main kinds of sedimentary sequences accumulated from the Carboniferous through Permian time. The first of these sequences is represented by thin-bedded siliceous mudstones, chert, siliceous shale, and volcaniclastic rocks. These siliceous rocks contain an assemblage of radiolarians, siliceous sponge spicules, and ammonoids. The area (fig. 2) where this rock association is developed is usually called the "black facies region." The second kind of these sequences is composed of medium- to thick-bedded limestones that contain highly diverse biotas of corals, foraminifers (including fusulinids), brachiopods, bryozoans, sponges, calcareous algae, and echinoderms, and the area where this association is developed (fig. 2) is termed the "white facies region."

These two sedimentary sequences represent deepwater basin or trough deposits, on one hand, and shallow-water platform deposits, on the other hand (Luo and others 1990, Sha and others 1990). Permian reefs are usually developed on margins of the shallow-water carbonate platforms (fig. 2).

THE HISTORY OF INVESTIGATION OF PERMIAN REEFS IN SOUTH GUIZHOU

The first report in recent years on ancient reefs in China was an unpublished report written by He Kegan in 1963.

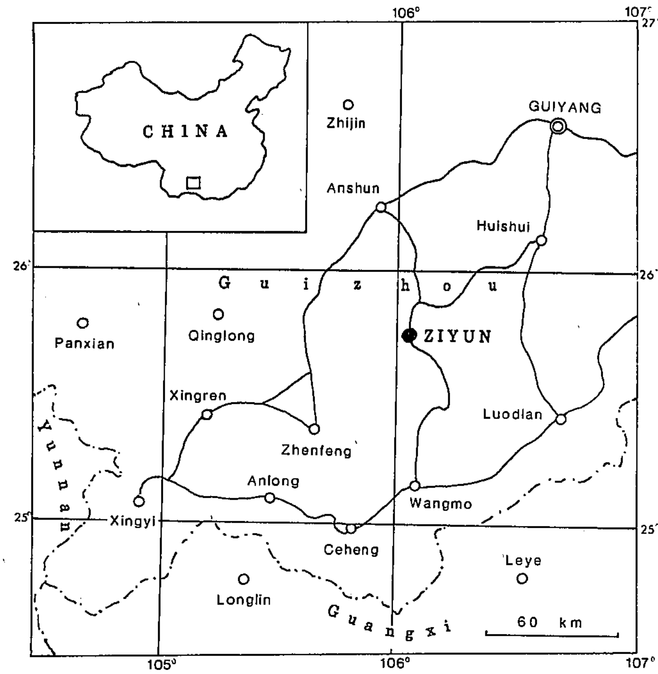


FIGURE 1.—*Index map showing the location of the study area in southwestern Guizhou Province.*

In his unpublished paper, he recognized Upper Permian reefs in Wangmo and Ceheng Counties in southern Guizhou and described the general features of rocks and the facies variation. He noted that the boundary between Upper Permian and Lower Triassic rocks is disconformable at the top of the Permian reefs. In an internal informal unpublished report written in 1973, Wang Zhihua and Zhong Youqing, of the Guizhou Petroleum Exploration and Exploitation Bureau, made a more detailed study on the Permian reefs and interpreted the relationship of reefs with petroleum potential in southern Guizhou Province. They discovered and reported additional Permian reef outcrops in this area. Liu Bingwen and Wang Zhihua wrote an unpublished internal report in 1979 about the Permian reefs exposed in southern Guizhou and dealt with organic and inorganic characters of these reefs. A comprehensive study of the Permian reefs in South China, including paleontology, stratigraphy, sedimentary facies and models, as well as a comparison with the Permian reef complex in the Guadalupe Mountains, West Texas and New Mexico, was published by Fan and others (1990). Fan and Qi (1990) published a detailed study of the Permian reefs in Longlin County, northwestern Guangxi.

All of these studies documented that the reefs in southwestern China are mainly made up of calcisponges, hydrozoans, corals, and calcareous algae. The encrusting alga(?) *Archaeolithoporella* plays an especially important role in

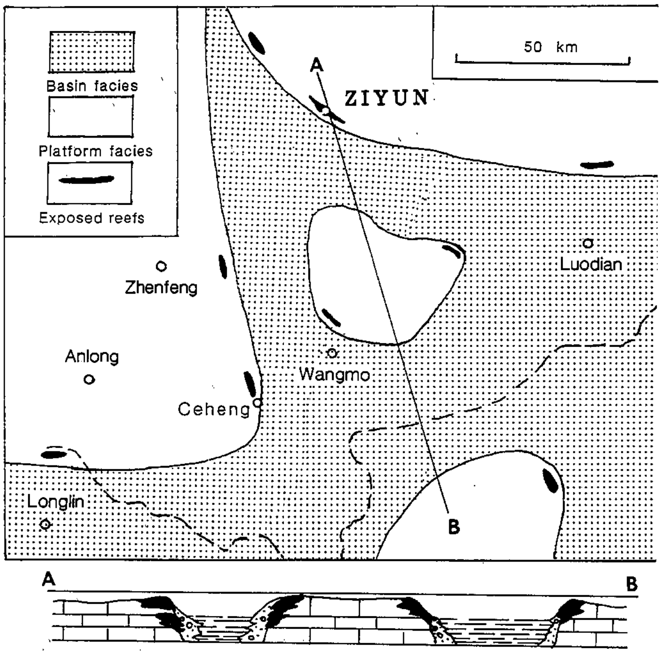


FIGURE 2.—*The distribution of the "black" or basin facies region, "white" platform facies regions, and outcrops of the Permian reefs. The cross section below shows the generalized sedimentary model of the Permian rocks of the region.*

binding the reef framework. The accessory biota that lived in the reef is an extremely diverse one.

Zhang and others (1988), in a detailed study of the Permian strata in southern Guizhou, proposed a threefold division of the Permian System in southern Guizhou. The correlation of the Permian strata in South Guizhou with other parts of the world, based largely on fusulines, and the horizons of the Permian reefs in Ziyun County is shown in figure 3. These reefs developed during the Middle Permian Maokouan stage (*Cancellina-Neoschwagerina-Yabeina* fusulinid zones) and the Upper Permian Changxingian stage (*Palaeofusulina* zone). In a few localities, such as at Laibin County, Guangxi Province (Yang 1987), and Ziyun County, Guizhou (this paper), small bioherms and biostromes were developed in the intervening Wujiapingian stage (*Codonofusiella* zone).

STRATIGRAPHY OF PERMIAN AND LOWER TRIASSIC ROCKS IN THE SUBURBS OF THE TOWN OF ZIYUN COUNTY

The town of Ziyun County is situated about 70 km south of Anshun City, a major city in western Guizhou (fig. 4). An area of 32.5 square kilometers around the town has been mapped, as part of this study, and ten stratigraphic sections were measured. The study area is located at the southern end of the Baiyan-Tianba anticline and is broken by a strike-slip fault that cuts in arcuate fashion across its southern part.

Stratigraphy of Permian and Triassic rocks was first studied in the region, in detail, by Wang and others (1959). They provided detailed descriptions of their measured sections and listed their fossils. This was of great help to our research. However, their study only dealt with the shallow-water carbonate deposits exposed in the northern part of the present study area. Some names of lithostratigraphic units that were utilized are not appropriate. For example, the lithostratigraphic unit Wujiaping Formation was used to represent limestones that contain the fusulinid zone fossil *Conodofusiella*. This apparently produces some confusion and intermixed biostratigraphic, chronostratigraphic, and lithostratigraphic units. Furthermore, the limestones included by them in the Wujiaping Formation are of different lithology than those of the type locality of the formation, the lithostratigraphic unit, in Shaanxi Province.

Some new lithostratigraphic units are proposed here to clarify stratigraphic and facies relationships within the Maokou and Mobo Formations and the new Jiyaopo Formation. They are shown in figure 5. The characteristics of these lithostratigraphic units are briefly discussed in following pages.

MIDDLE PERMIAN ROCKS

MAOKOU FORMATION

Rocks of the Middle Permian Maokou Formation are exposed in the central and northwestern part of the area and form the exposed core of the anticline. The lower boundary of this formation is not exposed, but the upper boundary is well exposed and marked by an ancient weathering crust. The formation consists of thick-bedded to massive, light-colored packstones and grainstones that contain a diverse fossil assemblage of fusulinids (figs. 6, 8.3), brachiopods, calcareous algae (fig. 7), rugose corals, and hydrozoans. The fusulinids are mainly *Neoschwagerina* (fig. 6.5), *Parafusulina, Verbeekina, Sumatrina,* and *Pseudodoliolina.* The highest fusulinid zone of *Yabeina,* which is common in South China, is absent, presumably removed by erosion. Rocks of this formation represent shallow-water carbonate deposits. The new Ziyundong and Lawang Members form the Middle Permian reef complex within the Maokou Formation as two members of this formation (fig. 5). Ziyundong rocks represent the reef-core facies, and Lawang beds the reef slope facies.

Ziyundong Member

Exposures of the Ziyundong Member occur on the southwestern flank, at Ziyundong, and on the southeastern

SERIES	FUSULINID ZONES	STRATIGRAPHIC CORRELATIONS			PERMIAN REEFS IN ZIYUN	
		South Guizhou	Russia	North America	Duration	Types
UPPER PERMIAN	*Palaeofusulina*	Chaingxingian	Tatarian	Ochoan		Barrier and patch reefs
	Codonofusiella	Wujiapingian	Kazanian			Biostromes
MIDDLE PERMIAN	*Neomisellina* *Yabeina* *Neoschwagerina* *Cancellina*	Maokouan	Ufimian	Guadalupian		Barrier reefs
	Armenia *Misellina*	Qixian				
LOWER PERMIAN	*Chalaroschwagerina* *Pamirana* *Staffella*	Yangchangian	Kungurian	Leonardian		
			Artinskian			
	Sphaeroschwagerina *Pseudoschwagerina uddeni*	Zisongian	Sakmarian Asselian	Wolfcampian		

FIGURE 3.—*Subdivision of the Permian system in southern Guizhou and correlation with the Permian in Russia and North America. The duration and types of Permian reefs in the Ziyun area are shown in columns on the right. The subdivision and correlation of the Chinese Permian are mainly based on Zhang Zhenghua and others (1988).*

flank of the anticline. Outcrops of the member have been mapped at the small village of Qincaiyuan (fig. 4), in the suburbs of Ziyun, and on small hills named Guanyinshan and Yinshan in the town. These outcrops are made up of reefal limestones and will be described below in detail. A fusulinid assemblage of *Neoschwagerina* and *Verbeekina* was found in the member. This member was erroneously correlated with the uppermost Permian reefs by Lin (1992).

Lawang Member

The Lawang Member is exposed on the southwestern flank of the anticline and in the southwestern part of the map area, south of the fault (fig. 4). The member is composed of fragments of reef rock and fragments of sponges and hydrozoans. Graded bedding is locally developed. *Neoschwagerina, Parafusulina,* and *Verbeekina* are common fossils in this member, which represents foreslope facies of the Middle Permian reef complex.

WULIBEI LIMESTONE

The Wulibei Formation (fig. 5) is exposed in the southwesternmost part of the map area, south of the fault, and at the foot of a hill named Wufengshan (fig. 4), west of the town of Ziyun. The Middle Permian formation is composed of thin- to medium-bedded, black to dark gray, micritic limestones intercalated with chert beds and nodules. Breccias of bioclastic limestone and graded bioclastic packstones locally occur in the formation. *Neoschwagerina, Sumatrina, Parafusulina,* and *Pseudodoliolina* have been found in this unit. This formation represents basin or trough deposits of Middle Permian age equivalent to the Maokou Formation and, in part, to the Maokou reef complex.

UPPER PERMIAN ROCKS

JIYAOPO FORMATION

This newly established Wujiapingian lithostratigraphic unit is exposed on the northeastern flank of the anticline (figs. 4, 5). The formation is composed of gray, medium- to thick-bedded packstones and grainstones (fig. 9.1) and contains a diverse assemblage of foraminifers, bryozoans, calcareous algae, tabulate corals, and sponges. A number of biostromes composed of corals occur in the formation (figs. 9.2, 10). Fusulinids found in the unit include *Codonofusiella* (fig. 6.2) and *Reichelina*. Several thin-bedded mudstones are intercalated in the lower part. The lower boundary is defined in the northern part of the map area by an ancient weathering crust (fig. 5). The crystalline dolomite Qincaiyuan Member has a thickness of about 40 m and occurs in the lowermost part of the formation at Qincaiyuan, the type locality. An undulatory paleokarst separates the dolomite from the underlying reef rocks (fig. 8.1). The formation is covered by a 1-m-thick silty mudstone that contains "condensed beds" of the brachiopod *Squamularia* (fig. 9.6) and dendroid burrows (fig. 9.5). Wang and others (1959) noted that this bed extends some distance toward the north, thickens to more than 20 m, and was there called the "Ganqiao Sandstone." These deposits contain chlorite, altered biotite, and other dark minerals and is probably of volcanic origin.

MOBO FORMATION

The Changxingian Mobo Formation, originally called the "Mobo Limestone" by Wang and others (1959), is exposed in the northeastern part of the study area. In the area north of Huadizai (fig. 4), it consists of dark gray wackestones interbedded with layered and nodular cherts. These represent shallow-water carbonate platform deposits. The biota of the unit consists mainly of foraminifers and calcareous algae. Nodular and bedded cherts are common. The Monan, Shitouzai, and Gengdan Members are the three new members of this formation (fig. 5). Together they form the Changxingian reef complex located at the margin of the carbonate platform, and with contemporaneous reefs in Hubei Province are among the youngest Paleozoic reefs known. These three members of the Mobo Formation are briefly described below.

Monan Member

The Monan Member is exposed in the northeastern part of the study area. The member is made of thick-bedded to massive, light-colored packstone and grainstone. North of the small village of Monan, this member is partly or completely dolomitized. The member has a very diverse assemblage of foraminifers, brachiopods, calcareous algae (fig. 7), crinoids, sponges, and some problematic fossils. *Codonofusiella* is common in the lower part, and *Palaeofusulina* and *Nankinella* (fig. 6.7) are abundant in the middle and upper parts of the member. The Monan Limestone is viewed as deposited in back-reef bioclastic sand shoals.

Shitouzai Member

This member is exposed near the villages of Tanluzai and Shitouzai, north of the fault, and near Daditou, Qingcaichong, south of the fault. The member makes up the reef-core facies of the uppermost Permian reef complex. *Palaeofusulina* is common in these rocks, and *Parareichelina* has also been found (fig. 6.4).

Gengdan Member

This member crops out in the south, near the village of Gengdan, and is composed of fragments of reef rocks, fragments of reef-building organisms including sponges, hydrozoans, and pieces of calcareous algae, plus foraminifers, brachiopods, and problematic microfossils. *Codonofusiella* (fig. 6.1) is abundant in the lower part, and *Colaniella* and *Palaeofusulina* (figs. 6.6, 6.8) are found in middle and upper parts. The member is capped by a 2-m-thick, laminated, microcrystalline dolomite in the map area.

LINGHAO FORMATION

The Linghao Formation (fig. 5) includes basin facies equivalent to the Wujiapingian and Changxingian reef and platform deposits widely exposed in southern Guizhou and northern Guangxi. The Linghao Formation crops out in the southwestern and southern parts (fig. 4) of the study area. The formation is composed of variegated laminated tuffs and thin-bedded, black, siliceous rocks that contain common sponge spicules (fig. 9.10). Intercalated bioclastic limestones that contain the fusulinid *Codonofusiella* (figs. 6.3, 9.9) are found in Liaoqing and Ziyundong. The formation represents trough or basin deposits, in part equivalent to the Mobo Formation (fig. 5), but includes all Upper Permian basin deposits of the area.

TRIASSIC ROCKS

LUOLOU FORMATION

The Luolou Formation was proposed by Wang and others (1959) for exposures in Ziyun County. It is composed of thin- to medium-bedded, gray, micritic limestones that are intercalated with shales. This formation is absent at Tanluzai, but it appears south of the village and thickens toward the south. Between the village of Tunshang and Tanluzai (fig. 4), this formation grades to laminated micritic dolomite beds that are intensively brecciated in some places. A wedge-shaped deposit of conglomerate made of flat pebbles of gray micritic limestones is exposed in the north. The conglomerate is intercalated with micritic dolomite and shell beds that yield the bivalves *Claraia aurita* (fig. 6.9) and ammonoids (fig. 6.10), which indicate an Upper Griesbachian to Dienerian Lower Triassic age. In the south, near Gengdan, a 2-m-thick, deformed, laminated dolomite is exposed. It is intercalated with shell beds, similar to those exposed in the north. Also, conglomerates up to several meters thick are intercalated within the Luolou Formation, south of Gengdan.

THE PERMIAN REEFS IN ZIYUN

Permian reefs exposed in the suburbs of the town of Ziyun include two horizons, a lower one that is of Middle Permian Maokouan stage, and an upper one of uppermost Permian Changxingian stage (figs. 3, 5). A middle biohermal horizon of Upper Permian Wujiapingian stage occurs in the Jiyaopo Formation (fig. 5).

Ten stratigraphic sections have been measured in order to document facies variation and to reconstruct depositional models for the reefs.

MIDDLE PERMIAN BARRIER REEF OF THE MAOKOUAN STAGE

DISTRIBUTION

Middle Permian barrier reefs of the Maokouan stage have a northwest–southeast trend through the Ziyun area. Sporadic outcrops occur at the villages of Qincaiyuan, Guanyinshan, and Yinshan in the town, and at a quarry near Ziyundong, 2 km to the southwest (fig. 4). Because of karst topography and burial by rocks within the quarry, no complete section can be measured. Only two incomplete sections have been measured. One is on the southeast flank of the Baiyan-Tianba anticline in Qincaiyuan (fig. 4) and includes the uppermost part of the reef-core facies; the other is in Wulibei (fig. 4) and is in basin facies. A synthetic sequence was developed by combining observations at several localities (fig. 10).

FACIES

Reef-Core Facies

Outcrops of the reef-core facies, the Ziyundong Limestone (fig. 5), are scattered in Qincaiyuan, Guanyinshan, and Yinshan (figs. 4, 11). Three types of rocks can be distinguished, using the classification of carbonate rocks proposed by Embry and Klovan (1971). Bafflestones were locally produced by a few sponges and hydrozoans. These coarser fossils are scattered in fine-grained bioclastic and lime mud matrix. Some of these sponges and hydrozoans occur in upright position, but many are overturned. This facies forms a dominant part of the reef-core facies.

Framestones were produced where frame-building organisms, including calcisponges, bryozoans, and *Tubiphytes,* were encrusted by the alga (?)*Archaeolithoporella.* Peloidal grains and fibrous cements are common within the framework (fig. 8.4). Framestones form only a subordinate part of the reef-core facies.

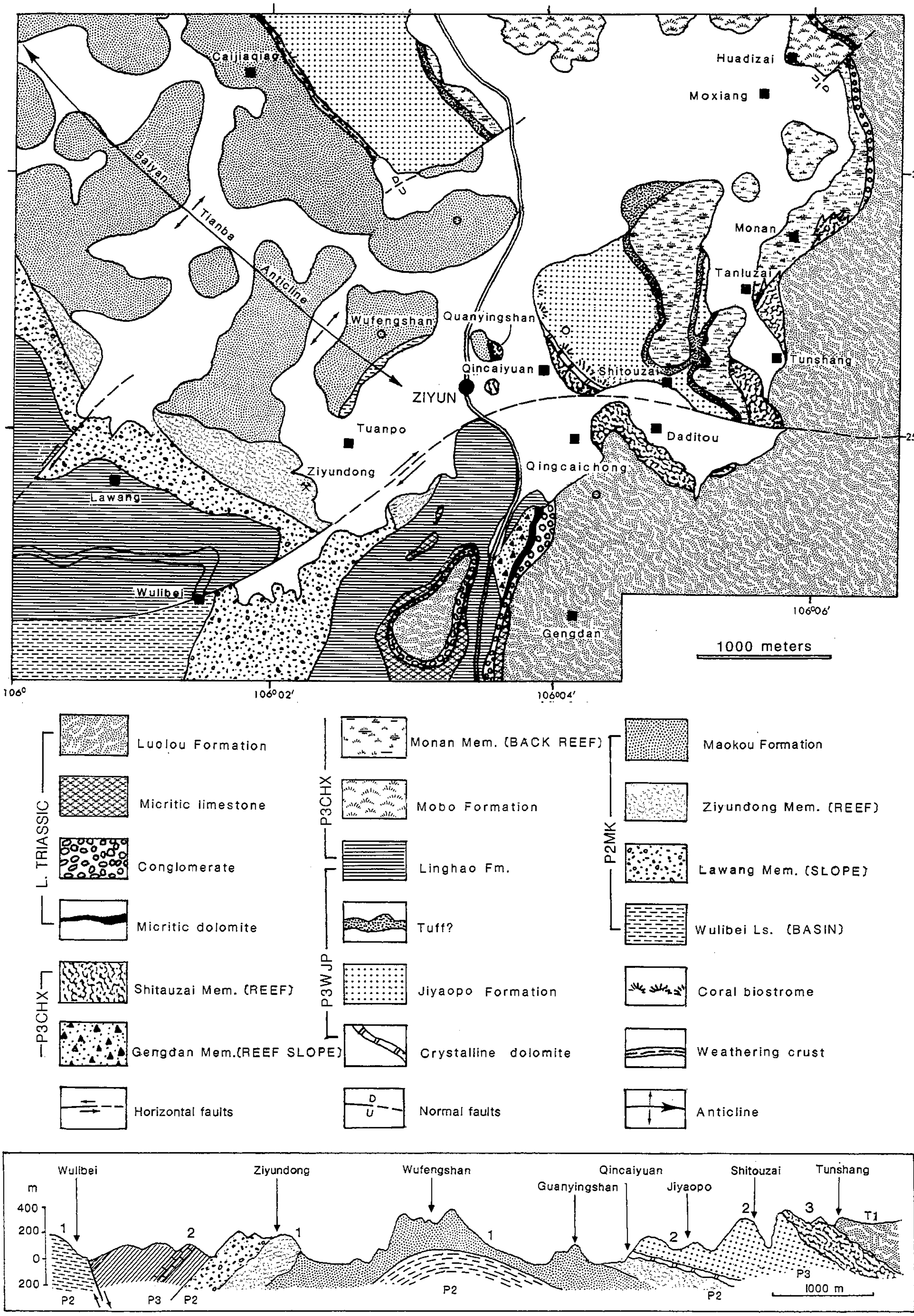
In many areas framestones were broken into angular fragments to form breccias of the rudstone facies. Radiaxial calcite cements are abundant and are impregnated by hydrocarbons (fig. 8.2). The angular, locally derived fragments of the breccias imply that they were broken essentially in situ. Rudstone is the dominant rock type in the reef-core facies.

Reef Slope Facies

Outcrops of slope facies occur in the southwestern part of the map area (fig. 4) and are here included in the Lawang Limestone (fig. 5). Three types of rocks occur in this facies.

Conglomerate beds occur intercalated with other rock types throughout the formation. The fragments are poorly sorted and commonly contact each other at stylolites (fig. 8.5). Matrix is not abundant. The fragments are mainly bioclastic wackestones and packstones. They may represent upper collapsed masses and coarse upper or proximal ends of debris flows.

FIGURE 4.—A, *Geological map of the region around the town of Ziyun County. B, Cross section shows relationships parallel to the trend of the fault trace; occurrences of 1,* Neoschwagerina, *2,* Codonofusiella, *and 3,* Palaeofusulina *are shown diagrammatically.*


Caijiaqiao
Huadizai
Moxiang
Baiyan
Tianba
Anticline
25°52′
Monan
Tanluzai
Wufengshan
Quanyingshan
Qincaiyuan
Shitouzai
Tunshang
ZIYUN
Tuanpo
Daditou
25°50′
Ziyundong
Qingcaichong
Lawang
Wulibei
Gengdan
106°06′
1000 meters
106°
106°02′
106°04′
L. TRIASSIC
Luolou Formation
Micritic limestone
Conglomerate
Micritic dolomite
P3CHX
Shitauzai Mem. (REEF)
Gengdan Mem.(REEF SLOPE)
Horizontal faults
P3CHX
Monan Mem. (BACK REEF)
Mobo Formation
Linghao Fm.
P3WJP
Tuff?
Jiyaopo Formation
Crystalline dolomite
D
U
Normal faults
P2MK
Maokou Formation
Ziyundong Mem. (REEF)
Lawang Mem. (SLOPE)
Wulibei Ls. (BASIN)
Coral biostrome
Weathering crust
Anticline
Wulibei
Ziyundong
Wufengshan
Qincaiyuan
Guanyingshan
Jiyaopo
Shitouzai
Tunshang
m
400
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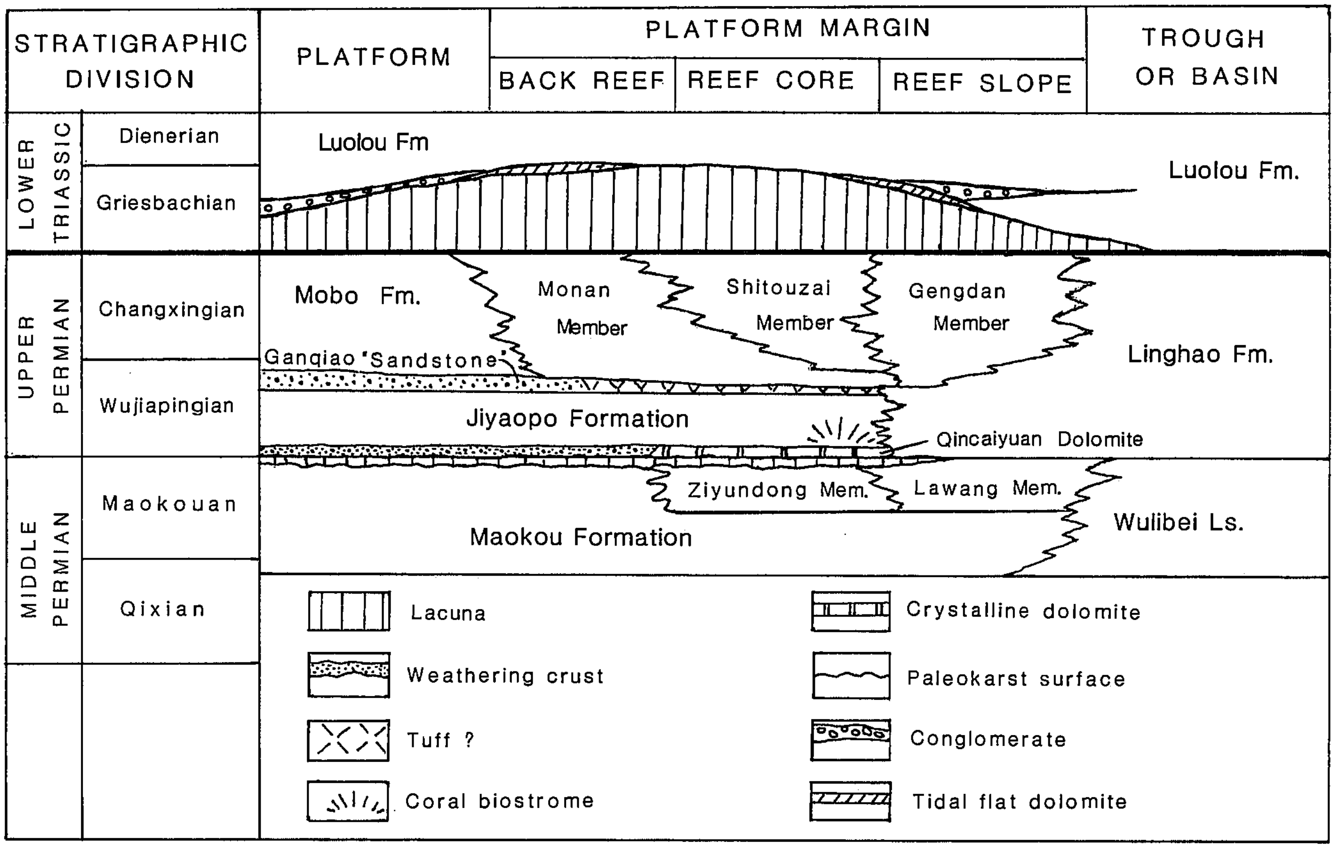


FIGURE 5.—*Diagram showing correlation of stratigraphic units in the Ziyun area.*

Rudstones and floatstones of the facies consist of breccias and coarse bioclastic units. Bioclasts include mainly sponges and hydrozoans. Graded bedding is common (fig. 8.6). These rocks represent middle and lower or distal ends of debris-flow deposits.

Wackestone and packstone are somewhat finer grained and are composed of bioclasts and lime muds. They are generally medium- to thick-bedded and light gray. These types of rocks make up the predominant part of the slope facies.

Back-Reef Carbonate Shoal Facies

This facies is widely distributed in the core of the Baiyan-Tianba anticline (fig. 4) and comprises most of the Maokou Formation. Fossils of the facies are mainly abundant fusulinids (50%–80%). Other minor microfossils and bioclasts include smaller foraminifers, calcareous algae, crinoids debris, and brachiopods, with gastropod fragments. These facies served as the base for the overlying Changxingian Shitouzai reef-core facies (fig. 5), as well as the back-reef clastic sand deposits of the Monan Limestone (fig. 8.3).

Basin Facies

Basin facies rocks of the Maokou deposits are exposed in the southwestern part of the area (fig. 4) and are included in the Wulibei Limestone (fig. 5). This facies is composed mainly of thin- to medium-bedded, black lime mudstones and intercalated chert beds and nodular chert units. This lime mudstone contains only calcispheres as common fossils (fig. 8.7). Other fossils are rare. Several intercalated beds of bioclastic packstone and fusulinid packstone occur in the facies. Some of the fusulinids were deformed (fig. 8.8). Underlying rocks were fractured during Wulibei deposition, and these cracks were filled by breccias and bioclasts.

DEVELOPMENT OF MIDDLE PERMIAN REEFS IN THE ZIYUN AREA

Middle Permian reefs of the Ziyun area developed at the edge of a carbonate platform adjacent to the Ziyun trough (Sha and others 1990). Reconstruction of the reefs shows relationship of the facies and the depositional model for accumulation of the Maokouan rocks of the area (fig. 12).

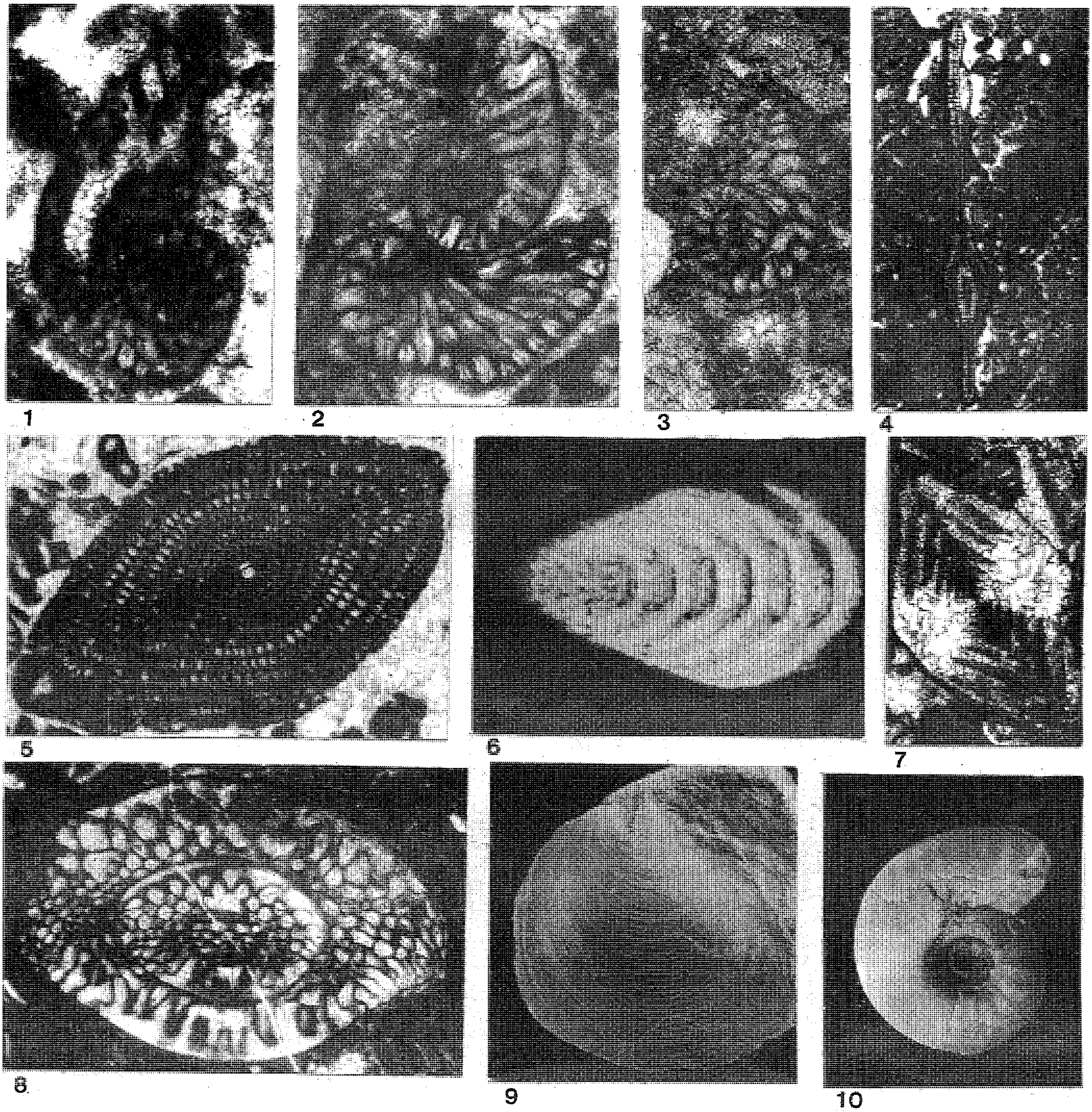


FIGURE 6.—1–3, Codonofusiella; 1, *GD4-3, Gengdan Member, Mobo Formation X60;* 2, *QCY-8, Jiyaopo Formation, X36;* 3, *ZY4-1, Linghao Formation, X60.* 4, Parareichelina, *STZ23-2(A), Shitouzai Member, Mobo Formation, X16.* 5, Neoschwagerina, *GYS-1, Maokou Formation, X16.* 6, Colaniella, *QCC-2, Gengdan Member, Mobo Formation, X23.* 7, Nankinella, *TLZS1-1, Monan Member, Mobo Formation, X24.* 8, Palaeofusulina, *QCC6-2, Gengdan Member, Mobo Formation, X24.* 9, Claraia aurita, *Luolou Formation, X1.* 10, *Ammonoid, Luolou Formation, X1.*

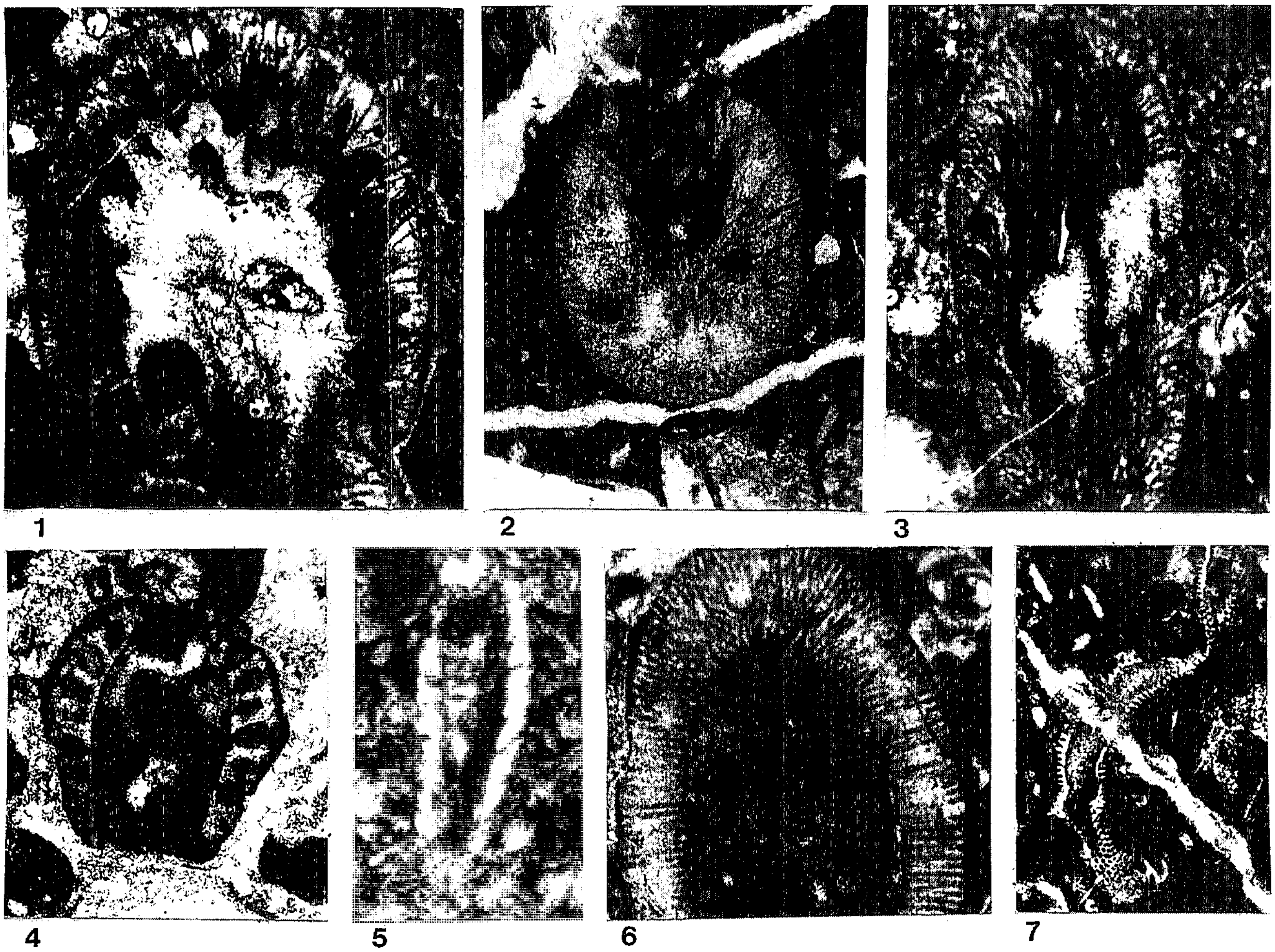
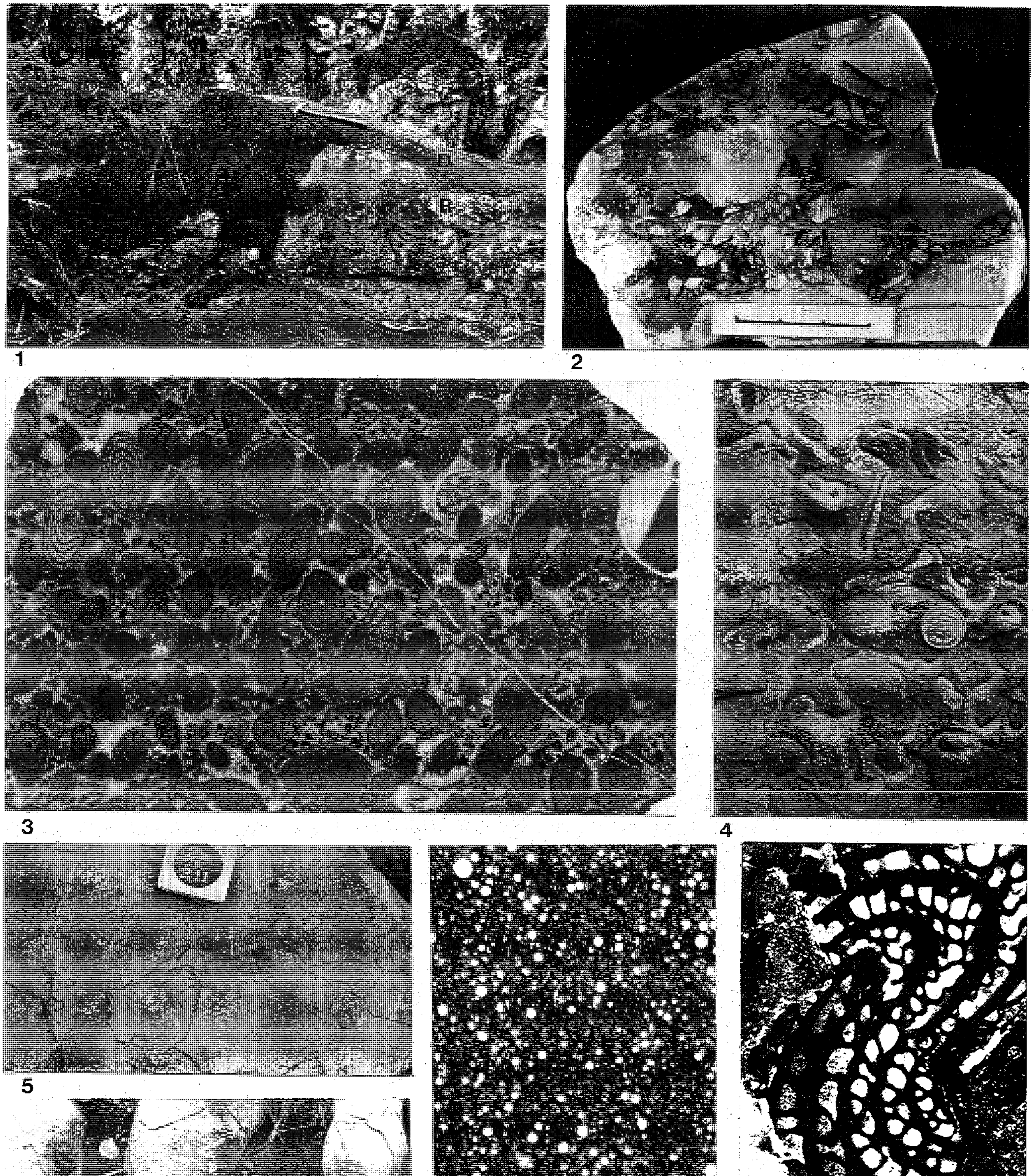


FIGURE 7.—*Photomicrographs of calcareous algae. All but five are from the Mobo Formation.* 1–3, Permocalculus; 1, *STZ14-1;* 2, *STZ3-1; 3, STZ14-1, Shitouzai Member, all X16.* 4, Mizzia, *GD5-1, Gengdan Member, X24.* 5, Gymnocodium, *QCY9-1, Jiyaopo Formation, X24.* 6, Anthroporella, *GD9-4, Gengdan Member, X16.* 7, Pseudovermiporella, *TLZS1-1, Shitouzai Member, X16.*

FIGURE 8.—1, *Paleokarst surface atop the Ziyundong Member of the Maokou Formation. The reef limestone (R) was capped by crystalline dolomite (D). The boundary is irregular.* 2, *Rudstone consists of unsorted fragments of framestone cemented by radiaxial fibrous calcite cement, Ziyundong Member, scale bar in centimeters.* 3, *Fusulinid grainstone of Maokou Formation with geopetal structure on right parallel to elongations of fusulines, thin section, GYS-10, X1.5.* 4, *Framestone consists of branching sponges and* Archaeolithoporella *crusts. Radiaxial fibrous calcite cements are extensively developed, Ziyundong Member.* 5, *Conglomerate with stylolitic boundaries between fragments, Lawang Member, 5-cm-wide ruler case for scale.* 6, *Graded bedding in rudstone exposed on promontories of the Lawang Member, between darker, soft, terra rosa areas.* 7, *Wackestone consists mainly of calcispheres floating in lime mud matrix, photomicrograph, WLB-3, Wulibei Limestone, X24.* 8, *Fractured fusulinid* Parafusulina, *photomicrograph, Wulibei Limestone, X16.*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The reefs developed upward from a base on a fusulinid shoal. Rapid growth of the reefs led to facies differentiation during their development. In late Maokouan time, the reefs and the carbonate platform upon which they were built were uplifted. A paleokarst surface developed on the top of the reefs, and a weathering crust formed on the top of the back-reef carbonate platform deposits (figs. 5, 12).

UPPER PERMIAN CORAL BIOSTROMES OF THE WUJIAPINGIAN STAGE

Five coral biostromes have been found in the Jiyaopo Formation (fig. 10). Excellent exposures are located near the village of Qincaiyuan (fig. 4). The biostromes are traceable laterally for several tens of meters and maintain relatively uniform thicknesses.

Four of the biostromes are made up of the dendroid rugose coral *Pseudohuangia* (figs. 9.3, 9.4), which forms fan-shaped patches with radii of up to 50 cm (fig. 9.2). The patches are closely spaced to form coral thickets 0.5–1.5 m thick. Because of compaction by overlying deposits, some of these coral patches deformed and collapsed. Spaces between the branched corals were filled by bioclasts and lime muds. Only one biostrome in the measured section (fig. 10) consists of the massive coral *Ipciphyllum* (figs. 9.7, 9.8). That biostrome has a thickness of 50 cm. However, sparsely distributed patches of this massive coral commonly occur in the formation. Some of the coral biostromes are associated with bafflestones made mainly of small calcisponges, such as *Sollasia* and *Peronidella.*

The accompanying biota is highly diverse and includes foraminifers, crinoids, various calcareous algae, brachiopods, gastropods, and ostracods. The predominant fusulinid is *Codonofusiella,* although *Reichelina* is also common. The biota and rocks of the Jiyaopo Formation represent a shallow-water carbonate platform environment.

UPPER PERMIAN REEFS OF THE CHANGXINGIAN STAGE

DISTRIBUTION

Outcrops of the uppermost Permian reefs were mapped in and near the villages of Monan, Tanluzai, Tunshang, Shitouzai, Qingcaichong (fig. 4), and northwest of Gengdan, on the eastern flank and nose of the Baiyan-Tianba anticline (fig. 4). Seven stratigraphic sections (fig. 13) of these rocks were measured in order to document facies variation and obtain information about organic and inorganic characteristics of the reef complex (fig. 4).

From Huadizai, in the northeastern corner of the investigated area, to Gengdan, in the south, within about 6 km along the outcrop belt, facies of restricted platform, back-reef sand, reef-core, fore-reef slope, and deepwater trough environments are exposed (fig. 4).

FACIES

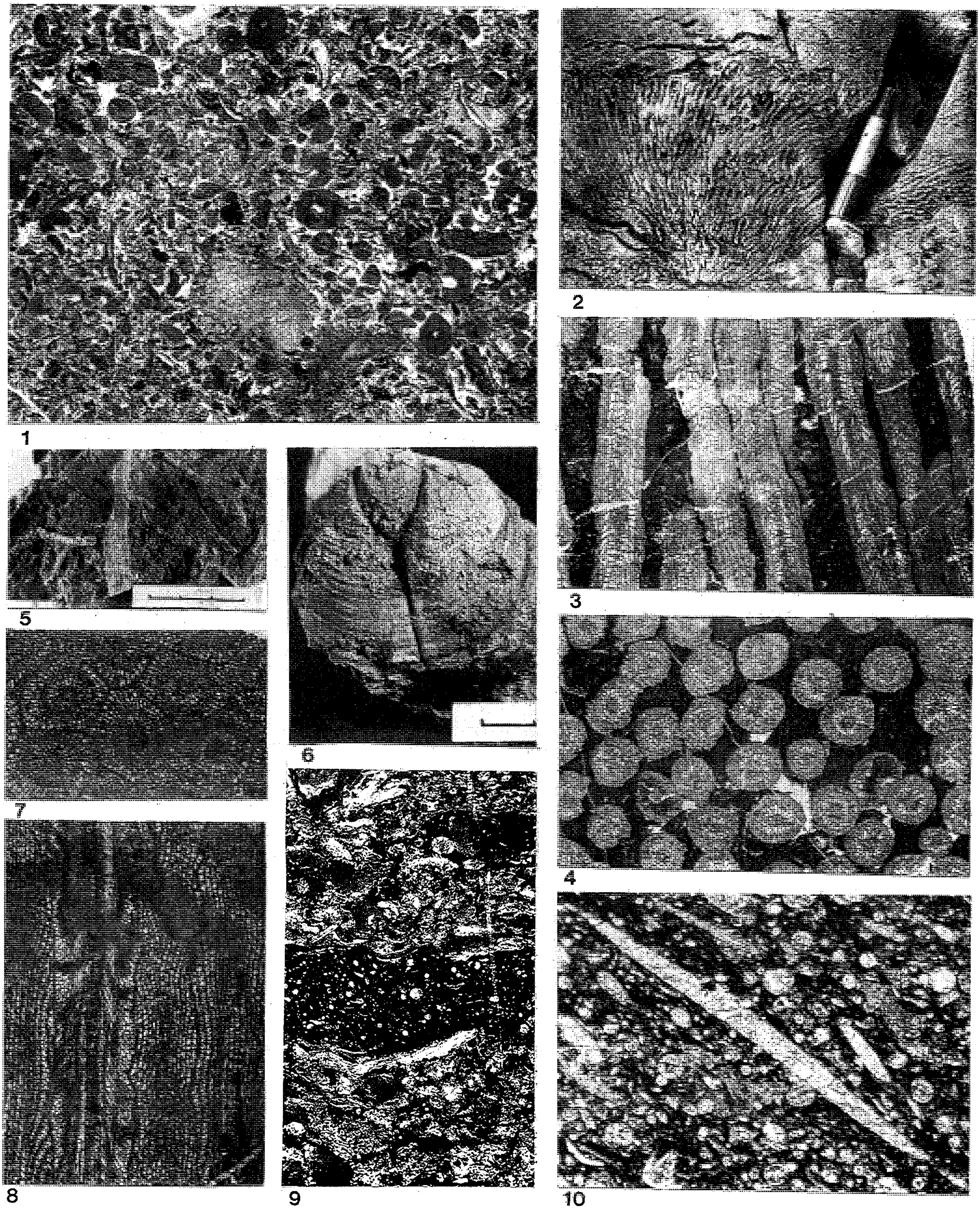
Reef-Core Facies

Reef-core facies is differentiated as the Shitouzai Limestone (figs. 5, 13), which crops out in or near Shitouzai, Tañluzai, Tunshang, Daditou, and Qingcaichong (fig. 4). It includes several rock types.

Framestones of the facies are composed of frame-building and binding organisms and have biotas like other Permian reefs of Guizhou and Guangxi Provinces, as discussed in papers cited below. Submarine cements of various types are abundant in these rocks. Frame-building organisms include mainly calcisponges and hydrozoans. *Tubiphytes* is also abundant as a binder.

The calcisponges include sphinctozoans, inozoans, and tabulozoans (sclerosponges). Most of the sphinctozoan sponges are delicate, and their structures are obscure because of recrystallization and dissolution. Only large individuals are well preserved. Most of the common

FIGURE 9.—1, *Bioclastic grainstone, thin section, QCY12-2, Jiyaopo Formation, X1.5.* 2, *A patch or head of the rugose coral* Pseudohuangia *in a coral biostrome, Jiyaopo Formation, marking pen for scale.* 3, 4, *Longitudinal and transverse sections of* Pseudohuangia. *Thin sections, QCY12-4A and QCY12-4B, Jiyaopo Formation, X1.5.* 5, *Dendroid burrows, Ganqiao "Sandstone," scale bar in centimeters.* 6, *Steinkern of the brachiopod* Squamularia, *Ganqiao "Sandstone," Shitouzai, scale bar in centimeters.* 7, 8, *Transverse and longitudinal sections of* Ipciphyllum, *QCY11-3A, B, Jiyaopo Formation, X1.5.* 9, *Bioclastic packstone with interbedded layer of spiculitic radiolarian wackestone, photomicrograph, ZY2-1, Linghao Formation, X16.* 10, *Calcified sponge spicules and radiolarians(?), photomicrograph, ZY2-2, Linghao Formation, X23.*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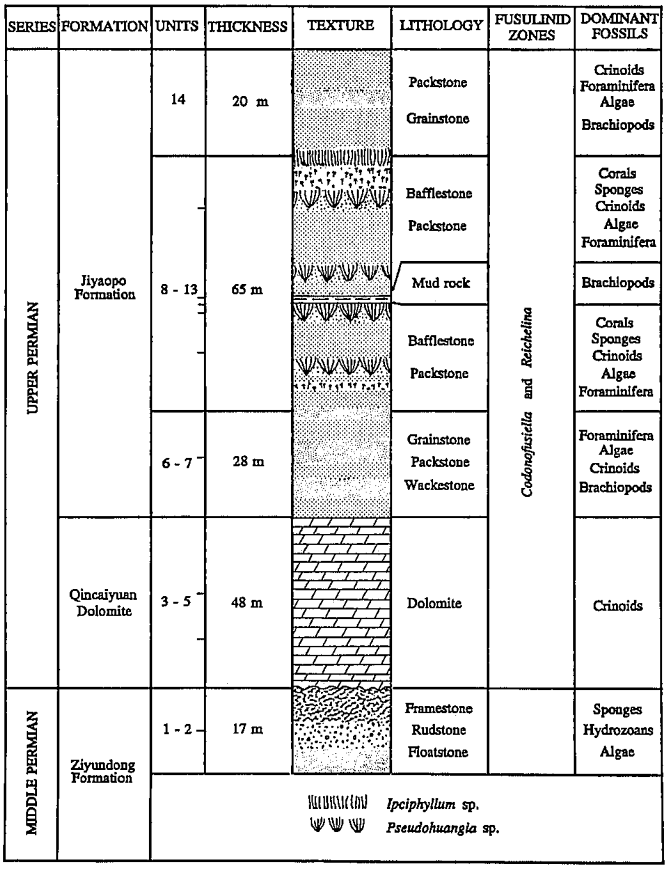


FIGURE 10.—*Composite stratigraphic section of the lower part of the Jiyaopo Formation Qincaiyuan Dolomite and upper part of the Ziyundong Formation. The irregular line near the base indicates a paleokarst surface separating the two latter formations. Coral biostromes are shown in the upper part of the section.*

genera are those previously reported from southwestern China by Fan and Zhang (1985), Fan and others (1987), and Rigby and others (1989a, 1989b). These include sponges such as *Amblysiphonella* (fig. 14.7), *Intrasporeocoelia* (fig. 14.8, 15.1), *Glomocystocoelia* (fig. 14.5), and *Sollasia.* Some new taxa have been discovered as part of this study, including a large sphinctozoan sponge (figs. 14.2, 14.3, 14.6), and these are being studied and will be described in a separate paper.

Inozoan sponges are small dendroid species (fig. 14.4). Most of their structures have been destroyed in extensive recrystallization and dissolution. Relicts of the cerebrum-shaped structure indicate that most of these inozoan sponges belong to the genus *Peronidella.* Large columnar to massive forms, mainly *Stellispongia,* are also common.

Tabulozoan sponges are common in the framestone, especially in the leeward part of the framestone facies. The shapes of tabulozoan sponges are robust columnar to massive (fig. 15.2).

The hydrozoans(?) include the widely distributed common genus *Disjectopora* (fig. 15.3), the platy dubious hydrozoan *Pseudopalaeoaplysina* Fan, Rigby, and Zhang (1991) (fig. 15.5), and an undescribed form called *Phragmorpha* by Wang and others in an unpublished manuscript (fig. 15.4).

Tubiphytes (fig. 15.7) is quite abundant in the Ziyun reefs. Its affinity has long been controversial, and it has been included among the blue-green algae, foraminifers, hydrozoans, Problematica, and sponges by various workers (see Riding and Guo 1992). Well-preserved specimens from the Ziyun reefs will provide valuable additional information about its structure. A variety of types of central tube systems and a meshwork comparable to spongin networks in modern demosponges suggest that *Tubiphytes* may belong to the demosponges. A detailed study of *Tubiphytes* is underway.

Tubiphytes acted as a binding agent in the reef framework. However, its binding function is limited, and, in fact, it also served as a minor frame-builder in the Permian reefs in South China.

Binding organisms play a major role in reef fabrics of the region, as in modern reefs, but they are not taxonomically diverse. *Archaeolithoporella* crusts (fig. 15.6) are extremely abundant in framestones of the facies and locally attain thicknesses exceeding 5 mm. They make up 10%–30% of volume of the framestones. *Archaeolithoporella* is very important and helped the delicate sponges to form rigid wave-resistant frameworks. Without its participation the framestone could not have formed.

To date there is no unanimous opinion about the affinity of *Archaeolithoporella.* Finding relicts of vertical partitions in the layers imply the existence of a cellular structure, and the existence of some types of voids in specimens from the Ziyun reefs strongly supports Endo's (1959) conclusion that *Archaeolithoporella* has a coralline red algal affinity. Nature of its structure and relationships are subjects of a paper to be published separately.

Five kinds of submarine cement have been recognized in the Ziyun reefs. Micritic peloid calcite cement crusts locally form columns imitating the morphology of stromatolites (fig. 16.3) and laminated crusts (fig. 16.7).

Micritic calcite cements consist of peloids (fig. 16.2), and a dentate halo often occurs around the peloids (fig. 16.6). A few bioclasts, such as sponge spicules, foraminifers, crinoids, and ostracods, were trapped in the peloidal crusts. Fragments of the peloidal crusts are common in reef-core facies and fore-reef talus (fig. 16.4).

Peloidal micritic calcite crusts are extensively developed in modern reefs, such as in Panama (MacIntyre 1977), Great Barrier Reefs in Australia (Marshall 1986), Caribbean reefs (Lighty 1985), Miocene reefs in Spain (Riding and others 1991), and Jurassic reefs in Britain

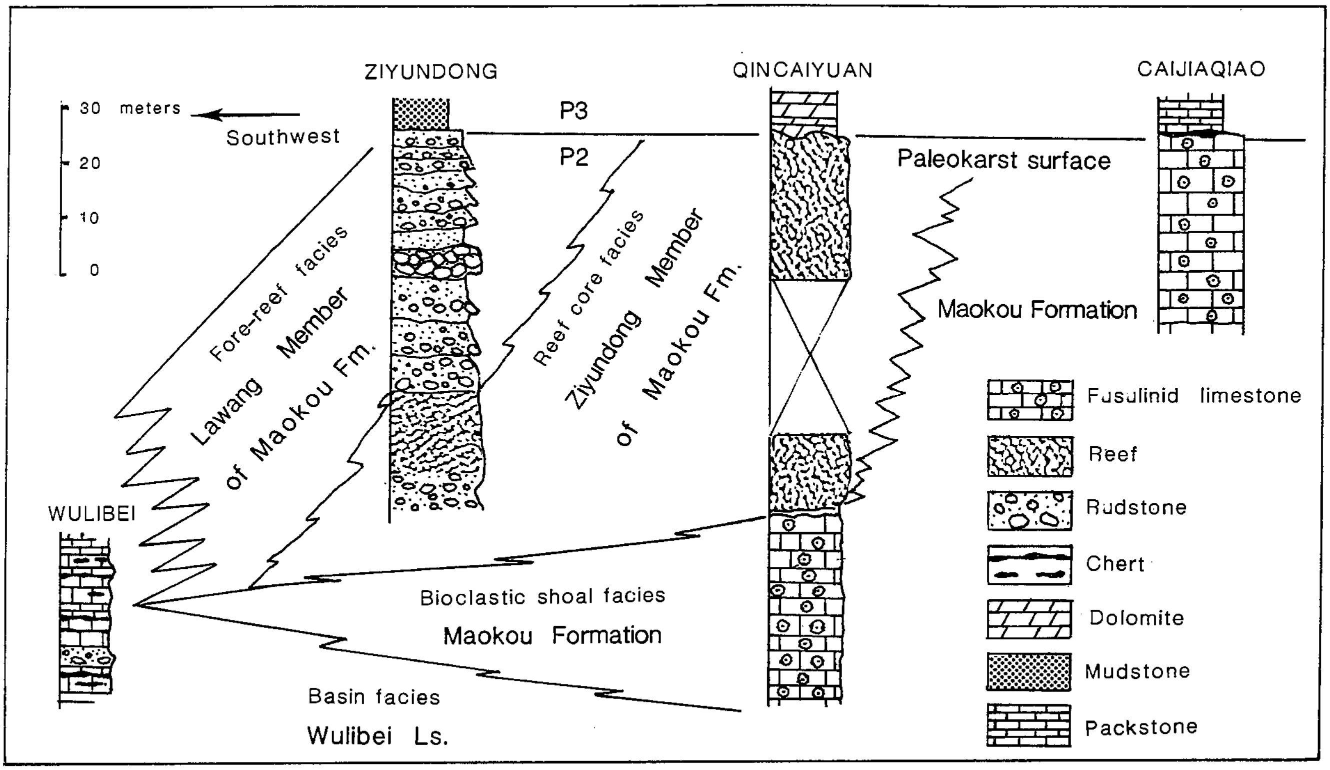


FIGURE 11.—*Measured stratigraphic sections showing facies and lithostratigraphic units of the Maokouan reef complex near Ziyun.*

(Sun and Wright 1989). These micritic calcites are, without exception, magnesium calcites, mineralogically. This also may have been true of the micritic crusts in the Permian reefs.

Two main origins have been proposed for these types of cements. MacIntyre (1977) proposed an inorganic origin for the peloids, based on their bimodal size distribution, and he also emphasized their multiple nucleation. Riding and others (1991) studied micritic calcite crusts in Miocene reefs in Spain and proposed a cyanobacterial origin because of their domal and columnar morphologies, which are comparable with stromatolites. Guo and Riding (1992) documented and identified three types of micritic crusts in the Permian reefs of South China. Based on a comparison with bacterial deposits in Recent travertines, they concluded that the Permian peloidal micritic crusts might be of bacterial origin.

Sun and Wright (1989) studied the peloidal crusts in Jurassic coral bioherms of Britain and concluded that the columns made up of peloidal micritic calcites exhibit both organic and inorganic characteristics.

Because the peloidal crusts consistently appear to be the earliest stage of cementation, even prior to encrustation by the alga *Archaeolithoporella,* and because the crusts directly attach to frame-building organisms, they act as cements rather than internal deposits. Columnar forms are quite common in the Ziyun reefs and, thus, might be relicts of bacterial assemblages.

It must be noted that peloids in the Ziyun reefs locally take the place of frame-builders, and many have spicule-like objects in them (fig. 16.5). This implies that the peloids may have connections with decay of frame-building organisms without well-preserved skeletons. Fragments of peloid cement are abundant, both in reef-core facies and fore-reef talus, which implies that peloidal micritic cements lithified early and occur in great quantity.

Acicular calcite cements in the Ziyun reefs consistently appear as thin rims or laminated crusts around frame pores and occupy intraorganism pores (figs. 17.1, 17.2). Tops of the rims are smooth, and the rims thicken into the concave parts of the substrate. Crystals of acicular cements form straight boundaries where they meet. Acicular calcite cements may have been originally aragonite but became calcite through early recrystallization. In many cases recrystallization has changed the acicular crystals to bladed crystals, but their tops still remained flat (fig. 17.2).

Acicular or bladed calcite cements usually occupy only a small part of the frame pores. The remaining space may be filled by radiaxial calcite cement and blocky calcite

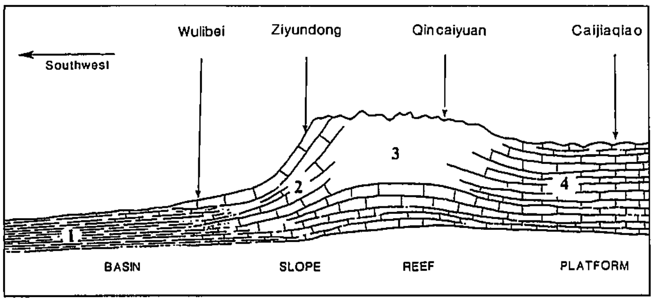


FIGURE 12.—*Generalized and restored cross section of the Middle Permian Maokouan reef complex, not to scale. 1, Wulibei Limestone and members of the Maokou Formation, including the 2, Lawang Member; 3, Ziyundong Member; and 4, a fusulinid platform limestone of the Maokou Formation.*

(figs. 18.1, 18.2) or internal bioclastic deposits (fig. 17.2). Acicular calcite cements are frequently intergrown with laminae of *Archaeolithoporella* (fig. 17.4). Fragments with acicular cements are common. These facts suggest that acicular or blade calcite cements are syndepositional in origin, like in modern reefs.

Botryoidal calcite cements are common in the Ziyun reefs (fig. 17.3) and are characterized by radially arranged elongate crystals, several millimeters to several centimeters long. Botryoidal cements are usually found in framestones where primary cavities are well developed. In many cases the crystals were changed to calcite mosaics by recrystallization, but ghosts of the radial crystals have been locally preserved.

Locally botryoidal calcite cement developed on a base of acicular calcite cement in some cavities. Elsewhere they attached directly to frame-builders or binders, such as *Archaeolithoporella,* and were then cemented over by acicular cements. The flat terminations of crystals or pseudomorphs of the crystals suggests that they were originally aragonite.

Radiaxial calcite cements are very common in the Permian reefs in Ziyun. Radiaxial calcite is characterized by an arrangement of distally convergent optic axes within the subcrystals and corresponding curvature to cleavage (fig. 18.4), as was schematically shown by Kendall (1985, fig. 1). Kendall (1985) reviewed the previous hypothesis of radiaxial cement developing by replacement of acicular

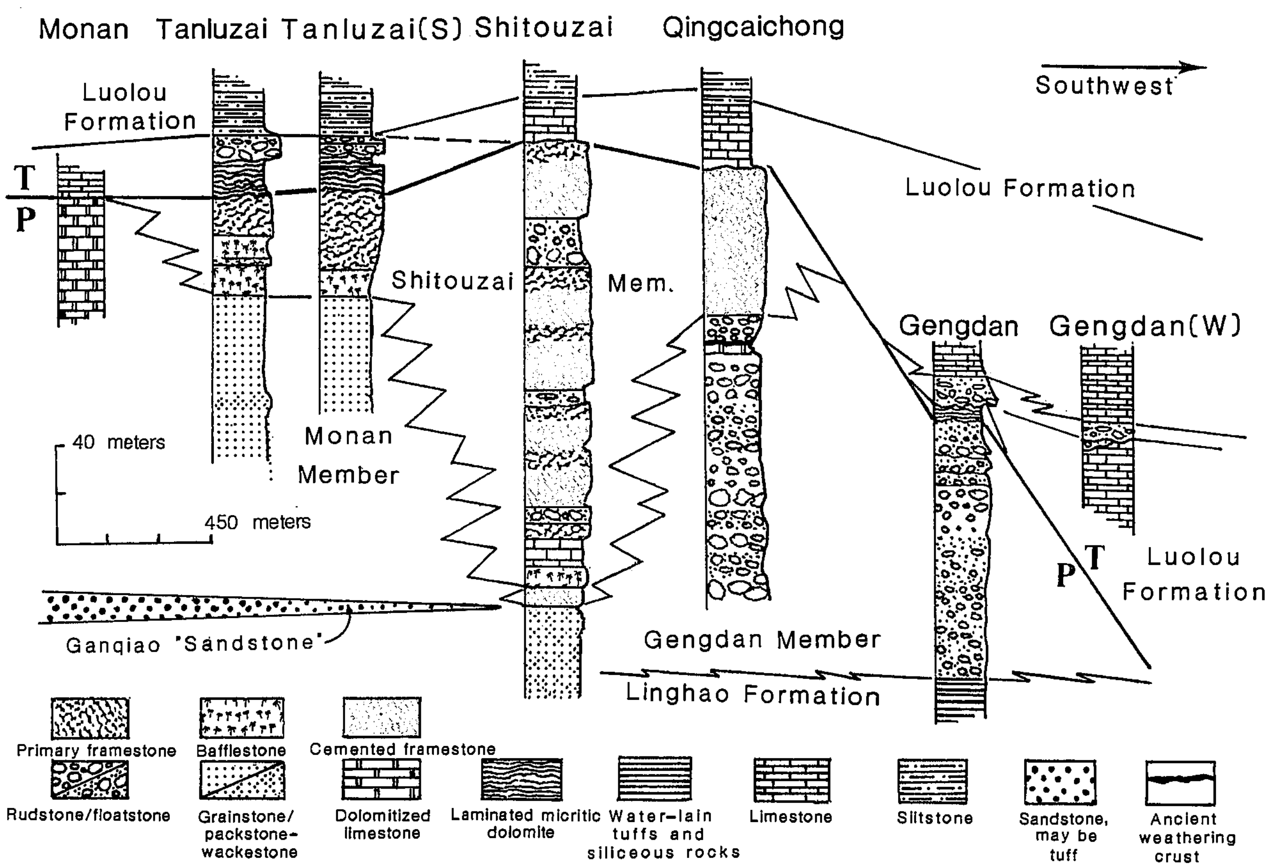


FIGURE 13.—*Measured stratigraphic sections showing facies and rock types in the Changxingian reef complex near Ziyun.*

cements and concluded that radiaxial cements were primarily Mg-calcite cements. The radiaxial calcite cements in the Permian reefs in Ziyun fully support Kendall's conclusion by having well-preserved rhombic terminations of crystals in a cavity subsequently filled by vadose silts (fig. 18.4). Fragments of crusts of radiaxial cements preserved as interclasts suggest that the crusts were formed in the marine phreatic realm.

Blocky calcite cements are characterized by equant white calcite that is clear in thin sections (fig. 18.1, 18.3). This kind of cement apparently formed during later diagenesis.

Two types of internal deposits can be distinguished in the Ziyun reefs. The first one is characterized by bioclasts of smaller foraminifers, fusulinids, calcareous algae, and micrite. This type of internal deposit accumulated immediately following encrustation by an organism, peloidal micritic crust, and acicular calcite cements.

The second type of deposit is represented by dark silty materials, rarely accompanied by any bioclasts. These internal deposits usually occur in pores rimmed by radiaxial calcite cements. This kind of internal deposit resembles and may be vadose silt, or some fills may be of primary silt-size debris.

Cemented framestone within the reef facies consists of angular fragments and boulders of various framestones that accumulated on the reef and were syndepositionally cemented by radiaxial calcite cements (fig. 18.3). Radiaxial cement is the fundamental constituent in forming the cemented framestones. These cements are usually dark, multiple-layered crusts, tens of millimeters thick, and are unevenly distributed in outcrops.

This kind of framestone occurs in the seaward parts of reef-core facies and may be explained as products of erosion by periodically intense storm waves, which broke up the contemporaneous framestone. Some of the boulders and breccia fragments remained essentially in place. These fragments accumulated in great quantities in intergranular pores and in large sheltered cavities that were relatively isolated from the seawater–sediment interface. Energetic water circulation through the intergranular cavities brought sufficient supersaturated solutions and provided enough Ca^{2+} and CO_3^{2-} to form the radiaxial calcite cements. In this process the broken boulders and angular fragments were soon lithified by rapid cementation by the radiaxial calcite cements. Such cemented framestones might be broken and cemented again if they were subsequently exposed.

A difference between cemented framestones within the reef and fore-reef talus is that the clasts in cemented framestone were poorly sorted and composed only of framestone. Matrix is volumetrically unimportant. Fore-reef talus deposits usually have variable amounts of matrix, and marine cements are rare in them.

Bafflestone in the reef facies was usually formed by branching sponges that trapped fine sediments, usually bioclasts and micrite (fig. 19.3). These rocks mostly developed in the leeward part of the reef-core facies, adjacent to and interfingering with back-reef bioclastic sand deposits. Bafflestone also may form a preliminary stage in reef development. Encrusting organisms are rare, and submarine cements are not developed.

Rudstone and floatstone have been found interbedded with framestones and cemented framestones in reef-core facies, especially in the seaward part. Rudstones consist of fragments of framestone, fragments of frame-builders and encrusters (crusts of *Archaeolithoporella*), and marine cements (mostly blocks of peloids), all of which are grain-supported. Floatstones consist of angular fragments in fine matrix, mainly bioclasts and intraclasts.

Grainstones and packstones were formed of sand-size bioclasts and intraclasts of various fabrics of the reef-core facies. These rock types are usually irregularly distributed in the reef-core facies. They might represent channel deposits or cavity fills.

Several neptunian dikes have been observed in the reef-core facies. These dikes are several centimeters to tens of centimeters wide and extend both vertically and obliquely. Most of the dikes consist of micrites without any fossils and resemble the overlying or laterally deposited lower Triassic deposits. Ages of the dikes are uncertain. They could be contemporaneous and Permian or slightly later and Triassic.

Foreslope Facies

The foreslope facies is exposed near Qingcaichong (fig. 4) and Gengdan and is represented by the Gengdan Member of the Mobo Formation (figs. 5, 13).

The proximal subfacies is represented by the lower and middle parts of the section at Qingcaichong. This subfacies is composed of rudstones and floatstones in which boulders of framestone and skeletal pack-grainstone range up to tens of centimeters in diameter. Marine cements are rare in this subfacies, and spaces between coarse clusters are filled with finer matrix.

An ancient weathered crust has been identified in the middle part of the section. It is about 1.5 m thick and caps the upper micritic dolomite, which is about 2 m thick. A paleosol and boulders of the underlying rock were found in the Ziyun area.

Distal foreslope talus deposits are exposed in outcrops northwest of Gendan and are characterized by rudstones and floatstones in which breccia fragments are smaller than those in the proximal subfacies (figs. 19.1, 19.2). Graded bedding and associated depositional erosion surfaces are locally developed (figs. 19.4, 19.5). Rudstones and floatstones consist of angular fragments and boulders of framestone, fragments of *Archaeolithoporella* crusts, blocks of peloidal micritic cement, and parts of large framebuilders, such as sponges. Foraminifers, brachiopods, calcareous algae (fig. 7), and *Tubiphytes* are also common and appear as transported debris. Packstones are also important constituents of the subfacies.

Back-Reef Bioclastic Sand Facies

This facies is mainly exposed from Tanluzai to Huadizai in the northeastern part of the study area (fig. 4). These rocks are included in the Monan Member of the Mobo Formation (fig. 5) and are mainly bioclastic packstones-grainstones. Predominant organisms include calcareous algae, such as *Gymnocodium, Permocalculus, Mizzia,* and *Pseudovermiporella* (fig. 7), smaller foraminifers, fusulinids, including *Palaeofusulina, Nankinella,* and *Reichelina,* and *Tubiphytes.* Sporadic sponges, hydrozoans, and rugose corals also occur. Most fossils have been transported and broken, but all are essentially in place. They clearly characterize the facies.

In the upper part of the Tanluzai section, conglomerate lenses interfinger with the Shitouzai Member. These conglomerates consist of rounded fragments of pack-wackestones and framestone/bafflestone, and they have fibrous calcite cements. Multiple generations of vadose silts also can be observed in them (fig. 20). These indicate that the back-reef bioclastic sand facies was formed in shallow-water environments, probably in the upper subtidal to intertidal zone.

Carbonate Platform Facies

This facies occurs north of Huadizai and northeast of the study area. The facies is characterized by medium- to thick-bedded, dark, cherty mud-wackestones that contain a biota mainly composed of foraminifers and calcareous algae.

Deepwater Trough or Basin Facies

This facies is represented by rocks in the upper part of the Linghao Formation, which occurs in the southern part of the study area. Volcanic tuffs and siliceous rocks that contain great quantities of siliceous sponge spicules and conspicuous radiolarians are included here. Interbedded packstone and floatstone, with an Upper Permian biota, have been found in the formation near Liaoqing, a locality about 1 km southwest of the town of Ziyun County.

EROSION SURFACES

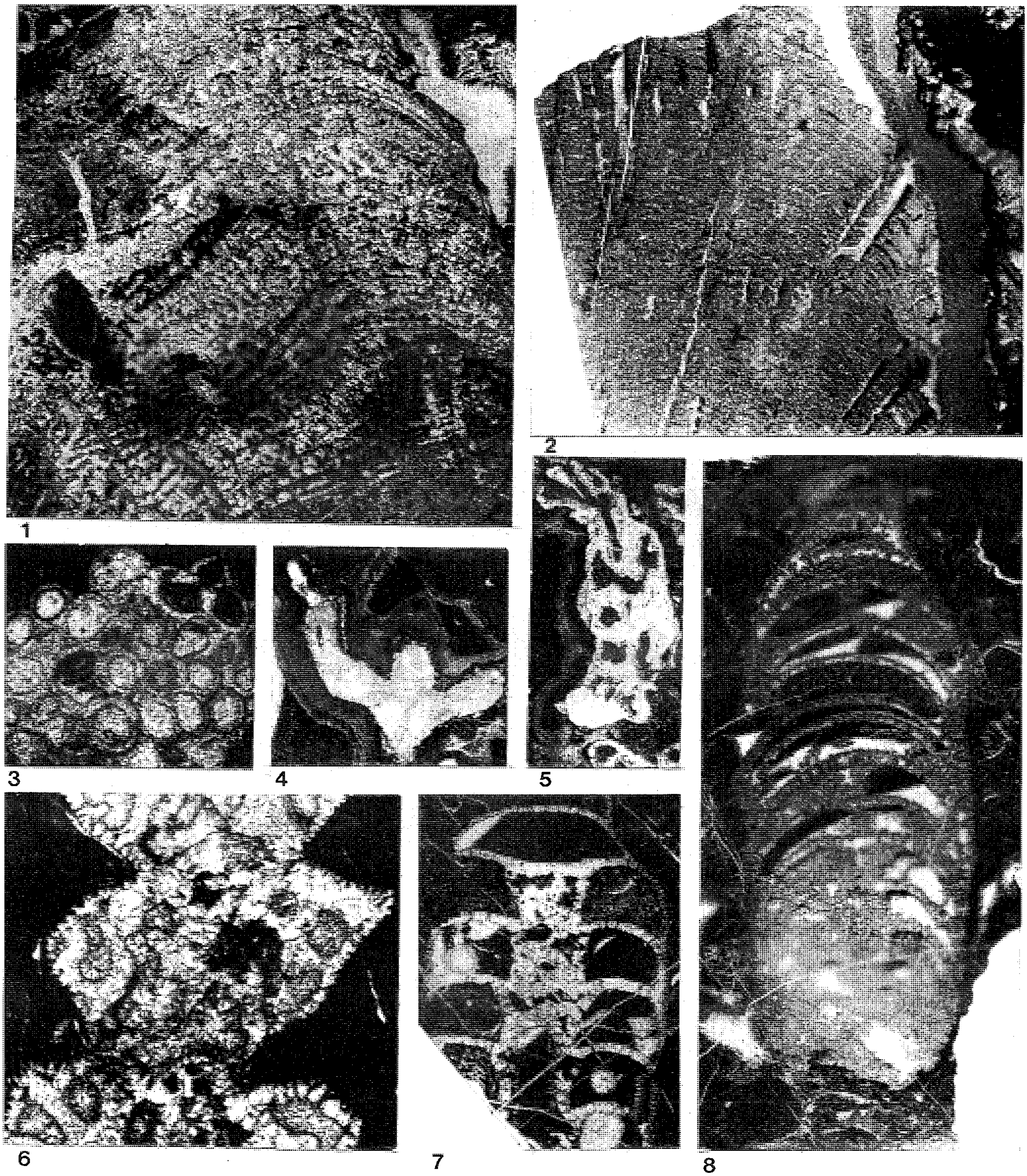
The most typical and best developed erosional surface is at the top of the reef-core and serves as the boundary between Permian and Triassic formations. The surface is undulating to irregularly uneven, and numerous fragments and boulders accumulated in depressions on the surface. In one spot in the village of Tunshang, the reef rocks were broken and the fissures were filled by fibrous calcite cements and vadose silts. Ancient weathering crust and discontinuous wavy surfaces, accompanied by laminated micritic dolomite, can be observed in the interior parts of the reef-core facies.

DEVELOPMENT OF THE PERMIAN REEFS OF ZIYUN

The Permian reefs in Ziyun are situated at the margin of a carbonate platform. Development of these reefs can be divided into two stages (fig. 21).

The first stage occurred in late Maokouan, in the fusulinid zone of *Neoschwagerina,* and perhaps lasted into the *Yabeina* zone. During late Qixian through Early Maokouan, a fusulinid shoal facies developed along the margin of the carbonate platform, northeast of and laterally from a basin facies made up of micritic limestone (Wulibei Limestone). Reef-building organisms, such as sponges and hydrozoans, started to colonize the shoal in the late Maokouan. These pioneering frameworks were

FIGURE 14.—*Reef-building organisms of the Changxingian reef complex.* 1, *Vertical section of a large sphinctozoan sponge, thin section, QCC 5B, Gengdan Member, X1.5.* 2, *Vertical section of a sponge(?), thin section of a breccia in laminated dolomite in the Triassic Luolou Formation directly capping the Permian Gengdan Member, GD11-2B, X1.5.* 3, *A sphinctozoan sponge with recrystallized calcite skeleton, photomicrograph, STZ-10, Shitouzai Member, X16.* 4, *Branching inozoan sponge, thin section, STZ, Shitouzai Member, X1.5.* 5, Glomocystocoelia, *thin section, STZ, Shitouzai Member, X1.5.* 6, *A sphinctozoan sponge, photomicrograph, thin section, STZ20-3(1), Shitouzai Member, X16.* 7, Amblysiphonella, *thin section, GD6-3, Gengdan Member, X2.* 8, Intrasporeocoelia, *thin section, STZ, Shitouzai Member, X1.5.*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broken by strong storm waves and are now largely preserved as breccias cemented by radiaxial fibrous calcite cements. A period of exposure in late Maokouan time terminated development of the reef and subjected the formation to erosion and weathering. A weathering crust developed atop the Maokou Formation and on the top of the reef (Ziyundong Limestone Member). Rocks of the *Yabeina* and *Neomisellina* zones, the two fusulinid zones widespread in South China (fig. 3), are missing here and give a measure of the lengths of time of exposure at the crust surface. This erosional break may be attributed to regional uplift in South China, which took place between late Maokouan and early Wujiapingian deposition.

During the early Wujiapingian, numerous coral biostromes formed on the margin of carbonate platform, at the same time that waterlain tuffs and interbedded siliceous spicular rocks of the Linghao Formation accumulated in basin environments. Several units of intraclast packstones and floatstones, several meters thick, were intercalated in the volcanic-siliceous deposits near the margin of the platform. During this stage, the sea was deeper and activities of volcanos prevented development of reef frameworks. Several beds of silty rocks, only tens of centimeters to 1.5 m thick and too thin to be shown on figure 21, were intercalated with limestone on the margin of the platform and restricted sedimentation of carbonate deposits. In the upper Wujiapingian, a bed of mud rock, 1.5 m thick, extended to the north and thickened to tens of meters thick. It was formerly named the Ganqiao Sandstone (Wang and others 1959). However, this bed contains great quantities of dark minerals, such as chlorite and altered biotite, and had a volcanic origin. Abundant pyrite crystals and nodules were also included in the unit. This implies that the bed was likely formed by volcanic materials and can serve as time datum for correlation. The brachiopod *Squamularia* accumulated in packed layers in these rocks.

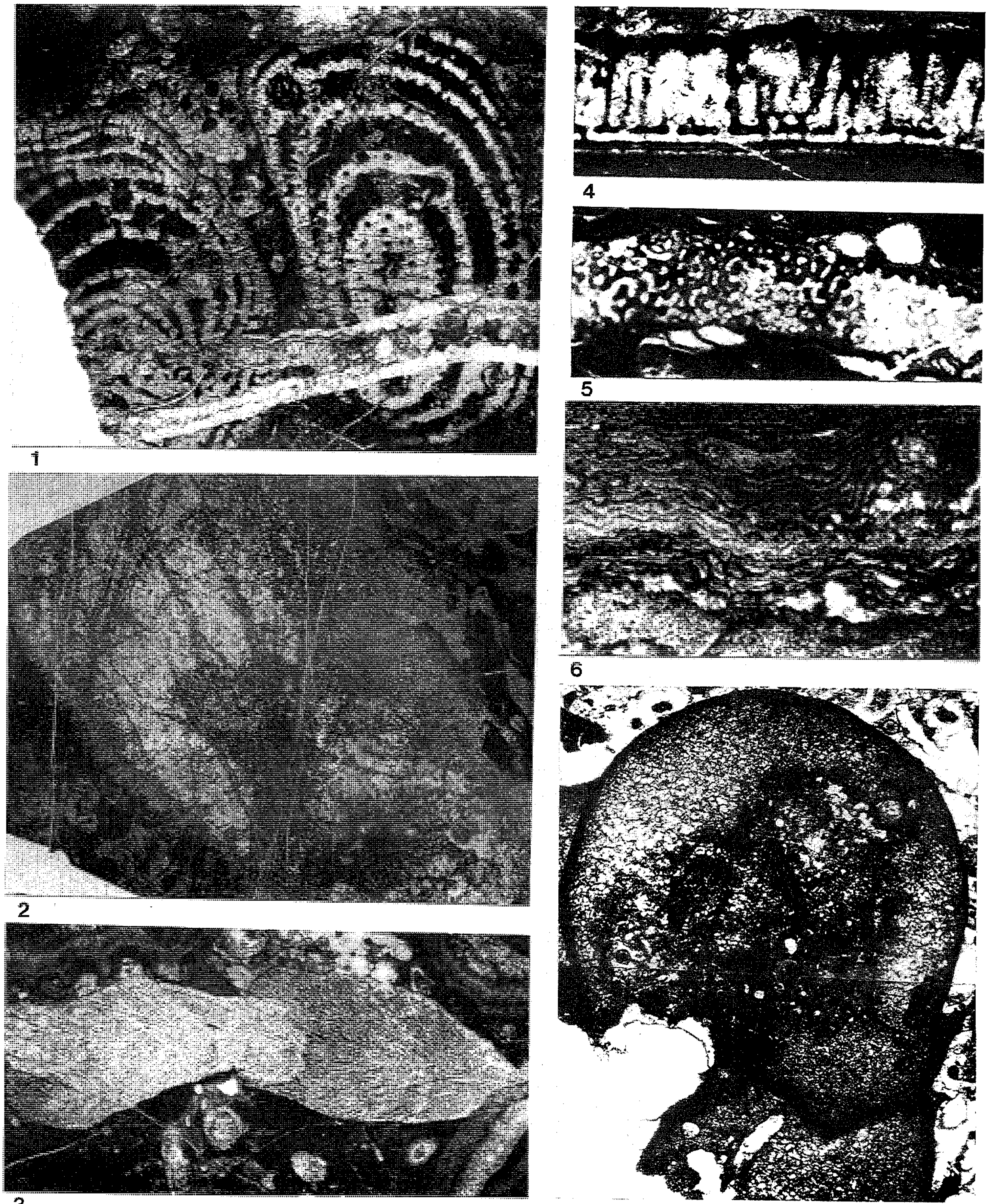
The second stage of reef development occurred during uppermost Wujiapingian and Changxingian time (fig. 3). A crinoidal shoal served as the base of the reefs. Facies differentiation is distinct and cyclic development is typical. During reef growth, periodic subaerial exposure was common, i.e., ancient weathering crusts have been observed. Multiple generations of vadose silts and dissolution voids filled with calcite cements also document several times of exposure.

By the end of Changxingian time, part of the carbonate platform was emergent and became an island. The top of the Mobo Formation is irregular because of Permian erosion. This island existed from the latest Changxingian through the Griesbachian of the Early Triassic. This led to a disconformity between the Permian and Triassic rocks on the carbonate platform. It is postulated that Permian and Triassic sedimentation was continuous in the basin facies.

TRIASSIC HISTORY

The Lower Triassic facies differentiation atop the Changxingian reef clearly outlines the paleotopography of the reef. During the Griesbachian, carbonate sedimentation was restricted to the trough environment where rocks of the Luolou Formation accumulated. In the late Griesbachian, however, a transgression began, and typical arid tidal flat deposits accumulated around the island. The deposits are characteristically supratidal laminated micritic dolomite (figs. 22.1, 22.5) that contain pseudomorphs of anhydrite crystals (fig. 22.4). Coarse fragments are locally preserved in it (figs. 22.2, 22.7). The biota of the thick dolomite consists mainly of bivalves and ammonoids (figs. 22.3, 22.6). The bivalves are mainly *Claraia aurita,* which has a chronostratigraphic range from Upper Griesbachian to Dienerian. In the back-reef platform area, extensive intertidal deposits of platy pebble conglomerate accumulated. These tidal flat deposits in the Ziyun area are like those of a sabkha environment and appear to record the great change of paleoclimates between the Permian and Triassic.

FIGURE 15.—*Reef-building organisms of the Changxingian reef complex, from the Mobo Formation.* 1, Intrasporoecoelia, *thin section, GD, Gengdan Member, X1.5.* 2, Tabulozoa, *thin section, TLZ11-2B, Shitouzai Member, X1.5.* 3, Disjectopora, *thin section, STZ17-2-2, Shitouzai Member, X1.5.* 4, *Vertical section of* "Phragmorpha," *photomicrograph, STZ10, Shitouzai Member, X16.* 5, *Platy* Pseudopalaeoaplysina, *photomicrograph, STZ10-2, Shitouzai Member, X16.* 6, *Laminae of* Archaeolithoporella; *the structure in lower part is well preserved, but the structure in the upper part was destroyed and produced dark-light doublets, photomicrograph, S-5, Shitouzai Member, X16.* 7, Tubiphytes, *the skeletal meshwork is well preserved, photomicrograph, STZ24-2, Shitouzai Member, X16.*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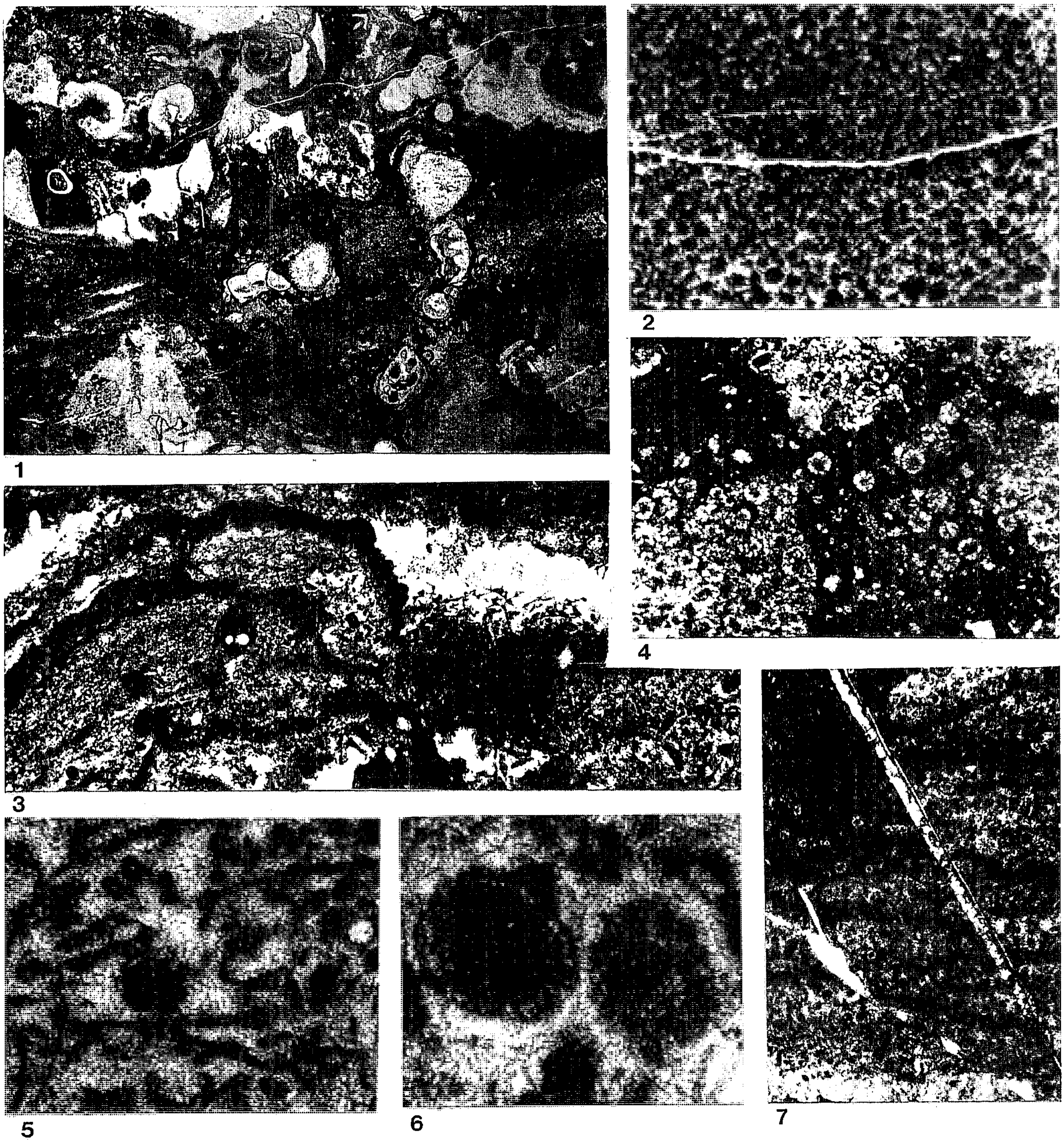


FIGURE 16.—*Framestones of the Changxingian reef complex.* 1, *Framestone formed by small sponges and* Archaeolithoporella *crusts cemented by peloidal micrites. Thin section, STZ21-2, Shitouzai Member, X1.5.* 2, *Peloidal texture, photomicrograph, STZ10-2A, X16.* 3, *Columnar or moundlike structure of peloidal textures; bioclasts were enclosed; spicule-shaped objects occur in the right, photomicrograph, STZ21-2, Shitouzai Member, X16.* 4, *Breccias of peloidal aggregates, bimodal nature of the peloids is characteristic, photomicrograph, STZ10-2A, Shitouzai Member, X16.* 5, *Spicule-shaped objects or borings in peloidal micrite, photomicrograph, ZY1-3, Linghao Formation, x36.* 6, *Bimodal sizes of peloids, photomicrograph, TLZ11-2(2), Shitouzai Member, X60.* 7, *Laminated peloidal textures, photomicrographs, GD4-1, in a fragment, Gengdan Member, X16.*

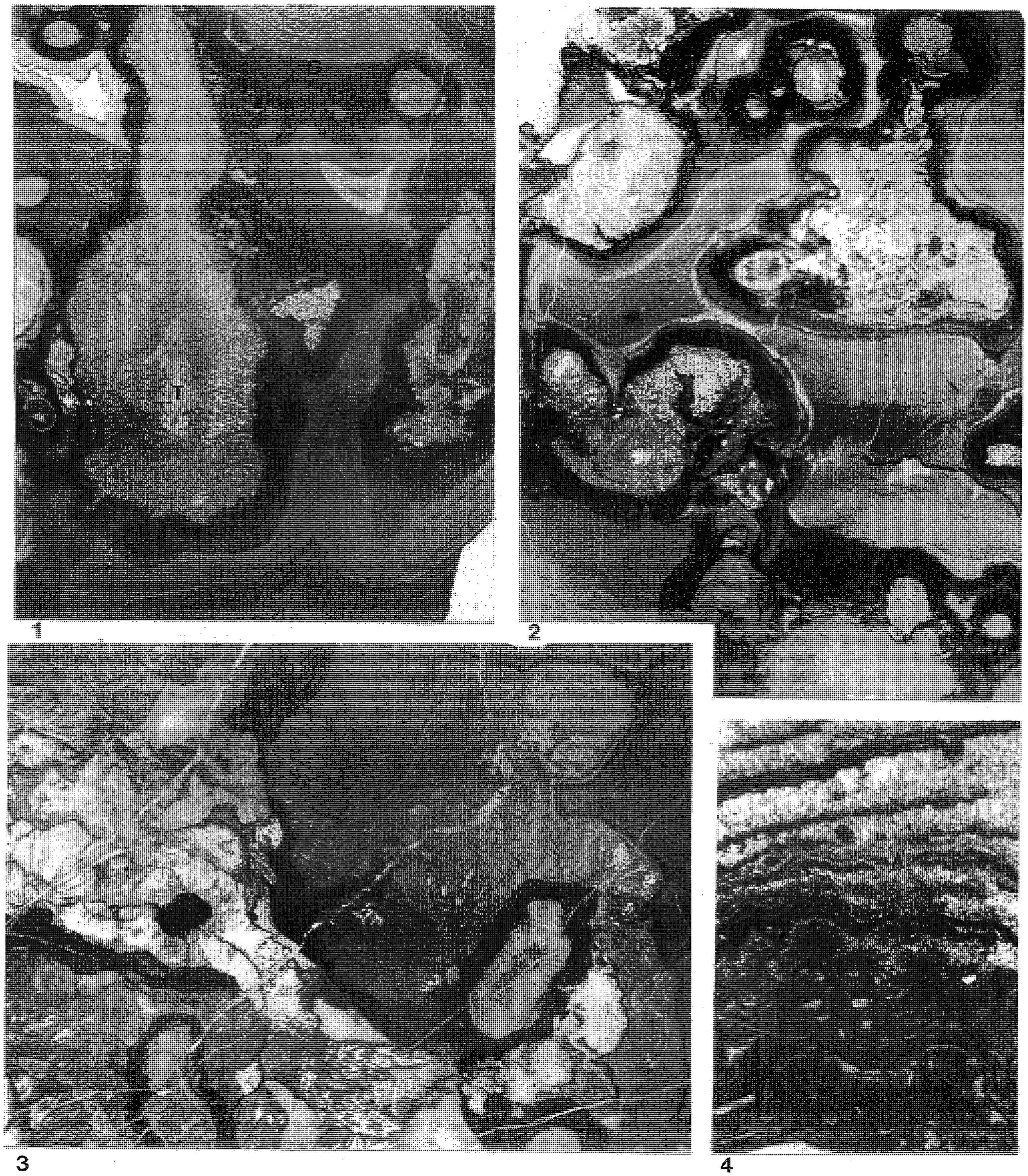


FIGURE 17.—*Framestones of the Changxingian reef complex, from the Mobo Formation. 1, Framestone composed of tabulozoans (T) and* Archaeolithoporella *(A); multiple-layered acicular cements are well developed; geopetal fabrics (G) occur in the upper part, thin section, TLZ, Shitouzai Member, X1.5. 2, Framestone made up of light sponges and dark* Archaeolithoporella*; isopachous acicular cements rim the frame pores; internal silty deposits fill the remaining cavities, thin section, S-5, Shitouzai Member, X1.5. 3, Botryoidal fabrics in large cavities of a framestone, thin section, TLZS3-1, Shitouzai Member, X1.5. 4, Alternating layer of isopachous acicular calcites and laminae of* Archaeolithoporella *(A), photomicrographs, thin section, S-5, Shitouzai Member, X24.*

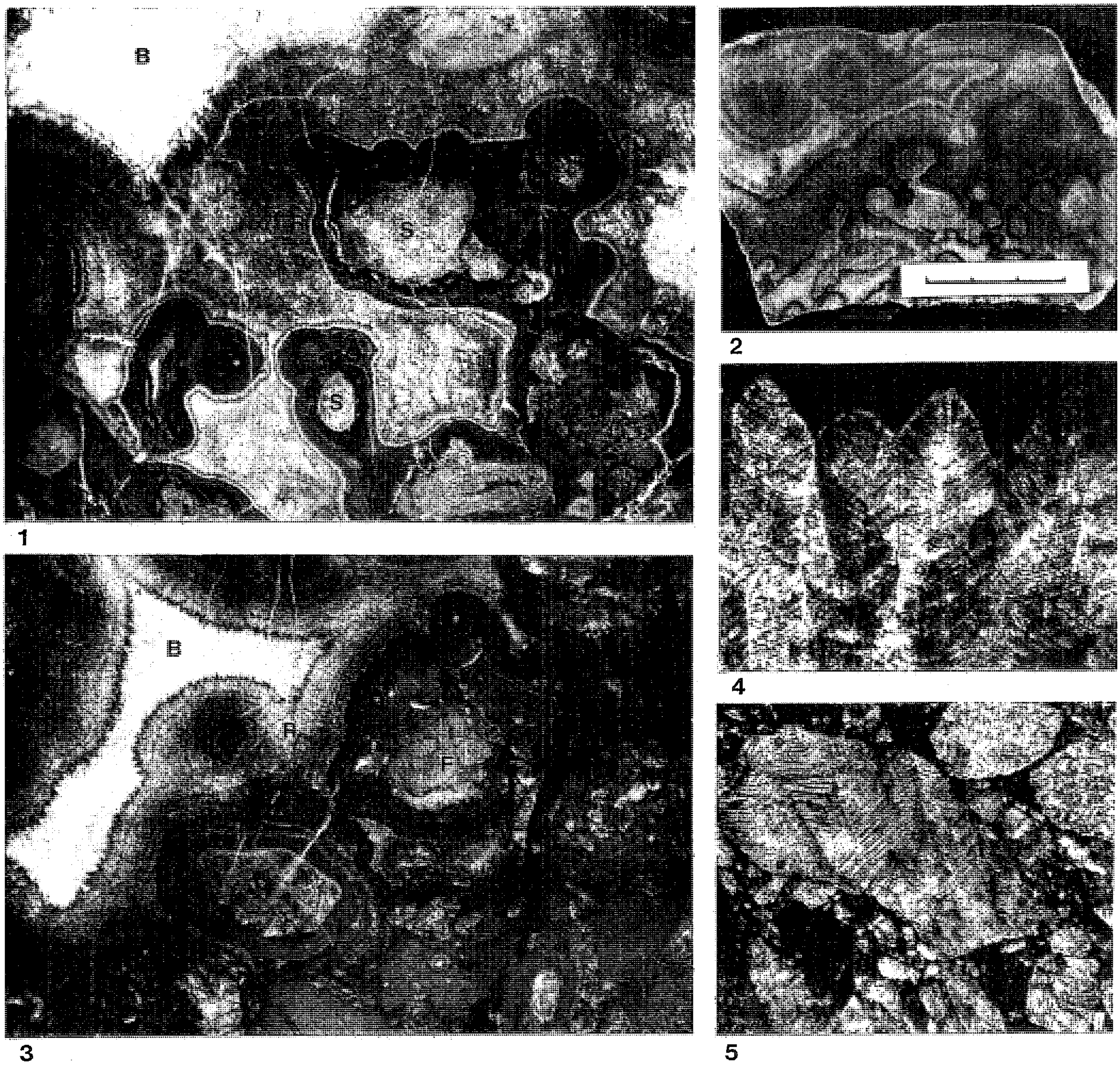


FIGURE 18.—*Framestone of the Changxingian reef complex, Mobo Formation. 1, Framestone composed of sponges (S) encrusted by* Archaeolithoporella *(A) and cemented by radiaxial fibrous cement (R); the blocky calcites (B) are the latest cements, thin section, QCC-A, Shitouzai Member, X1.5. 2, Polished slab showing well-developed radiaxial fibrous calcite cements in a framestone; cement distribution reflects the extensive primary cavities in the framework, STZ15-3, Shitouzai Member, scale bar in centimeters. 3, Cemented framestone composed of broken pieces of second-cycle primary framestone (F), which are cemented by radiaxial fibrous calcite cements (R) and blocky calcite (B), thin section, STZ9, Shitouzai Member, X1.5. 4, Crystals of radiaxial fibrous calcite with rhombic terminations and curvature of cleavage, photomicrograph, Q-1, Shitouzai Member, X16. 5, Fragments of radiaxial fibrous calcite as intraclasts, photomicrograph, thin section, STZ15-2, Shitouzai Member, X16.*

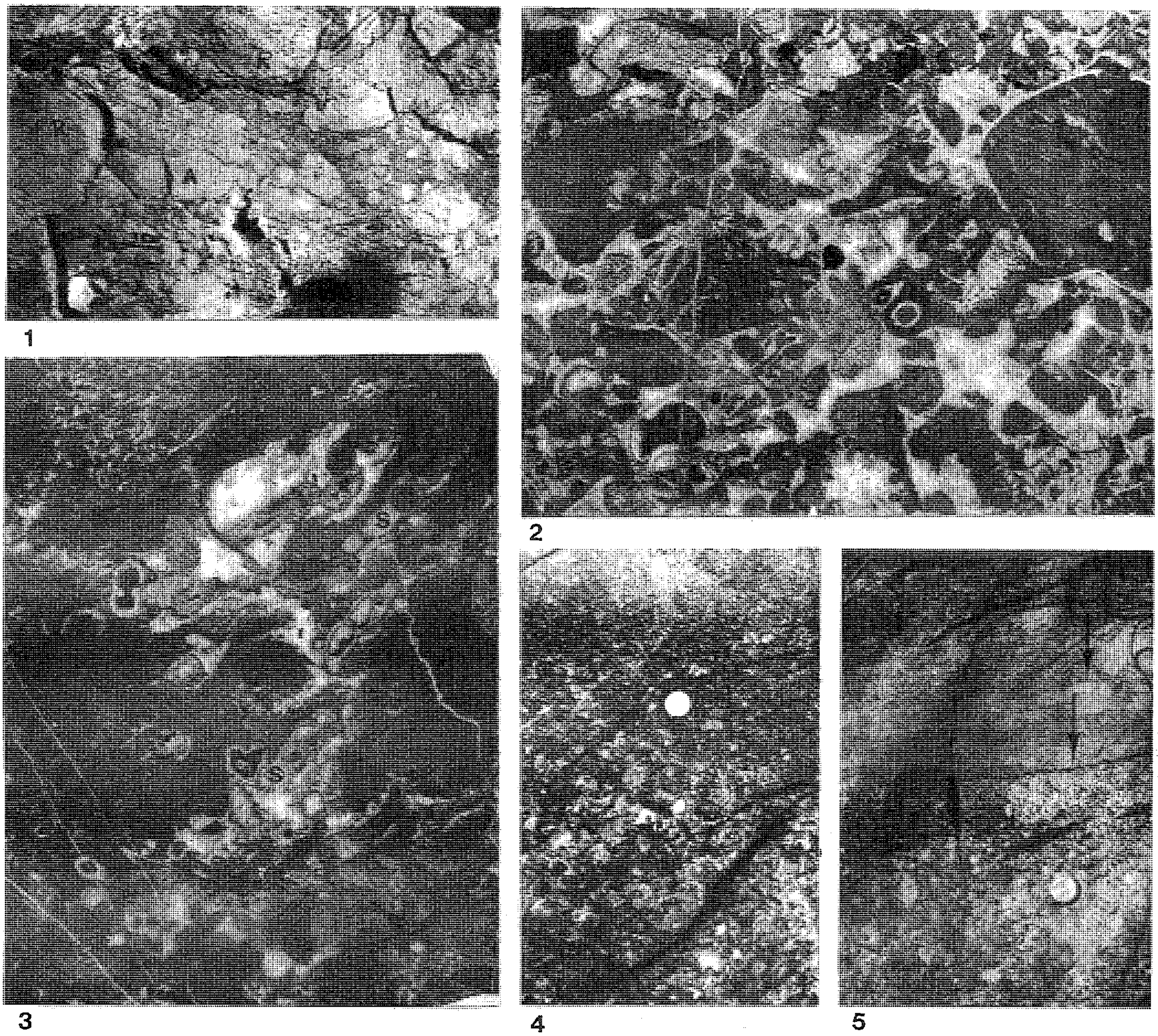


FIGURE 19.—1, *Rudstone (R) of reefal limestone and algal bioclastic pack-grainstone (A), outcrop of the Gengdan Member, scale at lower left.* 2, *Rudstone of the fore-reef facies, thin section, GD9-1, Gengdan Member, X1.5.* 3, *Bafflestone composed of the beadlike sphinctozoan* Sollasia *(S) and fine bioclasts, thin section, STZA7-1, Shitouzai Member, X1.5.* 4, *Graded bedding in rudstone outcrop, Gengdan Member at Gengdan.* 5, *Graded beds separated by erosional surfaces (arrows), outcrop of the Gengdan Member at Gengdan. All are from the Mobo Formation.*

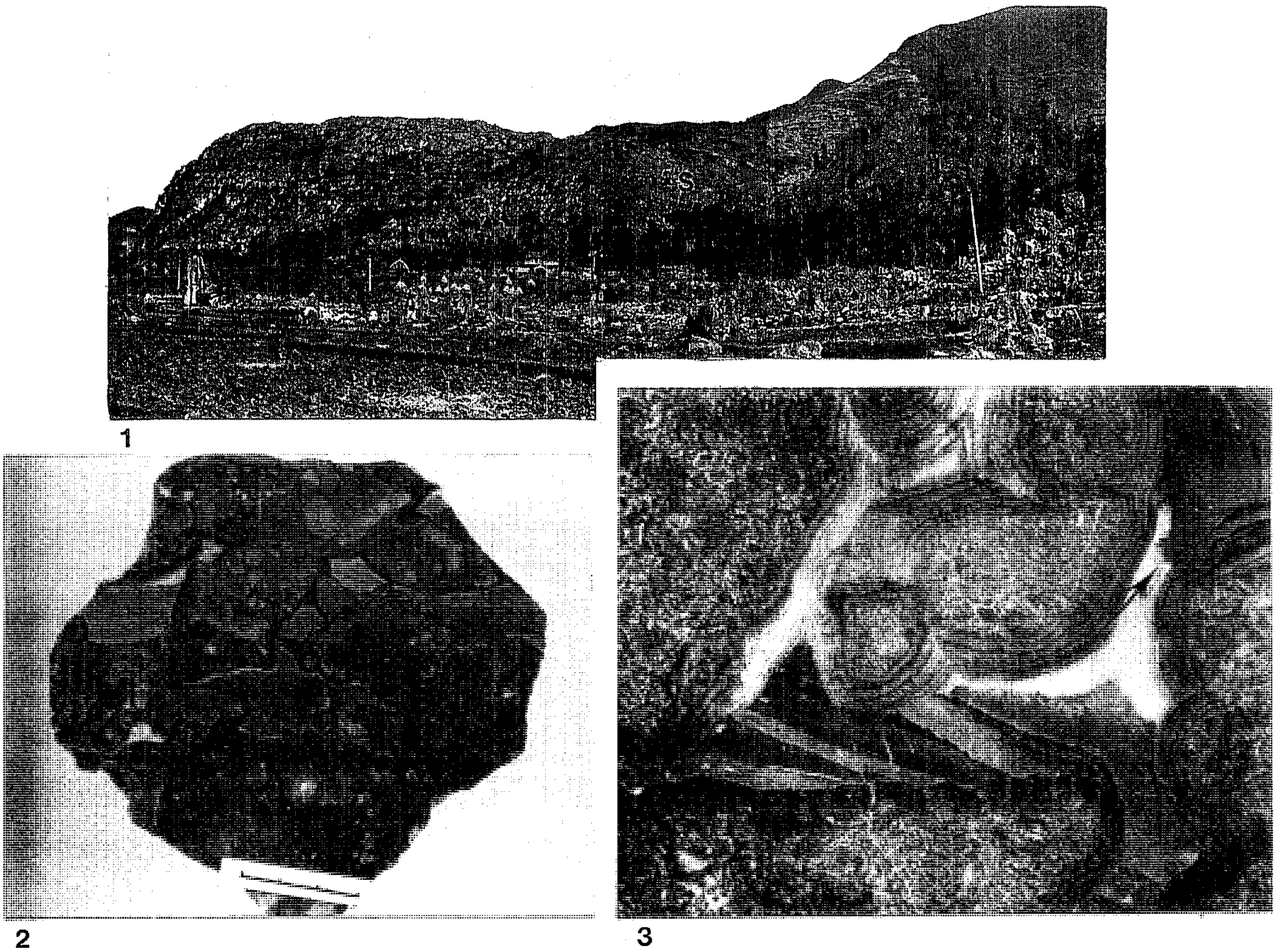


FIGURE 20.—1, *View of the contact of the bedded back-reef bioclastic sand deposits of the Monan Member (M) on the left, and the massive reef-core facies of the Shitouzai Member (S) on the right, near the small village of Tanluzai.* 2, *Conglomerate composed of angular fragments of reefal limestone; intergranular cavities were filled by radiaxial fibrous calcite cements and laminated internal deposits, polished slab, TLZ-10, scale bar in centimeters.* 3, *Conglomerate consists of rounded fragments of bioclastic grainstone; intergranular cavities were filled by radiaxial fibrous cement, blocky calcite, and multiple generations of vadose silts; arrow points upward, thin section, TLZ11-3, Monan Member, X1.5.*

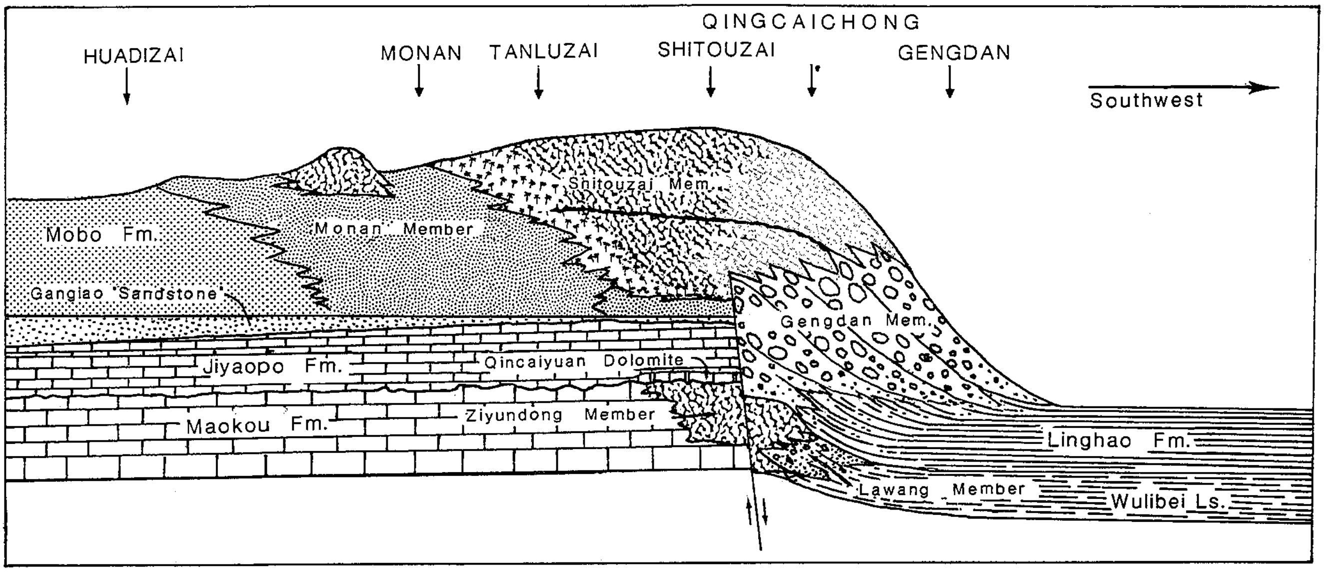


FIGURE 21.—*Depositional model and stratigraphic nomenclature of the Permian reef complex in Ziyun.*

CONCLUSIONS

1. The Permian reefs in Ziyun include barrier reefs and patch reefs. Biostromes also occur.

2. The reefs developed in Middle Permian Maokouan and later Upper Permian Changxingian times. The Changxingian reefs are best developed and best preserved.

3. Biostromes of dendritic corals developed during lower Upper Permian Wujiapingian deposition.

4. The barrier reefs can be compared to the Holocene reefs, both in structure and texture, and especially the various submarine cements seem to be analogues of modern counterparts.

5. Both lithofacies and biofacies differentiation of the reefs, especially the Changxingian reefs, is distinct. Well-defined basin facies, foreslope facies, reef-core facies, back-reef sand facies, and carbonate platform facies all occur within distances of less than 6 km in the Ziyun area.

6. The major frame-building organisms include calcisponges and hydrozoans; *Tubiphytes* and bryozoans are minor frame-builders. *Archaeolithoporella* is extremely well and widely developed. It was an effective binder and formed crusts on the frame-builders to help produce rigid wave-resistant frameworks; the overall biota is similar to those of Permian reefs in other parts of Guizhou and Guangxi Provinces.

7. The Changxingian reef terminated at the end of the Permian. These reefs in South China are among the latest known Paleozoic reefs in the world. Extinction of Paleozoic reef biotas essentially coincides with mass extinction of organisms, documented by others worldwide, near the boundary between the Permian and Triassic.

8. A change of paleoclimate between the Permian and Triassic is postulated for the Ziyun area, based on accumulation of Triassic arid tidal flat deposits.

ACKNOWLEDGMENTS

Zhao Jiaming, Chen Chuzhen, Mu Xinan, Zhang Linxin, Wan Yujing, and He Guoxiong from the Nanjing Institute of Geology and Paleontology, Academia Sinica, helped to identify the corals, bivalves, calcareous algae, fusulinids, and ammonoids, respectively. Zhu Xiufang, from the Chinese Academy of Geological Sciences, also helped to check identifications of part of the fusulinids. Zhang Shouxin, Sha Qingan, Yin Jixiang, Wu Haoruo, and Wang Yao from the Institute of Geology, Academia Sinica, have provided beneficial discussions during the project and during manuscript preparation. The fieldwork was conducted with Wu Yasheng of the Institute of Geology. Thin sections were cut by Su Zhizhen and Zheng Yushan of the Institute of Geology, State Bureau of Seismology. Zhang Yaguang of the Institute of Geology printed the photographs. L. T. Bird of Brigham Young University helped in editing and final manuscript and illustration preparation. J. A. Fagerstrom and D. F. Toomey provided helpful critical reviews of the manuscript and illustrations.

REFERENCES CITED

Embry, A. F., and Klovan, J. E., 1971, A late Devonian reef tract on northeastern Banks Island, N. W. T. (Canada): Bulletin of Canadian Petroleum Geology, v. 19, p. 730–81.

Endo, 1959, Stratigraphical and paleontological studies of the Later Paleozoic calcareous algae in Japan, XIV: Fossil algae from the Nyugawa Valley in the Hida Massif: Saitama University, Scientific Reports, Series B, v. 3, p. 177–207.

Fan Jiasong and Qi Jingwen, 1990, The Permian reefs in Longlin County, Guangxi: Geology Press, Beijing, 118p.

Fan Jiasong, Rigby, J. K., and Qi Jingwen, 1990, The Permian reefs of South China and comparisons with the Permian reef complex of the Guadalupe Mountains, West Texas and New Mexico: Brigham Young University Geology Studies, v. 36, p. 15–55.

Fan Jiasong, Rigby, J. K., and Zhang Wei, 1991, "Hydrozoa" from Middle and Upper Permian reefs of South China: Journal of Paleontology, v. 65, p. 45–68.

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

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.

Guo, L., and Riding, R., 1992, Microbial micritic carbonates in uppermost Permian reefs, Sichuan Basin, southern China: Some similarities with recent travertines: Sedimentology, v. 39, no. 1, p. 37–53.

Kendall, A. C., 1985, Radiaxial fibrous calcite: a reappraisal: In Schneidermann, N., and Harris, P. M. (eds.), Carbonate cements: Society of Economic Paleontologists and Mineralogists, Special Publication No. 36, p. 59–77.

Lighty, R. G., 1985, Preservation of internal reef porosity and diagenetic sealing of submerged early Holocene barrier reef, southeastern Florida shelf: In Schneiderman, N., and Harris, P. M. (eds.), Carbonate cements: Society of Economic Paleontologists and Mineralogists, Special Publication No. 36, p. 123–51.

Lin Qixiang, 1992, Nature and evolution of Late Permian reefs in Ziyun, Guizhou Province: Earth Science, v. 17, no. 3, p. 301–07.

Luo Zhili, Jin Yizhong, and Zhao Xikui, 1990, The Emei Taphrogenesis in the Upper Yangtze Platform: Geological Magazine, v. 127, no. 5, p. 393–405.

MacIntyre, I. G., 1977, Distribution of submarine cements in a modern Caribbean fringing reef, Galeta Point, Panama: Journal of Sedimentary Petrology, v. 47, p. 503–16.

Marshall, J. F., 1986, Regional distribution of submarine cements within an epicontinental reef system: Central Great Barrier Reef, Australia: In Schroeder, J. H., and Purser, B. H. (eds.), Reef diagenesis: Springer Verlag, Berlin and Heidelberg, p. 8–26.

Riding, R., and Guo, L., 1992, Affinity of *Tubiphytes:* Palaeontology, v. 34, p. 37–49.

Riding, R., Martin, M., and Braga, J. C., 1991, Coral-stromatolite reef framework, Upper Miocene, Almeria, Spain: Sedimentology, v. 38, no. 5, p. 799–818.

Rigby, J. K., Fan Jiasong, and Zhang Wei, 1989a, Sphinctozoan sponges from the Permian reefs of South China: Journal of Paleontology, v. 63, no. 4, p. 404–39.

________, 1989b, Inozoan calcareous Porifera from the Permian reefs in South China: Journal of Paleontology, v. 63, no. 6, p. 778–800.

Sha Qingan, Wu Wangshi, and Fu Jiamo, 1990, Comprehensive research of the Permian in Guangxi and Guizhou and its petroleum potential: Science Press, 215 p.

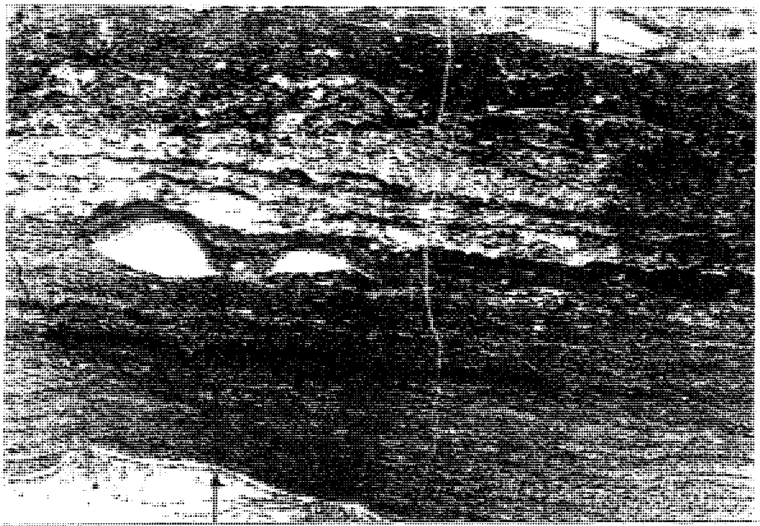
Sun, S. Q., and Wright, V. P., 1989, Peloidal fabrics in Upper Jurassic reefal limestones, Weald Basin, southern England: Sedimentary Geology, v. 65, p. 165–81.

Wang Yu, Sheng Jinzhang, Chen Chuzhen, and Lu Linhuang, 1959, Two Permian stratigraphic sections from the village of Tanbianzai, Puan County, and from the town of Zisong, Wangmo County, southern Guizhou: In A collection of papers for a field stratigraphy conference in southern Guizhou, China, All-China Stratigraphy Congress, Beijing, p. 73–91.

Yang Wanrong, 1987, A bioherm of Wujiaping Formation, Laibin, Guangxi: Oil and Gas Geology, v. 8, no. 4, p. 424–28.

Zhang Zhenghua, Wang Zhihua, and Li Changquan, 1988, A suggestion for classification of Permian of South Guizhou (in Chinese): Guizhou People's Publishing House, Guiyang, 113p.

FIGURE 22.—*Tidal flat deposits of Lower Triassic rocks capping the reef complex.* 1, *Laminated, perhaps algal mat, micritic dolomite, with thin-shelled bivalves in the lower and upper parts (arrows); supratidal flat facies, thin section, TLZ13-4, Tanluzai, Luolou Formation, X1.5.* 2, *Conglomerate consisting of fragments of laminated micritic dolomite cemented by radiaxial fibrous calcite cements, outcrop at Tanluzai, Luolou Formation.* 3, *Sample of a shell bed composed of* Claraia aurita, *subtidal facies, scale bar in centimeters.* 4, *Anhydrite pseudomorphs in micritic dolomite in the middle part; the sponge (top) was preserved in a fragment in the supratidal flat deposits, polished slab, GD11-2, Gengdan, scale bar in centimeters.* 5, *Mudcracks and broken flat pebbles of laminated micritic dolomite; the open cracks were filled with micrite, supratidal facies, thin section, GD11-2, Gengdan, X1.5.* 6, *Bed of packed bivalve shells arranged in a parallel manner, indicating reworking by marine currents, subtidal facies, photomicrograph, MN6-2, Monan, X16.* 7, *Laminated micritic dolomite fragmented by storm waves; laminated micrites were deposited in a depression beside the pebble (arrow), polished slab, TLZS, scale bar in centimeters, Luolou Formation at Tanluzai.*



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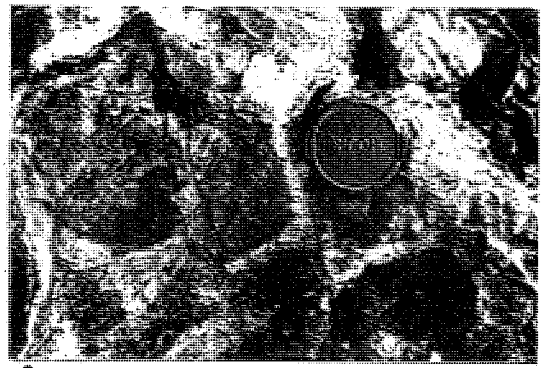

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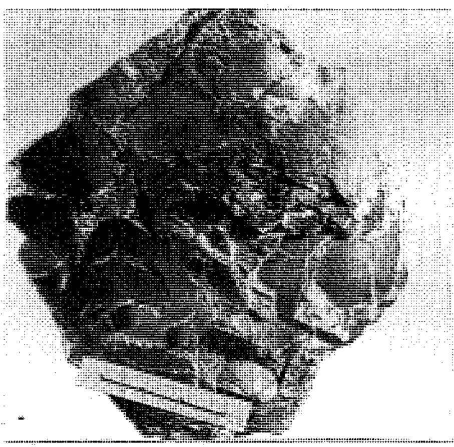

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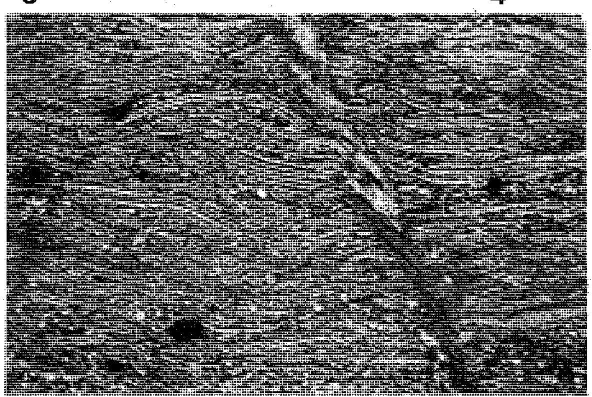

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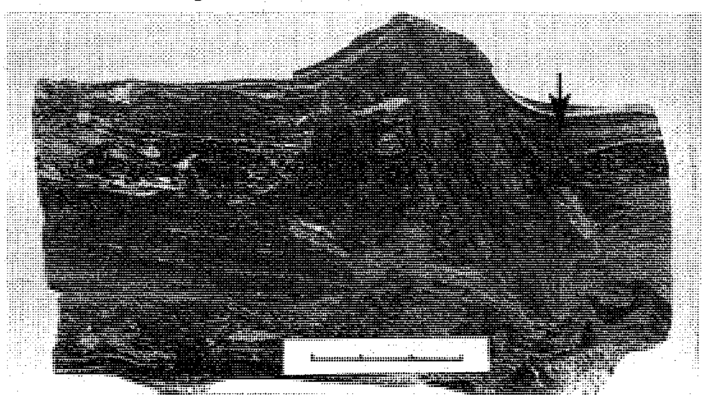

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